# ASPECTS OF THE MIDDLE AND UPPER PLEISTOCENE OF THE UPPER OUSE BASIN.

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# Abstract.

The thesis undertakes a lithostratigraphical examination of terrace and fluvioglacial gravels of the Upper Great Ouse basin, and part of the Nene basin, in order to provide a foundation for a Middle and Upper Pleistocene stratigraphy of a relatively little-researched area. Pebble-counts are used as a basis for stratigraphic interpretation following the work of Green and McGregor on the terrace gravels of the Proto-Thames.

The thesis first examines the characteristics of the study area which influence superficial deposits. This is followed by a discussion of previous research in surrounding areas so that comparisons and correlations may subsequently be made. Field and laboratory methods employed are discussed, and each site sampled is described.

The analysis of the gravel is divided into two parts. Firstly the lithological composition of each sample is ascertained. Each lithology present is described and the probable source geology discussed. Secondly the lithological composition of all samples is compared in order to determine the spatial patterns (using trend surface analysis) and the stratigraphical patterns (using cluster analysis) among the samples. The statistical tests involved are discussed and the results of the analyses are described and interpreted with particular reference to the source geology.

At Stoke Goldington, an interglacial deposit of richly-organic clay is reported which contains a wide range of fauna and flora. Associated with the clay are two separate suites of gravel. A description of the site is presented together with a preliminary report on the biological evidence.

Finally, the lithostratigraphic results, together with the biological evidence from Stoke Goldington, and evidence from the literature of the Ouse basin and surrounding areas are brought together, and a succession incorporating all the available evidence is presented. Correlations with the surrounding regions are suggested.

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# Chapter I. Introduction.

The Quaternary history of the Great Ouse basin upstream from Huntingdon has, for the most part, been ignored in recent years. The area examined (figs. 2.1; 3.1; 3.2; 5.1) lies immediately to the north of the Chalk escarpment, between Stevenage and Pitstone, and northwards toward Northampton and St. Neots. Apart from some recent work by Horton (1970) and Horton *et al.* (1974), describing the superficial deposits of part of the Ouse and Nene basins and the geology of Milton Keynes respectively, very little research has been published since the turn of the century and no useful stratigraphy has been built up. Clayton (in Straw and Clayton, 1979, p186) discusses the general morphology of the area to the south of the river Ouse, but states that

> "The development of both the Ivel and the Ouzel has not so far been studied, and the two rivers pose many problems."

The Geological Survey also do not have available either the old 1:63360, or new 1:50000 drift maps for the area. Only three maps are, in fact, presently available, each of which covers only a small part of the area under examination. These maps are the 1:63360 Towcester map (sheet 202), covering the northwest of the area, and the 1:50000 Biggleswade (sheet 204) and Huntingdon (sheet 187) drift maps, covering the extreme northeast margin of the study area. Of these, only sheets 187 and 204 are accompanied by a Memoir, prepared by Edmonds and Dinham

(1965). It is also interesting to note that the area is conspicuously unrepresented in the Geological Society's "A Correlation of Quaternary Deposits in the British Isles" (Mitchell et al., 1973).

The present study therefore, sets out to conduct a lithostratigraphic examination of terrace and fluvioglacial gravels of the Upper Ouse basin, and part of the Nene basin, in order to provide a foundation for a Middle and Upper Pleistocene stratigraphy of the area.

S.H. Beaver (1968) discussing the Geology of Sand and Gravel quotes a definition of gravel given by H.B. Milner as

> ". . . a naturally occurring deposit of pebbles composed either of uniform or diverse rock types, which are usually rounded, incoherent, or loosely cemented with finer material, and for the most part fall within the size limits 2mm to 64mm (0.08 to 2.5 inches)."

Following the work of Green and McGregor (1978), Green, McGregor and Evans (1980) and McGregor and Green (1978; 1983a), on the terrace gravels of the Proto-Thames, it is assumed that within the Ouse basin individual stratigraphic units can be separated on the basis of gravel lithology, and, hence, that each unit has a unique lithological composition. It follows from this assumption that gravel samples with a similar composition are part of the same stratigraphical unit. These assumptions are shown, by Green and McGregor, to provide a workable basis for stratigraphical interpretation in the Thames basin, and although the "pebble-count" technique has not yet been fully developed, its potential for stratigraphic analysis has been demonstrated.

The pebble-count technique is used here as the basis for stratigraphic interpretation, and the results obtained from this lithological procedure are analysed to determine both spatial and stratigraphic relationships within the gravels. The results obtained are discussed with reference to the source geology of the contained lithologies, and with reference to fossil evidence examined in the present study, and from the literature.

The thesis first examines the characteristics of the study area which influence the deposits under discussion. Chapter II examines the solid geology of the study area - important for its influence on the lithologies which may be expected in the local gravel suites. Chapter III outlines the present morphology of the study area in terms of its relief and drainage, both of which reflect the influence of the underlying geological strata and the geomorphological development of the area throughout the Pleistocene. The drift geology of the study area is described in Chapter IV as it is described in the literature. These drift deposits occupy an important place in the present landscape, and are significant in the Pleistocene succession of the basin.

The development of a stratigraphic succession for the Ouse basin, based on gravel lithology, must take account of the successions already developed for the surrounding regions. A discussion of previous research in these regions is therefore presented in Chapter V, so that comparisons and correlations may, subsequently, be made.

Chapter VI discusses the field and laboratory methods employed in the present research. In the attempt to standardise procedures, these techniques are developed from among those most commonly applied to gravel analysis. The sites sampled in the present study are described in Chapter VII.

The analysis of the gravel in the present study is divided into two parts. Firstly, the lithological composition of each sample is ascertained. Each lithology determined during this analysis is described in Chapter VIII, and the probable source geology of each is discussed. Secondly, the lithological composition of each sample is compared to every other sample, to determine the spatial and stratigraphic patterns present among samples. Two techniques are used: trend surface analysis is used to examine spatial variability; and cluster analysis is used to establish stratigraphic divisions. The statistical analyses involved in each of these tests are discussed in Chapter IX. The results of both the statistical analyses are described in Chapter X, together with an interpretation of the gravel suites identified.

At Stoke Goldington, in the Ouse basin, a potentially significant interglacial deposit is reported. Up to 1.72m of richly organic clay is present containing a wide range of fauna and flora. A description of the site, and a preliminary report of the biological evidence, is presented in Chapter XI, the conclusions of which have important implications for the fluvial and glacial stratigraphy of the upper Ouse basin.

Finally, Chapter XII brings together the lithostratigraphic results, the biological evidence from Stoke Goldington, and evidence from the literature of the Ouse basin and surrounding areas. A succession incorporating all the available evidence is presented and correlations with the surrounding regions are suggested.

# Chapter II. The Solid Geology of the Upper Ouse and Nene Basins.

## Introduction.

The geology forms an important part of the study, as it forms the basis of the argument that gravel differentiation can be made in terms of its composition. Each stratum is discussed in detail, giving particular attention to those considered to be of major importance to the following discussions and arguments.

Only Mesozoic geological formations are present at the surface (those of the Jurassic and Cretaceous Systems), albeit covered by drift (fig. 2.1). The older rocks outcrop in the northwest, with the younger strata succeeding as one proceeds southeast. All the strata have a gentle, but steady, dip of one to two degrees to the southeast. The full succession is as follows:-

Cretaceous: Chalk - Upper.
- Middle.
- Lower.
  - Cambridge Greensand.

: (Upper Greensand-not present at the surface).
: Gault.
: Lower Greensand - Junction Beds
- Leighton Nodule Beds.
- Shenley Limestone.
- Silty Beds.

- Woburn Sands - Potton Beds.
- Brickhill Beds.
Jurassic: Purbeck.
: Portland Stone.
Sand.
: Kimmeridge Clay (Hartwell Clay).
: Corallian - Ampthill Clay.
- Elsworth Rock.
: Oxford Clay.
: Kellaways Beds - Sands.
- Clays.
: Cornbrash.
: Great Oolite - Great Oolite Clay (Blisworth clay).
- Great Oolite Limestone (Blisworth Limestone).
- Upper Estuarine Series.
: Inferior Oolite - Lincolnshire Limestone.
- Lower Estuarine Series.
- Northampton Sands and Ironstones.
: Lias - Upper.
- Middle.
- Lower.

## A. Lias.

The oldest stratum is the Lias, which flanks the Nene and its tributaries, and those areas of the Tove river which have cut through the overlying Oolite series. It is as a consequence of this "exposure by incision" that the

Lower Lias Beds outcrop only in the headwaters of the river Nene, to the west of Northampton.

The Lias, as a rule, is a relatively uniform lithology across the country, usually of argillaceous rocks: clays, shales and thin muddy limestones (Rayner, 1967; Bennison and Wright, 1969). The Lower Lias, in the Midland region, consists of monotonous, bluish-grey clays with occasional thin cementstone bands, and with nodules of this, or clay ironstone (argillaceous siderite mudstone), scattered throughout the upper Lower Lias (Taylor, 1963). The soft, unresistant nature of the stratum leads to 'wide clay vales' where it is exposed northwest of the present area (Arkell, 1933). Only further north, in Lincolnshire, where all the Liassic divisions, and consequently the outcrops, become thinner, is there any sign of a more resistant stratum in the Lower Lias. Here can be found the Frodingham Ironstone, a chalybite oolite (Bennison and Wright, 1969), best described

> ". . . as a ferruginous oolitic limestone." (Arkell, 1933).

Weathering, however, reduces the carbonate ooliths of the rock and, consequent upon this, the rock becomes soft and incoherent. Both above and below this ferrous band, the clays persist, although some limestone does appear interstratified with the shales (Arkell, 1933).

The Middle Lias, of which the lower part is clay and the upper part ferrous marlstone, is usually regarded as a source of iron ore near Banbury and Grantham (Bennison and

Wright, 1969). The lower, grey, micaceous silts and silty clays frequently have angular quartz grains in the groundmass, but cannot be regarded as a source of erratic material. More resistant to erosion than the underlying and overlying clays, the marlstone frequently forms a scarp, when exposed in the Jurassic Uplands to the west of the area (Bennison and Wright, 1969). The marlstone itself is a sandy, oolitic limestone; the iron occurring mainly in the form of carbonate, with some silicate.

Above the Marlstone Rock is a discontinuous band of highly fissile limestone, succeeded by soft paper shales, pale grey in colour. Above this is an irregular, rubbly limestone, commonly shelly and, frequently, with "false ooliths" of calcite (Taylor, 1963). These are the Upper Lias rocks found flanking most of the banks of the river Nene and Tove, notably between Haversham and Castlethorpe (Horton et al., 1974), and in the gravel pits at Great Linford, in the Ouse valley (Lukey, 1974). The most notable feature of the Upper Lias is the phosphatic lumps and nodules, described by Horton et al. (1974); an occurrence that will be discussed later (Chapter VIII.I).

## B. Inferior Oolite.

Of rather more importance to the gravels of the Ouse Basin is the Inferior Oolite. As with the Lias formation, this also outcrops on the flanks of the Nene and Tove rivers; the regional dip to the southeast, of approximately half a degree, leading to greater exposures north of the Nene than anywhere else in the region.

According to Rayner (1967), almost all the Inferior Oolite is calcareous, including sands, rubbly limestones and pisolithic and oolitic freestones. Of much greater lateral variability than the Lias below it, the Inferior Oolite is divided into three beds in Lincolnshire and Northamptonshire:

a) Lincolnshire Limestone,
b) Lower Estuarine Series,
c) Northampton Sands and Ironstone.

Only the lower beds are present in the study area, with the Northampton Sands and Ironstone dominant. The Lincolnshire Limestone develops only north of Kettering, through to Lincolnshire and consists of

> ". . . bewilderingly rapid and frequent changes of facies . . ." (Arkell, 1933),

mainly an oolitic limestone in a very fine calcite matrix, which may contain up to 30% quartz (Taylor, 1963; Rayner, 1967). Large amounts of broken shells, and skeletal debris, form the remainder of the rock, which may be hard when freshly exposed, but which weathers to a soft, friable oolitic sand (Arkell, 1933).

The beds immediately overlying the Upper Lias clays, the Northampton Sands and Ironstone, extend in a broad tract towards Towcester and Northampton from the river Cherwell, gradually thickening and becoming more ferruginous in the lower part. The base includes a layer of phosphatic pebbles (Rayner, 1967), above which the rock is oolitic; the ooliths being of chamosite, limonite, and, more rarely, kaolinite, set in a matrix dominated by siderite and calcite. On the whole it is more sandy than any of the rocks above or below it, especially towards the base, where it passes down into green, ferruginous sandstone (Arkell, 1933). Much of the rock has oxidised to the ferric state and, consequently, the grey and green colours of the deposit have given place to brown or reddish brown (Taylor, 1963). Redistribution of the ferric oxide within the rock, caused by infiltrating water, frequently gives rise to characteristic "box structures", so called because their formation in the vertical joint planes and horizontal bedding planes causes hard, dark brown structureless limonite to enclose the rock in box-like concretions (Arkell, 1933; Taylor, 1963). Once in this state, the rock has a high resistance to weathering and erosion.

The Lower Estuarine Series is described in the Little Linford area by Horton et al. (1974), who state that it is difficult to locate in the field. Not as hardwearing as the Northampton Ironstone below, it tends to have much smaller areas of outcrop. Light and dark grey fine sands, silts and clays characterise the stratum, a fair proportion of which is mudstone (Taylor, 1963; Rayner, 1967; Horton et al., 1974), although it shows rapid horizontal and vertical changes in lithology (Lukey, 1974). Northwards, towards the Humber, it becomes a flaggy limestone, which passes through many gradations, into calcareous sandstone and brown sand (Hollingworth and Taylor, 1951). None of these softer rocks are considered likely to have contributed much material greater than 0.25mm (a figure given by Taylor, 1963) to any later geological formation.

## C. Great Oolite.

Soft, non-durable lithologies continue the sequence through the lower part of the Great Oolite, where the Upper Estuarine Series overlie the Inferior Oolite. Clays, silts, and sands form the majority of the succession, with occasional rubbly, argillaceous limestones and massive, shelly limestones (Taylor, 1963). The stratum outcrops, in northwest Bedfordshire, beneath the Blisworth Limestone feature in the Ouse valley area (Horton et al., 1974), but is very irregular in its occurrence (Harrison, 1877). By far the most significant part of the formation is the Blisworth Limestone, which forms the prominant outcrop, both in northwest Bedfordshire (Nicholls, 1947) and north Buckinghamshire, usually in the form of a plateau or shelf (Taylor, 1963). It can be traced from Cold Brayfield, by Carlton and Harrold, north to Podington and Farndish and along the Ouse valley to the western suburbs of Bedford (Harrison, 1877; fig. 2.1). Frequently termed 'white limestone' (Harrison, 1877; Arkell, 1933), the rock is generally creamy or pale buff, rubbly and flaggy, composed of rolled shell fragments and occasionally associated with superficial ooliths and pellets (Horton et al., 1974). In places the rock, by reason of the total absence of ooliths, becomes difficult to distinguish from the shelly lower Cornbrash (Arkell, 1933). Rayner (1967) also compares the Blisworth Limestone to the Lincolnshire Limestone, although it is stated to contain more skeletal debris. Variations in the proportions of the shelly fragments, ooliths and rolled carbonate grains, produce bands of alternating hardness within the limestone. The extreme top of the limestone, beneath the Blisworth clay, is commonly ferruginous, giving rise to ferrous-limestones. Non-calcareous sand grains are also present in varying proportions (Taylor, 1963).

Soft clays (the Blisworth Clay) again outcrop above the Blisworth Limestone, separating it from the Cornbrash. The clays are variegated bluish, greenish or purplish grey, black or yellow with impersistant sandy bands and ironstone nodules (Arkell, 1933; Taylor, 1963). Calcareous beds are also present. The outcrop of this narrow band is restricted mostly to the Ouse valley; bordering the Ouse, between Turvey and Stevington (Nicholls, 1947; Horton *et al.*, 1974).

### D. Cornbrash.

The Cornbrash occurs in a band across the study area from Buckingham in the west, through Wolverton, Newport Pagnell and north to Rushden where many Nene spurs are capped by broad spreads of Cornbrash Limestone (fig. 2.1). Its outcrop, like much of the lower and middle Jurassic, has been dissected by the river Ouse and its tributaries. As a result, a remarkably even outcrop, of approximately 0.3km, occurs along the Ouse valley to Bedford (Harrison, 1877). North of the river, the Cornbrash outcrops at the summits of hills (Horton *et al.*, 1974); elsewhere it forms a shelf or plateau.

In general, the Cornbrash is a hard, detrital shelly limestone which, in its lower part, varies from light brown to grey, blue-hearted, marly rubble, with much fine to medium, well rounded shell debris (Arkell, 1933; Taylor, 1963; Rayner, 1967; Bennison and Wright, 1969; King, 1969; Horton _et al._, 1974). Ooliths are occasionally present, and, locally, the limestone may be ferruginous, especially where poorly developed.

The Upper Cornbrash, though similar in nature, contains a much higher proportion of coarse shell debris, and tends to be more massive (Taylor, 1963; Horton _et al._, 1974). Horton _et al._ (p 25) also note the presence of

> ". . . scattered homiolithic and phosphatised pebbles."

in the upper part. The top of the upper bed is, normally, highly ferruginous. Petrological examination (Taylor, 1963) showed that skeletal debris, fine grained carbonate groundmass, and clear calcite cement are the only important fabric elements. Quartz is occasionally present, but usually replaced by the surrounding calcite. Although this description does justice to the stratum in general, it is important to note that minor lithologies exist, including mudstones, with some silts and marls, and that the main limestone formation itself varies in its proportion of matrix and shell debris. Such local variability makes a positive identification of almost any shelly limestone difficult away from its source area and, in addition, also explains the variety in the brown to fawn rubbly and shelly limestones found in the present study (Chapter, VIII.E).

## E. Kellaways Beds and Oxford Clay.

Forming the major part of the Ouse Basin, through to the Vale of Aylesbury, are the "Great Clay Strata" (Rayner, 1967) of the Kellaways Beds and the Oxford Clay. The Kellaways Clay, with its sandy upper division, can be traced continually above the Cornbrash, but is only important in the region of Bedford. The Kellaways Clays are uniform, medium to dark grey, somewhat shaly mudstones, above which the Kellaways Sands - fine grained sands and silts - exist (Taylor, 1963; Horton *et al.*, 1974). Fresh colours of these sands are pale to medium greenish greys, but when weathered become pale grey, or occasionally lemon tinted, silty sands which may locally be bound by calcite. More commonly they are uncemented.

Far more important than the Kellaways Beds, purely through its width of outcrop, is the overlying Oxford Clay. This is a black, grey or bluish grey clay which is richly fossiliferous in ammonites, lamellibranchs and belemnites. Taylor (1963) believes the formation to be homogeneous in nature, but Nicholls (1947), Rayner (1967) and Horton *et al.* (1974) suggest that this is not true. Some beds are more sandy than others (Rayner), some are more calcareous (Horton *et al.*), and, in the northeastern part of the area, some limestone and ferrous nodules may also be found in the clay (Edmonds and Dinham, 1965).

Several tens of metres thick, the Oxford Clay covers a large part of the Ouse valley, ranging in width from approximately 10km, southwest of Bletchley, to 29km north of St. Neots (fig. 2.1). Division of the Oxford Clay, usually made on faunal evidence (Arkell, 1933; Horton _et al._, 1974), has shown that it is the lower part that outcrops over the greater part of the area, north of the line through Bletchley, Fenny Stratford, Wavendon to Bedford and Huntingdon. The brickworks at Calvert, in the Thame basin are in these lower clays. Those pits of the London Brick Company, to the south of this line, at Kempston Hardwick, Stewartby, Ridgmont and Millbrook, are thus exposing the upper part of the formation, generally only present beneath the Woburn Sands on the Lower Greensand escarpment. The soft, easily weathered nature of the stratum, has led to its low lying, sometimes marshy character.

### F. Corallian.

The geological sequence now becomes much less clear, as the strata overlap and overstep. As a rule the strata between the Oxford Clay and the Lower Greensand of the Lower Cretaceous consist of alternating beds of clay and limestone. In practice, however, the intervening strata only exist in part of the region. First is the Corallian, a varied stratum, which ranges from a calcareous grit in Yorkshire, to an iron shot oolitic limestone, underlying the Ampthill Clay, in Bedfordshire and Cambridgeshire (Edmonds and Dinham, 1965; Rayner, 1967). In the Great Ouse valley, outcrops of the Corallian Limestone are not common. Eight kilomtres east of Oxford, the limestone ceases, and the predominantly argillaceous facies of the

Ampthill clay begins and continues eastwards. This is a dark grey, or black, tenaceous clay in which there are several thin bands of hard, nodular and argillaceous limestone (Arkell, 1933). Very often the basal bed of the clay is a soft weathering, cream coloured, iron shot, oolitic limestone - the Elsworth Rock. For the most part the rocks are overstepped, and exposures of either do not occur much further west than Old Warden (Edmonds and Dinham, 1965). Durable material is unlikely to be derived in large amounts from the formation exposed within the Ouse Basin. Further north, in Lincolnshire and Yorkshire, where gritty limestones compose scarps above the Oxford Clay, more durable material is much more prominant. In the Lower Calcareous Grit of the Lower Corallian, in Yorkshire, siliceous spicules of the distinctive sponge 'Rhaxella perforata Hinde' (Wilson, 1938) occur. The sponge is locally so abundant at certain horizons that they give rise to beds of Rhaxella Chert, a lithology discovered in the glacial gravels of the Thames basin (Green and McGregor, 1978; Green, McGregor and Evans, 1982).

### G. Kimmeridge Clay.

In Bedfordshire, the Kimmeridge, Portland and Purbeck strata are usually fully overstepped by the Lower Greensand. Only to the southwest of Leighton Buzzard, and in the Vale of Aylesbury, do these Upper Jurassic strata emerge. The Kimmeridge (or Hartwell) Clay tends to form a vale as it comprises soft, uniform marine muds and shales, bluish grey in colour and highly fossiliferous (Sherlock, 1922; Rayner, 1967; Anderton et al., 1979). Some argillaceous limestone occurs as thin layers, or nodules, and sandy glauconitic clay can also be found in places. The base is ill defined

> ". . . and its mapping depends largely upon the tracing of occurrences in ditches, ponds and pits of a basal phosphate bed." (Edmonds and Dinham, 1965),

consisting of phosphatic nodules and fossils, mainly ammonites.

H. Portland and Purbeck.

The competent Portland and Purbeck limestones form a low lying, northwest-facing scarp, overlooking the river Thame, in their most northerly outcrop (Ballance, 1963). Nowhere, in fact, do these beds outcrop in the Ouse basin; their nearest appearance is at Stewkley on the Ouse/Thame watershed (fig. 2.1). The Portland limestones, and interbedded sandstones, contain at their base a pebble bed of small, well-rounded, highly-polished quartz and siliceous 'lydite' pebbles, with locally derived Kimmeridgean phosphatic pebbles (Ballance, 1963). Huddleston (in Sherlock, 1922) points out that

> ". . . this bed, when protected from atmospheric solvents, is of intense hardness, and markedly different from its condition when exposed at the surface."

Overlying this is a rubbly, glauconitic limestone (the Aylesbury Limestone) which is hard, blue-hearted and fossiliferous, and which grades into a bed of fine- to medium-grained, orange sand - the Crendon Sand (Arkell, 1933; Ballance, 1963). The uppermost bed of the Portland is again a limestone, creamy in colour, which becomes white as the succession ends. The Purbeck, only occurring in a few outliers to the south and southwest of Aylesbury, is a thin, strongly calcareous clay (Ballance, 1963; Anderton et al., 1979) and of little importance to the present study.

## I. Lower Greensand.

Above the Jurassic rocks, described in the previous paragraph, the Cretaceous system is overstepped by the Lower Greensand deposits, divided into the Woburn Sands and the Junction Beds (Keen, 1968). The stratum is exposed in a band, varying in width from 3-10km, stretching northwest from Linslade and Leighton Buzzard by Great Brickhill and Wavendon to Ridgmont, Eversholt, Flitwick, thence by Ampthill and Shefford to Biggleswade, Sandy and Potton (Harrison, 1877), and forms a striking scarp above the Oxford Clay Vale.

Forming the majority of the stratum, northwest of Woburn, are the Woburn Sands - up to 61m of medium to coarse, poorly cemented, yellow glauconitic quartz sands, but with all shades of iron staining from red to orange and brown, with the frequent development of iron pans along planes of bedding and joints (Edmonds and Dinham, 1965; Rayner, 1967; Keen, 1968; Horton et al., 1974). Beds of a harder, gritty sandstone (or Carstone) are also present. These are poorly-graded bodies of coarse sand with large "millet seed" grains (Edmonds and Dinham, 1965). The basal layer of the Woburn Sands is amongst the most interesting beds found in the study area, for it contains many Palaeozoic pebbles and rolled phosphatised nodules (Rayner, 1967; Anderton et al., 1979). It rests unconformably on the planed surface of the Oxford Clay. Erratic pebbles (excluding, for the moment, the phosphatic nodules), described by Harrison (1877), Rastall (1919), Nicholls (1947), Wells and Gossling (1947), Kirkaldy (1947), and Rayner (1967), include quartz, chert, ferrous sandstone, quartzite, Palaeozoic grit, slate, and even Rhaxella Chert (Kirkaldy, 1947). More significant, however, are the remanié phosphatic nodules. They are mainly fossils, washed from the Kimmeridge Clay, which have been preserved in calcium phosphate while on the sea floor (Edmonds and Dinham, 1965). Recognisable casts and moulds of bivalves and ammonites can be found. At Little Brickhill, 4km east of Bletchley, 10m of sand with scattered nodules rests on Oxford Clay (Casey, 1961). At Potton, indigenous fossils occur in ferrous layers, and indurated gastropods, lammellibranchs and several species of brachiopod have been found (Casey, 1961). In places, the basal phosphate bed is replaced by the Shenley Limestone, usually occurring in lenticles; each lenticle having a character of its own - the fauna being unique (Casey, 1961).

A second bed, the Potton Nodule Bed, lies in the upper part of the formation (Brodie, 1866; Edmonds and Dinham, 1965; Keen, 1968), forming lenticular masses, up to 1.8m thick, above the base of the Lower Greensand. Most of the nodules are between 0.6 and 7.6cm in diameter (Edmonds and

Dinham, 1965). Their colour ('red', distinguishing them from the 'black' nodules of the Cambridge Greensand), is light brown on the outside and much darker, often black or brown, within. Frequently, the nodules envelope an organic body, generally an ammonite (A. Lamberti) of the Oxford Clay. The nodules are of all shapes, rounded and elongated, and frequently pitted on the surface (Brodie, 1866; Edmonds and Dinham, 1965).

The upper Junction Beds can only be seen in the Leighton Buzzard district, and are characterised by their variability (Keen, 1968). The main part is a fine, sandy clay, (the sand frequently glauconitic), the base of which is a conglomerate, containing worn ironpans and a few pebbles of Shenley Limestone.

### J. Gault Clay.

Reduced rates of terrigenous clastic supply, following the deposition of the Lower Greensand, produced a clayey facies of condensed and phosphatic nodular horizons - the Gault Clay. The Gault is a dark to light grey, stiff and tenaceous clay, becoming more calcareous upwards (Ballance, 1963; Rayner, 1967; Keen, 1968). Across Bedfordshire and Buckinghamshire it forms a narrow strip of country, immediately below the Chiltern escarpment, its most northerly margin running from Thame to Aylesbury, Leighton Buzzard, Toddington, Shillington, Arlesley, Henlow and north to Dunton, 5km east of Biggleswade (fig. 2.1). Again, bands of phosphatic nodules can be found at two horizons, the base of both the upper and lower Gault

(Harrison, 1877; Sherlock, 1922; Nicholls, 1947; Keen, 1968). The seam found in the upper Gault can be seen at Puttenham, just upstream of Rowsham (site 42; Chapter VII). Westward, the Gault Clay passes laterally into the glauconitic sands of the Upper Greensand, which oversteps the earlier deposits (Anderton et al.,1979). This stratum does not appear in the study area; its first appearance being southwest of Aylesbury.

### K. Cambridge Greensand.

At a point six kilometres west of the A6, at Barton in the Clay, a deposit of very similar nature to the Lower Greensand appears, and extends northwest into Cambridgeshire. It is 30-60cm (max. 2-3m at Totternhoe) thick consisting of glauconitic sandy marl, which grades upwards into the Chalk (Hawkes, 1943; Edmonds and Dinham, 1965; Keen, 1968). Frequently referred to as the Upper Greensand, it has, for many years now, been recognised as the Cambridge Greensand, and part of the Lower Chalk. The Cambridge Greensand has a thin occurrence above the Gault, and is not significant in itself, but, like the Lower Greensand, it is important for the erratic pebbles and rolled phosphatic nodules contained within it.

The erratics were first reported by Sedgwick (1860), as

> ". . . rolled specimens of palaeozoic rocks . . ." (in Hawkes, 1943),

which range in size from 5 to 55cm, and include granite, gneiss, schist, rhyolite, quartzite, chert, basalt, vein quartz and various sandstones (Seeley, 1866; Hawkes, 1943; Rayner, 1967; Keen, 1968; Bennison and Wright, 1969). These erratics are probably of western derivation - from the Bunter Pebble Beds and, for the igneous types, either southwest England or Wales (Hawkes, 1943; Rayner, 1967). The phosphatic nodules in this bed, and in the Lower Chalk above, are all remanié deposits, probably derived locally from the Upper Gault (Rayner, 1967; Keen, 1968).

## L. Chalk.

Forming the southeastern margin of the area, the highest ground and the youngest stratum of the solid geology, is the Chalk. This dips to the southeast, at approximately two-thirds of a degree, and is normally divided by geologists into the Lower, Middle and Upper Chalk. As far as the present study is concerned, it is unnecessary to describe each of these in detail, it being sufficient to state that within the normally soft, white to grey chalk there are three hard grounds, caused by increases in the shell and foraminiferal components (Pringle et al., 1922; Rayner, 1967). These are the Totternhoe Stone, the Melbourn Rock and the Chalk Rock, occurring in the basal parts of the Lower, Middle and Upper Chalk respectively (Sherlock, 1922; Edmonds and Dinham, 1965; Rayner, 1967). Of these, the nodular Melbourn Rock is the hardest. In the basal part of the Chalk can, again, be found erratics (described by Hawkes, 1951), which are of similar derivation to those described in the Cambridge

Greensand (Hawkes, 1943; Bennison and Wright, 1969).

Local variations in the chalk can be of great significance, such as the existence of the Red Chalk Beds - peculiar to the Lincolnshire strata (Casey, 1961; Kent, 1967; Greensmith, 1978). Flint is also peculiar to the Chalk, first appearing at the top of the Middle and, becoming more prominent, in the Upper Chalk (Sherlock, 1922; Nicholls, 1947; Rayner, 1967; Keen, 1968).

A summary of the characteristics of each stratum, described above, is provided in table 2.1. The lithologies which are available, and their relative hardness, is also indicated.

# Chapter III. Relief and Drainage of the Upper Ouse and Nene Basins.

## A. Relief.

The relief of the Upper Ouse basin reflects closely the underlying geological strata and past geomorphological processes. Bounded on three sides by major watersheds, it might be expected that high land should dominate the landscape, but this is not so. Only the escarpments of the Lower Greensand and Chalk, to the south and southeast of the study area, present a contrast with the generally low-lying relief (fig. 3.1).

The Chalk uplands - or Chiltern Hills - run approximately southwest - northeast from Goring, through Princes Risborough, Wendover and Tring, to Dunstable and Luton (fig. 3.1). To the northwest they present a steep scarp face, rising abruptly from the clay vales to the north. Southeast of the crest, descent is more gradual into the vale of St. Albans and the London Basin. The highest point of the watershed, in the study area, is at Aston Hill (260m), to the west of Tring (SP891100), and overlooks the clay vale on which Aylesbury stands. From here, the height gradually decreases northeastwards to 249m southeast of Ivinghoe, and 243m on the Dunstable Downs, where Whipsnade Zoo is situated. Northwest of Luton, the scarp changes in character. The 100m contour is broken for the first time by the Hitchin-Stevenage Gap, northeast of which the height of the escarpment is much reduced, and its orientation changes to almost west-east.

The wind gaps and dry valleys which score the Chiltern plateau, of which the Hitchin-Stevenage gap is one of the former, generally trend southeast, and only rarely do they cut the escarpment. Studied by many authors (Gregory, 1914; Barrow, 1919; Hawkins, 1923; Sherlock, 1924; Earle, 1928; Ollier and Thomasson, 1957; Sparks and Lewis, 1957; Avery, 1964; Brown, 1969; French, 1972), several theories have been put forward to explain their salient features - those of narrow, flat floors, low gradients, asymmetrical and symmetrical cross-profiles, occasional right angle bends, and their presence on a stratum which is permeable.

French (1972) recognises 4 forms on the Chilterns :

a) Shallow symmetrical valleys and gullies, often elongated or "paddle shaped".

b) Normal asymmetrical valleys i) broadly U-shaped.

c) Normal asymmetrical valleys ii) more clearly defined - asymmetrical and V-shaped.

d) Symmetrical U-shaped - broadly flat.

The gaps which penetrate the escarpment are widely spaced (Hawkins, 1923) and are found at several levels. They range from 90m, at Stevenage, to 213m in the Hampden Gap, with the Tring Gap at 131m and the Goring Gap at 137m (Gregory, 1914). Additionally, as the Chilterns are followed northeastwards, the gaps, both minor and major, become shallower and less steep-sided, until the Hitchin gap is reached.

Between the Chiltern scarp and the ridge of the Lower Greensand, is a narrow tract of land, formed by the Gault Clay, which imitates closely the morphology of the Oxford Clay vale further north. The Lower Greensand ridge, northeast of Leighton Buzzard, rises to its maximum elevation (171m) just to the east of Bow Brickhill, and to 161m at Milton Bryant. Northeastwards from there, like the Chilterns, the scarp decreases in altitude past Ridgmont and Lidlington to Ampthill, Clophill and Shefford, where it is broken by the gap through which the river Ivel passes. Beyond Shefford, the scarp, much reduced, turns north through Sandy Warren and Tetworth and on into Cambridgeshire (King, 1969).

At the southwestern limit of the Lower Greensand exposure, the River Ouzel cuts across the geological boundary of the Lower Greensand and the Gault Clay, leaving, to the west of Leighton Buzzard, Bletchley and Buckingham, the relatively high ground which forms the watershed between the Great Ouse and Thame Basins. Dissected on all sides by first order streams, from both catchments, the watershed reaches its highest point at Quainton Hill, Quainton, approximately 100m above the surrounding plain.

North of the Lower Greensand scarp, and east of Bletchley and Stony Stratford, is the "Vale of Bedford" (King, 1969); a broad, gently undulating lowland on Oxford Clay - there being nowhere a greater range in altitude than 60m. The greatest expression of relief, in this relatively flat countryside, is west of Bedford, where the River Ouse occupies a relatively narrow meandering valley, cut through the Oxford Clay into the Great Oolite Series. Although gentle in form downstream from Deanshanger, the entrenchment is much deeper and narrower at Buckingham, where the river begins to cut through Cornbrash strata. This entrenchment extends west and south until the watersheds of the neighbouring basins are reached. East of Bedford, the valley, frequently marshy, opens out into a broad plain, decreasing gently in altitude from 30m O.D. at Bedford to about 15m O.D. at St. Neots and Huntingdon.

The Ouse-Nene watershed runs from Litchborough (SP630545) to Blisworth and Salcey Forest, where it turns northeast, past Bozeat Grange, Great Hayes Wood (SP964617) and on to Raunds. It has no great prominence above either river, reaching a maximum of 80m above the Ouse at Salcey Forest (west of Ravenstone), where the Great Oolite Series forms the outcropping geology.

Outside the Ouse basin, the low, gentle landscape continues. In the Thame basin to the west, away from the Oxford Clay watershed, the river flows across an undulating plain at a relatively constant 76m O.D., below the Chiltern escarpment. In the small segment of the Nene examined, the relief is similar to the upper reaches of the Ouse valley, with a narrow floodplain, rising to the Jurassic plateau (East Midlands Plateau of Kellaway and Taylor, 1952), north of Northampton. This plateau is reported to be an old erosion surface by Swinnerton (1929).

## B. Drainage.

The low, featureless relief of the Ouse basin, described above, is almost certainly significant in an analysis of the development of the basin. Unlike the Thames valley to the south, which has revealed a complete river terrace 'staircase' throughout its height range (Wooldridge, 1938; Wooldridge and Linton, 1955; Green and McGregor, 1978), the Ouse, through past phases of erosion, has had much of the available relief removed. Consequently, the terrace sequence is altitudinally compressed; the lower terraces frequently grading into each other (Horton, 1970).

### 1. The Great Ouse.

Within the upper Ouse basin, southwest of Huntingdon, there are four main drainage channels: the rivers Tove, Ouzel, Ivel and Great Ouse (fig. 3.2). The Great Ouse itself flows almost due northeast, following the strike of the Oxford Clay, from Buckingham to Wolverton, Great Linford and Newport Pagnell, and through to Bedford, Great Barford and Tempsford, where it turns on a more northerly course to St. Neots and Huntingdon. The major deviation from this general course is between Newport Pagnell and Bedford where a great meander occurs to the north, to pass through Gayhurst, Olney, Turvey, Harrold, Radwell, Milton Ernest, Clapham and Bromham.

The only tributary of importance entering the Great Ouse from the north, is the river Tove, which flows east from Towcester for about 7km, before turning southeast until its confluence with the Ouse, at Cosgrove. South of the Great Ouse, drainage is predominantly in a south to north direction, via the tributaries of the Ouzel and Ivel, which rise from springs near the base of the Lower Chalk (King, 1969; Lukey, 1974). The Ouzel flows north from Leighton Buzzard, for about 30km, before it meets the Ouse at Newport Pagnell. The Ivel, with its tributaries of the Flit and Hiz (the former flowing along the strike of the Gault Clay), flows north from Hitchin, through Clifton, Biggleswade and Sandy, to meet the Ouse at Tempsford. The remainder of the basin is crossed by numerous first and second order tributaries in a more or less dendritic pattern.

In profile, the Great Ouse has a gentle gradient for almost its entire length, but apparently has three 'knickpoints' and a valley which

> ". . . generally suggests a more complex record than does that of the Nene." (Dury, 1952).

On the trunk stream, these knickpoints (fig. 3.3) were reported to occur

> ". . . a little above Bedford, at Stafford Bridge [south of Milton Ernest], and at Newport Pagnell (Lathbury Bridge). There is also a small irregularity at Buckingham, which is regarded as a true knickpoint of lesser amplitude. The profiles of the Twin and of the Ouse above Buckingham seem to be smooth, but there is a break on the profile of the Tove above Towcester." (Dury, 1952).

The evidence for the knickpoints is supposedly supported by the presence of three river terraces along the banks of the Ouse and its tributaries; terraces which cannot easily be correlated downstream, due to differences in steepness, the profiles below Bedford apparently being steeper than those in the Buckingham-Olney reach (Dury, 1952). Dury places the terraces at 50' (15.2m), 20' (6.1m) and 10' (3.1m) above the alluvium, respectively. This, although generally accurate, does not coincide with the views of Horton (1970) and Horton <u>et al.</u>,(1974), who describe the third terrace converging with the alluvium downstream (Chapter IV.E). This terrace is apparently not found upstream from Bedford. The lower terraces (terraces one and two), to the west of the river Ivel, between Biggleswade and Sandy, apparently grade into each other and also grade into glacial gravels away from the river (Edmonds and Dinham, 1965). Horton (1970, p21) describes the area east of the river as

> ". . . combined First to Second Terrace [which] have an average surface level of 5 to 6 ft [1.5-1.8m] above the alluvium but attain a height of 10ft [3.1m] at the back edges of the outcrop. West of the river the terrace surface is from 0 to 3ft [0-0.9m] above the alluvium."

Further downstream, at St.Neots, the two lower terraces have been separated; the second with a surface at 9 to 16' (2.7-4.8m), and the first at 4 to 5' (1.2-1.5m) above the alluvium, although the latter is often only just above the alluvium, as at Godmanchester (Horton, 1970, p21).

The same pattern also exists on the Ouse, upstream from the Ivel confluence, towards Bedford. Third terrace deposits have been separated, but the lower first and second terraces have not yet been mapped as separate units.

Upstream from Bedford, along the rivers Tove, Ouzel and Ouse, third terrace deposits die out and only first and second terraces have been recognised, with their surfaces described at approximately 2 to 5' (0.6-1.6m) and 10-15' (3.3-4.9m) above the alluvium (Horton, 1970; Horton *et al.*, 1974). Although the second terrace is more scarce than the first, the Ouzel valley contains sizeable second terrace deposits around the villages of Milton Keynes and Broughton. Further south, small remnants are described at Caldecotte, northeast of Fenny Stratford, and on both banks of the valley from Water Eaton to Stoke Hammond (Horton, 1970).

First terrace deposits have been mapped almost to the source of both the river Tove and the river Ivel. On the Great Ouse, it has been noted by Dury (1952) that gravels

> ". . . mapped simply as undifferentiated Valley Gravel . . . arrange themselves in two main groups, aligned respectively on the alluvial profile above the Newport Pagnell knickpoint and on the alluvial profile of the Ouse above Buckingham."

From this Dury concludes ". . . that two terraces are present."

### 2. The Nene.

The river Nene, although not of primary importance in the following discussion, does form the northwestern boundary to the study area. Draining solely from the Jurassic strata, it flows east from Weedon Bec, through Nether Heyford, Kislingbury and Northampton, and on to Cognehoe and Earls Barton, where it takes a more northerly course past Wellingborough, Rushden and on to Thrapston (fig. 3.1). Once past Rushden, the Nene roughly follows the strike of the Jurassic strata, and is, thus, what Dury (1948) terms a 'strike stream'. Like the Ouse, the Nene has a low height range, with the resulting 'compressed' terrace system and, until recently, most discussions concerning the Nene were about the evolution of the 'dip and scarp' tributaries, such as the river Ise, Harpers Brook and Willow Brook - which flow off the Jurassic escarpment to the north and west, and their relationship to the river Welland, rather than with the terrace deposits (Sargent, 1930; Thompson, 1930; Dury, 1948; 1949; 1950; Kellaway and Taylor, 1952).

Dury (1950) described an "arrangement of terrace remnants in short flights" in a discussion of the knickpoints of Calender Brook, but more useful work on the terraces of the basin was started by Taylor (1963) and Castleden (1976; 1977; 1980a; 1980b). Taylor recognised three terraces of the Nene (later confirmed and quoted by Horton, 1970), all

> ". . . at a lower altitude than the base of the boulder clay in their vicinity." (Taylor, 1963).

The height of each terrace above the alluvium is :

Third terrace 35-55' (10.6-16.8m) (usually 45-50' (13.7-15.2m)).

Second terrace 15-30' (4.6-9.1m) (Mean 25' (7.6m)).

First terrace 4-8' (1.2-2.4m), although it is 15' (4.6m) in places.

Castleden, working in the mid-Nene valley, undertook a much closer look at the terraces and their development. Three terrace deposits were shown to occur as dissected, level-bedded sands and fine to medium gravels resting on a periglacially cut bench or pediment (Castleden's term). The basal, planar bench is best seen between Northampton and Wellingborough, where it has a maximum width of 1300m at Earls Barton. At other places, lithology appears to have affected a major control on the development. Where developed in Lias Clays, the bench tends to be open and wide, but where in Great Oolite and Cornbrash it has steeper sides and is much narrower, normally having a width of 0.5-1km (Castleden, 1977; 1980a). Resting on this basal pediment are both the first terrace and the floodplain deposits, of which the former are an 'undissected extension' which are separated topographically by a step of approximately 2m (Castleden, 1976; 1980b). The second terrace deposits rest on a valley side bench, whose floor is only 1m above the surface of the first terrace.

# Chapter IV. Drift Geology.

## Introduction.

> "There is probably no branch of British Geology which has excited more controversy, or has more special literature devoted to it, than that dealing with the superficial deposits. Their production has been attributed to diluvial, marine, or ice agency by various writers, and opinion on them is, even now, by no means settled." (Salter, 1905).

Within the present study area, 'superficial deposits' of one type or another cover the vast majority of the solid geology, and thus form an important feature of the present landscape. They can be divided into five main categories:

A. Lacustrine Clay.
B. Milton Sands.
C. Glacial Till.
D. Glacial Gravel.
E. River Terrace Deposits.
  1. The Great Ouse.
  2. The Nene.

In the following discussion where authors have used Imperial units these are stated with the equivalent metric units in parenthesis.

## A. Lacustrine Clay.

Infilling a series of deep channels, beneath the present courses of the Ouse, Ouzel, Ivel, and Nene rivers, is a range of sediment, from chalky till and sand and gravel to lacustrine clay (Early, 1956; Horton, 1970; Horton _et al._, 1974). The lacustrine clay is described under the Power Station at Northampton (Early, 1956), and outcropping at the surface in the modern Ouzel valley, from Stoke Hammond to Milton Keynes village, and from Great Linford to Stony Stratford in the Great Ouse valley (Horton et al., 1974). Most of the evidence, however, is from boreholes, the most important of which is at Deanshanger (Horton, 1970), because most of the clay is covered by more recent deposits.

Horton (1970) describes the deposit as dull brown clays with paler olive grey silt partings, within which are pebbles either of a single lithology (many chalk), or of composite till fragments. These may occur either as distinct pebbles or in gravelly bands. In the upper part of the sequence, the lake clays lie beneath, and are interdigitated with, chalky till. The base of the deposits grade downwards into slightly coarser, lacustrine sediments of silt and very fine sand (82%), sand (15%) and clay (3%); the proportion of sand increasing downwards. The upper lake clays show distinct varves of annual periodicity (Horton, 1970; Horton et al., 1974), each lamination being two to seven millimetres thick. These laminations are usually horizontal, although distortion around the pebbles occurs. Horton interprets this as indicating that the pebbles are drop-stones from floating ice. Horton suggests that the deposit is identical to that found by Early (1956), at Northampton, where over 300 micro-laminations have been counted in a few major varves. Early (1956) suggested that these represent diurnal cycles, and calculated that the series represents a period of 500-1000 years.

Consolidation tests by Early suggest that the top level of the sediment was never much higher than the present floodplain in the Nene basin. The overall picture, from the sedimentary characteristics, is indicative of deposition in quiet water, probably associated with the chalky till ice front (Horton, 1970; Horton et al., 1974).

## B. Milton Sand.

The Milton Sand was first identified by Thompson (1930) in a number of pits at Nether Heyford, Bugbrook, Rothersthorpe, Milton Malsor, Collingtree, Courteenhall and Preston Deanery. It has since been discussed by Dury (1949), Horton (1970), Horton et al. (1974), Castleden (1980c) and Clarke and Moczarski (1982). Scattered occurrences of similar gravel are described further east, at Little Houghton, Yardley Hastings and Chadstone (Thompson, 1930), in the Kettering district at Yarwell, Benefield (near Oundle) (Thompson, 1930; Horton et al., 1974) and Brigstock (Richardson and Kent, 1938), and north of Flore to Daventry (Thompson, 1930) and Kilsby (Clarke and Moczarski, 1982).

Thompson (1930) described the deposit in the sand pits at Wootton and Milton Malsor, where sand and gravel, with some clay boulders, is composed entirely of local material, mostly pieces of ironstone, from the ironstone casings of box-stones, derived from the Northampton Sands. Some Jurassic limestone was also reported, mostly from the cephalopod-rich limestone at the base of the Upper Lias. Dury (1949) confirmed the local lithology, but Horton (1970; Horton et al., 1974) claims that, in addition to the local component, well-rounded, large quartz and quartzite pebbles of the Bunter-type occur throughout, together with weathered flint or chert. Thompson (1930) had also noted the presence of flint and Bunter pebbles at a few sites (such as Bugbrook), but he suggested these were incorporated from the overlying till (see IV.C below) by post-depositional disturbance. Castleden (1980c) re-examines Thompson's sites, and confirms the findings of Thompson and Dury that erratic material is absent. His analysis shows a composition of Jurassic limestone (18-53%), sideritic ironstone (45-68%) and sandstone (2-14%), and he, therefore, disagrees with Horton and states that

> ". . . it is only possible to assume that he [Horton] has inadvertently included data from later gravels adjacent to the Milton Sand." (Castleden, 1980c, p196).

Clarke and Moczarski (1982) also support the local composition; the Sand comprising 93% (ferrous) sandstone, the bulk of the remainder being shelly Lias material (5%).

Horton (1970), Castleden (1980c) and Clarke and Moczarski (1982), however, all show that the Milton Sand is lithologically distinct from the chalk-flint outwash gravels associated with the chalky till.

The Milton Sand is principally medium and course sand, only ten percent of the deposit having a particle size greater than 5mm (Castleden, 1980c; Clarke and Moczarski, 1982). Thompson described the deposit as sandier at the top, and more gravelly below. The deposit is usually about 3m thick (Castleden), although thicknesses of 43' (13m) at Kislingbury (Thompson, 1930) and 40' (12m) at Rothersthorpe (Castleden) have been recorded.

At many of the sites described by Thompson (1930) the Milton Sand is overlain by chalky till, for example at Kilsby Tunnel 40' (12m) of till is recorded. Castleden (1980c) confirms this and also claims that

> "In places the sand overlies the Lower Boulder Clay yet, curiously, contains no erratic material derived from it."

The similar gravels in the Kettering district are also reported to overlie lower till and underlie chalky till (Hollingworth and Taylor, 1946a; Horton et al., 1974).

The bulk of the Sand is reported, by Thompson, to lie in a channel which falls in altitude, to the south-southeast, from 285' (87m) at Nether Heyford, to 257' (77m) at Rothersthorpe and 238' (72m) at Preston Deanery. Thompson believed this is continuous and represents a single stream system, crossing the Ouse-Nene watershed. Sub-horizontal bedding in the Sand suggests it is water laid, and fabric analysis at Rothersthorpe, by Castleden, confirms that a stream flowed from the north, northwest or west. Dury (1949) and Horton (1970), however, can find no eastern outlet at Yardley Chase, and Horton reports that the Sand lies in an enclosed hollow. The source of the Milton Sand is, therefore, uncertain, but all authors believe that the entirely local composition is indicative of a nearby source.

## C. Glacial Till.

Within both the Ouse and Nene basins, and in most of the surrounding regions, till has been described at all altitudes covering both the high and low ground, including the interfluves. Varying in thickness from a few metres to over 50m, the till also fills hollows in the pre-glacial land surface, and plugs the sub-drift valleys, present beneath the Ouse, Ouzel, Ivel, Tove and Nene rivers (Hill, 1908; 1912; Horton, 1970; Horton et al., 1974). Within the present study area two tills have been described. In the following discussion (and throughout the thesis) the term 'till' is used rather than 'boulder clay' conforming to modern nomenclature (Francis, 1975). Thus the term chalky till will be used for deposits previously referred to as chalky boulder clay.

### 1. Lower Till.

This is the less well exposed of the two tills, and is reported to occupy hollows beneath the chalky till (see C.2 below), under which it thins, on high ground. It is found in the Nene basin, to the south and southwest of Kettering (Hollingworth and Taylor, 1946a; 1951; Kellaway and Taylor, 1952; Taylor, 1963), and

> ". . . as a narrow belt on the valley sides of these [sic] small streams which drain the drift-covered country north of Buckingham, but as most of the outcrops occur on the lower valley slopes, exposures are rare." (Horton, 1970; pl).

Apart from the areas described above, the only other report of material comparable to the lower till of the Towcester area is near Haversham, west-northwest of Newport Pagnell (Horton et al., 1974).

The till comprises a drab, grey, gritty-textured, tenaceous clay with a low proportion of erratics and a preponderance of local material - mainly limestone and derived fossils, including "Pentacrinus" ossicles and Gryphaea, together with some Bunter pebbles, and minor weathered flint and race (calcareous concretions). Chalk is invariably absent (Horton, 1970; Horton et al., 1974). The lithology is similar to that described, by Hollingworth and Taylor (1946a; 1951), Kellaway and Taylor (1952) and Taylor (1963), in the Kettering district, where the lower till is free of chalk and flint, and is characterised by Jurassic and Bunter material.

2. Chalky Till.

Chalky till is described covering the high ground, masking the interfluves of the Ouse and Nene basins, and frequently overlying the deposits of the lower till, from which it is occasionally separated by a layer of glacial gravel (Woodward, 1897; Hill, 1908; 1912; Barrow, 1919; Harmer, 1928; West and Donner, 1956; Taylor, 1963; Edmonds and Dinham, 1965; Horton, 1970; Horton et al., 1974; Dennes, 1974). It is this till which is reported to fill the subdrift channels beneath the Ouse, Ouzel, Ivel, Tove and Nene (Horton, 1970; Horton et al., 1974).

A wide variety of erratics has been described within the till, the matrix of which is stated to vary

> ". . . with the character of the different Oolitic and Liassic rocks along the strike of which it passed." (Harmer, 1928, p123).

In the Ouse basin, Oxford Clay is believed to comprise much of the matrix (Dennes, 1974). Perrin et al. (1979) analysed the chalky till of eastern England for the calcium carbonate, heavy mineral and insoluble residue content of the matrix. Trend surface analysis of the results showed distributions with northwest to southeast trending isolines, indicating an ice direction from the northeast, and the presence of only one chalky till in eastern England.

The most detailed study of the till, in the present study area, is that of Horton (1970) and Horton et al. (1974), who describe the till as usually medium bluish grey to dark grey clay, with an abundance of chalk, commonly as pebbles of 25mm diameter or less, and flour (comminuted silt-grade chalk grains). Other far-travelled pebbles include flint, Bunter-derived quartz, quartzite and sandstone of Carboniferous type, together with fragments of Jurassic limestone, possibly of local origin, and locally-derived mudstone fragments, nodules and fossils (particularly Gryphaea). Frequently, an upper weathered zone (up to 1.5m) is shown by pale grey and yellow mottling.

Variations within the till occur both locally and across the region. For example, in the Huntingdon area, the till is not its usual blue-grey colour, but consists of an olive grey to greenish grey clay, with abundant chalk pebbles, numerous flints and a high proportion of Jurassic limestone and mudstone. The colour variation is attributed to variations in the chalk flour content of the till (Horton, 1970).

Locally, the distribution of erratics within the till varies, some horizons being almost chalk free. There is also a general tendency for the proportion of local material to increase towards the base (Horton, 1970). At Milton Keynes, two types of chalky till are recognised: an upper sandy and coarse and a lower clayey. These are occasionally separated, vertically, by bedded and sorted deposits. The upper till is characterised by the presence of abundant angular and subangular, mainly unstriated, boulders, high proportions of sand and gravel and a small amount of clay. The lower till has a much higher proportion of silt and clay and is usually dark brown in colour (distinguishing it from the brown or yellow brown of the upper till). Inclusions of both tills include chalk and flint with occasional small erratics, from pre-Jurassic and Jurassic strata. The local variation in the area has been explained by comparison, of the upper sandy till to flow tills of Spitzbergen, and the clayey till to lodgment till (Dennes, 1974; p299).

West and Donner (1956) described four sites, within the present area, at Ippollitts (TL194258); Meppershal (TL157374); Bedford (TL044519) and Maids Moreton (SP708345). Fabric analysis places the first of these in the "Lowestoft" glaciation, of Baden-Powell (1948), while the last three sites are "Gipping" in age (Chapter V.A). The implication from this is that two chalky tills exist in the area, which Edmonds and Dinham (1965) confirmed.

As with the lower till, the description of the chalky till in the Ouse basin compares closely to that given for chalky till in the Nene basin, by Hollingworth and Taylor (1946a; 1951), Kellaway and Taylor (1952) and Taylor (1963).

## D. Glacial Gravel.

Closely associated with the till deposits, in the study area, are those gravels referred to by previous authors as 'glacial'. They are found both within, and beneath, the chalky till in the Nene basin (Richardson and Kent, 1938; Hollingworth and Taylor, 1946a; 1951; Taylor, 1963; Clarke and Moczarski, 1982; Harrisson, 1983), where they are reported to contain flint (20%), chalk (10%) and Bunter pebbles (10%), in addition to local Jurassic pebbles (about 58%)(Clarke and Moczarski, 1982). In the Ouse basin similar scattered occurrences of glacial gravel have been described (Salter, 1905b; Edmonds and Dinham, 1965; Horton, 1970; Horton <u>et al.</u>, 1974; Gatliff, 1981). Edmonds and Dinham (1965; p69) describe the glacial gravels identified near Biggleswade as

> ". . . well-bedded chalky gravel [frequently] overlain by brown decalcified flint gravel which extended

> downwards into the chalk gravel as long irregular pockets."

Screened material greater than 1" (2.5cm) diameter in a pit (TL171391), open in 1946, 500yds.(457m) east-southeast of Clifton church, showed a ratio of flint to chalk of 60:30. The corresponding figures for the medium grade (about 0.5-0.75" (1.27-1.9cm)) were 25:70 and for the fine grade (about 0.25" (0.63cm)) 10:75. Percentages of Bunter quartzite, ironstone and other pebbles varied from 5 to 15.

Horton _et al._ (1974; p41) describe the glacial sand and gravel in the Milton Keynes district as comprising

> ". . . the coarser more resistant fraction of the boulder clay, the chalk, flint and other rock fragments being left when the softer material was fragmented and transported with the matrix away from the source area."

The gravel found within the till is generally poorly-sorted and ill-bedded, while gravel that is bedded is probably extraglacial. In general

> "The Glacial Sand and Gravel outcrops are rarely exposed in section and little is known of the thickness, grading and geological relationship of most accumulations." (Horton _et al._, 1974; p41).

E. River Terrace Deposits.

Within the study area defined above, parts of two river systems are enclosed; those of the Nene and Great Ouse. Both have terraces described.

1. The Great Ouse.

The Ouse system comprises four main streams: the rivers Tove, Ouzel, Ivel, and the Great Ouse itself (Chapter III.B). Three terraces are reported and have been mapped by the Geological Survey, although

> ". . . no connected account appears to have been published." (Dury, 1952; p137),

until those of Edmonds and Dinham (1965), Horton (1970) and Horton et al. (1974).

a) Third Terrace.

Dury (1952) records third terrace gravel at a height of 50' (15.2m) above the alluvium - a height that agrees reasonably well with that of Edmonds and Dinham's (1965, p66) 48-58' (14.6-17.6m) above the alluvium, although their heights are assumed, their measurements relating to the height above the base of the sub-alluvial gravel. Horton (1970) criticises Edmonds and Dinham's datum, since the gravels on this datum form part of the deposit which also forms the terraces beyond the floodplain. In addition, this datum is undulating. To reduce error, and relate the terraces to a consistent base level, Horton (1970) and Horton et al. (1974) use the surface of the alluvium as their datum.

Horton (1970) reports that the third terrace is only found in the lower Ouse and Ivel valleys, downstream from Bedford and, unlike the lower terraces, converges with the alluvium downstream, being at a height of 53-59' (16.1-18.0m) above the alluvium at St. Neots, but only 28' (8.5m) at Holywell, near St. Ives. At the latter site, a borehole (TL34017135) proved 19' (5.8m) of gravel. Patches of gravel ascribed to this terrace are also described, by Edmonds and Dinham (1965; p69), west and southwest of Great Barford, at Wyboston (TL152566) and at Buckden (TL195657).

b) First and Second Terraces, below Bedford.

Below Bedford, especially below the confluence with the river Ivel, the lower terraces of the Ouse and Ivel are usually shown as "combined first and second terrace" on Geological Survey Maps, because they cannot be distinguished, in terms of elevation. The separate terraces are only specified individually in a few localities (e.g. on the west bank between Roxton (TL155545) and Eaton Socon (TL170595))(Edmonds and Dinham, 1965; Horton, 1970). Edmonds and Dinham (1965) show that screened material from the Ivel terrace deposits, greater than 1.5" (3.8cm), is composed of 70% flint and 30% Bunter quartzite. Chalk is absent, but becomes commoner in the finer fractions. In the '0.5" (1.27cm) gravel', the ratio is: chalk 50%, flint 45%, quartzite 5%. A similar analysis, at St. Neots, showed chalk 60%, flint 20% and quartzite 10% in the finest fraction, and up to flint 60% plus and quartzite 30% plus in the pebbles greater than 1.5" (3.8cm) diameter. Gatliff (1981) gives a similar composition to Edmonds and Dinham; flint 70%, quartz and quartzite 10%, sandstone (ferrous) 10%, chalk and limestone 10%. He also states that the composition of all the terraces is similar.

Horton (1970), re-evaluating Edmonds and Dinham's (1965) data, assigns to the combined terrace gravels on the east bank of the Ivel at Biggleswade, an average surface level of 5-6' (1.5-1.8m) above the alluvium, although they attain a height of 10' (3.1m) at the back of the outcrop.

West of the river, the terrace is 0-3' (0-0.9m) above the alluvium, into which it grades. The maximum gravel thickness locally reaches 14'9" (4.5m). Where the terraces have been separated at St. Neots, the first terrace gravel has a surface 4-5' (1.2-1.5m) above the alluvium and a maximum recorded thickness of 10' (3.1m) (TL17471980), while the second terrace gravel has a flat at 9-16' (2.7-4.8m) above the alluvium and a maximum recorded thickness of 8' (2.4m)(TL17015792) (Horton, 1970).

Within the gravels of the lower terraces, at St. Neots, Little Paxton and between St. Ives and Huntingdon, some archaeological and faunal material has been discovered (De La Condamine, 1853; Tebbutt, 1927; Paterson and Tebbutt, 1947). In all three areas, the gravels are inferred to underlie the first terrace. Near St. Ives, De La Condamine (1853) found land and freshwater shells (Pupa marginata; Helix hispida; Valavata piscinalis; Succinea oblonga; Limneus pereger; Bithinia tentaculate; Planorbis marginata; P. spirorbis; Cyclas cornea; and Pisidium amnicum), together with mammals (Bos; Sus; Equus; and Cervus elaphus) and flint implements, in the gravels. Similar discoveries were made at St.Neots and Little Paxton, where the bones and teeth of Mammuthus primigenius (Mammoth), Coelodonta antiquitatis (Woolly Rhinoceros), Rangifer tarandus (Reindeer), Equus ferus (Wild Horse) and Bos (aurochs) have been found in ferruginous, fluviatile deposits (Tebbutt, 1927; Paterson and Tebbutt, 1947). Such species are considered as "typically glacial" by Renfrew (1974). At these sites, flint implements of

> ". . . a fine Levalloisian core technique has been overlain by an Acheulian biface or 'wood technique' of preparatory working." (Patterson and Tebbutt, 1947, p43),

an industry which Paterson and Tebbutt (1947) and Renfrew (1974) suggest is "probably Mousterian". The hand-axes found, in association with 'typically glacial' mammalia, led Renfrew to suggest that they

> ". . . are most likely to date from a very early stage of the last glaciation, possibly during the initial cold episode which preceded the Brørup/Chelford interstadial." (Renfrew, 1974)

(i.e. early Devensian). Such an age implies that first terrace deposits are of a similar age; an age which agrees with the evidence in the Nene basin (Morgan, 1969; see IV.E.2 below).

### c) Second Terrace, above Bedford.

Upstream from Bedford, the only description of the terraces of the Tove, Ouzel and Great Ouse rivers, is that of Horton et al. (1974). Along the valleys of these rivers, two terraces have been determined, at 2-4.5m above the alluvium, and at 0.6-2.0m above this datum (Horton et al., 1974; p53).

Deposits of this terrace are delineated in each of the river valleys. In the Tove valley, only the lower reaches are reported to contain second terrace gravel, near the confluence with the Ouse, around Castlethorpe and Cosgrove. The Ouse valley contains spreads of the second terrace gravel in the areas covered by the village of Passenham, and the "lower 'flat' part of Stony Stratford" (Horton *et al.*, 1974). Smaller patches also occur on the valley sides near Wolverton, Bradwell, Haversham and Little Linford. Horton *et al.* report that the second terrace deposits in these valleys are reflective of their source area, and contain, in addition to erratic material (chiefly flint, chalk and occasionally Bunter-derived pebbles), a reasonable proportion of local Jurassic limestone, with lesser amounts of ironstone.

More extensive deposits of second terrace gravels are described along the valley of the Ouzel, around the villages of Milton Keynes, Broughton, Caldecotte, northeast of Fenny Stratford, and on both sides of the valley from Water Eaton to Stoke Hammond. At the Broughton Quarry, of GFX Hartigan Ltd., the gravel is stated (Horton *et al.*, 1974) to be 2-3.5m thick, chiefly fine to medium gravel with some coarse pebbles. Flint is reported to be the dominant component, with some chalk and Jurassic limestone and ironstone pebbles, in a sandy matrix. Derived Jurassic and Cretaceous fossils, such as Belemnites, thick shelled Gryphaea and phosphatic casts of ammonite chambers, are fairly numerous in the gravel. The base of the gravel is stated to lie between 60.4m and 62.5m O.D. in this area; that is, only 1-2m above the level of the present floodplain.

### d) First Terrace, above Bedford.

Deposits of this terrace are widespread on the floors of the Tove, Ouzel and Ouse valleys. Traced almost to the source of the first two rivers, the deposits have an average thickness of 3-4m (the maximum thickness which has been worked). Horton et al. (1974; p54) describe the terrace gravel, in the Ouse, as

> ". . . mixed in grade with an appreciable element of 'fines'. The components are chiefly flint and Bunter-derived pebbles with minor proportions of Chalk, Jurassic and other erratic rocks."

In the Ouzel the deposits

> ". . . are much thinner than their counterparts in the Ouse valley . . . The terrace top is usually from 0.6 to 2.0m above flood-plain level, and has a capping of brown stony sand loam up to 1.0m thick. The gravels beneath this are thin, varying in grade from fine to coarse with a brown sandy matrix; iron-cemented sandstone pebbles derived from the Woburn Sands outcrop are common constituents, in addition to the flints and Bunter-derived pebbles noted in the Ouse valley terraces." (Horton et al., 1974, p54).

The terrace has a gentle, riverward slope, which passes almost imperceptibly into the floodplain surface (Horton et al., 1974; p54). The maximum thickness proved, by Horton et al., in the Ouzel valley, is 3.5m between Fenny Stratford and Simpson, but, in general, sections suggest that the terrace deposit averages about 1m, only rarely exceeding 2m. The widest extension of the terrace occurs around Newport Pagnell, where it attains a width of over 1km. The surface of the first and second terraces, being broadly parallel to that of the alluvium, led Horton (1970; Horton et al., 1974) to believe that the terraces in the Milton Keynes area are probably

> ". . . co-extensive [sic] with the similar deposits of the Lower Ouse, below Bedford, and the river Ivel." (Horton et al., 1974, p52)

Upstream from Deanshanger, and between Newport Pagnell and Bedford, there is a large gap in the knowledge of the terrace deposits. Horton's (1970) work, and that of Edmonds and Dinham (1965), is confined to deposits downstream from Bedford, while Horton et al. (1974) discuss in detail only those deposits in the Milton Keynes area. Except for the early literature on the gravel deposits around Bedford (Wyatt, 1861; 1862; 1864; Prestwich, 1861; 1864; Evans, 1897; Doubleday and Page, 1904; Banton, 1924; Mantle, 1926), where an upper- and lower-division is made, no description is available. The early authors primarily concerned themselves with four or five sites around Bedford, of which the most significant are at Biddenham, a Railway Cutting and Summerhouse Hill. Wyatt (1861; 1862; 1864) and Prestwich (1861; 1864) were the first to discover flint implements, together with land, and freshwater, shells and mammal remains (table 4.1), in a "high-level" gravel at Biddenham, approximately 2 miles (3.2km.) west-northwest of Bedford. The gravel at Biddenham caps a low hill and reaches a maximum elevation of 59' (18.0m) above river level (Prestwich, 1864; Evans, 1897), with a recorded thickness of 13' (4.0m). According to Prestwich (1861), Evans (1897), and Doubleday and Page (1904), the gravel is principally composed of fragments of flint, local oolite debris, pebbles of quartz and sandstone of the New Red Sandstone 'conglomerate', with fragments of various old rocks. The flint implements, found at the site, were usually in the basal layers of the gravel. Banton (1924), on the basis of both supposed Acheulian and supposed Mousterian flint implements having been found, suggested that two different deposits of different ages are present at the site. Banton (1924) also stated that the work of Prestwich and Wyatt, at the site, needed revision, because no recent list of the mollusc or mammal fauna exists. Both Wyatt (1862) and Evans (1897) unfortunately combined their records with species from other sites, at Harrowden (Wyatt and Evans) and Summerhouse Hill (Evans), which represent two separate levels.

At a level 20-30' (6.1-9.1m) below the Biddenham site (approximately 30-40' (9.1-12.2m) above the river) another series of sites are identified: at Kempston (Wyatt, 1862), Harrowden (Wyatt, 1861; 1864; Banton, 1924), Clapham (Wyatt, 1861), Bletsoe and Radwell (Wyatt, 1861), and a Railway Cutting on the Great Northern Line, 1mi. (1.6km) north of Bedford (Prestwich, 1861; 1864). The sites at Bletsoe, Radwell and the Railway Cutting all follow the Great Northern Line, and have a wide range of fauna (table 4.1). The significant site appears to be the Bedford Railway Cutting. Here, Prestwich (1861; 1864) described abundant Hippopotamus, which he claimed (1864) is absent at Biddenham. Significantly the Railway Cutting is also reported to contain <u>Equus</u> (horse), which is not recorded with Hippopotamus at any present day sites (Shotton, 1982). Hippopotamus has also been recorded downstream at Brampton, near Huntingdon (Tebbutt, 1927; Patterson and Tebbutt, 1947), in second terrace deposits of the Ouse.

At Summerhouse Hill, 4 miles (6.4km) downstream from Bedford, similar finds of fauna and flint implements have been made (table 4.1). This site is at a lower level than that at Biddenham, being approximately 5-10' (1.5-3m) above river level (Wyatt, 1864). Prestwich (1862) believed that the gravels at the two sites formed under different conditions, a belief confirmed by Wyatt (1864; p184):

> "Without doubt I have found this lower portion of the Drift exhibit some features not met with in the higher levels, namely, a marked difference in the grouping of the fauna and in the types of Flint Implements. Although, as might have been expected, there are several species of Mammals in common, yet the section under notice contains some species not known in the localities considered to belong to the upper-level deposits; and the same remark holds good with reference to the land and freshwater Shells."

The presence of Hippopotamus at this site (Wyatt, 1864) may correlate to the gravels of the Bedford Railway Cutting, but, altitudinally, it appears to be at too low a level. The possibility that identification, at either site, may be at fault, cannot be removed. The numerous finds at the Railway Cutting, and the finds in the second terrace at Brampton, suggest that the Summerhouse Hill descriptions may be inaccurate, but the report of horse at the Railway Cutting suggests that this may be inaccurate. Other low level sites have been described downstream at Willington (Banton, 1924; Mantle, 1926; Bate, 1926), Great Barford (Mantle, 1926), St. Neots (Tebbutt, 1927, Patterson and Tebbutt, 1947), and Little Paxton (Tebbutt, 1927). Tebbutt (1927) regarded these deposits as the lowest terrace of the Ouse, being at a lower level than the second terrace at Brampton, and correlated them to the lowest terrace of the Cam, which is generally regarded as late Pleistocene. The fauna from the sites (table 4.1) led Bate (1926) to suggest a cold climate, which is probably late Pleistocene in age. Archaeological material, from the St. Neots and Little Paxton sites, also suggests an early Devensian age (see E.1 above).

All the sites mentioned above have since been refilled and would require careful re-excavation before they could be fitted into the terrace sequence described today.

### e) Alluvium

The recent floodplain alluvium infills a channel, cut into the gravels of the first terrace, in the Ouse basin. In the upper Ouse basin, and in the valleys of the Tove and Ouzel, the alluvium consists of soft brown, silty clay with scattered pebbles, becoming dark grey with depth. Borings, in both the Ouzel and Ouse valleys, prove the alluvial fill to depths between 0.6-2.8m, below which gravels of the first terrace are encountered. One

> ". . . interesting section (90874392), 500m S 30 [degrees] east of Hill Farm, shows 0.6 to 1.0m of dark brown alluvial clay loam, resting on 0.6m of coarse to medium gravel with cobbles up to 0.25m, in the stream bank, below which up to 0.3m of blue grey Chalky Boulder Clay was seen in the stream bed." (Horton *et al.*, 1974; p56).

Below Bedford, in the lower Ouse valley and the Ivel valley, Edmonds and Dinham (1965) and Horton (1970) describe similar sections in alluvium, consisting of silty clay with scattered stones (mostly flint with some chalk - Edmonds and Dinham, 1965) and a varying proportion of organic detritus. The alluvium in this area appears to

At Biggleswade the maximum thickness is 9' (2.7m).

St.Neots . . . . . . . . . . . . . . 14'6" (4.4m).
Offord . . . . . . . . . . . . . . . 16'6" (5.0m).
Godmanchester . . . . . . . . . . . . 20' (6.1m).

(Horton, 1970; p21).

2. The Nene.

As in the Ouse basin, three terraces have been recognised in the Nene valley (Kellaway and Taylor, 1952; Taylor, 1963; Castleden, 1976; 1977; 1980a; 1980b; Clarke and Moczarski, 1982; Harrisson, 1983).

a) Third Terrace.

The third terrace gravel rests on a bench cut in the Jurassic rocks of the valley side. Taylor (1963) showed that the surface of the gravel is at a height of 33-55' (10.6-16.8m) above the alluvium, usually between 45-50' (13.7-15.2m). The constituents of the gravel are stated to be predominantly flint, Bunter quartzite, ironstone, limestone, brown sandstone, quartz grit, silicified limestone and a gneissose granite. This agrees closely with the analysis of Castleden (1980b), in which the gravel comprised local material, from the bedrock in the Nene (shelly and oolitic limestone, sideritic ironstone and sandstone), and some erratics, "probably winnowed from glacial deposits" (Bunter quartzite, gritstone, flint, chalk and pink gneissose granite). The gravel is also described as positively skewed (mostly fine), containing both sub-rounded (27.5%) and sub-angular (24.5%) pebbles. The greatest recorded thickness is 3m.

Clarke and Moczarski (1982) give the composition of the terrace gravels as flint 18%, quartz/quartzite 8%, sandstone 7%, limestone 7%, chalk 1%, ironstone 58% and others 1%; a composition which Harrisson (1983) states is similar to the other Nene terraces, and is governed by the nature of the local bedrock.

b) Second Terrace.

More dissected than the first terrace, but less so than the third terrace, the second terrace is preserved, according to Taylor (1963), at a level of 15-30' (4.6-9.1m) above the Nene floodplain (average height of 25' (7.6m)). This conflicts with Castleden's (1977) height of 4m above the floodplain. The composition of the gravel, however, is similar in both descriptions, containing local shelly and oolitic limestones, sideritic ironstone and sandstone, and erratics of Bunter quartzite, white quartz, flint, chalk and feldspar (table 4.2). The gravel reaches a maximum thickness of approximately 20' (6.1m) downstream from Rushden. Undisturbed implements have been found within the gravel of this terrace, near Woodston (Kennard and Woodward, 1922; p128; in Kellaway and Taylor, 1952). The age of the implements was said to be Mousterian, which, by analogy with the deposits in the lower Ouse terraces, would imply a Devensian age for the terrace.

c) First Terrace.

This forms a low shelf, 4-8' (1.2-2.4m) above the level of the floodplain, occasionally rising to a height of 15' (4.6m) above it. As with the first terrace of the Ouse, the alluvium rests in a channel within this terrace (Taylor, 1963), and separated topographically from it by a step of about 2m (Castleden, 1976). A maximum thickness of 13m is found at Northampton. At Great Billing, 4.5mi (7.2km) east of Northampton, Morgan (1969) described 11-14' (3.3-4.3m) of coarse gravel, with pebbles usually less than 1" (2.54cm) in diameter, but with occasional cobbles reaching 5" (12.7cm) in size, beneath the alluvium.

Lithologically, the majority of the gravel is sub-rounded to angular flint, with the larger pebbles and cobbles consisting of

> ". . . rounded flints and shelly limestones, the latter probably being derived from nearby outcrops of the Great Oolite Limestone and Upper and Lower Estuarine Series." (Morgan, 1969; p109).

Castleden (1976) also reports the presence of chalk, quartzite and hornblende-gneiss erratics, in this terrace.

Within the gravels, at Great Billing, an organic deposit has been discovered (Morgan, 1969). This contains a wide variety of fauna and flora, including mammals (Coelodonta antiquitata; Mammuthus primigenius and Rangifer tarandus), Mollusca (mainly gastropoda) and Arthropoda (dominated by Coleoptera). The Coleopteran and Molluscan assemblages, suggest conditions of small, shallow pools rather than open water, a conclusion supported by the flora, which consists of aquatic mosses, sedges and rushes, with dwarf shrubs and various types of low growing perennials. The climate, indicated by the flora and fauna, is similar to that of sub-arctic tundra today. A comparison of the flora and fauna from this site, with other sites, shows similarities with the sites at Brandon Terrace (Coope, 1968) and Upton Warren (Coope et al., 1961), together with others of similar age. A carbon-14 date for the deposit at Great Billing, of 28,225 +/- 330yrs BP., also shows a close similarity to dates from the Brandon Terrace (30,000yrs BP.). The evidence, therefore, points to a Devensian age for first terrace deposits, of both the Ouse and Nene basins.

In the Nene valley, reconstructed terrace surfaces are parallel to each other, and to the surface of the alluvium (Castleden, 1980a), and thus differ from the terrace sequence described in the Ouse basin (see E.1 above).

A summary of the terrace characteristics of both the Ouse and the Nene, is presented in table 4.3.

# Chapter V. Previous Research.

## Introduction.

The Middle and Upper Pleistocene stratigraphy of the British Isles has always been a subject of contention, and is likely to continue to be so. In many cases the controversy arises out of a lack of information, while in some cases the disagreement is between two, or more, forms of evidence in a multidisciplinary subject.

The concern of the present study is with the stratigraphy of the upper Ouse basin, an area where very little recent research has been undertaken. The surrounding regions of East Anglia, the Thames basin, and the Midlands have been the foci for the majority of the research (fig. 5.1). The type of evidence used to build up the regional stratigraphies includes lithology, morphology, biology, and geochronometric data. However, the application of more than one of these approaches to a particular problem has often led to different conclusions between, and within, regions. The deposits most usually associated with the Quaternary are tills, gravels and sands, most commonly associated with colder episodes, together with the deposits of the intervening warm episodes, particularly organic clays, muds and peats. It is with these deposits that most research is concerned and which, therefore, need to be discussed here.

Because most research is undertaken at specific sites, or in particular regions, the review is divided into five sections:

A. East Anglia.

B. The Midlands and Upper Thames.

C. The east Midlands and south Lincolnshire.

D. The Middle and Lower Thames.

E. The Upper Ouse basin.

The development of ideas on the stratigraphy of these areas is considered, and previous correlations between areas are noted.

Although the records from oceanic cores - e.g. V28-238 (Shackleton and Opdyke, 1973) suggest that since the beginning of the Quaternary there have been up to seventeen major cold periods, there is no direct evidence of glacial deposition (till) for periods older than the Anglian (Mitchell et al. (1973). Indirect evidence is available, however, from Thames river gravels where Green and McGregor (1978), McGregor and Green (1978, 1983a) and Green, McGregor and Evans (1982) have identified three pre-Anglian periods when far-travelled pebbles were introduced into the fluvial system, apparently by ice. Hey (1980) has also suggested that Rhaxella chert was introduced into north Norfolk by a North Sea glacier during the Pre-Pastonian. A similar age is put forward by Shotton (1982) for the earliest deposits of the Northern Drift in the Oxford area.

The deposits with which the present study is most concerned, however, are those which are related to glacial till, and therefore the discussion is restricted to the post-Beestonian sequence of the Middle and Upper Pleistocene, as defined by West (1963) and Mitchell et al. (1973).

## A. East Anglia.

It is now generally accepted that the glacial drift of East Anglia is the product of more than one ice advance. The exact number of glacial episodes, and the relationship of interglacial deposits to each episode, however, is still uncertain, despite the wealth of information presently available.

The early views of Harmer (1904; 1907; 1928) and Boswell (1914; 1916), reflected the views of S.V.Wood, and suggested that the glacial drift in Norfolk and Suffolk was the product of a single glacial episode - the Great Eastern Glaciation. Harmer (1928) identified changes in the till matrix which he suggested were caused by distinct, but confluent, ice streams following slightly different courses south. However, Boswell (1931) and Solomon (1932), re-examining the evidence, suggested that a multiple glacial sequence provided a better explanation for the drift (table 5.1) which Solomon (1932) considered

> ". . . to be the product of four distinct ice-sheets, belonging to four important periods of ice advance."

Nowhere are the deposits comprising the succession seen in a single sequence, but three broad deposits were recognised. The earliest drift is recognised at Corton, North Suffolk, and comprises a deposit known variously as the North Sea Drift, Contorted Drift, Cromer Till or Norwich Brickearth. Separating this from an upper chalky till, at Cromer, is a series of sands forming the Corton Beds. The chalky till, which covers much of Suffolk and Norfolk, is the most widespread of the East Anglian drifts. The most recent till (Newer Drift), representing the last glacial episode, is the Brown or Hessle Till of Hunstanton, generally only found further north in Lincolnshire, and therefore not considered further here.

The proportion of Jurassic material contained in the matrix of the chalky till varies considerably, and while Harmer (1928) considered all types to be contemporaneous, Boswell (1931) and Solomon (1932) suggested that there were two chalky tills; a lower one with a predominantly Jurassic matrix, and an upper with a greater proportion of chalk. Baden-Powell (1948) named these the Lowestoft and Gipping Tills respectively. He explained the Jurassic matrix of the Lowestoft Till by ice moving southeast across Lincolnshire and into East Anglia from the south Pennines, while the greater amount of chalk in the Gipping Till he thought indicated movement across a greater outcrop of Chalk. A more southerly course along the strike of the Chalk was therefore suggested (Baden-Powell, 1948). Therefore, three pre-Hessle Till glaciations were recognised by Baden-Powell.

West and Donner (1956) used fabric analysis to determine the direction of movement of the East Anglian drifts, and distinguished three successive episodes of ice movement, each episode representing an ice advance. The first advance - the Cromer Till advance - crossed into north Norfolk from the northwest. The second Lowestoft advance, appeared to contain two fabrics indicating two ice movements, a lower to the south of east and an upper to the north of east, suggesting advance in two stages. At Gipping the fabric conformed with Baden-Powell's southerly movement from the centre of the Wash. The similar fabric of the Cromer and Lowestoft Tills suggested that, despite the separation of the drifts by the Corton Beds, they may be part of the same advance. The upper (Stage II) fabric of the Lowestoft Till was related to the retreat of the Lowestoft Stage. West and Donner therefore considered that only two glaciations were represented by the multiple till sequence. The first, between the Cromer Forest Bed Series and the Hoxne interglacial (see below), included the Cromer Till Series and the Lowestoft advance, while the second succeeded the Hoxne interglacial and included the Gipping advance (table 5.1).

The subdivision of the East Anglian 'Older' drift into three ice advances, as part of two glacial episodes, was accepted with minor modification until the early 1970's (Baden-Powell and West, 1960; West, 1963; Straw, 1965; Banham, 1968). The succession also came to be supported by biological evidence from several interglacial sites, for example Hoxne, Suffolk (West, 1956), the Nar Valley, Norfolk (Stevens, 1959) and Bobbitshole, Ipswich (West, 1957; Sparks, 1957).

At Hoxne, a hollow in the Lowestoft Till contains a series of organic lake clays. Covering the clays a series of soliflucted clay, sand and gravel was described, which Baden-Powell (1948) interpreted as outwash from the Gipping glaciation, an interpretation which West (1956) accepted. A similar stratigraphy was described in the Nar Valley (Stevens, 1959). A lower till, correlated with the Lowestoft Till by a comparison of the texture, erratics and fabric, is overlain by interglacial lacustrine clay. An upper till with a north-south fabric overlies the lacustrine clay and was correlated with the Gipping advance (Stevens, 1959). Similar pollen diagrams from both sites were described, and suggested a four stage vegetation cycle from late-glacial, through temperate, to early-glacial climates (West, 1956).

At Bobbitshole, a demonstratably different pollen diagram suggested a different age for the interglacial deposits (West, 1957). The deposits occupy a lake basin in a terrace deposit, within a valley cut in chalky till. It lies at a level within 1m of sea level. West assigned the chalky till to the Gipping advance, and therefore the interglacial deposit was assigned to the last (Ipswichian) interglacial. Analysis of the molluscs (Sparks, 1957) confirmed the distinction.

The publication of the Geological Society's "A correlation of Quaternary deposits in the British Isles" (Mitchell et al., 1973) defined stage names for the glacial and interglacial episodes recognised by West and Donner (1956) and West (1963). Three glacial episodes were named. The first (Anglian) comprised the Cromer Till Series, the Corton Sands and the Lowestoft Till and represented the two periods of ice advance of West and Donner (1956). In north Norfolk the Anglian was identified in the contorted complex of three tills separated by sands and gravels, defined by Banham (1968), who suggested that they were equivalent to the Cromer and Lowestoft Tills at Corton, Suffolk. In Essex, the Springfield and Maldon Tills of Clayton (1957a) were believed to represent this stage.

Overlying the Lowestoft (Anglian) Till, in the Nar Valley (Stevens, 1959), at St. Cross (West, 1961), Marks Tey (Turner, 1970), Clacton (Turner and Kerney, 1971) and Sicklesmere (West, 1981b), are organic lacustrine deposits with temperate fauna and flora similar to those at Hoxne. These were therefore placed in the Hoxnian Interglacial.

The second glacial stage, the Gipping (Baden-Powell, 1948; West and Donner, 1956), was termed the Wolstonian, deriving its name from the type site in the Midlands (Shotton, 1953; see V.B below). The cold floras found in late Hoxnian sediments, and below the later Ipswichian deposits, were believed to confirm the existence of a cold stage after the Hoxnian. However, the stratigraphical relations of the deposits are unclear, the complete sequence never being present at any one site.

The Ipswichian interglacial, believed to post-date the Wolstonian, has its type site at Bobbitshole, near Ipswich (West, 1957; Sparks, 1957). Similar sites at Ilford (West, Lambert and Sparks, 1964), Aveley and Grays (Blezard, 1966; West, 1969), Wortwell (Sparks and West, 1968) and Wretton (Sparks and West, 1970) are all within present valley systems and are related to low level terrace deposits. These are often overlain by terrace deposits or by till of the last (Devensian) glacial episode.

The existence of the Hoxnian - Wolstonian - Ipswichian succession in East Anglia is questioned by Bristow and Cox (1973a; 1973b), and by Perrin, Davies and Fysh (1973), who suggest that only one chalky till is present there. Bristow and Cox (1973) report that there is no evidence of a Gipping Till in East Anglia that conforms to Baden-Powell's definition of being post-Hoxnian. They suggest that the till examined was deposited in a pre-Hoxnian episode because, although frequently underlying Hoxnian and Ipswichian deposits, nowhere in East Anglia is it confirmed overlying Hoxnian deposits. The absence of the till intervening between the Hoxnian and Ipswichian interglacial deposits precludes the direct stratigraphic evidence for the relative position of the Hoxnian and Ipswichian which Bristow and Cox (1973a) suggest are the product of a single interglacial, probably separated by a cold oscillation (table 5.1).

Perrin, Davies and Fysh (1973) come independently to similar conclusions. They examine the physical, chemical and mineralogical properties of chalky till from East Anglia and the Midlands. The analyses reveal that while the chalky till is different from the Cromer Tills, there is no systematic mechanical or heavy mineral difference between the Lowestoft and Gipping tills.

> "The remarkable constancy of composition of its matrix over a considerable area makes it difficult to believe that the Chalky Boulder Clay could be the product of more than one glaciation." (Perrin et al., 1973).

The till beneath the interglacial deposits at Hoxne, proving to be part of the chalky till, indicates a Lowestoft (Anglian) age for the entire drift, it being impossible

> ". . . to find any persistent sheet of till with a lithology sufficiently constant to confirm the evidence of a later, or Gipping, Glaciation." (Perrin et al., 1973).

The deposit overlying the organic clay at Hoxne, previously regarded as evidence of a Gipping ice advance, does not resemble any known till, and is interpreted as a locally-derived deposit, which Wymer (1974) supports. Other sites where differences in mechanical composition are noted, are interpreted as reworked 'Lowestoft' residues, for frequently they are mineralogically similar.

Perrin, Rose and Davies (1979), extend the work of Perrin et al. (1973), and conclude that all pre-Devensian tills in eastern England are the product of two major ice sheets which were penecontemporaneous in age. The tills of each ice sheet are identified: (1) The North Sea Group consisting of the three Cromer Tills (Banham, 1968; 1975; Banham, Davies and Perrin, 1975), the Contorted Drift (Banham, 1968; 1975), and the Norwich Brickearth (Boswell, 1914; Harmer, 1928; West, 1963); (2) The Lowestoft Till Group comprising the Lowestoft Till (Baden-Powell, 1948) and the Wragby and Calcethorpe Tills of Lincolnshire (Straw, 1969). Both till groups underlie Hoxnian sediments and must therefore be Anglian.

The chalky Gipping Till and the Lowestoft Till, accepted to be part of the same till unit (Bristow and Cox, 1973; Perrin et al., 1973), are described as laterally equivalent to the chalky till of the East Midlands, recognised by Hollingworth and Taylor (1946a) and Horton (1970), and to the Oadby Till in Leicestershire (Rice, 1968) (see V.B below).

This poses problems for correlation between East Anglia and the Midlands because chalky (Oadby) till in the Midlands is correlated with the Wolstonian type sequence (Rice, 1968; 1981; Shotton, 1976; Douglas, 1980), while in East Anglia chalky till underlies Hoxnian deposits at Hoxne (West, 1956) and Marks Tey (Turner, 1970). This either suggests that similar chalky tills were deposited during both the Anglian and Wolstonian glaciations or that the Wolstonian type sequence is Anglian, a correlation which would require a reinterpretation of sites such as Nechells (Kelly, 1964) and Quinton (Horton, 1974) in the Birmingham area, and at Welton-le-Wold (Alabaster and Straw, 1976) in Lincolnshire, where chalky till overlies deposits of presumed Hoxnian age. Shotton et al. (1977) dismiss the latter suggestion on the grounds that similar lithologies indicate similar source area, not necessarily synchroneity. Straw (1979; in Straw and Clayton, 1979), while recognising the uniformity of the chalky till, also suggests that both Hoxnian and Wolstonian advances are represented, with the Wolstonian margin lying across north Norfolk, following West (1977). Inside the limit Straw claims that tills are nowhere overlain by fossiliferous sediments of proven Hoxnian age or older, while both Hoxnian and Ipswichian interglacial sites are found outside the limit. Straw (1979, p543) also suggests that Wolstonian deposits rest directly on bedrock as every ice sheet destroys most of the pre-existing drift. This is the reason put forward for the lack of Hoxnian deposits inside the limit, while they survive further south.

Straw's (1979) conclusion

> ". . . is that the tills of Lincolnshire, the East Midlands and central and west Norfolk were emplaced during that glaciation which immediately preceded the Ipswichian, that is the Wolstonian."

The supposed Hoxnian sites at Narborough (Stevens, 1959) and Kirmington (Boylan, 1966), inside the Wolstonian limit, are dismissed as having highly uncertain ages, and even if they are Hoxnian, are considered to represent enclaves in the Wolstonian glaciation (Straw, 1979). Straw supports a Wolstonian age with the organic deposits at Welton-le-Wold where chalky Calcethorpe Till overlies periglacial valley gravels which contain a meagre mammalian fauna of Hoxnian character (Alabaster and Straw, 1976). The Calcethorpe

Till, must therefore post-date the Hoxnian and be Wolstonian in age.

In a review article, Cox (1981) dismisses the Wolstonian margin drawn by West (1977) and Straw (1979) because it is drawn across the centre of the unified till sheet of Perrin et al. (1979). Cox also states that the interglacial evidence is not properly related to the litho-stratigraphy and

> "The recognition of the Hoxnian and Ipswichian deposits in East Anglia is therefore based solely on the pollen profiles and is unrelated to either topography or stratigraphy."

This situation is clearly unsatisfactory, as West (1981a) points out. Cox (1981) also questions the correlations of the pre- and post-Hoxnian sediments at Nechells, Quinton, and Welton-le-Wold. In conclusion Cox states that

> "In vain I have searched for the line separating the 'Wolstonian' and 'Anglian' glaciations. Straw's work (1979) is perhaps the only evidence for a till that separates Hoxnian from Ipswichian deposits, but the evidence for this is tenuous and indirect."

Straw (1982), in reply to Perrin et al. (1979), Catt (1981) and Cox's (1981) questions about the age and stratigraphic relation of the Lincolnshire Tills, again argues for a Wolstonian age and notes that

> ". . . whilst it is currently fashionable to regard all pre-Devensian tills of eastern England as Anglian, the field evidence does not yet support such an opinion."

B. The Midlands.

In the Midlands, the glacial stratigraphy proposed by Shotton (1953) in the Coventry-Rugby area, forms the backbone of later research (table 5.2). The glacial drift forms an overlapping sequence within a great pre-glacial valley which runs northeast from the region of Bredon Hill towards Leicester, and which caps the present Avon-Soar watershed.

The type sequence, described at Wolston (Shotton, 1953), consists of a basal gravel, named the Baginton-Lillington gravel, which grades upwards into the Baginton Sands which overlap onto the valley sides. To the north of the area, from Wolston to Baginton, the gravel is composed wholly of Bunter-derived pebbles while to the south, around Lillington, the proportion of Jurassic material increases. The intercalation of both types at Cubbington Hill demonstrates synchroneity.

Within the Baginton-Lillington gravels, and the Baginton Sands, a mammalian fauna is described at Lillington, Baginton and Kings Newnham. Both cold (*Mammuthus primigenius*, *Coelodonta antiquitatis*) and warm (*Palaeoloxodon antiquus*, *Equus*) animals are present suggestive of a cold steppe, rather than a tundra, biotcpe (Shotton, 1953, p220).

A red, largely stoneless, silty clay is locally preserved beneath the sands and gravels at Bubbenhall and near Coventry. It is described resting on the Keuper Marl, from which it is distinguished by the occasional presence of laminations and scattered Bunter quartz and quartzite pebbles. Shotton (1953) named this the Bubbenhall Clay.

Overlying the Baginton Sands at Wolston is the tripartite Wolston Series, with a thick sand layer separating two beds of clay. The Wolston Clays form the bulk of the deposit and appear, from laminations, to be lacustrine deposits, although part of the Lower Wolston Clay contains scattered pebbles and may be interpreted

> ". . . as till of an unusually clayey character." (Shotton, 1953, p223).

The interpretation of the Wolston Clay as a lacustrine deposit was supported by the Wolston Sand, which was thought to be of deltaic origin (Shotton, 1953). To the northeast and northwest of Wolston, the Wolston Series is interbedded with chalky till and Triassic till respectively, indicating that the lake producing the Wolston Series (Lake Harrison) was ponded by two ice streams. The pebble content of the Wolston Series changes from Bunter- and Keuper-rich, in the Lower Wolston Clay, to a flint gravel (the overlying Dunsmore Gravel) and was interpreted as indicating that a northern Triassic-rich ice stream was gradually pushed aside by chalky eastern ice throughout the deposition of the sequence. The Dunsmore Gravel, overlying the upper Wolston Clay and capping the high ground of the area was believed to be the lateral extension of the Eastern Till which overlies the Wolston Series further north (Shotton, 1953).

The tripartite sequence described by Shotton, south of Coventry, was also recognised in the Middle Trent valley by Clayton (1953) and was later traced south to Moreton-in-the-Marsh (Bishop, 1958), and northeast to Leicester (Rice, 1968). Shotton (1976) presenting the results of a borehole survey along the M69 motorway, bridging the 24km gap between his early work (1953) and that of Rice (1968), confirmed and revised the sequence, which was later traced in the Charnwood forest area (Bridger, 1975, 1981), in western Leicestershire (Douglas, 1980), and in southern Leicestershire (Rice, 1981)(table 5.2).

The major addition to Shotton's (1953) stratigraphy was provided by Rice (1968). Overlying the Thurmaston Sands and Gravels (correlated with the Baginton-Lillington Gravels - table 5.2), and interdigitated with, and overlain by, the Glen Parva and Rotherby Clays, is the Triassic-rich, Thrussington Till. Rice considered this to represent the first stage in the ponding of Lake Harrison by northwest ice. The interdigitation of the Thrussington Till with the Glen Parva Clay and the overlying Rotherby Clay (Lower Wolston Clay) suggested a fluctuating ice margin. The change to the Wigston Sand and Gravel (Wolston Sands) was considered to represent a transitional bed from the dominance of northwestern (Triassic) till to northeastern (Oadby) till. The gravel, therefore, has the characteristics of both till sheets with flint and chalk becoming dominant upwards, in a similar manner to that described by Shotton (1953) throughout the Wolston Series.

Rice (1968) equated the overlying Oadby Till, in Leicestershire, with the Upper Wolston Clay and recognised a change from Triassic-rich to Chalk-rich till upwards. Rice, therefore, separated these into the Lower and Upper Oadby Tills. The advance of the upper chalky till ice over the lacustrine clays was equated with the ice advance which Bishop (1958) stated deposited the Moreton Drift at Moreton-in-the-Marsh.

Shotton (1953) considered the sequence to represent the infilling of the proto-Soar valley during a single glacial episode. The advance of northern ice into the lower proto-Soar valley, and its main tributaries, ponded up a large proglacial lake, Lake Harrison, against the Jurassic escarpment to the southeast. The advance deposited the Thrussington Till of Leicestershire, while causing the change from northeast-flowing river gravels (Baginton-Lillington Gravels) to finer sands and then lake clays. The presence of the Wolston Series at an altitude of 404' O.D. (123m) suggested that the surface of Lake Harrison reached a maximum of 410' O.D. (125m), a height requiring that the outlets to the northeast, north, and southwest were blocked. Independent evidence was provided by an erosional 400' (122m) to 410' (125m) bench, cut across structures, along the northwest face of the Jurassic escarpment from the extremity of the North Cotswolds to a point south of Rugby (Dury, 1951). At Daventry, Fenny Compton, and Dassett cols cross the Jurassic scarp at levels about 410'. Dury (1951), tracing the 'lake-bench' through the Fenny Compton Gap suggested that it may have functioned as a spillway to the Cherwell valley. Shotton (1953) and Bishop (1958) agreed and related high level terraces of the Cherwell and Evenlode to the overflow stages (see below).

During the existence of Lake Harrison, the lithological evidence suggests that Triassic northern ice gave way to Chalky eastern ice. The latter eventually overran the Wolston Clay preceded by the deposition of a sandur (the Wolston Sands). The maximum extension of the ice to Moreton was thought to have resulted in Lake Harrison rising locally to 435' O.D. (132.6m) allowing overflow into the Evenlode to occur at Moreton, while the overflows further north were blocked by ice. Following the retreat of the ice the Fenny Compton overflow again became active and ponding again occurred, depositing the Upper Wolston Clay, while the outwash from the retreating ice deposited the Dunsmore Gravel (Shotton, 1953; Bishop, 1958; Rice, 1968; Douglas, 1980).

The age of the succession has, like the deposits in East Anglia, been a matter for debate. Shotton (1953) considered the sequence to be older than the Avon terraces, which date to the last (Ipswichian) interglacial and later (see below). He placed the Wolston Series and the related ice advances in the preceeding (Saalian) glaciation. He supported this with the cold fauna in the Baginton-Lillington Gravel, which is not recorded elsewhere before the Saale period. The Bubbenhall Clay, antedating this episode and associated with glacial action, was therefore assigned to the antepenultimate (Elster) glaciation. A similar sequence was reported in Northamptonshire, where chalky till was found overlying non-chalky till (Hollingworth and Taylor, 1946a), which Shotton equated with the Wolston Series and Bubbenhall Clay respectively.

Unfortunately, the sequence is nowhere related stratigraphically to either younger or older interglacial deposits. However, further west, palynological support is present at Nechells (Duigan, 1956; Kelly, 1964) and Quinton, Birmingham (Horton, 1974). At both sites Hoxnian interglacial deposits overlie and underlie glacial drift, thereby providing evidence for post- and pre-Hoxnian glacial episodes. The basal deposit at both sites is a till containing Welsh erratics. Overlying this are Hoxnian lake deposits followed by Bunter-rich sand and till. Although the exact relationship of the till at these sites is uncertain (Horton, 1974), it is generally believed that the overlying tills are contemporary with the Wolston Series.

West and Donner (1956), however, correlated the northwestern Thrussington Till of the Leicester area with the Lowestoft Till of East Anglia, and the northeastern Oadby Till with the Gipping episode. Posnansky (1960) accepted and elaborated this chronology in the Middle Trent basin. Here he identified a western Pennine Drift which he correlated to the lower till, found beneath the chalky till by Hollingworth and Taylor (1946a) in Northamptonshire, and thereby to the Lowestoft Till (Baden-Powell, 1948; West and Donner, 1956) in East Anglia. He related an overlying chalky till, with a northern limit on the north side of the Trent valley, and a contact zone with the Pennine Till at Derby, to the Gipping episode. This, however, is inconsistent with the Wolston Series - including the Thrussington Till - forming during a single glacial episode (Rice, 1968). Rice therefore supported Shotton that the sequence is of Saale age.

A Wolstonian age is put forward by Mitchell _et al._ (1973) and is restated by Shotton (1976), Douglas (1980) and Rice (1981). This, however, is difficult to reconcile with the work of Bristow and Cox (1973) and Perrin _et al._ (1973) in East Anglia, who demonstrated the existence of only one chalky till (see A above) which demonstrably antedates the type Hoxnian. Perrin _et al._ (1979) support this finding and suggest that the chalky till of East Anglia and the Midlands (Oadby Till) are equivalent, although only one sample of Oadby Till is examined. If this is true, then it follows that the Wolston Series must be pre-Hoxnian (Anglian) in age.

Remapping of the Midland Drift by Sumbler (1983a) led to a similar conclusion. The stratigraphy proposed (table 5.2) is essentially identical to that of Shotton (1953, 1976), Rice (1968, 1981) and Douglas (1980) except that

> "No evidence was found of the supposedly Anglian 'Bubbenhall Clay' (Shotton 1953; Mitchell, Penny, Shotton and West, 1973) beneath the type Wolstonian deposits." (Sumbler, 1983a).

Agreeing that the deposits must pre-date the Ipswichian, since the Avon third terrace is incised into the glacial drift and has yielded an Ipswichian fauna (Shotton, 1953), Sumbler argues that the evidence for a post-Hoxnian date is not clear. The mammalian evidence from the Baginton Sand and Gravel, interpreted by Shotton (1953) and Shotton, Banham and Bishop (1977) as indicating a post-Hoxnian age, is dismissed because many specimens have an uncertain origin, and those remaining are also found in pre-Hoxnian deposits.

Sumbler (1983a), on the basis of lithology, also equates the lower till at Quinton with the type Wolston till in the Redditch area, therefore proposing a pre-Hoxnian date for the type Wolston. This correlation he supports with Perrin et al.'s (1979) evidence from East Anglia, even though Shotton et al. (1977) state that similar lithology does not necessarily imply synchroneity. Sumbler also reinterprets the Avon terrace sequence implying that the gravels formed during the Hoxnian, therefore the glacial drift must be pre-Hoxnian. Shotton (1983b), replying to Sumbler, reaffirms that the sequence is Wolstonian, claiming that the possible absence of the Bubbenhall Clay and the absence of positive evidence for Hoxnian deposits beneath the Wolston Series is not sufficient to prove a pre-Hoxnian age, although he still maintains a Hoxnian age for the Baginton mammalian fauna.

Sumbler (1983b), however, maintains that his main purpose

> ". . . was to highlight the fact that the supposed post-Hoxnian pre- Ipswichian age of the type Wolstonian glacial deposits is unproven, and that in the absence of convincing proof it is highly

> unsatisfactory to use these deposits as the stratotype of a chronostratigraphic division. The evidence bearing on their age is mainly indirect and circumstantial, and facts suggesting a post-Hoxnian age are counterbalanced by facts suggesting a pre-Hoxnian age."

The terrace deposits of the Midland area may be divided into two types; those found outside the Wolston glacial limit, and those which are inside. The former includes the terraces of the Upper Thames in the Cherwell and Evenlode valleys, while the latter includes the terraces of the Avon, Soar, Severn and Trent.

a) In the Upper Thames catchment the oldest terrace is the Sugworth Terrace (although Arkell (1947) identified two higher outwash terraces, the Coombe and Freeland terraces, associated with the Northern Drift), with the Hanborough, Wolvercote, Summertown-Radley and Floodplain terraces forming successively. The Hanborough Terrace has, since Sandford (1924) described a warm fauna, been assigned to the period preceding the deposition of the Moreton Drift. Arkell (1947), on the basis of lithology and altitude, correlated the terrace with the Paxford gravels at Moreton. However, Shotton (1953) correlating the Paxford gravels with the 'cool' Baginton-Lillington gravels, placed the Hanborough Terrace in the preceding warm period (Hoxnian), a relationship supported by the warm mammalian fauna described by Tomlinson (1963) in the basal gravel. A post-Northern Drift (Anglian - Shotton, 1973) age was implied by the derived Northern Drift erratics in the Hanborough terrace (Sandford, 1924; Arkell, 1947; Bishop, 1958; Kellaway et al., 1971).

The Wolvercote terrace, described as a down-valley extension of the Moreton Drift by Sandford (1932), has been correlated with the outwash of the chalky till ice which overflowed at Moreton during the maximum ice extension, and overflowed at Fenny Compton during ice retreat (Arkell, 1947; Bishop, 1958; Tomlinson, 1963).

The younger Summertown-Radley terrace has two depositional phases; the lower (earlier) containing evidence for a cold climate, the upper, containing Hippopotamus and Rhinoceros, indicating a warm climate (Sandford, 1924; Bishop, 1958). Both were considered to post-date the chalky till at Moreton. The terraces were related to the stage names by Bishop (1958) and Mitchell _et al._ (1973) following the generally accepted succession (table 5.3).

Briggs and Gilbertson (1973; 1980), however, in an analysis of the molluscan fauna in the Hanborough Terrace, suggest a cool climate. The terrace, antedating the cold (Wolstonian) Wolvercote Terrace must, therefore, represent an earlier phase of the Wolstonian or a late phase of the Anglian, forming after the Northern Drift from which its erratics are derived. Briggs and Gilbertson (1973) prefer an early Wolstonian age because it provides a better explanation for the derived warm mammalian fauna at the base. Organic evidence from Sugworth (Briggs _et al._, 1975; Shotton _et al._, 1980), however, suggests that the Northern Drift is a composite deposit forming both before and after the Cromerian, and Shotton (1982) suggests that the earliest age of the Northern Drift may be as early as the

Pre-Pastonian (West, 1981a). Deposits truncating the Cromerian Sugworth material, though also of Northern Drift type, must be Anglian. The Hanborough Terrace post-dating these deposits is, therefore, early Wolstonian, with the warm mammalian fauna at the base representing the Hoxnian after the Anglian at Sugworth. It is this correlation which is restated by Shotton (1983b) in support of a Wolstonian age for the Wolston Series.

b) Within the glacial limit, the terraces of the Avon are incised into the deposits of the Wolston Series and, therefore, must post-date them (Shotton, 1953). The highest terrace (Number 5), absent north of Stratford-upon-Avon, was considered to have developed while the chalky till ice was near Warwick, therefore preventing development upstream. The flow to the southwest, away from the ice margin, initiated the reversal of the proto-Soar drainage. The fifth terrace is probably of similar age to the cold lower stage of the Summertown-Radley terrace (table 5.4). Recent faunal finds, however, suggest a temperate climate, but with some species (e.g. _Pupilla muscorum_) indicative of cold steppe conditions (Shotton, 1977b).

The deposits of the third and fourth terraces were believed to be part of a continuous aggradational sequence (Shotton, 1953; Tomlinson, 1963), with the third terrace formed during downcutting. The third terrace deposits are therefore older than those of terrace four. The fourth terrace was reported to contain a fauna which indicated cold, probably treeless conditions (_Mammuthus primigenius_, *Coelodonta antiquitatis*, *Equus*, *Bison*, *Rangifer Tarandus*, together with *Pupilla muscorum*). The third terrace deposits in places underlie those of the fourth terrace and yield a fauna indicative of an Ipswichian age. They contain *Hippopotamus*, *Palaeoloxodon antiquus*, *Bos primigenius*, *Megaloceras* and *Elephas primigenius*, together with the diagnostic molluscs *Belgrandia marginata* and *Potomida littoralis* (Shotton, 1953; 1977b). The contained fauna suggested a change from a warm third terrace gravel to a cool fourth terrace deposit. Continuation of the climatic deterioration was considered to occur because the second terrace deposits contain abundant *Elephas primigenius*, *Tichorhinus antiquitatis*, *Coelodonta antiquitatis*, and *Rangifer Tarandus*, together with other species of arctic character (Shotton, 1977b).

The development of the Trent drainage appears similar to that of the Avon. Posnansky (1960), Straw (1963; 1969), Rice (1965) and Jones *et al.* (1979) have claimed that the Trent originally drained east through the Ancaster Gap at the same time as the proto-Soar flowed northeast. During the Wolstonian this outlet was blocked by ice and became filled with drift. On retreat of the ice, meltwater cut through the drift forming the present valley system and leaving three terraces. The highest terrace (the Hilton terrace) was claimed, by Clayton (1957b; 1977) and Posnansky (1960), to be Late Wolstonian, post-dating the chalky till and is therefore the same age as the Avon fifth terrace (table 5.4). Straw (1963), however, claimed an Ipswichian age.

The Beeston terrace, containing Hippopotamus, Elephant, Rhinoceros, Brown Bear, Hyaena, Red Deer, Ox/Bison (Jones and Stanley, 1974), was regarded as contemporary with the Avon third terrace (Tomlinson, 1963) and the upper Summertown-Radley terrace (Bishop, 1958), although Rice (1968) placed it with both second and third Avon terraces. The low (floodplain) terrace of the Trent, with *Elephas primigenius* and *Tichorhinus antiquitatis*, appeared to be the same age as the Avon second terrace (Shotton, 1953; Tomlinson, 1963; Rice, 1968).

Correlation of the terraces with the recognised Quaternary stages, and with each other (table 5.4), is usually based on mammalian evidence (Shotton, 1953; Tomlinson, 1963; Rice, 1968; Mitchell *et al.*, 1973). For example, the warm fauna of the Upper Summertown-Radley terrace (Bishop, 1958) and the Hippopotamus-bearing terraces of the Trent (Beeston - Tomlinson, 1963; Jones and Stanley, 1974) and Avon (third terrace), indicate an Ipswichian age for each. The cold fauna of the second Avon terrace suggests a correlation with the low terrace of the Trent, which Tomlinson (1963) stated is Devensian (Upton Warren) in age, and the floodplain gravels of the Evenlode (Shotton, 1953; Tomlinson 1963; Rice, 1968).

Sumbler (1983a), however, disputes Shotton's (1953) correlation of the Avon terraces, believing that cutting of the third terrace bench into pre-existing gravels would involve reworking and destruction of its contained fauna. He therefore suggests that the third terrace must post-date the fourth terrace. The fourth terrace is therefore pre-Ipswichian and, containing a cold fauna, must be Wolstonian. This forces the older glacial deposits (Wolston Series) into the Anglian, a correlation which Shotton (1983b) disputes.

### C. The east Midlands and south Lincolnshire.

The middle and late Pleistocene stratigraphy of the area directly to the north of the present study area, through to the Lincolnshire Wolds, may be equated with both the stratigraphies of East Anglia and the Midlands, despite the disagreement between these areas.

The glacial deposits are found burying a number of east-flowing sub-glacial valleys (Kellaway and Taylor, 1952; Taylor, 1963), and consist of a lower till, free from chalk and flint and characterised by Jurassic and Bunter erratics. This is overlain, at low levels, by Mid-glacial sands and gravels with, either a similar 'local and Bunter' pebble content (Hollingworth and Taylor, 1946a; Poole et al., 1968) or also containing chalk and flint (Taylor, 1963; Poole et al., 1968). The gravels thin as the high ground is reached, allowing a chalk-rich till to overlap onto the lower till and cover most of the high ground (Hollingworth and Taylor, 1946a; 1946b; 1951; Sabine, 1949; Taylor, 1963; Poole et al., 1968).

The lower till, because it contains Triassic pebbles, was considered by Hollingworth and Taylor (1946a; 1951), Sabine (1949) and Taylor (1963) to be derived from the north, along a route lying to the west of the Lincolnshire

Wolds. Shotton (1953) suggested it was the lateral equivalent of the Bubbenhall Clay in the west Midlands, while West and Donner (1956) and Taylor (1963) equated it with the Lowestoft Till in East Anglia (Baden-Powell, 1948). The overlying gravel, containing no chalk or flint, was considered by Hollingworth and Taylor (1946a) to be outwash, deposited during ice retreat. Poole et al. (1968), supported this interpretation southeast of Market Harborough. To the southeast of Market Harborough, however, the gravel contains flint and was believed to have been deposited by the meltwaters which fed Lake Harrison. Poole et al. suggested that both gravel suites were deposited at the same time since Hollingworth and Taylor (1951) recorded that non-chalky gravel may be interstratified with a locally-derived till and a chalky till. The gravels were therefore correlated with the Wolston Sands of Shotton (1953).

The chalky till, capping the high ground of the Kettering area (Hollingworth and Taylor, 1946a; 1951; Taylor, 1963), is confluent with, and passes up into, a sandy, Trias-rich till to form a composite till sheet near Market Harborough (Poole et al., 1968). The chalk content of the till led Harmer (1928) and Baden-Powell (1948) to suggest an origin east of north, correlating the till with the Gipping Advance (Baden-Powell, 1948; West and Donner, 1956). The presence of Charnian and Bunter erratics, however, led Sabine (1949) and Poole et al. (1968) to suggest that the ice responsible must have come from distinctly west of north. Poole et al. therefore suggested that, on lithological grounds, the chalky till was better correlated with West and Donner's Lowestoft advance, with the Gipping advance represented by the Trias-rich upper part of the till. The correlation of the lower till in the Kettering district also with the Lowestoft advance (Taylor, 1963), therefore, led Poole _et al._ to conclude that both the upper and lower tills may have been deposited during separate minor phases of the same (Lowestoft) episode.

In south Lincolnshire, the stratigraphic succession includes deposits of the last (Devensian) glaciation. Straw (1969) separated the 'Newer Drift' of this episode from the 'Older Drift' of preceding episodes. The Older Drift comprises tills of varying character which Straw identified by their type areas as the Calcethorpe Till, Belmont Till, Wragby Till and Heath Till. The changing composition was believed to arise from the fact that the parent ice moved from the north or north-northwest, generally along, or slightly obliquely to, the strike, and therefore along the outcrop of the underlying Cretaceous and Jurassic rocks. All the tills were thought to be contemporary. Straw (1969) dated the Older Drift in the Lincolnshire area in the same way that he dated the tills in East Anglia (see A above), suggesting that

> ". . . it is extremely unlikely that any glacial episode could have occurred between the emplacement of the Wragby and Calcethorpe Tills and their correlatives and the Marsh Till [Newer Drift], and have left no manifestation."

Dating the Newer Drift to the last (Devensian) glaciation, Straw therefore assigned the Older Drift to the penultimate (Gipping) episode (Wolstonian).

Straw (1979; 1982) and Straw (in Straw and Clayton, 1979) states that the Lincolnshire sequence must be Wolstonian because no interglacial deposits of proven Hoxnian age or older have been found overlying the till, while Ipswichian deposits have (e.g. at Wing (Hall, 1980)). Straw also cites the deposits at Welton-le-Wold (Alabaster and Straw, 1976) where till, similar to the Calcethorpe Till, overlies flint valley gravels which contain a sparse mammalian fauna of Hoxnian character. Only to the south of the supposed Wolstonian limit, in East Anglia, are Hoxnian sediments found overlying till (see above). Despite the claims of Perrin et al. (1979) and Cox (1981), that the Calcethorpe and related tills are the product of the Anglian glaciation, Straw (1982) maintains his views.

The subdrift topography, described in the Nene and Welland area by Kellaway and Taylor (1952) and in Lincolnshire by Straw (1970), suggested that the preglacial drainage comprised a series of easterly and southeasterly flowing streams, although the present drainage is aligned north-south. Kent (1939), without detailed knowledge of the subdrift surface, had previously suggested that the north-south pattern originated as overflow channels during the eastward retreat of ice which deposited the chalky till. Kellaway and Taylor (1952), however, disagreed, claiming that dissection must have occurred after ice retreat - all terraces post-dating the chalky till with which the pre-glacial valleys are filled. This, therefore, follows a similar pattern to the Trent and Avon systems.

The terrace systems of the rivers of the area (Nene and Welland) are not well documented. However, two terraces are described in the Welland valley (Kellaway and Taylor, 1952) and three in the Nene valley (Hollingworth and Taylor, 1946a; Taylor, 1963; Horton, 1970; Castleden, 1976; 1977; 1980a; 1980b).

The highest terrace of the Nene (third terrace) is suggested, by Horton (1970), to be Ipswichian, correlating it to the third terrace of the river Cam, a correlation supported by Mitchell <u>et al.</u> (1973) and Straw (in Straw and Clayton, 1979). The second and first terraces are argued to be mid-Devensian and late-Devensian/early-Flandrian respectively. The second terrace is reported to be

> ". . . firmly fixed as Middle Devensian by its beetle fauna (Morgan, M.A., 1969) and radiocarbon dating (Birm-75, 28225+/-330 BP)." (Mitchell <u>et al.</u>, 1973).

Morgan's (1969) description is, however, of a

> ". . . gravel beneath two to three feet of yellow-brown modern alluvial clay . . .",

a stratigraphic position more consistent with first-terrace gravels rather than second terrace. This conclusion is also reached by Castleden (1976), who believes that the gravel beneath the floodplain and the gravel of the first terrace, although differentiated topographically by a 2m step, are similar in character and age. The fauna and flora identified in the gravel (Morgan, 1969) suggest tundra, interstadial conditions similar to those of the Upton Warren stage. Organic remains have not been found in either second or third terraces (Castleden, 1977), but Castleden (1980b) claims that the third terrace deposits contain erratics from the "Wolstonian" chalky till and, therefore, must be Ipswichian or Devensian. The third terrace, overlying the Ipswichian Woodston Beds, he dates as Devensian, thereby implying that all three terraces are substages of the Devensian.

## D. The Middle and Lower Thames.

The Pleistocene stratigraphy of the Middle and Lower Thames has been the focus for a number of recent review papers (Baker and Jones, 1980; Green and McGregor, 1980; Jones, 1981). These, however, concentrate, as has most research, on the development of the Thames prior to its existence in the present valley.

The early workers focused their attention on archaeological interpretations of the river terraces and, where palaeolithic artifacts were absent, on the composition, provenance and distribution of river gravels (Salter, 1905b; Sherlock and Noble, 1912; Deeley, 1916; Barrow, 1919; Breuil, 1931; King and Oakley, 1936; Bull, 1942) to define the lower terrace succession in the present Thames valley (table 5.5). Wooldridge (1927; 1938), however, argued that more attention should be paid to the downvalley continuity and relative elevation of the deposits. He therefore used the morphological expression of the deposits to trace terraces down-valley, produce a vertical sequence, and provide an explanation of the Thames development.

Wooldridge (1938), followed by Hare (1947) and Sealy and Sealy (1956), and elaborated by Wooldridge and Linton (1955) and Wooldridge (1960), defined a sequence (table 5.5), and proposed a model which involved two diversions caused by two separate ice advances. The first, by the ice sheet which deposited the Chiltern Drift on the Chilterns, diverted the Thames from the Vale of St. Albans, a course previously suggested by Salter (1905b), Sherlock and Noble (1912) and Sherlock (1924), to the Finchley Depression, from where it joined the former course near Ware. The second, or Great Eastern Glaciation, which deposited the chalky till, diverted the Thames from the Finchley Depression to its present course. These diversions occurred before the Higher Gravel Train, and during the Winter Hill Terrace stages respectively (table 5.5). Subsequently Wooldridge and Henderson (1955), followed by Clayton (1957a), traced the course of the Thames in Gravel Train times east from Ware in a northeasterly trending valley (the Mid-Essex Depression) within the subdrift surface, towards Chelmsford, Colchester and the Blackwater Estuary.

Within the depression Clayton (1957a), Clayton and Brown (1958) and Brown (1959), identifed three chalky tills; the Hanningfield Till, the Maldon Till and the Springfield Till, the last of which is interdigitated with the deposits of a proglacial Lake Hertford. Clayton

(1957a) and Clayton and Brown (1958) correlated the earlier Hanningfield Till with Wooldridge's Chiltern Drift and equated it with the Lowestoft Stage of West and Donner (1956). They placed the upper, Maldon and Springfield Tills in the Gipping, suggesting that the latter caused the final diversion of the Thames. This, however, implied a post-Hoxnian age for the diversion from the Finchley Depression which conflicts with the Hoxnian age for the subsequent Boyn Hill Terrace (West, 1977). Clayton later modified the stratigraphy (1960) suggesting that the Springfield Till was equivalent to the Gipping stage, while the Maldon and Hanningfield Tills were correlated with the Lowestoft and Cromer Tills respectively.

Since 1965 there has been a change of emphasis from the morphological analysis of terraces (Wooldridge, 1927; 1938; Hare, 1947; Sealy and Sealy, 1956), to more detailed quantitative examinations of the deposits (Hey, 1965; 1980; Walder, 1967; Gibbard, 1977; 1979; Green and McGregor, 1978; McGregor and Green, 1978; 1983a; Green, Hey and McGregor, 1980; Green, McGregor and Evans, 1982). The main emphasis still, however, is on the pre-Boyn Hill Terrace deposits.

Hey (1965) and Walder (1967) both examined the pebble composition of deposits of different stages and demonstrated that consistent lithological differences are apparent between successive stages. Elaborating the lithostratigraphic analyses (Gibbard, 1977; 1979; Green and McGregor, 1978; McGregor and Green, 1978) shows the interpretation of Wooldridge (1938), Hare (1947), and

Wooldridge and Linton (1955) to be at fault. Gibbard (1977) identifies two chalky tills in the Vale of St. Albans, a lower Ware Till and an upper Eastend Green till. These are associated with lacustrine deposits. Associated with the Ware Till is a series of gravels, which Gibbard correlates with the Winter Hill Gravels further west, the Ware Till representing the first influx of Anglian ice. Gibbard believes that the sequence indicates that the proto-Thames continued to use the Vale until the beginning of Winter Hill Terrace times, when Anglian (Eastend Green) ice blocked the Vale, and after a period of ponding forced the river south to form the Black Park Terrace (Hare, 1947). The Finchley Depression, he believes, was never used by the Thames, lithological analysis indicating that the Depression represents the course of the proto Mole-Wey flowing northeast to join the Thames near Ware (Gibbard, 1979). The chalky till in the Finchley Depression is correlated with the Eastend Green Till in the Vale of St. Albans.

Green and McGregor (1978) and McGregor and Green (1978; 1983a) confirm that the Thames used the Vale of St. Albans continuously from Westland Green times through to Winter Hill times. Catchment changes are shown to occur between each stage, which Green and McGregor (1978) interpret as indicating at least three episodes of glaciation before the Anglian. Hey (1980), Green, Hey and McGregor (1980) and Green, McGregor and Evans (1982) extend the analysis into Essex and East Anglia and confirm that the Kesgrave Formation, identified by Rose, Allen and Hey

(1976) and Rose and Allen (1977) in East Anglia, is part of the Thames system, correlating it with the Westland Green Gravels and the Gravel Trains to the west. Green, McGregor and Evans, following Baker and Jones (1980) and Jones (1981), suggest that the lack of Thames gravels later than Lower Gravel Train in Essex indicates that the Thames must have been diverted from the Mid-Essex Depression before the diversion of the Thames from the Vale of St. Albans in late Winter Hill times (Gibbard, 1977; Green and McGregor, 1978).

This model involving only one, albeit complex, incursion of chalky ice into the Thames basin in Winter Hill times (Gibbard, 1977), conforms with the recently accepted stratigraphy in East Anglia of a single chalky till (Bristow and Cox, 1973; Perrin et al., 1973; Rose and Allen, 1977; Perrin et al., 1979). The till is believed to be Anglian in age because it underlies Hoxnian interglacial deposits at Hatfield (Sparks et al., 1969) and Fishers Green, Stevenage (Gibbard and Aalto, 1977), and pre-dates the Boyn Hill Terrace which is considered to be Hoxnian (Kellaway et al., 1973).

The terraces of the post-Anglian Thames follow the course of the present river valley and are well established in the stratigraphic column. Much of the present work on the terraces is concerned with the contained interglacial deposits. A morphological sequence of terraces has been identified (table 5.5) with a general decrease in age with height, although in places where the terraces are separated by vertical intervals of less than six metres, the order may be reversed (Shephard-Thorn and Wymer, 1977).

Early analyses of the biological deposits from the terraces followed the stratigraphy which was accepted by Mitchell et al. (1973). The separation of the interglacial deposits was based solely on pollen assemblages, equating new deposits with the type sites at Hoxne (West, 1956) and Bobbitshole (Sparks, 1957; West, 1957). This placed organic deposits in the Boyn Hill Terrace at Swanscombe in the Hoxnian interglacial (Kerney, 1971). The plant remains at Ilford (West, Lambert and Sparks, 1964) and Aveley (West, 1969) in the Taplow Terrace and at Trafalgar Square (Franks, 1960), in the Upper Floodplain, were assigned to the Ipswichian.

Re-examination of the deposits at Swanscombe (Wymer, 1974; Shephard-Thorn and Wymer, 1977) and Hoxne (Wymer, 1974; Turner, 1977), however, indicates that the earlier interpretations are erroneous. The Swanscombe deposits are divided into three stages. The basal deposit (Stage I) is a gravel with an overlying loam. The gravel contains a temperate fauna and flora indicative of a large body of well-oxygenated, flowing, calcareous water (Kerney, 1971). The overlying loam changes upwards from swampy and marshy environments to more open grassland (Kerney, 1971). Pollen from the loam is reported to be Hoxnian (Ho II), becoming cooler upwards (Wymer, 1974; Shephard-Thorn and Wymer, 1977). Stage II is subdivided into Lower Middle Gravel and Upper Middle Gravel, the former containing temperate snails (Kerney, 1971) and mammals (Wymer, 1974), indicative of moving water in a mixed oak forest. The Upper Middle

Gravel contains cool molluscs and mammals of more gently flowing water and open grassland (Wymer, 1974; Shephard-Thorn and Wymer, 1977). The Stage III deposits are preserved in a channel in the Upper Middle Gravel and consist of soliflucted clay with ice wedge casts, overlapped by a loam containing pollen. Overlying the loam is a soliflucted gravel (Shephard-Thorn and Wymer, 1977). Wymer (1974), and Shephard-Thorn and Wymer (1977) suggest that the deposits of stages of Stages I and II are Hoxnian in age, with a period of erosion represented by the intervening cool deposits. The upper loam of Stage III, underlain and overlain by soliflucted deposits, appears to represent a warm period between two cold episodes. Pollen from the loam suggests zone II of an interglacial. Two interpretations are placed on this sequence:

1) If the pollen in the upper loam is Ipswichian, then the cold episode preceding it is Wolstonian, while the cold gravel above is Devensian.

2) Both the cold episodes may be within the Wolstonian, in which case there appears to be an interglacial between the Hoxnian and the Ipswichian (Wymer, 1974; Shephard-Thorn and Wymer, 1977).

Reinterpretation of the deposits at Hoxne (Wymer, 1974; Turner, 1977) has given similar results. Overlying the Anglian chalky till, and the clays and muds which contain the Hoxnian pollen spectrum (West, 1956), is a complex series of fluviatile sediments. The silts and chalky gravels at the base of these sediments, which are reworked and contain ice wedge casts, appear to represent a cold period. Silt overlying this contains a warm mammal fauna suggesting it was the floodplain of a river which periodically flooded. A further cold period is represented by coarse, soliflucted gravels with cold climate features (ice wedges), previously described as a till by Baden-Powell (1948). Both the post-Hoxnian cold periods were regarded by Wymer (1974) as Wolstonian, and Turner (1977), discussing the warm fluviatile bed, states that

> "There is no doubt this bed represents a period separated from the Hoxnian interglacial by an interval of cold climate, but it is still uncertain whether this should be regarded as a separate interglacial period, . . . or simply as a later interstadial interval within the Wolstonian (Saalian) glacial stage."

Archaeological material has been found at both these sites but the sequence at Swanscombe is the reverse of that at Hoxne. Wymer (1974) therefore suggests that

> ". . . it can now be accepted that different traditions of hand-axe manufacture were existing side by side during this part of the Pleistocene. It is no longer tenable to use their typology as palaeontological markers, as I have previously suggested (Wymer, 1961, 1968)."

Another interglacial deposit is described at Yiewsley in west London by Collins (1978). It appears to be immediately preceded by the chalky till glaciation, and pollen evidence suggests a Hoxnian (Ho II) age. However, Collins states it is almost certainly NOT Boyn Hill Terrace (Hoxnian) in age, and suggests it may be similar to the deposits at Lynch Hill (See below).

Further evidence for a post-Hoxnian / pre-Ipswichian warm period has been put forward from an examination of the mammalian remains from the sites at Ilford, Aveley and Trafalgar Square (Sutcliffe, 1975; 1976). The deposits from the Taplow Terrace at Ilford (West, Lambert and Sparks, 1964) and Aveley (West, 1969), and from the Upper Floodplain at Trafalgar Square (Franks, 1960), were originally regarded on palaeobotanical grounds as Ipswichian in age, despite the difference in altitude. However, Sutcliffe (1976) states that

> "The faunal [mammalian] assemblages of Aveley and Ilford on the one hand and of Trafalgar Square on the other are so different that it is difficult to believe they are contemporary.",

and suggests that the Ipswichian may be subdivided into two separate interglacial episodes. The major difference is that the deposits at Aveley and Ilford contain a fauna characterised by a primitive mammoth (Mammuthus trogontherii), while the Trafalgar Square deposit contains abundant Hippopotamus (characteristic of Ipswichian deposits), which the former sites lack (Sutcliffe, 1976). The deposits at Trafalgar Square are also reported to be banked up against the Taplow Terrace (Shephard-Thorn and Wymer, 1977), supporting a pre-Ipswichian age for the latter.

Shotton (1983a) supports the distinction and quotes other sites

> ". . . which are demonstrably post-Hoxnian, which have pollen assemblages broadly similar to those of the Ipswichian, but which for a variety of reasons appear to fit better into an older warm period."

Sites mentioned are Stoke Tunnel (Turner, 1977) and Sutton near Ipswich; Lynch Hill (Stanton Harcourt) near Oxford; Harkstead; Maidenhall; Marsworth (Green *et al.* - in preparation); and Brundon in Suffolk, all of which are described as geomorphologically discordant with Bobbitshole. At each of these sites a *Mammuthus-Equus* fauna is described, lacking the *Hippopotamus* fauna, in a similar manner as in the lower Thames (Sutcliffe, 1976). Evidence for a critical separation of the two interglacials is beginning to be accumulated from the beetle fauna (Coope) where the presence, or absence, of *Anotylus gibbulus* may serve to distinguish each episode, but this is as yet unproven (Shotton, 1983a).

Although the presence of a mid-Wolstonian interglacial in Britain is unproven, a similar site has been found at Weimar-Ehringsdorf, Germany (Jager and Heinrich, 1982), where a travertine deposit is believed, from faunal and floral evidence, to be mid-Saalian in age. The biological evidence from the lower Thames terraces shows that since the marker horizon of the chalky till (Anglian - Perrin *et al.*, 1979) there have been at least two temperate episodes (Hoxnian and Ipswichian), between which a glacial episode (Wolstonian) may be subdivided by an additional interglacial.

## E. The Upper Ouse basin.

The upper Ouse basin lies centrally among the four areas described above. It is therefore critical in attempting to correlate the stratigraphies of East Anglia and the Midlands. Despite this, the area has remained virtually unexamined since the early part of the century, apart from the work of Horton (1970) and Horton et al. (1974), and the area is noticeably absent in the Geological Society's "A Correlation of Quaternary Deposits in the British Isles" (Mitchell et al., 1973).

The drift deposits of the basin (Chapter IV) may be divided into those of fluvial origin, and those of glacial origin, and any stratigraphic interpretation necessarily has to take account of both types. Early workers in the area suggested that the Ouse valley was invaded simultaneously by three ice lobes from the north or northeast (Harmer, 1907; 1928; Deeley, 1916). One travelled along the main valley of the Ouse to Buckingham and beyond, another travelled southwest to Leighton Buzzard, while the third moved south, down the Ivel, to Dunstable (Deeley, 1916; Harmer, 1928) where it passed through a deep gap in the Chiltern escarpment at Hitchin, into the Vale of St. Albans (Harmer, 1907; Hill, 1908; 1912). The ice was considered to be confluent with that which formed the chalky till in the Trent basin and in Leicestershire, and was regarded as the product of the Great Eastern Glaciation.

> "As far as can be made out, all the boulder-clays we have considered seem to belong to one cold period, but this is by no means certain." (Deeley, 1916).

The work of Baden-Powell (1948) and West and Donner (1956), in East Anglia (see above), however, suggested that two chalky tills exist, belonging to two glacial episodes.

Within the upper Ouse basin West and Donner examined four sites, correlating one with the earlier Lowestoft Glaciation (Ippollitts), and the remainder to the Gipping. Edmonds and Dinham (1965), in the Biggleswade-Huntingdon area, confirmed this, but stated that while two tills were present, the

> ". . . available evidence does not permit any detailed separation."

Horton's work (1970, Horton et al., 1974) is the only recent examination of the area. Horton identifies two tills: a non-chalky lower till, and an upper chalky till - the former mainly found in the Towcester region. The lower till Horton describes as similar to the lower till found in the Kettering district by Taylor (1963), and is similar to that described in the Nene basin by Castleden (1976). The upper chalky till, forming the bulk of the drift, is correlated to the chalky till of that area. However, despite the claims of West and Donner (1956), and Edmonds and Dinham (1965), that two chalky tills are present, Horton (1970) finds no evidence of a lithological difference between an upper and lower chalky till and concludes that

> ". . . there is no evidence to suggest that the deposits were formed during more than one glaciation."

Horton considers the chalky till ice to have advanced up the deep channels proved beneath the present Ouse, Ouzel, Tove and Ivel valleys, causing a series of proglacial ribbon lakes, in a manner similar to that envisaged by Shotton (1953) for Lake Harrison. These lakes resulted in the deposition of the thick lacustrine clays (Chapter IV.A) which are interbedded with the chalky till. Evidence, from the Deanshanger borehole, suggests a sequence of three ice advances, each followed by a retreat stage and the formation of a lake. The drop-stones present in the lake clays are considered to indicate the proximity of the ice front (Horton, 1970). Beneath, and overlying the chalky till, glacial sand and gravel is frequently present, and Horton et al. (1974) suggest that the majority is outwash which issued from the ice front rather than being sub- or en-glacial.

Horton (1970; Horton et al., 1974) suggests that the chalky till advance is Gipping (Wolstonian) in age, the lower, non-chalky till representing the Lowestoft (Anglian) advance. This, therefore, implies a stratigraphy similar to that proposed by Shotton (1953; 1976) near Coventry and which is confirmed by Castleden (1976) in the Nene basin. Such an interpretation, like so many of the sequences described above, conflicts with the work of Bristow and Cox (1973) and Perrin et al. (1979).

In support of a Wolstonian age, Horton (1970) correlates the local Milton Sand, which underlies the chalky till south of Northampton (see Chapter IV.B), with to the lithologically-similar Paxford and Snitterfield gravels in the Evenlode valley and the Baginton-Lillington gravel (suggested by Shotton to be early Wolstonian). The Milton Sand, also reported to overlie the lower till (Hollingworth and Taylor, 1946a), is therefore placed in the interval between the Anglian and the Wolstonian (Castleden, 1980c).

Thompson (1930) regarded the Milton Sand as a fluvial deposit, representing the main course of the Nene flowing southeast to join the Ouse near Olney. Horton (1970), however, finding no evidence for a col in the Ouse-Nene watershed, suggested a fluvioglacial origin. Because of the lack of far-travelled material, known to exist in both the Anglian and Wolstonian Tills, Castleden (1980c) disagrees and supports Dury (1949) that it is a periglacial deposit, formed by a periglacial river at the onset of the Wolstonian.

As with the terraces in the Midlands (Shotton, 1953), and of the Trent (Clayton, 1957b; Posnansky, 1960), the three terraces of the Great Ouse are all reported to post-date the chalky till (Dury, 1952). Edmonds and Dinham (1965) equate the third terrace of the Ouse, downstream from Bedford, with the third terrace of the river Cam near Barrington, Cambridgeshire, which has yielded Hippopotamus and is therefore considered as Ipswichian in age (Worssam and Taylor, 1969; Gibbard and Stuart, 1975). This terrace is also correlated with the third terrace of the Nene (Horton, 1970). An Ipswichian age for both is stated by Straw (in Straw and Clayton, 1979, p47).

The first and second terraces of the Ouse post-date the glacial deposits, as in places they extend over the glacial drift (Horton *et al.*, 1974). Organic deposits are unknown within the terraces upstream from Bedford, but while Horton (1970) recognises that the limited vertical range of the terraces presents problems for correlation, he tentatively relates the first and second terrace of the

Ouse with the first and second terraces of the Cam. These are regarded as late-Devensian/early-Flandrian, and Mid-Devensian respectively (Horton, 1970; Horton et al., 1974). At Earith, 9.6 kilometres east of St. Ives, second terrace gravels of the Ouse are reported to contain arctic and alpine flora, of Mid-Devensian age (Bell, 1970), which therefore supports Horton's correlation.

The early literature of the Bedford area, however, suggests a more complicated succession (Wyatt, 1861; 1862; 1864; Prestwich, 1861; 1864; Evans, 1897; Banton, 1924; Mantle, 1926; Bate, 1926). High level gravels (60' (18m) above river level), described at Biddenham (Chapter IV.E)(Prestwich, 1861; 1864; Wyatt, 1862) and Honey Hill (Wyatt, 1864), are reported to contain a different mammalian fauna (table 4.1) from the sites 20 to 30' (6.1 to 9.1m) lower at Kempston, Harrowden, Radwell and the Bedford Railway Cutting (Prestwich, 1861; 1864; Wyatt, 1861; 1862). The Biddenham fauna appears to be temperate in character but lacks Hippopotamus, which is reported from the Bedford Railway Cutting, which also has a temperate fauna (Prestwich, 1861; 1864; see Chapter IV.E). Correlating downstream, Tebbutt (1927) and Patterson and Tebbutt (1947) describe a Hippopotamus fauna from the second terrace deposits at Brampton. In terms of the accepted mammalian stratigraphy (Stuart, 1982), Hippopotamus would place these gravels in the Ipswichian interglacial - not, as suggested by Horton, in the Mid-Devensian. The report of Horse in the Railway Cutting is rather problematical as Hippopotamus and Horse are nowhere reported together in other British sites (Shotton, 1983a).

The low level deposits described at Willington, St. Neots and Little Paxton (Banton, 1924; Mantle, 1926; Bate, 1926; Tebbutt, 1927; Patterson and Tebbutt, 1947), have cold faunas which are thought to indicate an early-Devensian age. This date is confirmed by the contained archaeological material. However, the low-level gravel at Summerhouse Hill (Wyatt, 1864) is also reported to contain Hippopotamus. This may, therefore, correlate with the Bedford Railway Cutting unless one of the reports of Hippopotamus is inaccurate, or a Devensian terrace has been cut into deposits of Ipswichian age.

## Conclusions.

There are at present two schools of thought regarding the post-Cromerian succession in Southern England. Two glacial episodes were put forward by Mitchell _et al._ (1973), on the basis of reports of two tills, apparently separated by interglacial deposits (Hoxnian). Lithological evidence, however, is now believed to support a single, chalky glacial episode of pre-Hoxnian age (Bristow and Cox, 1973; Perrin _et al._, 1979). In the Midlands, however, Shotton (1976), Douglas (1980) and Rice (1981) maintain that a chalky till was deposited by a post-Hoxnian ice sheet, despite claims by Perrin _et al._ (1979) and Sumbler (1983a) that the sequence is contemporary with the East Anglian succession. The solution to the problem initially appeared to be the evidence from biological sources. Two warm interglacials were identified on the basis of pollen assemblages. Unfortunately, as Shotton *et al.* (1977) point out

> "Nowhere outside a stratigraphical table is an Ipswichian sequence known to occur vertically above a Hoxnian sequence.",

and stratigraphic control is weak. This lack of control enabled Bristow and Cox (1973) to suggest that both interglacial episodes are the product of a single interglacial, probably separated by a cold oscillation, and occurring after the main chalky till glaciation. More recent faunal data, from a limited number of sites in the Thames basin, East Anglia, and the Upper Ouse basin, however, suggest that the Hoxnian and Ipswichian are separated by a substantial cold period, which itself may be subdivided by a third interglacial episode.

# Chapter VI. Field and Laboratory Methods.

## Introduction.

The data collection of the present research can be examined under two main headings - field procedure, and laboratory procedure - both of which are dependent upon the proposed analysis. The field procedure is concerned primarily with the collection of samples, both over a wide area and, more locally, at a particular site. The laboratory procedure concerns both the mechanical analysis of the sample (washing and sieving), and the lithological analysis of the sample.

The majority of the techniques and methods discussed are in common use in Pleistocene geomorphology. However, every case is different and the requirements on a particular method may change, not only from project to project, but also over time. Differences between methods, however, may cause results to be incompatible both between different investigations and within the results of a single project. Frequently, methods used are not specified (e.g. Gibbard, 1979), preventing comparative work. It is important, therefore, in any scientific research that internal consistency is maintained, especially where an analytical procedure is repeated many times. Consequently, it is not only necessary to specify beforehand the type of analysis intended, but also the methods to be used. The methods must then be rigorously adhered to.

## A. Field Procedure.

The collection of samples, in geographical research, has been a much discussed subject in recent years, both from theoretical and practical points of view. Attempts have been made to rationalise and standardise the techniques, but due to the uniqueness of many research problems, generalisations become meaningless.

Otto (1938) gives four reasons for geological sampling:

1) engineering sampling - for economic use.
2) descriptive sampling - detailed petrographic description of the unit, for which more than one sample is required.
3) environmental sampling - to find the areal variation of a sedimentary unit.
4) correlation sampling - to find similarities or differences between sites for geological correlation.

Within the present context, the reason for sampling is to trace gravel deposits, by lithological comparison of samples at each site, so that different suites may be traced from site to site, and a stratigraphy built up on the results. This encompasses both Otto's types 3 and 4.

The aim of sampling is to collect a small, representative part of the population (gravel deposits), defined as

> ". . . an aggregate or class of objects or events which have one or more common attributes." (Chorley, 1966),

such that its characteristics correspond closely with those of the whole population (Chorley, 1966; Reynolds, 1975). It is desired that the correspondence is close enough that any conclusions reached from an analysis of the sample will be applicable not just to the sample, but to the overall site conditions where the sample is taken.

1. Sampling an Area.

The first stage in the sampling plan involves sampling, as representatively as possible, a large area. Once this has been done, 'within-site' sampling needs to be considered, so that the most representative sample is obtained at each location.

Ideally, when sampling a large area where gravel deposits cover the whole area, and every element is equally available, the best method would be to take random samples, where each individual is separately drawn (Chorley, 1966). In geomorphology, five types of random sampling are commonly recognised:

a) Random serial sampling.
b) Simple random sampling.
c) Stratified sampling.
d) Systematic grid sampling.
e) Multistage (nested) sampling.

These are termed 'probability samples' by Dixon and Leach (1978) and they require that each element in the population has a known chance of selection.

a) Random serial sampling is used mainly for linear features where sample points are selected at predetermined, and usually equal, intervals. The sample interval is usually dependent on the magnitude of the phenomena studied and the number of samples required. The first sample point is chosen randomly, thus giving equal chance of selection to all points.

b) Simple random sampling requires that all the population has an equal chance of selection (Dixon and Leach, 1978), and involves the selection of sampling points over an area by random numbers; these being used to define coordinates. In areal studies, a square grid is usually used to locate the coordinates. The method may, however, result in sample clustering - generally considered to be undesirable. A major problem occurs when selected sites fall on areas devoid of gravel.

c) Stratified sampling can be undertaken when some knowledge of the distribution of the population exists. The area is 'stratified' into zones, where gravel exists, and sample points generated, as in b) above, are only selected when they fall within these zones (Chorley, 1966; McGregor, 1973).

d) Systematic grid sampling is less tedious than the above methods, but is not, however, as random. A grid is laid arbitrarily over the area to be sampled so that either the number of intersections, or the number of squares, are equal to the number of samples required. Samples are then taken from beneath each intersection, or from the centre, of each grid square. So that the method is not too rigid, the shape of the grid can be altered to take account of the natural conditions (Krumbein and Pettijohn, 1938; Chorley, 1966; McGregor, 1973). This method, like b) above, makes the assumption that each sample point will fall within an area of gravel.

e) Multistage (nested) samples are used to study local variations in a large area. The area is divided into a number of major units of equal size, and random numbers are generated to select which of the units are to be sampled. The selected units are broken down into a number of smaller regions and the process repeated. This procedure continues until the required level of detail is achieved (Haggett *et al.*, 1977). Problems can occur when the areal limits are undefined and the selection of locations is essentially governed by the availability of suitable sampling sites.

The main limitation of the methods described above, to the present study is in the availability of usable sites. Dixon and Leach (1978) suggest that these sampling strategies

> ". . . are easily applied to maps, but are more difficult in the field."

Gravel deposits are rarely equally available and, although sampling points selected, by one of the above methods, may fall within a gravel deposit, sampling may be rendered impossible by obstacles (such as buildings), and/or lack of access. The lack of detailed knowledge about the location of gravel, within the study area, precludes the use of theoretical techniques. Sample sites within the present study are thus restricted very strongly to locations where gravel is exposed, in a pit or quarry (either natural or man-made). Where gravel is known to exist, but is unexposed at the surface, hand augering might be used, but in gravel this is not particularly effective. Power-borers have been used by the IGS, and excavation by mechanical digger may be effective, but these are usually impractical because of the cost and accessibility. Fisher (1982) also proves that the results from power-borers are incompatible with results from hand samples.

### 2. Within-site Sampling.

The distribution of gravel deposits over a wide area identifies two dimensions of a population which is three-dimensional. Sampling the third, or vertical, dimension is as important as sampling the horizontal dimensions. If the sediment is homogeneous then an isolated spot (or discrete) sample, taken at a particular point on the outcrop (Apfel, 1938; Krumbein and Pettijohn, 1938; Otto, 1938; Plumley, 1948; Griffiths, 1959; Chorley, 1966) and chosen randomly, is usually adequate (Ehrlich, 1964). The spot sample is scooped out from a square or circular zone, generally to a depth equivalent to the sample diameter, and the material collected in a bag, so that none is lost. This, however, presupposes that the sampler can see, and identify, the 'average' sedimentary unit in the field, and that he can state that the pit is homogeneous before analysis (McGregor, 1973).

Problems may occur because the assumption, that a single gravel sample, taken from a pit face, will represent the entire deposit, is often false, due to the possible existence of unexposed variation. Where stratification occurs, Otto's (1938) "sedimentation unit" must be identified and each unit sampled as a homogeneous sediment (Ehrlich, 1964). The sedimentation unit is defined by Otto

(1938) as:

> ". . . that thickness of sediment which was deposited under essentially constant physical conditions."

This requires that homogeneous units can be selected in the field; random spot samples being taken from each unit. Problems, however, may occur where individual units are thin, or where the exposure is insufficient to trace such a unit (Plumley, 1948).

Sampling a sedimentary unit, once identified, can be undertaken in several ways. To cover a pit face thoroughly, serial samples (stratified grid samples (McGregor, 1973)) may be used in an identical manner as in 1d, above (Krumbein and Pettijohn, 1938), with spot samples taken at grid intersections. If, however, stratification within the unit is not recognised, this may not produce meaningful results for the pit as a whole (Steinmetz, 1962).

A variation of the spot sample is the channel sample, taken as a continuous strip of material from top to bottom of the exposure - normally orthogonal to the bedding. The depth of the sample is made about equal to the diameter of the largest pebble in the sampling zone (Twenhofel and Tyler, 1941; Krumbein and Pettijohn, 1938; Plumley, 1948). The sample is collected in a bag, or on a tarpaulin, placed at the base of the channel. The method ensures a representative sample but tends to mask detail, and individual beds cannot be separated. The method also becomes impractical where an exposure is over 2-3m in depth. To compensate for these difficulties, shorter channels may be taken - either from individual units, or randomly. In this manner, hidden variation may be disclosed which could remain unobserved in a single channel (Krumbein and Pettijohn, 1938).

Compound sampling forms a further method to sample a sedimentary unit. Spot samples are spread widely over the quarry, within the identifiable unit, these being combined to form an aggregate sample. This may mask detail, but reduces the possibility of "probable error" (Twenhofel and Tyler, 1941; Krumbein and Pettijohn, 1938).

In testing the channel, spot, and stratified sampling methods, Griffiths (1959) found results inconsistent from one sampling scheme to another. Steinmetz (1962) analysing the different methods, but using Otto's sedimentary unit rather than random spot samples (taking samples from a conformable line within a layer), concluded that: ideally the sediment unit is best for well-layered deposits; a channel is best for homogeneous sediments; and a grid is most suitable for massively bedded deposits. More usually, however, the choice of sample type is limited by the nature of the deposits and their exposure (Plumley, 1948).

In the present study, where sedimentary units are, in the majority of cases, easily identifiable, spot samples are taken randomly from each unit at a point considered to have 'average' conditions; the assumption being made that each unit is homogeneous and so one sample will be representative of the whole. In some cases, second samples were taken for confirmation. Internal consistency in the method attempted to keep sampling instability (Griffiths, 1959) to a minimum. The location of all sample sites, and the number of samples taken, is recorded in Chapter VI, and in figure 6.1.

When sampling in the field, certain precautions need to be observed. The surface of the face must be cleaned so that no slumped material is included, affecting the sample and consequently the results. It is also necessary to be absolutely certain that the material sampled has not been disturbed by man. In addition, the size of the sample needs to be considered. Chorley (1966) states that it should be large enough so that inferences can be made regarding the characteristics, but not so large that the extra data is unnecessary. Samples of fine material tend, in general, to contain too many individual particles, but as the particles become larger the sample size becomes nearer to the optimum, for the laboratory, owing to the increased labour of handling very large samples (Krumbein and Pettijohn, 1938). Wentworth (1926) specified sample size, for mechanical analysis, depending on the size fraction required for analysis. However, Chorley (1966) states that the optimum size of a sample is essentially a matter of experience. The present study found that bulk samples of approximately 20kg is of sufficient size to provide the required number of pebbles, in the relevant size fraction, and is manageable in the field. Reduction of the sample size, by field sieving (a technique used by Hey (1976)), to sample only the required size fraction (see

B.2 below) was not found to be practical, due partly to the greater time taken in the field, and partly to the difficulty of ensuring the retained fraction did not contain consolidated finer sediment.

B. Laboratory Procedure.

1. Mechanical analysis.

Preparation of the samples, for analysis, follows a similar pattern to that used by Green and McGregor (1978) and McGregor and Green (1978). Fine material is first removed, by dry hand sieving, through a 3.5mm mesh. Prior to washing, lithologies thought likely to break down, during washing and mechanical sieving are removed by hand, wherever possible. These are later processed manually. The remaining fraction is washed, on the 3.5mm sieve, and spread evenly in aluminium trays and left overnight in an oven to dry thoroughly before mechanical sieving.

To sieve the gravel, a standard Ro-tap shaker (150 blows/minute) is used, with a cluster of 7 sieves, for 15 minutes. The sieve apertures used are at half-phi intervals from 31.5mm (-5.0 phi) to 4.0mm (-2.0 phi), the sieves being of the standard 8" diameter, square mesh type.

The object of the sieving process is to separate the sediment according to standard size fractions.

> "However despite its long usage and technological refinements the method of screening still is neither a precise nor accurate technique of particle size measurment. . . . An ideal particle size analysis done by sieving should reflect only characteristics of the sample and not the sample analysis method." (Ludwick and Henderson, 1968).

Due to the errors caused by:

a) particle factors: shape, surface characteristics, hygroscopicity (Sahu, 1965; Ludwick and Henderson, 1968; Janke, 1973),

b) screen factors: including differences between actual and ideal mean opening size, non-uniformity in opening size, and shape and dimensional instability (Ludwick and Henderson, 1968), and

c) sieving procedure: size of sample sieved (Janke, 1970; 1973), duration of sieving time (Ludwick and Henderson, 1968),

internal consistency, within the present study, is deemed to be of prime importance. Consistency with other studies is less likely. For example, Hey (1976) sieves in the field. Other researchers fail to mention the method of analysis used (e.g. Gibbard, 1979). The method described above, however, conforms with that described by Green and McGregor (1978) and McGregor and Green (1978).

At every stage in the washing, drying, and sieving process, each sample is labelled to avoid mixing of samples. When sieving is complete, each size fraction for each sample is bagged, and labelled with the sample number and the size of the sieve mesh on which it lies. In the following discussion, size fractions will be described in terms of the retaining sieve mesh diameter.

### 2. Lithological analysis.

Analysis of gravel lithologies, by counting the number of pebbles of stated lithological types, within a gravel sample is becoming increasingly utilised, and more refined, in studies of Pleistocene fluvial and fluvioglacial sediments. The work of Hey (1965; 1976; 1980), Green and McGregor (1978), McGregor and Green (1978; 1983a), Green, McGregor and Evans (1982) and Gibbard (1979; 1982), exemplifies the use to which such analyses can be put. There is, however, great variety in the detail in which the analysis is done and the way in which the analysis is used. Frequently, the details of the results are only used descriptively and only the presence of certain lithologies is noted (Edmonds and Dinham, 1965; Morgan, 1969; Horton, 1970; Horton et al., 1974 being cases in point).

The increase in the use of the pebble count technique has not resulted in the standardisation of the analysis. The work of Davis (1958) and Boggs (1969) has demonstrated that, due to the differing resistance of lithologies to erosion and attrition, the relative frequency of rock types commonly varies with particle size, and different rock types reach a maximum abundance in different grade sizes. Davis (1958) analysed alluvial and outwash gravel, together with till, to determine grade size and lithology. He discovered that in till, clasts larger than 2mm are predominantly limestone, while those smaller than 0.25mm are predominantly quartz. Between 0.25mm and 2mm most lithologies were found to be present in representative proportions. This variation was also present, but to a larger degree, in the alluvial gravel, while the results of the outwash gravel were intermediate. Boggs (1969) reports similar findings in the proportions of sandstone, chert, igneous and metamorphic rocks in alluvial gravel. Analysis found sandstone to be more abundant in the finer grades, while igneous and metamorphic rocks are more important in the coarse range. Chert and other lithologies are uniformly distributed. The differences identified were found to follow a consistent pattern. Because of this variation, Davis and Boggs conclude that an accurate description of gravel lithology can only be made by first separating the sample into grade sizes, and then restricting the pebble count to one grade size only. Comparison between samples must, therefore, always be based on the same size fraction. There are, however, exceptions to every rule and, while Davis points out that frequently the use of a single grade size is all that is necessary, if the reason for analysis is to search for indicator stones, then a wider range of grades may be more appropriate.

Internal consistency has been adopted by most recent investigators, however, consistency between workers has not. Hey (1965; 1976; 1980) examines pebbles in the 16-32mm fraction, although the 10-16mm fraction is studied where possible (1976); Walder (1967) examines all pebbles larger than 5mm; Rose (1974) examines the 4-16mm fraction; Green and McGregor (1978), McGregor and Green (1978; 1983) and Green, McGregor and Evans (1982) restrict themselves to the 11.2-16.0mm fraction; while Gibbard (1979; 1982) examines the 33, 16 and 8mm sieve grades. The work of Green and McGregor, being most closely related, spatially and structurally, to the present work, is that with which comparison is most likely. Consequently the present study concentrates on the 11.2-16.0mm size fraction. Results may not, therefore,

> ". . . be comparable in detail with earlier studies." (Green and McGregor, 1978).

The 11.2mm size fraction is the largest size fraction, within the majority of the present samples, which provides an adequate number of pebbles for analysis (see below). The sample size, of the size fraction used, again depends in part on the analysis intended, but, more importantly, depends on the variants in the population - the larger the number of variants, the larger the sample needs to be. A study of the literature suggests that between 250 and 300 pebbles is adequate to describe the characteristics of a sample of this size grade. For example, Steinmetz (1962), in an analysis of quartz pebbles of 4 to 64mm, concludes that a total of 213 pebbles will estimate size parameters of outcrops with the same precision as 3600 pebbles. Green and McGregor (1978) state that their average sample size of 285 pebbles is adequate, although they later increase their average sample size to 467 pebbles (Green, McGregor and Evans, 1982), and 580 pebbles (McGregor and Green, 1983a). Gibbard (1979) has sample sizes ranging from 226 to 575 (mean 389) for 22 samples, while Gibbard (1982) has a range of 205 to 728 pebbles (mean 398) for 39 samples. Hey (1980) uses 300 pebbles where possible, but has a range of 113 to 796 (mean 333) for 34 samples. In the present study, large samples, in the 11.2-16.0mm fraction, are riffled to provide a representative sample of 300 to 350 pebbles. The resulting 20068 pebbles, analysed from 65 samples, give a mean sample size of 308.7 (309) pebbles.

The lithological analysis involves the use of a low power (x20) binocular microscope of a type similar to that described by Wells (1939). This gives sufficient magnification, and a wide enough field of view, to identify pebbles far more accurately than with the naked eye, or with a hand lens; methods used by Davis (1958). Wells (1939), in fact, implies that, on polished pebble sections, petrographic information obtained from such an instrument may be as useful as information from thin sections.

> "In experience it has been found that the stereoscopic examination of a pebble supplements considerably the information gained by study of a thin section, and has more than once corrected wrong conclusions drawn from such." (Wells, 1939).

This is partly due to the three-dimensional effect that can be achieved with the binocular microscope. Each pebble is treated in a uniform manner, each examined under a strong artificial light and classified·according to the categories set out in Chapter VIII. Initially, every size fraction was examined in turn, from the largest (31.5mm) down to, and including, the 8.0mm fraction. However, at later stages only the 11.2mm fraction is used.

Flints, usually the most common single component and the most readily identifiable, are first separated from the bulk of the sample. The remaining pebbles are, subsequently, numbered consecutively, enabling a record to be kept of the identity of each pebble. The lithological units identified are set out in Chapter VIII. At the end of each analysis, the number of pebbles in each lithological group is counted and bagged separately within the sample bag. The percentage of each lithology is then calculated for each sample (Appendix 1).

### 3. Thin Sections.

Within the lithological units identified, a number contained types which required closer identification so that a source area might be more positively located. The lithologies sectioned are phosphatic nodules (previously unidentified), limestone, and igneous (Chapter VIII), with all pebbles taken from the 11.2mm fraction analysed. The method used to prepare the thin sections is standard and is similar to that set out in Allman and Lawrence (1972; p43-46), which forms the basis of the following description.

The pebble is ground on a horizontal lapping wheel to produce a rectangular block, approximately 3-5mm thick, with as large a surface area as possible. One face of the block is then polished on a rotating lead lap using a paste of carborundum 400 abrasive and water. The block is hand held and moved from the centre to the edge of the wheel. When smooth, the block is washed and the process repeated using carborundum 600 to give a polished flat surface. The block is then dried, using a paper tissue, and placed on a hot-plate, prepared-face up, to dry thoroughly. While this is drying, a glass slide is selected and the pebble number inscribed on one side, using a diamond pencil. The slide is then cleaned and placed on the hot-plate, labelled side down.

Lakeside 70C thermoplastic mounting cement is then melted onto the block and glass slide. Having allowed the cement to penetrate the block, it is placed on the slide using tweezers. Light pressure applied to the centre of the block holds it firmly to the slide. The slide is then removed from the hot-plate and placed, block down, on a pad of paper and examined for air bubbles. These are removed by applying pressure to the back of the glass. The slide is then allowed to cool, and harden, for about five minutes.

To grind the slide down to the required thickness, the slide is mounted, in wax, on a steel box plate (Allman and Lawrence, 1972; p35), which is then attached to the magnetic chuck of a horizontal spindle surface grinding machine. The chuck is moved back and forth, in a horizontal plane, beneath the grinding wheel, slowly being moved upwards until the section is about 0.5mm thick. The final smoothing stage is undertaken on a glass plate, by hand. A paste of carborundum 400 and water is used, with the slide placed face down on the plate. It is moved backwards and forwards across the plate, using a firm pressure on the back of the slide. This continues until the section is approximately 60 microns in thickness. The process is then repeated, using a paste of carborundum 600 until a thickness of 30 microns is attained. The slide is then cleaned and excess cement removed with a razor.

A cover slip is next placed over the slide to protect the section. Canada balsam is melted onto both the slide and a cover slip and allowed to cook for 3 minutes; the cooking being complete when a cooled segment of the balsam will snap rather than deform. When ready, the cover slip is "hinged" down onto the section to reduce the possibility of trapping air bubbles. Gentle pressure, applied to the cover slip, removes excess balsam. The slide is then removed from the hot plate and allowed to cool; excess balsam being removed with methylated spirits. The slide is then washed in soapy water, dried and labelled.

# Chapter VII. Site Descriptions.

## Introduction.

A total of 43 sites was examined. Thirty three sites are in the Ouse Basin. Eight are located in the Nene basin and two in the Thame basin. The section below comprises a description of each site sampled and contains the following information:

a) Name of the locality (usually the nearest settlement). National grid reference of the sample(s), with the 1:50,000 O.S. map sheet number in parenthesis.

b) Owner, if known.

c) Height O.D. and height above the floodplain (in parenthesis) of the ground surface (all heights are estimated from 1:25,000 O.S. maps).

d) Underlying geology.

e) Date(s) of sampling and description.

f) Type of site.

g) State of site and exposure.

h) Description of superficial deposits and stratigraphy.

i) Sample number(s) and depth of the sample(s) from the gravel surface. (All samples are of "Bulk spot" type unless otherwise stated; Chapter VI.A.2).

j) Sites with similar stratigraphy.

k) References to the site in previous literature.

The location of each site sampled is shown by the site number in figure 6.1, the site names, site numbers and sample numbers are tabulated in table 7.1. The stratigraphy, and height above the floodplain, of each site is indicated in figure 6.2.

A. Ouse Basin.

1 a) Bow Brickhill. SP883350 (152).

b) Milton Keynes County Council.

c) 70m (2.5m).

d) Oxford Clay.

e) September 1981, March 1982.

f) Temporary extraction of gravel during preparations for the "new A5" by-pass.

g) Disused except for some backfilling.

h) Homogeneous, well-bedded sand and gravel (2.5m). No visible within-site variation in thickness. Extraction exposes solid geology.

i) S57 (1m), S69 (1.5m).

j) Broughton; Moor End, Radwell; Broughton Ground; Gt. Barford; Willington; Simpson.

k) Horton _et al._ (1974).

2 a) Broughton. SP885390; SP886391 (152).

b) GFX Hartigan Ltd.

c) 65.2m (4.2m).

d) Oxford Clay.

e) February, April 1981, March 1982.

f) Extensive gravel pit.

g) Active.

h) Horizontally bedded, coarse sandy gravel (2.5-4m) with occasional sand lenses. Internally homogeneous. Extraction exposes solid geology (Plate 1).

i) S23 (1m), S68 (1m).

j) Bow Brickhill; Moor End, Radwell; Broughton Ground; Gt. Barford; Willington; Simpson.

k) Horton <u>et al.</u> (1974).

3 a) Moor End, Radwell. TL000587 (153).

b) Steetley Construction Minerals Ltd., Radwell Quarry.

c) 42.6m (3m).

d) Great Oolite Clay.

e) April 1981.

f) Extensive gravel pit.

g) Active.

h) Horizontally bedded sandy gravel (2m) with sand lenses becoming increasingly sandy in its upper layers (top 0.5m). Solid geology exposed.

i) S16 (0.7m).

j) Bow Brickhill; Broughton; Broughton Ground; Gt. Barford; Willington; Simpson.

k) Wyatt (1861).

4 a) Broughton Grounds. SP920406 (152).

b) Private site, access kindly granted by the Bradwell Abbey Archaeological Trust.

c) 72m (2-3m).

d) Oxford Clay.

e) September 1981, March 1982.

f) Gravel pit. Recent excavation.

g) Active. Some tipping of building waste and till has occurred.

h) Well-bedded chalky gravel (3-4m) in a sandy matrix which may become more clayey in the upper parts. Bands of ironisation occur along some bedding planes. The solid geology is exposed.

i) S56 (2.5m), S67 (1m).

j) Bow Brickhill; Broughton; Moor End, Radwell; Gt. Barford; Willington; Simpson.

k) Horton <u>et al.</u> (1974).

5 a) Great Barford. TL122510 (153).

b) Redland Aggregates Ltd.

c) 22m (2.5-3m).

d) Oxford Clay.

e) April 1981.

f) Gravel pit. Recent excavation.

g) Active.

h) Sandy gravel (2.5-3m) with weak bedding. Uppermost metre is very sandy beneath which a band of oxidised, non-sandy gravel occurs (0.2m). Beneath this the gravel is again sandy. The solid geology is exposed. Gravel thickness decreases to 1m in the southwest as the present river is reached.

i) S13 (1.1m), S14 (2m).

j) Bow Brickhill; Broughton; Moor End, Radwell; Broughton Ground; Willington; Simpson.

k) Mantle (1926).

Edmonds and Dinham (1965).

6 a) Willington. TL100498 (153).

b) Amey Roadstone Corporation Ltd., (Eastern).

c) 23m (1.5m).

d) Oxford Clay.

e) April, July 1981.

f) Gravel pit.

g) Disused. A trench cut in 1966 through remaining gravel is now heavily overgrown.

h) Poorly-sorted, unbedded sandy gravel (0.7-0.8m) becoming more sandy upwards. Overlain by 0.6-0.7m of sand with few pebbles. Surficial 0.1-0.15m is strongly weathered into a soil. Total thickness of gravel is 1.5m.

i) S41 (1.1m).

j) Bow Brickhill; Broughton; Moor End, Radwell; Broughton Ground; Gt. Barford; Simpson.

k) Although this particular site has not been mentioned in the literature, several local pits (all backfilled) have been reported:

Banton (1924).
Mantle (1926).
Tebbutt (1927).
Edmonds and Dinham (1965).

7 a) Simpson. SP883353 (152).

b) Milton Keynes County Council.

c) 70m (2m).

d) Oxford Clay.

e) September 1981, March 1982.

f) Temporary trench.

g) Backfilled by March 1982.

h) Unbedded, poorly-sorted, clayey gravel (3m). Base not seen.

i) S54 (2m).

j) Bow Brickhill; Broughton; Moor End, Radwell; Broughton Ground; Gt. Barford; Willington.

k) Horton et al. (1974).

8 a) Great Linford. SP833422 (152).

b) Amey Roadstone Corporation Ltd.

c) 59.7m (3m).

d) Great Oolite.

e) February, April 1981.

f) Extensive gravel pit.

g) Active. Slight flooding.

h) Horizontally bedded gravel (3-3.5m) with occasional sand lenses, underlying dark grey flaky clay (50cm). Boundary between sand and clay is horizontal and 'clean'. The gravel has been excavated to the level of the local water table. Lower part of face is covered in fallen debris (Plate 2).

i) S24 (50cm).

j) Clifford Hill; Rushden.

9 a) Little Paxton. TL197633 (153).

b) Redland Aggregates Ltd.

c) 16m (3.0m).

d) Oxford Clay.

e) April 1981.

f) Gravel pit used for gravel processing.

g) Disused and flooded.

h) Poorly-bedded, sandy gravel up to 1.3m above water level. Apparently homogeneous.

i) S34 (1m).

j) Blunham.

k) Tebbutt (1927).

Edmonds and Dinham (1965).

10 a) Blunham. TL155495 (153).

b) Amey Roadstone Corporation Ltd.

c) 21.3m (0.5m).

d) Oxford Clay.

e) April 1981.

f) Gravel pit.

g) Flooded and contaminated by ammonium from a nearby fertiliser factory. Backfilling is occurring.

h) Poorly to non-bedded gravel to 1m above water level. Apparently homogeneous. Unknown depth.

i) S12 (0.7m).

j) Little Paxton.

k) Edmonds and Dinham (1965).

11 a) Stewartby. TL018413; TL019408 (153).

b) London Brick Company.

c) 48.7m (19.8m).

d) Oxford Clay.

e) September 1981, March 1982.

f) Clay Pit - for the Oxford Clay.

g) Active. Most of the overburden has been stripped.

h) Oxford Clay grades upwards into a light blue grey clay often containing pebbles (till). Infrequent lenses of gravel occur within the clay. In places this is overlain, or is cut into, by a clayey gravel

(0.5-1m).

i) S49 (0.6-0.7m from a gravel lense), S66 (0.3-0.4m).

j) Elstow; Millbrook; Kempston.

12 a) Kempston Hardwick. TL035450 (153).

b) London Brick Company.

c) 45m (16m).

d) Oxford Clay.

e) September 1981, March 1982.

f) Clay pit - for the Oxford Clay.

g) Active.

h) Silt and sand with inclusions of gravel (1-2m) locally overlie the Oxford Clay.

i) S50 (0.5m).

j) Stewartby; Millbrook; Elstow.

13 a) Elstow. TL050455 (153).

b) London Brick Company.

c) 29m (4.5m).

d) Oxford Clay.

e) September 1981, March 1982.

f) Clay pit - for the Oxford Clay.

g) Disused and flooded. Exposure partly overgrown, with some slumping.

h) Fine clayey gravel (up to 2m) of limited lateral extent. Gravel is apparently in a channel in the Oxford Clay (Plate 3). Clay occurs above the gravel in places, but this may be due to slumping.

i) S51 (0.5m), S64 (1m).

j) Stewartby; Kempston; Millbrook.

14 a) Millbrook. TL001402 (153).

b) London Brick Company.

c) 53m (32m).

d) Oxford Clay.

e) April 1981, March 1982.

f) Clay pit - for the Oxford Clay.

g) Disused and partly flooded.

h) Unstructured, sandy gravel (1.5m), below which there is a light blue grey stoneless clay (till) fingering into the gravel in irregular "flame" structures (Plate 4). Within the till there are pockets of sand.

i) S76 (1m).

j) Kempston; Stewartby; Elstow.

15 a) Fox Corner. SP925293 (165).

b) Hall Aggregates Ltd. (Churchways Pit).

c) 123m (41.1m).

d) Lower Greensand.

e) April 1981, March 1982.

f) Sand pit - for the Lower Greensand.

g) Active. Overlying gravel partly obscured by vegetation.

h) Overlying the undulating surface of the Lower Greensand, are large pockets of chalky, blue grey till (up to 9m). Above the till is a structureless, sandy gravel (0.5-2m, mode of 1m) into which the till grades. Nowhere is gravel found beneath the till.

i) S20 (1m), S70 (1.5m).

j) Rushings.

k) Bristow and Kirkaldy (1962).

16 a) Rushings. SP932283 (165).

b) Buckland Sand and Silica Company.

c) 138.5m (56m).

d) Lower Greensand.

e) April 1981, March 1982.

f) Sand pit - for the Lower Greensand.

g) Active.

h) Resting on the Lower Greensand is a non-chalky blue grey till (15m), above which is a thin irregular layer of clayey gravel (0.5-1m).

i) S21 (0.75m).

j) Fox Corner.

17 a) Leighton Buzzard. SP912238 (165).

b) Hall Aggregates Ltd. (Ledburn Road Quarry).

c) 90m (7m).

d) Lower Greensand.

e) February, April 1981.

f) Sand pit - for the Lower Greensand.

g) Active.

h) Unbedded, soily gravel (1.25m) overlies the Lower Greensand. A ridge of till crosses the pit from east to west. A section in the till showed a dark blue grey clay with no pebbles (2m plus) overlain by a chalky, light blue clay with numerous pebbles. No obvious erosional break exists between the tills. The ridge was reported to exist for only a short distance east and west of the pit by the site foreman. The till is nowhere seen overlying the gravel.

i) S5 (0.5m-sieved spot sample), S6 (0.3m), S7 (Bulk channel sample).

18 a) Bletchley. SP861325, SP859320 (152).

b) London Brick Company.

c) 91m (16m).

d) Oxford Clay.

e) July, September 1981.

f) Clay pit - for Oxford Clay.

g) Active.

h) To the east of the pit, is a thin, dark brown unbedded clayey gravel (1m) resting on the Oxford Clay. This has a limited extent. To the south of the pit the solid geology is overlain by chalky till (6-7m); the upper 1-2m being weathered and brown in colour. Within the till are several pockets of gravel up to 50cm in diameter.

i) S42 (0.5m), S46 (gravel pocket in till).

j) Ridgmont.

19 a) Ridgmont. SP966411 (153).

b) London Brick Company.

c) 61m (32m).

d) Oxford Clay.

e) July, September 1981.

f) Clay pit - for Oxford Clay.

g) Disused.

h) Overlying the Oxford Clay is a non-chalky, blue grey till (5m). Within the till (in the upper 2m) are pockets of clayey gravel (up to 1m diameter) with an uneven layer of sandy gravel (0.5-1m) overlying the till (Plates 5, 6). No structure is seen in either gravel type.

i) S47 (0.75m), S48 (gravel pocket in till).

j) Bletchley.

20 a) Upper Sundon. TL042274 (166).

b) Upper Chalksift Ltd. Quarry.

c) 152m (53.3m).

d) Chalk.

e) April 1981, March 1982.

f) Gravel pit.

g) Active, although a large part is now exhausted.

h) Well-bedded sand and gravel (20m max.) dips from the east and west at about 30 degrees, in a synclinal form (Plate 7). The gravel thins to the south and west to approximately 1m. Within, and overlying, the gravel, in patches and bands, is a stiff blue grey chalky till of varying thickness. Iron staining increases towards the till and an iron band may separate the deposits. Chalk is exposed beneath the gravel.

i) S17 (2m-above till), S73 (4m-below till).

j) Ippollitts; Winslow.

k) Keen (1968).

21 a) Ippollitts. TL192257 (166).

c) 98m (14m).

d) Chalk.

e) November 1981, March 1982.

f) Gravel pit.

g) Disused. Water filled to an unknown depth.

h) Horizontally bedded sand and gravel (5-6m) with iron staining giving colour variation from almost white to dark orange brown. Overlying the gravel is bluish grey, chalky till (3-4m) which becomes browner as the gravel is reached. Within the till are several sandy gravel lenses (Plate 8).

i) S58 (4m), S71 (gravel lense within the till), S72 (2m).

j) Upper Sundon; Winslow.

k) Bloom and Harper (1938).
West and Donner (1956).

22 a) Winslow. SP777274 (165).

c) 114m (23m).

d) Oxford Clay.

e) March 1982.

f) Sand and gravel pit.

g) Disused and vegetated.

h) Dark brown clayey gravel (2.5m), underlying a blue grey chalky till (1m). The gravel has been extracted to the level of the Oxford Clay.

i) S75 (1m).

j) Ippollitts; Upper Sundon.

23 a) St. Neots. TL170604 (153).

b) Hillson and Twigden, Kilroy New Housing Department.

c) 24.5m (9.1m).

d) Oxford Clay.

e) April 1981.

f) Building site. Foundation trench.

g) Clean trench face. Now developed.

h) Pale blue grey, chalky till (2m plus) becoming darker with depth and browner as the surface is reached. Within the till is a fine, apparently well-sorted, clayey gravel wedge (1.2m) which gets coarser upwards. This grades into the overlying brown till (Plate 9).

i) S35 (0.6m).

24 a) Aspley Guise. SP935343 (165).

b) Steetley Minerals Ltd. Fullers Earth Quarry.

c) 121m (61m).

d) Lower Greensand.

e) April, May 1981.

f) Sand pit - for Lower Greensand.

g) Active.

h) In a hollow in the Greensand surface is a plug of till which varies from a dark blue grey, non-chalky clay through typical blue chalky till to brown clay in the upper parts (maximum 15m - land-slipping obscures exact stratigraphic relations). In places the non-chalky till is separated from the chalky till by a band of horizontally bedded sand and gravel (1.5m). The overlying till contains smaller sandy gravel pockets.

i) S22 (gravel pocket), S38 (1m - gravel band).

25 a) Buckingham. SP702344 (152).

c) 86.8m (12.2m).

d) Great Oolite.

e) April 1981.

f) Gravel pit.

g) Disused and overgrown. Small exposure.

h) Well-bedded, poorly-sorted sandy gravel (2m) beneath a capping of sand (1m) at the base of a 9-10m face (upper face overgrown). Beneath the gravel is well-bedded sand to an unknown depth.

i) S25 (1m).

k) West and Donner (1956).

26 a) Buckingham. SP713347 (152).

c) 91m (16m).

d) Cornbrash.

e) July 1981.

f) Small gravel pit.

g) Disused with some tipping.

h) Poorly-bedded gravel (3-4m) with some cross-bedding and containing both coarse and fine material (Plate 10.)

i) S44 (1.5m).

27 a) Buckingham. SP711356 (152).

c) 110m (35.5m).

d) Cornbrash.

e) July 1981.

f) Road cutting.

g) Overgrown. Opposite a backfilled gravel pit used for pasture.

h) Unbedded sand and gravel (2-2.5m).

i) S43 (1.5m).

28 a) Clifton. TL171392 (153).

c) 39.5m (4.5m).

d) Gault Clay.

e) February 1981.

f) Gravel face in farmers field.

g) Field is grazed, but face is clean. Upper level has been developed.

h) Lower 'chalky' gravel (1m), underlying an upper hard, sandy non-chalky gravel (1m) which extends down into the lower gravel in long irregular pockets. Neither gravel appears bedded.

i) S1 (1.5m), S2 (0.5m).

k) Edmonds and Dinham (1965).

29 a) Lodge Farm. SP863412 (152).

c) 75m (15m).

d) Cornbrash.

e) September 1981, March 1982.

f) Archaeological excavation of Roman/Saxon trenches in a building site.

g) Clean face in trench. Developed by March 1982.

h) Very fine gravel (0.6m) associated with till, covered by head (0.3m). Coarser gravel had previously been exposed but the site had been developed. The surrounding area is covered by till.

i) S55 (0.3m).

30 a) Bromham. TL020521 (153).

b) Bedfordshire County Council.

c) 41.7m (11.2m).

d) Cornbrash.

e) May 1981, March, May 1982.

f) Gravel pit.

g) Disused and partly backfilled. Slight flooding in parts.

h) Clayey, unbedded gravel (2-3m) overlies a light blue sticky clay without stones (Plate 11).

i) S37 (1m), S62 (1.9m).

31 a) Lidlington. TL002384 (153).

c) 122m (92m).

d) Lower Greensand.

e) March 1982.

f) Cutting (1m) on a public footpath.

g) Partly vegetated.

h) Fine sandy gravel (0.6m plus) associated with a stiff dark blue grey till. No contact of the gravel with either till or Lower Greensand is visible.

i) S77 (0.3m), S80 (0-0.4m).

32 a) Toddington. TL000281 (166).

c) 145m (61m).

d) Gault Clay.

e) March 1982.

f) Road side ditch.

g) Vegetated, with no clean faces.

h) Structureless clayey gravel (0.15-0.7m) overlying a greyish clay (the Gault Clay). The clayey gravel is possibly fill.

i) S74 (0.3m). This sample may be rejected at a later date as a man made deposit.

j) 1:625 000 map and IGS data.
Doubleday and Page (1904).

33 a) Stoke Goldington. SP854490 (152).

b) GFX Hartigan Ltd. Ravenstone Quarry.

c) 61m (6m).

d) Upper Lias.

e) February 1981 to November 1983.

f) Gravel pit.

g) Active but in process of backfilling.

h) A face of gravel up to 6m thick divided into two suites separated by a pale grey clay. The lower, horizontally bedded gravel is up to 4m thick and encloses up to 1.72m of richly organic clay in a channel fill type deposit. The upper gravel is strongly involuted. A full description of this site can be found in Chapter XI.

i) S26 (2m from the surface of the lower gravel), S27 (1.5m from the surface of the upper gravel), S52 (3.5m from the surface of the lower gravel).

j) Shotton (1983a).
Keen (1983).
Young (in preparation).

B. Nene Basin.

34 a) Clifford Hill. SP797603 (153).
b) Mixconcrete Aggregates Ltd.
c) 61m (6m).
d) Upper Lias.
e) April 1981.
f) Gravel pit.
g) Active but almost worked out.
h) Horizontally bedded gravel (5m) with iron staining. Strongly associated with, and mostly occurring above, the gravel, is a blue grey clay without pebbles. No sequence break occurs.
i) S28 (4m).
j) Rushden; Gt. Linford.

35 a) Earls Barton. SP870626 (152).
b) Mixconcrete Aggregates Ltd.
c) 45m (3.5m).
d) Upper Lias.
e) February, April 1981.
f) Gravel pit.
g) Active with some tipping.
h) Horizontally bedded, poorly-sorted sand and gravel (3m) with iron staining. Overlying the gravel is a clay (0.5-0.7m), above which some filling has occurred. The Lias Clay is exposed below the gravel.
i) S32 (1m).
j) Clifford Hill; Rushden.

k) Richardson and Kent (1938).
   Hollingworth and Taylor (1946b; 1951).

36 a) Rushden. SP946694 (153).
   b) Amey Roadstone Corporation Ltd., (Eastern).
   c) 37.5m (3m).
   d) Upper Lias.
   e) February, April 1981.
   f) Gravel Pit.
   g) Disused and left for backfilling.
   h) Horizontally bedded gravel (3m) with an overlying, non-pebbly, blue grey clay.
   i) S33 (1m).
   j) Clifford Hill; Earls Barton.

37 a) Pitsford. SP753675 (152).
   b) Peter Bennie Ltd.
   c) 108m (36.5m).
   d) Inferior Oolite (Northampton Sands).
   e) April 1981.
   f) Iron stone pit - for the Northampton Sands.
   g) Active.
   h) 'Wedges' or 'gulls' let down into the Northampton Sands contain clay and clayey gravel. The structure investigated is 2.5m deep and 1.3m wide at the surface, tapering unevenly with depth. In contact with the Northampton Sands is a dark blue till (maximum thickness 1m), the gravel lying within this (Plate 12).
   i) S31 (1m).

k) Hollingworth and Taylor (1946a; 1951).

38 a) Milton Malsor. SP722562 (152).

b) Mixconcrete Aggregates Ltd.

c) 80m (9m).

d) Middle Lias.

e) April 1981, March 1982.

f) Sand pit - for "Milton Sands".

g) Active but being backfilled.

h) Unbedded sand ranging from 1m to over 4m thick. Overlying the sand in places, a metre or so of 'hoggin' was described by the site foreman as rather more pebbly than the sand, into which it graded. To the south of the pit, a trench (1m wide by 60cm deep) has been opened (February 1982) which, in parts, cut through a stiff blue to brown pebbly till. This rests entirely on the sands.

i) S30 (0.5m - probably incorporating "hoggin" - McGregor and Green, 1978), S61 (2m - from the sands).

k) Thompson (1930).
Dury (1949).
Horton (1970).
Horton et al. (1974).
Castleden (1980c).

39 a) Wootton. SP759557 (152).

c) 77.7m (4.5m).

d) Upper Lias.

e) April 1981.

f) Gravel pit.

g) Disused and overgrown. Some tipping. No clean exposures in a degraded face approximately 2m high.

h) Dark brown clayey gravel is the only visible deposit, its thickness being indeterminate.

i) S29 (1m).

k) Thompson (1930).
Dury (1949; 1950).
Horton (1970).
Horton _et al._ (1974).
Castleden (1980c).

40 a) Weedon Bec. SP635588 (152).

c) 97.5m (20m).

d) Middle Lias.

e) February 1982.

f) Gravel pit.

g) Disused and overgrown. Some tipping. No clean exposures in a degraded face approximately 4m high.

h) Structureless gravel is the only deposit visible, its thickness being indeterminate.

i) S59 (4m - base of face).

k) Thompson (1930).
Dury (1949).
Horton (1970).
Castleden (1980).

41 a) Nether Heyford. SP667584 (152).

c) 70m (1.5-2m).

d) Middle Lias.

e) February 1982.

f) Gravel pit.

g) Backfilled and used for pasture.

h) Sandy gravel (1-1.5m). The relationship to any underlying deposit is not visible.

i) S60 (0.75m).

k) Thompson (1930).
Castleden (1980).

C. Thame Basin.

42 a) Rowsham. SP846175 (165).

c) 77.7m (0m).

d) Kimmeridge Clay.

e) July 1981.

f) River bed.

i) S45.

43 a) Marsworth (Pitstone). SP930147 (165).

b) Tunnel Cement Ltd.

c) 134m (42.6m).

d) Lower Chalk.

e) May 1981.

f) Chalk pit.

g) Archaeological excavation by Aylesbury Museum.

h) A channel deposit in the Chalk is covered by cryoturbated, gravelly, coombe rock, into which is cut a second channel. The channel appears to originate from a spring near the base of the Chalk escarpment.

i) S39 (0.5m), S40 (2m).

k) Evans and Oakley (1952).

Evans (1966).

Shotton (1983a).

Green et al. (in preparation).

# Chapter VIII. Lithological Determination.

## Introduction.

The pebbles, in the gravels, are divided into eight main classes, some of which are subdivided, together with seven minor classes, to give a total of twenty lithologies used in the following analysis. These lithologies are:

A. Quartz.
B. Quartzite.
C. Sandstone 1. Hard sandstone.
    2. Soft sandstone.
    3. Calcareous sandstone.
D. Ferrous sandstone and Ironstone.
E. Limestone 1. Limestone.
    2. Ferrous limestone.
F. Chalk.
G. Flint.
H. Chert 1. Chert and Siliceous limestones.
    2. Rhaxella chert.
    3. Cherty sandstone.
I. Others 1. Phosphatic nodules.
    2. Igneous.
    3. Shells.
    4. Mudstone.
    5. Schist.
    6. Grit.
    7. Miscellaneous Hard.

A. Quartz.

a) Description.

The major problem with the identification of quartz is the separation from various forms of quartzite into which it may grade. To distinguish, quartz was defined as those large bodies of clear quartz in which no regular internal structure can be seen. Any visible matrix, separating a granular structure, would classify the pebble as a quartzite (See B).

Many coloured varieties of quartz exist, ranging from black, purple, pink and yellow to white or clear, all of which are semi-translucent. Most of the present specimens are of the white, or clear, variety. Quartz has an absence of cleavage and a well-developed conchoidal fracture. Although several specimens appeared to have an irregular fracture - these, at a higher magnification (X32), were found to be composed of multiple, small, conchoidal fractures.

b) Source.

Quartz is one of those lithologies which can be found in many geological strata, in one form or another. Outside the Ouse catchment, a major source of well-rounded quartz pebbles, put forward by previous authors, is the Triassic Bunter Pebble Beds of the Midlands (Hey, 1965; 1980; Green and McGregor, 1978; McGregor and Green, 1978; 1983) (The Bunter Pebble Beds have now been renamed the Kidderminster Conglomerate, or the Cannock Chase Formation (Warrington et al., 1980) in the Midlands, but to avoid confusion, the term Bunter Pebble Beds will be retained in the present study.). Bonney (1900) describes vein quartz, usually white, within the Bunter conglomerate, and Shrubsole (1903) quotes G.H. Moreton, who shows that the Bunter in the Liverpool district

> ". . . has a total thickness of 1950 feet [of which] 400 feet is a sandstone in which quartz-pebbles are dispersed and 600 feet is a true pebble bed. In this, however, the pebbles are principally white vein-quartz, quartzite and a few other rocks.",

quartzite being much more numerous than quartz (Hey, 1965).

Within the Ouse basin, however, further small sources of quartz are available. Brodie (1866), Harrison (1877), Barrow (1919), Nicholls (1947), Kirkaldy (1947) and Wells and Gossling (1947) all report that, at the base of the Lower Greensand, there is a pebble bed which contains, among other 'erratics',

> ". . . numerous pebbles of quartz . . ." (Harrison, 1877).

They range from large angular, unworn stones up to about 30mm in diameter, to well-rounded pebbles, of ovoid form (Wells and Gossling, 1947). Kirkaldy (1947) also reports quartz in the upper parts of the Woburn Sands, near Leighton Buzzard. Hawkes (1943; 1951) describes erratics, of which vein quartz is one of the more numerous, originating from the Cambridge Greensand and from the Lower and Middle Chalk. The erratics described range in size from 5 to 55cm in diameter, and up to 60kgm in weight, and most are sub-angular. Although in none of the local strata are the finds numerous, Hawkes (1951) states that

> "No particular significance can be attached to the abundance of finds at different localities. The stones have been found where the Chalk has been worked, and where they have been especially looked for."

In all of these strata, the pebbles are secondarily derived, especially where well-rounded pebbles are concerned, and as Wells and Gossling (1947) state

> "There is no possibility of tracing any of them back to their ultimate origin."

In the present study, some insight may be obtained into the likely source of the quartz pebbles. In the Thames basin, where the source, although varied, is generally believed to be the Bunter Pebble Beds, quartz appears to be a relatively important part of the gravels (table 8.1). In the Ouse basin, a similar analysis shows that quartz forms only a small part of the gravel. It thus appears likely that the quartz, in the two river systems, is derived from separate sources.

In a principal component analysis of the samples, from the Ouse basin (Chapter X.B.4), the second eigenvector is most heavily weighted by high proportions of quartz, soft sandstone, calcareous sandstone, cherty sandstone and miscellaneous hard; all of which can be related to Lower Cretaceous rocks, principally the Lower Greensand and the Cambridge Greensand. The lack of quartzite and hard sandstone in the vector can only be explained if quartz is derived separately.

### B. Quartzite.

#### a) Description.

The term quartzite has come to include both metamorphic, and sedimentary, rocks. The latter, 'ortho-quartzite', is an arenaceous rock where the sandstone has been completely, and solidly, cemented by secondary quartz. The metamorphic variety, often termed a 'meta-quartzite', involves a complete chemical change in the textural arrangement of the rock - usually through recrystallisation. Quartzite is defined by Holmes (1920, p194) as

> ". . . a granulose metamorphic rock, representing a recrystallised sandstone consisting predominantly of quartz."

Under these conditions there is little or no trace of cementation. Although, under the binocular microscope, ortho-quartzite can be separated from meta-quartzite (the quartz grains of the former have a frosted appearance, the latter are clear (Pettijohn, 1975; Skolnick, 1965)), no such division has been made here. The main problem is the separation from hard lithified sandstones. To make the distinction, quartzites, due to their cementation or recrystallisation, are defined as those pebbles which fracture through, rather than around, the constituent grains (Krynine, 1948; Skolnick, 1965; Pettijohn, 1975; Pettijohn <u>et al.</u>, 1972).

Within this class are the Bunter quartzites. These have cementation which is so perfect that the individual grains are often difficult to see and the fracture sometimes becomes sub-conchoidal. They are usually reported to be 'liver-coloured', but have a wide range of colours, from almost white to dark greenish grey (Bonney, 1900). Although the 'liver-colouration' is usually characteristic, Hey (1980) demonstrates that many of the quartzites found in the Westland Green Gravels of the Thames may have been bleached, after deposition, leaving colourless quartzite pebbles in their place. In the present class, a wide range of types and colours exist and no subdivision is made.

b) Source.

As with quartz, the potential source of quartzite pebbles is wide. Again, the Bunter Pebble Beds of the Midlands comprise a major potential source (Bonney, 1900; Shrubsole, 1903), but locally the Cambridge Greensand and the Lower and Middle Chalk have had quartzites found in them (Seeley, 1866; Hawkes, 1951). Hey (1965) concluded that quartzites in the Thames gravels could be matched with those in the Bunter Pebble Beds, but that consistent differences in proportions of this, and other lithologies, suggest that many of the light coloured quartzites must

> ". . . have come from some source other than Bunter." (Hey, 1965; p416).

However, after discovering that bleaching is quite possible, Hey (1980, p289) concludes that

> ". . . there is little doubt that most were derived from the Bunter of the Midlands."

That "colour is no criterion of origin" is supported by Wells and Gossling (1947), discussing the origins of quartzite, in the Lower Greensand. Due to the large variation, within the quartzite class, it is obviously difficult to give a particular source.

> "It may be laid down as axiomatic that with such common and widely distributed rock-types as quartzites, sandstones and cherts, it is not sufficient to demonstrate that a certain pebble resembles, however closely, a known source-rock, but that it is dissimilar from all others of the same type. In the writer's opinion this calls for a far greater detailed knowledge of the variation of such rocks than anyone can reasonably be expected to possess. Further, the fact that one is comparing an outcrop existing today with a fragment broken off in some past geological period is liable to lead to faulty correlation; there is likely to have been variation down the dip as well as along the strike, and levels available for study today are are not those of yesterday. Secondly, the other great difficulty in a work of this kind lies the impossibility of being certain whether a given pebble is a first-hand contribution to the bed in which it occurred or whether it had been derived at second or third hand from some pre-existing pebble bed." (Wells and Gossling, 1947, p211).

C. Sandstone.

1. Hard sandstone. a) Description.

This category includes hard, lithified sandstones which are largely, if not solely, composed of quartz grains, together with hard, micaceous sandstones. The quartz grains are normally sub-angular, although occasionally rounded grains occur, with the cementing matrix invisible. The definition, and sorting, of the grains vary, giving rise to a variety of surface textures, the more usual type consisting of a smooth surface with occasional pits and fractures. Nearly all are reasonably well-rounded. With the gradation of this class into quartzites, differentiation was made on the presence of breakage around the individual particles, as oppose to across the particles (see B.a above). Again colour could not be used for differentiation, as, like quartzite, it ranges from dark reddish brown, through orange to buff.

b) Source.

As with the quartzites, the large variety within the class made absolute source location impossible. No assessment can be made on the amount derived from the Bunter Beds and little positive proof can be put forward for suggesting the Lower Greensand, or Cambridge Greensand, pebble beds as a source area. Evidence can be put forward, however, that the source of those pebbles, classified as hard sandstone, is similar to that for the quartzites. A correlation between the amount (in percent) of quartzite and hard sandstone of 0.63 is the highest correlation between two major lithologies. If it is assumed that both lithologies have a similar resistance to breakage and attrition, then a local source for only one would produce a low correlation, due to the 'flooding' effect of the local lithology. The relatively high correlation implies that both are either local, or both far-travelled. Of the sources put forward for these lithologies by previous workers, the Bunter Pebble Beds appear most likely (Barrow, 1919; Green and McGregor, 1978; 1983; Hey, 1980). The Bunter Pebble Beds continue, from their type area at Cannock Chase, Staffordshire, across to Leicester, Middlesborough and Doncaster to the North Sea (Warrington _et al._, 1980)(fig. 8.1). The hypothesised eastern source, for the Ouse basin, is rather smaller than that suggested for the Thames; the two areas separated topographically by the Pennines.

2. Soft sandstone. a) Description.

This class ranges from coarse-grained, reasonably well-cemented, sandstones through to fine grained, micaceous, or feldspathic sandstones. The former tend to be reasonably well-sorted, with the well-defined quartz grains always appearing fresh. The matrix is always visible and is usually opaque, or white, in colour. The finer variety is softer, usually with a grainy texture, in a yellow or brown matrix. Frequently black and white mica are scattered throughout the matrix with the consequent reduction in quartz grains. Other features are the occasional occurrence of pink feldspar crystals, and the presence of iron, in a few specimens. In all cases, the salient feature is the soft, friable nature of the pebble.

b) Source.

Separation from the hard sandstone class, mainly in terms of hardness, can be supported in terms of the source area. Hard sandstone, as indicated above, is durable and, thus, likely to be far-travelled. Soft sandstone, on the other hand, is not durable, and will disintegrate during transport. If a local source is indicated, excluding the possibility of in situ weathering of hard sandstones, the only potential supply is the Lower Greensand, to the southeast of the area (fig. 8.2). Although, again, no proof of this derivation can be put forward, its close association with quartz, and other 'Lower Greensand pebbles', in the principal component analysis, suggests that this is the most likely source.

3. Calcareous sandstone. a) Description.

This class appears much the same in character as the soft sandstone class, with grains of subrounded to angular, clear quartz cemented by small, to moderate, amounts of matrix. The matrix, however, is calcareous, reacting strongly to a solution of hydrochloric acid. A variety of grain sizes exist, within the class, but within any one pebble, sorting is moderately good. All of the calcareous sandstones are soft and non-durable.

b) Source.

The association of this class with soft sandstone and quartz in the principal component analysis and its non-durable nature, imply a local source, probably the Lower Greensand (Edmonds and Dinham, 1965), although other strata, such as the Kellaways Beds, contain some calcareous sandstone (Horton _et al._, 1974) (Chapter II.E; table 2.1). The presence of calcareous sandstone in samples outside the Ouse basin (notably at Wootton, Clifford Hill, Weedon Bec, Nether Heyford), however, suggests there is a second source. The most probable local source, present in both the Ouse and the local part of the Nene, are the Northampton Sand Beds, and part of the Lower Estuarine Series, of the Inferior Oolite (table 2.1).

## D. Ferrous Sandstone and Ironstone.

a) Description.

The ferrous sandstones are distinguished, from the sandstone class, by the black, or dark brown, matrix of iron oxide in which rounded and sub-rounded quartz grains are scattered. Sorting of the quartz grains varies from moderate to very poor. The matrix is usually dominant and well-solidified giving rise to a hard, durable, lithology. Occasionally, however, a coarser, iron-rich, gritty sandstone occurs which is softer, and not so well cemented, the matrix being subordinate. This latter type, only occurring occasionally, was not separated from the bulk of the ferrous sandstone class.

The ironstone, into which the ferrous sandstone grades, is brown or black in colour and has a general absence of quartz grains in a fine grained, iron oxide (limonite), structure. Occasionally botryoidal, the most common occurrence is in the form of box-stones and concretions, often formed around a dark yellow clay or mudstone nucleus. Red banding is visible in some ironstone that has been fractured. Often ferrous sandstone is present cemented to the outside of the 'box'. Invariably, the ironstone is hard and durable.

b) Source.

Both the sandstone and the ironstone, containing a matrix which is identical in form, are considered to come from the same source rock. Only two strata are considered as likely sources: the Lower Greensand and the Northampton Sand and Ironstone. Both occur within the study area, and so the class is considered to be 'local' in derivation.

The vast amount of limonite present, in the majority of the pebbles, favours the Northampton Ironstone Field. This is supported by the presence of box-stones and concretions which closely match the descriptions given by Arkell (1933) and Taylor (1963). Descriptions of the Lower

Greensand do not give prominence to the iron based matrix, the strata normally containing poorly cemented, glauconitic, quartz sands (Edmonds and Dinham, 1965; Rayner, 1967; Keen, 1968). It may be useful to point out, however, that the softer, coarse, iron-rich, gritty sandstone, occasionally found in the samples, is closely similar to the beds of harder, gritty sandstone, or Carstone, found in the Lower Greensand.

## E. Limestone.

### a) Description.

1. Limestone; A wide variety of limestone types is found ranging from hard shelly limestones, through soft shelly limestones, to both hard and soft oolitic limestones. An arbitrary classification was set up, within the class, in an attempt to identify the salient characteristics of the group. Of the twenty six or so initial groups, many were merged together as a gradation between classes became apparent. Four prominent types were identified, all of which had some similarities.

Type 1: is a white to cream or buff coloured oolitic limestone, in which shell fragments are scarce, in a fine calcite matrix.

Type 2: is a hard, shelly limestone in a calcite matrix, usually yellow or buff in colour, with iron staining present in some specimens. Rounding is usual because of its hardness. The matrix tends to be dominant.

Type 3: is rather softer in nature than either 1 or 2 and contains both shell fragments and ooliths; the latter normally worn and eroded. Similar in colour to type 2, there appeared to be a gradation between types 1 and 2 through this type.

Type 4: is a buff coloured, rubbly and flaggy limestone composed solely of shell fragments of all sizes which differs from type 2 in that the shell debris is dominant over the calcite matrix. Quartz grains are occasionally present in this type.

Thin sections were made of each type to help identify more closely the limestone source (Plates 13 to 16). For comments on the thin sections, I should like to thank Dr E.P.F. Rose of the Geology Department, Bedford College.

Type 1 is shown to be a bioclastic limestone, heavily altered, containing rounded and globular ooliths, which in some cases were heavily stained with iron. Fragments of echinoderm tests are scattered throughout the matrix (Plate 13).

Type 2 is shown to be composed mainly of echinoderms, gastropods, molluscs, and brachiopods, in a calcite matrix. The section showed that diagenesis had occurred to a greater degree than in any of the other types (Plate 14).

Type 3: echinoid tests are again present, within the bioclastic skeletal debris, together with the ooliths seen under the binocular microscope. No significant difference between this type, and the other types, was noticeable (Plate 15).

Type 4 is shown to be a fairly fresh, bioclastic limestone, again with echinoderms. Quartz is present, to a greater or lesser extent, within the matrix of calcium carbonate (calcite - CaCo3). The staining and clastic nature of this type is consistent with all other types (Plate 16).

Although between type variation is evident, in terms of shell fragment size and the proportion of matrix present, this type of variation can occur not only between strata, but also within stratum (Chapter II), and differentiation between strata, even in the field, can be difficult (Arkell, 1933; Taylor, 1963; Rayner, 1967).

2. Ferrous limestones; are present in a few samples and are separated from the bulk of the limestones by reason of the high proportion of iron present, both in the form of a fine groundmass, or as ooliths in the shelly calcite matrix.

b) Source.

Limestones are present in several strata, within the area, including the Upper Lias, the Inferior Oolite, the Great Oolite (Blisworth Limestone), the Cornbrash and the Corallian (table 2.1), all of which contain shell debris, and ooliths, to a greater or lesser extent, and which can locally be ferruginous (Arkell, 1933; Taylor, 1963; Rayner, 1967; Horton et al., 1974). Each formation varies rapidly, and frequently, within itself in the proportion of matrix and shell debris. This makes a positive identification, away from the source area, almost impossible (Taylor, 1963). With no significant difference apparent between the types, it is suggested that they are all derived from the same range of strata. The bioclastic nature of the limestone, the echinoids, the molluscs, and iron-staining suggest a Mesozoic age, most probably Jurassic; an age with which all the components are consistent. Ooliths and pisoliths formed of calcite, although not diagnostic, have been described from the

Middle Jurassic oolite beds of England (Greensmith, 1978). The limestone lacks the heavily crystalline structure that would be present if it were of Carboniferous age. The shell fragments suggest a Middle or Upper Jurassic age rather than a Lower Jurassic or Liassic origin. However, there is nothing age diagnostic which could closely define a source stratum within the Jurassic (Dr E.P.F. Rose, pers. comm.)

## F. Chalk.

### a) Description.

Present, and occasionally dominant, in many samples is chalk - a hard to soft, white to grey or yellow, carbonate rock, in which impurities are scarce or absent. Usually fine-grained, the chalk, occasionally, has a perceptible gritty texture, not unknown in the Chalk formations of Britain, where the proportion of Inoceramus prisms increase (Greensmith, 1978). Occasionally, the normal white colouration gives way to brick-red; a colour which is caused by granular haematite distributed unevenly through the rock (Greensmith, 1978). Thin sections of a selection of white and yellow coloured 'chalk' pebbles confirmed the identification by the presence of Globigerina foraminifera, which are only common in the Upper Cretaceous (Plate 17).

### b) Source.

The Upper Cretaceous Chalk Beds form the southern margin of the study area and extend northeast towards the Wash and north into Lincolnshire (fig. 8.3). No simple distinction can be made, either using the binocular microscope, or a petrological microscope between chalk exposed in any of the outcrops. Consequently, the amount of chalk from any one area is impossible to assess. The presence, in a few samples, of the red chalk is indicative of a Lincolnshire derivation, as this is the only known outcrop in Britain with this phenomenon (Greensmith, 1978).

### G. Flint.

#### a) Description.

In most samples, flint forms the most frequent single component. Formed of dense silica, without definite visible structure, flint is not translucent. The greatest variation within flint is the distinctive variation in colouration, usually irregular, and either sharply, or poorly, defined. Most pebbles are angular, or sub-angular, and display a clean conchoidal fracture. Occasionally, however, rounded flints do occur with diversified appearance, caused by weathering effects. The weathered surface is commonly matt, and is frequently scored by chatter marks. Such a weathered surface forms a distinctive rind, completely diagnostic of flint.

Some difficulty may be apparent in distinction from both chert (see H.1) and quartz. Where difficulty occurred, classification as quartz was based on the following features: the lack of a weathered rind; a lack of chattermarks; translucence.

#### b) Source.

In addition to the lithological differences between flint and chert, it is useful

". . . to restrict the term "flint" to cover only the

> occurrence of chert in the Chalk." (Wilson, 1938; p1).

Occurring in bands in the upper Middle Chalk, and becoming more frequent in the Upper Chalk, flint is considered to be derived from the outcrops to the north, and northwest, of the area - in Lincolnshire and East Anglia - as well as the local source of the Chilterns. The distance travelled is probably small, evidenced by the angular nature of most pebbles.

### H. Chert.

1. Chert and siliceous limestone. a) Description.

Differentiation between flint and chert is difficult in many cases, and has been for many years (Hill, 1908; p67, 93). In the present study, the following characteristics have been used to separate chert from flint: chalcedonic matrix; the absence of a weathered rind, or the absence of a white crust (Hawkes, 1951); a more uniform structure than that of flint; the presence of sponge spicules - which Folk and Weaver (1952), and Tresise (1961), suggest may be the predominant material - and fossils; and a tough, splintery and flat fracture (Pettijohn, 1975) rather than conchoidal, often giving a rough surface texture. The colour of chert is wide-ranging, more commonly light brown or grey, but also being white, pink, red, yellow or black. Chert, found in the past to vary widely in nature (Hill, 1911; Wells and Gossling, 1947; Pettijohn, 1975), was not subdivided unless a specific characteristic made its identification easy.

b) Source.

Although Tresise (1961) implies that the cherts from Devon, Dorset, Wiltshire and Somerset, tend to have characteristic colours, it is not posible use colour to define source areas (Wells and Gossling, 1947). Secondarily derived cherts have been found in varying amounts, and of various types, from the Lower Greensand strata (Hill, 1911; Hawkes, 1943; Wells and Gossling, 1947; Hawkes, 1951), and the Bunter Pebble Beds (Bonney, 1900), while chert in situ can be found in Carboniferous and Jurassic strata (Bridgland, 1980). Insofar as the class is durable, a far-travelled source cannot be ruled out.

2. Rhaxella Chert. a) Description.

Rhaxella chert is a clouded grey or blue, siliceous rock which has a dull, vitreous lustre and a splintery fracture (Davies, 1907; Wilson, 1938). Within the dense matrix, the chert is studded with minute ellipsoidal bodies, rather lighter in colour than the chert matrix and often surrounded by an outer clear zone. These are spicules of the sponge Rhaxella perforata, Hinde. A variety of forms is present within the samples analysed. Usually, only fractured surfaces are visible, and the Rhaxella are seen in section, showing the concentric structure. Occasionally, however, the sponge stands proud on the surface as tiny spheroids in the matrix. On some surfaces these spheres have disappeared, leaving empty spaces in a pitted surface. Normally spherical, or circular in form and of constant sectional diameter (0.1mm) (Davies, 1907), the spicules are occasionally ovoid and vary in size. Wilson (1938, p10) suggests

> "They may represent 'Rhaxella' spicules which have undergone some form of corrosion."

Some pebbles of limestone, albeit very few, also contain these siliceous Rhaxella spicules. While these should technically be termed limestone, they were considered to originate from the same source as the chert and were classified thus.

b) Source.

Rhaxella chert formations can only be found in two localities in Britain. Firstly, the Arngrove stone, in the Brill district of Buckinghamshire (19 kilometres east of Oxford)(Davies, 1907), and secondly, the western parts of the Tabular Hills in the Hambleton and Howardian Hills region of Yorkshire (Wilson, 1938). In both cases, it is Corallian beds of the Upper Jurassic that contain the chert (fig. 8.4). Davies (1907) showed that the chert, in both regions, is identical. The likelihood of material reaching the present study area from the southwest is small, leaving Yorkshire as the most probable origin - an origin put forward by most authors for the erratics of Rhaxella chert found in the gravels of the Thames and East Anglia (Hey, 1965; 1980; Bridgland, 1980; Catt, 1981; Green et al., 1982). Care needs to be taken in the identification of the source area, however, as Barrow (1919, p12) indicates:

> "At present the far too wide assumption is often made that certain rocks (e.g. Rhaxella Chert) can only come from a few specific localities. This assumes

> that we know all possible localities for this Chert, an assertion that lately-gained experience shows to be highly improbable."

The Yorkshire Corallian is composed of Upper Calcareous Grit; Osmington Oolite Series; Middle Calcareous Grit; Hambleton Oolite Series; Lower Calcareous Grit. Rhaxella chert has been reported to occur only from the lower two stratum of the succession - in the area lying to the west of Kirby Moorside and north of Helmsley, throughout the Hambleton Hills, and in the Castle Howard, Hovingham, Gilling and Coxwold districts of the western Howardian Hills (Wilson, 1938). All variations of Rhaxella chert found in the present study, can be found in the formation. Most of the chert beds is found in the Lower Calcareous Grit, but above this, the Hambleton Oolite Limestone contains irregular masses of chert.

> "Generally, the limestone is a hard gritty oolite, evenly and thickly bedded, well jointed and containing much comminuted shelly material and large numbers of siliceous Rhaxella spicules." (Wilson, 1938, p6).

Rhaxella chert has also been discovered as erratics in the Woburn Sand of the Lower Greensand (Kirkaldy, 1947), but its occurrence is considered to be infrequent enough to dismiss this as a significant source.

3. Cherty sandstone. a) Description.

A small proportion of samples contain hard, siliceous chert-like pebbles which contain quartz grains together with sponge spicules. Frequently the matrix, which is opaque to white or brown in colour, survives, with the disappearance of the detrital grains, to give a pitted to very rugged surface.

b) Source.

Like chert, a varied source is probable, both from outside and within the basin. The Lower Greensand again is a possible source, supported to some extent by the principal component analysis which associates cherty sandstone with other material thought to be from the Lower Greensand.

## I. Others.

Within each sample, a small number of minor lithologies occur. Some of these can be tied down to a particular source area, most cannot.

### 1. Phosphatic nodules.

Two forms of phosphates are observed. Firstly, there are nodules themselves, variously shaped from rounded to elongate, and secondly, there are remanié phosphatised fossils, usually the casts of ammonite chambers. The fossils are usually so worn they cannot be identified. Those found in the past in the Lower Greensand and Chalk have been shown to be derived locally from the Oxford or Kimmeridge Clays (Hawkes, 1951; Casey, 1961). The matrix of both types is identical. The matrix varies from dark brown to yellow but is more frequently pale grey in colour, with a surface that is frequently finely pitted. Scattered across the surface, in varying amounts, of many nodules - though not all - are sharply angular quartz grains, together with rather fewer grains of glauconite. Where no quartz or glauconite is present, the pebble often becomes dark brown in colour and has a fracture similar to that of some flints.

Thin sections of several nodules and fossils clearly showed the quartz and glauconite scattered throughout a fine, phosphatic (collophane) matrix (Plates 18a, b, ). All the characteristics described above agree closely with those of Brodie (1866), Hawkes (1943; 1952), Wells and Gossling (1947) and Balson (1980), who describe phosphate nodules from several Lower Cretaceous strata. Hawkes (1943) notes that the phosphate is usually of the collophane type which "effervesces with cold dilute acid", a useful distinguishing characteristic when dealing with those types resembling

> ". . . some types of chert." (Wells and Gossling, 1947).

Phosphatic nodules and fossils have been described from many of the local strata, usually in the form of thin pebble beds. The following stata have been shown to contain some phosphates (table 2.1):

Upper Lias (Horton <u>et al.</u>, 1974; Horton <u>et al.</u>, 1980).
Inferior Oolite (Taylor, 1963; Rayner, 1967).
Upper Cornbrash (Horton <u>et al.</u>, 1974).
Kimmeridge Clay (Edmonds and Dinham, 1965).
Portland Beds (Sherlock, 1922; Ballance, 1963).
Lower Greensand (Brodie, 1866; Harrison, 1877; Nicholls, 1947; Wells and Gossling, 1947; Casey, 1961; Edmonds and Dinham, 1965; Rayner, 1967; Keen, 1968; Horton <u>et al.</u>, 1974).
Gault Clay (Brodie, 1866; Harrison, 1877; Sherlock,

1922; Nicholls, 1947; Edmonds and Dinham, 1965; Rayner, 1967; Anderton et al., 1979).

Cambridge Greensand (Seeley, 1866; Hawkes, 1943; Edmonds and Dinham, 1965; Keen, 1968).

Chalk (Hawkes, 1951; Edmonds and Dinham, 1965; Rayner, 1967; Anderton et al., 1979).

Of these, the most prolific source, celebrated for its band of nodules or 'coprolites', is the Woburn Sands of the Lower Greensand. This lithology is regarded as a local component of 'unknown' derivation.

2. Igneous.

In the 65 samples studied, only 39 had igneous and volcanic pebbles. Out of a total of 20068 pebbles, in the 11.2-16.0mm fraction, only 69 were igneous (0.343% of the total). Most appeared to be fine-grained, with rectangular phenocrysts of feldspar and black mica (biotite). Micro-phenocrysts of quartz also occur in some specimens. They vary widely in their type and colour, from dark brown to red, pink and buff. More frequently, they are light in colour. Thin sections of a selection of the pebbles confirmed the fine, micro-crystalline matrix (Plates 19a, b, c). Plagioclase was present in all sections. Alteration, either by metamorphism or diagenesis, made positive identification difficult. Basic lavas, in the form of dolerite or basalt, appeared to comprise most of the pebbles. No distinctive features could be identified which could tie down a particular source, and most could probably be matched with several source areas.

The source, although probably from the igneous outcrops to the north of the country, or possibly, as is proposed for the volcanics in the Thames gravels, from Wales (Hey and Brenchley, 1977; Green, Hey and McGregor, 1980), may be of secondary derivation. Granites and rhyolites have been described from the Chalk (Salter, 1905b, p46; Hawkes, 1951), the Cambridge Greensand (Salter, 1905b; Hawkes, 1943), and the Lower Greensand (Salter, 1905b; Wells and Gossling, 1947). Wells and Gossling describe the Lower Greensand igneous erratics:

> "The colour-range of the pebbles is wide: the majority are pale buff, a few are light pink and one or two have a purplish tinge, . . .
>
> The distinctive feature of the typical rhyolites is the occurrence of microphenocrysts of beta-quartz up to about one millimetre in size."

However, only a 'probable' source is given for these rocks, as

> "The writer believes that these rocks are not of a sufficiently distinctive type to be narrowly localised; they could be matched with a moderate degree of accuracy in N.Wales, Armorica or Shropshire." (Wells and Gossling, 1947).

The pebbles in this study are also "not of a sufficiently distinctive type" and none of the types can be matched with any of the types attributed to a north Wales source (Green, Hey and McGregor, 1980). Salter (1905b, p49), discussing the erratics in the present study area, states

> "That the large majority of the varieties of igneous rocks which occur are mostly found near Lower Cretaceous strata, in which erratic rocks occur. Owing to the circumstances the evidence is at present very meagre on this point, but before assigning a more distant origin for these rock it is necessary to prove they did not come from this source."

It is, however, difficult to prove any source positively and, so here, the igneous pebbles are simply regarded as far-travelled.

3. Shells.

In the size fraction studied, only fragmented shells remained. Where larger fragments were found, they were mostly the thick, heavy tests of Jurassic Gryphaea. These are considered to be of local derivation.

4. Mudstone.

A soft, fine-grained lithology, usually yellowy-brown in colour, occasionally with iron staining. Only seen in a few samples, it is not considered as an important lithology. The non-durable nature suggests a local source, probably Jurassic, and related to the Northampton Ironstone Field from which it derives its staining. It closely resembles the clay nucleus often found in the box-stones of that class.

5. Schist and Grit.

Represented only once or twice among the 20068 pebbles, these are probably far-travelled - there being no known local origin. No localised source is put forward and it is not considered worthwhile to examine the source more closely for such minor components.

6. Miscellaneous Hard.

A few samples contained hard, unidentifiable lithologies. No two pebbles in this class are alike, and so no source can be put forward. Principal component analysis suggests that the Lower Greensand may be one potential source area, but a far-travelled source, such as the Bunter Pebble Beds cannot be ruled out.

# Chapter IX. Statistical Analysis.

## Introduction.

In examining the distribution of rock types, in the gravels of the study area, two factors are thought to be significant in determining the patterns observed.

1) A spatial pattern, arising from the redistribution of material by the advance of major ice-sheets across the area. This type of variability has been demonstrated by Perrin *et al.* (1973) and Perrin *et al.* (1979) in the tills of East Anglia and the East Midlands. In these investigations, mechanical composition, calcium carbonate content, heavy mineral content and clay mineral content of the till matrix are all shown to vary spatially, depending on the direction of ice movement and the outcrops most recently traversed.

2) A stratigraphic pattern, caused by bedrock outcrop changes due to progressive denudation, and by episodic influxes of glacially-derived material into the fluvial system. Each glacial influx is expected to constitute a recognisably new source of 'far-travelled' material, which is subsequently available for incorporation into successive terrace deposits.

To investigate these patterns and to group the gravel samples into stratigraphic units, two approaches are used.

A. Trend surface analysis is used to test for spatial variability, following the work of Beaumont (1971) in east Durham, and Perrin *et al.* (1979) in East Anglia.

B. A cluster analysis program CLUSTAN is used to test for stratigraphic divisions and to group the samples into stratigraphic units.

## A. Trend surface analysis.

Trend surface analysis is applied to the data using the relevant electives of the University of London Computer Centre SYMAP package, developed at Harvard University. Trend surface analysis is a technique used by geophysicists, geochemists, and geologists to separate regional trends of mapped variables from local fluctuations (Krumbein and Graybill, 1965; Norcliffe, 1969; Unwin, 1975; Mather, 1976). It has been widely used in geography following the work of Chorley and Haggett (1965) (Norcliffe, 1969; Unwin, 1975; Mather, 1976). It has been used to study the spatial trends of erosion surfaces (King, 1969), pebble count data in till (Beaumont, 1971), glacier cirques (Unwin, 1973), the mechanical and chemical composition of tills (Perrin *et al.*, 1973; Perrin *et al.*, 1979), and raised shorelines (Gray, 1978).

Trend surface analysis is a special form of multiple regression analysis, which attempts to fit power-series polynomial surfaces of increasing complexity to a set of points in three dimensions such that the trend of the data is adequately expressed (Krumbein, 1959; Chorley and Haggett, 1965; Norcliffe, 1969; Davis, 1973; Unwin, 1975; Mather, 1976). The points are defined by spatial coordinates (independent variables) and a variable (dependent variable). The technique assumes that any spatial distribution can be divided into:

a) a 'large-scale', systematic change that extends from one map edge to another,

b) small scale fluctuations that are superimposed on the large scale patterns due to local effects, and

c) random fluctuations, including errors of measurement (Krumbein, 1959; Chorley and Haggett, 1965; Krumbein and Graybill, 1965; Davis, 1973; Mather, 1976).

The last of these (b and c), are impossible to separate.

The trend surface is calculated in exactly the same manner as for multiple regression, using the method of 'least squares'. It is given by a polynomial of degree 1 (where 1 = p + q in formula 1 below) that best fits the observed data, such that the variables in the equation

> ". . . define a surface from which the sum of all the residual values squared is as low as it possibly can be for that surface shape." (Unwin, 1975).

The function used is of the form:

$$Z = A_{00} + A_{10}U + A_{01}V + A_{20}U^2 + A_{11}UV + A_{02}V^2 + \dots$$
$$\dots + A_{pq}U^pV^q \qquad (1)$$

where Z is the areally distributed variable,

U and V are the locational rectangular coordinates

and A is a variable (Krumbein, 1959; Chorley and Haggett, 1965; Krumbein and Graybill, 1965; Mather, 1976). The generation of the terms in the trend equation is usually performed sequentially - that is, the first order, or linear, terms are calculated first, followed by the terms for each successively higher order, each making the surface more flexible (Chorley and Haggett, 1965;

Mather, 1976). It is possible to continue adding functions until eventually the trend and the observations coincide, at which point there are no residuals. However, there would then be no separation of the data into components, and the purpose of the exercise is defeated (Davis, 1973). Usually, the expansion does not continue past the fifth or sixth level because of the problem of providing theories which adequately account for the convolutions of such complex surfaces, and because of the practical limits imposed by computer facilities (Norcliffe, 1969; Davis, 1973; Unwin, 1975). The local departures of the original data from the surface comprises the local effects, or residuals (Unwin, 1975).

To avoid the errors caused by the distribution of sample points, sample number, and map shape (Chorley and Haggett, 1965; Norcliffe, 1969; Davis, 1973; Mather, 1976), there are three requirements that have to be met in the original data.

a) There must be more data points than coefficients in the equation, otherwise the degrees of freedom will be negative, and will inhibit hypothesis testing (Mather, 1976).

b) The data points should be evenly distributed. Norcliffe (1969) suggests that

> ". . . data sets with regularly and randomly spaced points are acceptable, but significantly clustered ones are not."

Frequently, nearest neighbour analysis is used to test for non-clustered points but

> ". . . no generalisation[s] about 'acceptable' values of . . . the nearest neighbour statistic are possible." (Mather, 1976; p124).

c) The map should be square.

Once the trend surface is computed, it is necessary to know the proportion of the total map variability the fitted surface explains, and whether the surface is a valid expression of the large scale variations in the mapped variable, or whether it may have arisen by chance (Chorley and Haggett, 1965; Krumbein and Graybill, 1965; Norcliffe, 1969).

The "goodness of fit" of the surface is normally calculated as the percentage reduction in the sum of the squares achieved, or RSS% (Davis, 1973; Unwin, 1975). This is simply the ratio, expressed as a percentage, of the corrected sum of squares of the computed trend, SSt (= $\Sigma(\hat{Y}-\bar{Y})^2$) to the corrected sum of squares of the observations, SSo (= $\Sigma(Y-\bar{Y})^2$), where $\bar{Y}$ is the observed variable, and $\hat{Y}$ is the predicted value. The difference between these gives the sum of squares due to the residuals, SSr (= (SSo-SSt)) (Davis, 1973; Unwin, 1975). The percent "goodness of fit" of the trend is:

$$RSS\% = \frac{SSt}{SSo} \cdot 100\ (\%) \qquad (2)$$

where 100 % represents a perfect fit, and 0 % represents no fit. This can be transformed to a correlation coefficient, r, (between the trend and the observations) by:

$$r = \sqrt{RSS\%/100} \qquad (3)$$

to describe the trend (Davis, 1973; Unwin, 1975). However,

> "Irrespective of how close to 100% the RSS is, we still need to know if this fit is significant." (Unwin, 1975).

This, as Beaumont points out, is still difficult to accomplish satisfactorily, but, by making use of the fact that the trend surface model is a variant of the multiple regression model (Norcliffe, 1969), an analysis of variance technique can be employed to compare the variance due to the trend, to the variance due to the residual (Davis, 1973). If the data satisfy certain conditions, then this can be tested against an F-distribution (Krumbein and Graybill, 1965; Norcliffe, 1969; Beaumont, 1971; Davis, 1973; Unwin, 1975; Mather, 1976; Perrin *et al.*, 1979). The conditions allowing F values to be interpreted are:

a) the residuals have a normal distribution,

b) the residuals have an expected mean of zero,

c) the variance of the residual is constant over the area,

d) the residual terms are not spatially autocorrelated (Davis, 1973; Unwin, 1975; Mather, 1976). When these assumptions are not satisfied, the F values should only be used as cut-off points for deciding whether or not to fit the next higher degree surface (Krumbein and Graybill, 1965; Beaumont, 1971)(see equation 5 below).

To test the null hypothesis that the nth order trend surface does not account for a statistically significant proportion of the total sum of squares of the dependent variable, the variance ratio, F, is calculated as:

$$F = \frac{\%RSS / df1}{(100 - \%RSS) / df2} \qquad (4)$$

where: df1 is the degrees of freedom associated with the surface, equal to the the number of constants in the trend surface equation less one for the base term, and

df2 is the degrees of freedom of the residuals; that is, the total degrees of freedom in the data less df1, those associated with the trend. The total degrees of freedom is N (sample number) less one, so that df2 = N - 1 - df1 (Unwin, 1975).

The F value obtained is compared with tabulated values of F (Krumbein and Graybill, 1965), at df1 and df2 degrees of freedom, to see if it is significant. Because many investigators fit a series of equations of successively higher degrees (Davis, 1973), a number of trend sum of squares is produced, each larger than the preceeding sum. When this occurs, the analysis of variance may be expanded to examine the contribution of the additional coefficients and to test that the trend surface of order p + 1 is a significant improvement over p, and is not caused by chance (Davis, 1973; Unwin, 1975; Mather, 1976). If the F value is not significant, nothing has been gained by fitting the higher degree polynomial (Davis, 1973). However,

> "It would seem illogical to suggest that, because a given surface is a poor fit to the data a more

flexible surface should not be considered." (Mather, 1976).

F is calculated as:

$$F = \frac{(\text{Extra \%RSS given by surface of order } p+1\text{, over one of order } p)/df3}{(100 - \text{total \%RSS accounted for by the surface})/\ df2} \qquad (5)$$

where: df3 is the degrees of freedom associated with the added components, 3 for a quadratic over a linear, 4 for a cubic over a quadratic and so on.

This test is, probably, that which is most frequently used in trend surface analyses, especially when the conditions for F, set out above, are not met (Krumbein and Graybill, 1965; Beaumont, 1971; Davis, 1973; Mather, 1976). Surfaces with an F value equal to, or greater than, the 95% significance level are usually considered to describe spatial patterns that differ from random (Beaumont, 1971; Gray, 1978; Perrin et al., 1979) and this level is used here.

In the present study, the data tested for spatial variation are ratios of chalk as a percentage of non-durable (nd), ferrous sandstone as a percentage of nd, limestone as a percentage of nd, quartz/quartzite and hard sandstone, phosphatic nodules/quartzite and hard sandstone, and quartzite/hard sandstone, together with gross percentages of chalk, ferrous sandstone and limestone. This, it may be seen, concentrates on the most common lithologies. An analysis of many of the far-travelled components - such as igneous and Rhaxella chert would be more difficult since the proportion of these lithologies is low and there may be doubt about the actual frequencies - indeed they are often absent. Ratios, together with gross percentages, are used because these should avoid the effects of local bedrock changes (see B.2 below) (Plumley, 1948). Local components figure prominently, to examine the possible directions of movement away from the source rock (defined in Chapter VIII), as the proportion is expected to decrease away from the source area. The durable components (quartzite and hard sandstone) are used as standards, as these are considered least likely to diminish in frequency with transport. In this analysis, where duplicate samples are taken from a single site, the mean value is taken in each case.

## B. Cluster Analysis.

The principal hypothesis of the present research - that within the Ouse basin the individual stratigraphic units can be separated on the basis of gravel lithology - assumes that each unit has a unique lithological composition. Within this assumption, there is a second, but related, assumption, that gravel samples with similar compositions are part of the same stratigraphic unit. From these relationships, the tracing of stratigraphical units between sites is believed to be possible.

If, as in the Thames basin, the lithological characteristics of each stratigraphical unit are known (Green and McGregor, 1978; McGregor and Green, 1978; 1983a; Green, McGregor and Evans, 1982), then classification of individual samples into their respective units could be based on a technique such as Linear Discriminant Analysis (Mather, 1976). However, in the present study area there is no a priori knowledge of the natural distribution of gravel deposits, and the lithology of the gravel deposits which exist has, until now, remained obscure. Assuming, therefore, that each stratigraphical unit is unique and distinct from any other unit, it is necessary to group together those samples which are more similar to one another than to samples in other groups. However,

> "When as many as twenty or thirty or more measurements are made on one hundred or more samples, the resulting table of data is so large that interpretation "by eye" becomes difficult." (Parks, 1966).

A statistical technique developed specifically for this purpose is Cluster Analysis. This encompasses a number of strategies, of which one may be suitable for the task in hand.

The aim of the clustering procedure is to reduce the large number of individuals (samples) to an unknown number of distinct groups, with the individuals in each group being more similar to each other than to the individuals in all other groups. Each of the statistical procedures available involves a different clustering strategy and it is necessary that the requirements of the study are known so that the most suitable strategy can be applied.

There are six requirements of the present research that are considered to be important:

a) all the variables need to be considered at each stage in the clustering process. No grouping should be made on the basis of only part of a group's characteristics.

b) weighting of individual lithologies resulting from differences in the proportions of several rock types should be kept to a minimum. These differences may result either from differences in the area of the source outcrop, or from the addition or removal of lithologies by natural processes.

c) the groups obtained must have maximum within-group homogeneity and maximum between-group heterogeneity; that is, the clusters must be as tight as possible.

d) related to c) above, Johnston (1970) suggests that samples which occupy a zone of overlap between two existing groups should form a third group, or 'transition zone'. This is more satisfactory than the grouping together of the two groups, or the inclusion of the samples in the groups that they are most closely related to, thereby causing the creation of heterogeneous groups.

e) samples which are unusual should stand alone and not be forced into a group (Johnston, 1970). Some methods have been praised because they produce groups of equal size, but this has disadvantages if the groups produced are heterogeneous owing to unusual samples.

f) the strategy should keep chaining (whereby individuals are added sequentially to a single group (Lance and Williams, 1967; Mather, 1976)) to a minimum, as this is considered to be undesirable, especially if a number of separate groups is believed to exist within the samples. It is also difficult to interpret. Backward linkages in the dendrogram (see below; fig. 9.1) are also considered undesirable. These join two groups at a lower level of similarity than the level of similarity resulting in the formation of the original pair of groups.

Cluster analysis was developed by psychologists. It has been used extensively by biologists and is becoming increasingly utilised throughout geography, although mainly by human geographers (Johnston, 1965). The technique has, however, been used with some success by geologists (Parks, 1966; Davis, 1973; Khaiwka _et al._, 1981; Fisher, 1982). Parks (1966), for example, re-examines 200 samples of recent Bahamian bottom-sediment, previously classified by Purdy (1960), without the benefit of cluster analysis. An analysis of the constituent particle composition of each sample resulted in twelve variables being identified. The original analysis of Purdy recognised six major facies groups within the sediments. Using cluster analysis, the six groups are apparent when only forty of the samples are analysed. When, however, all the samples are used the results are rather different, indicating that there are more than the six facies originally recognised. The conclusion of Parks (1966) is that

> "Cluster analysis is a useful technique for analyzing large tables of data where many different measurements are made on each of many samples."

A similar investigation was undertaken by Khaiwka et al. (1981) on thirteen samples with twelve petrographic variables, derived from thin sections. The result of the cluster analysis is tested against the results obtained by subjective appraisal of the same data. The conclusions reached are similar to those of Parks; that the analysis shows good agreement of station (sample to sample) distribution compared with the results of a previous investigation, and relationships among variables are meaningful.

> "The degree of interpretative resolution achieved by applying cluster analysis, even with limited control, is quite satisfactory and can be profitably applied in frontier areas where data are limited." (Khaiwka et al., 1981).

Fisher (1982) proves the usefulness of the technique for gravel analysis: in an examination of Thames gravels previously classified by Green and McGregor (1978); and in his own work.

### 1. The Method.

Cluster analyses can be divided into two basic types agglomerative and divisive. Those most commonly used by geographers are agglomerative (Johnston, 1970). These take each individual (sample) separately and regard each as a separate unit in its own right. The individuals are grouped or 'clustered' together using a set of predetermined rules (which vary according to the strategy used) according to levels of similarity in terms of the chosen criteria (Johnston, 1976). The divisive strategies proceed in the reverse manner. All the individuals are regarded initially as one group, which is split into parts, in stages - a different criterion being used at each stage.

> "The major deficiency of many of the divisive algorithms presently in use is that they tend to split the population on a single characteristic [monothetic], rather than on a measure of overall similarity or dissimilarity [polythetic] as generally used in agglomerative approaches."
>
> "Divisive algorithms . . . are therefore wasteful in their use of the analytical information . . ." (Johnston,1970).

A comparison of divisive and agglomerative methods by Lambert and Williams (1966) suggests that agglomerative methods are superior. This conclusion arose, however, because only the agglomerative techniques available at the time were polythetic. Polythetic divisive techniques, however, have theoretical advantages (Lambert et al., 1973), but their complexity makes them impractical for more than sixteen individuals. Despite this, Lambert et al. put forward two polythetic divisive techniques (AXOR and MONIT) which they tested against expected answers for an 'ideal' data set. The results (table 9.1) indicate that the new methods are significantly better than the previous monothetic divisive methods and the polythetic agglomerative methods. Such techniques, however, are still rarely used, usually because of their lack of availability. Most taxonomists still show a preference for the polythetic agglomerative techniques (Lambert et al., 1973).

Agglomerative methods can be further subdivided into hierarchical or nucleated strategies (Mather, 1976). The former assumes that each group is part of a larger group at a higher level and will, therefore, produce a 'universal' group at level n-1 (where n is the number of samples). This will result in the eventual clustering of even the most dissimilar groups. Where groups cannot be seen to merge together at higher levels, it is probably better to try to represent the structure in terms of discrete, non-overlapping clusters. The samples are viewed in terms of multi-dimensional space (there being as many dimensions as samples), and those samples which are in relatively high densities are regarded as 'nucleated' and thus form a group or cluster (Mather, 1976). Hierarchical strategies are those most freely available and the discussion which follows concentrates on these.

The general method underlying each of the hierarchical clustering strategies is similar. The similarity between each pair of individuals, with their 'm' number of variables, is calculated using one of a number of similarity measures. The two closest individuals (or groups of individuals based on a previous clustering step) are put together to form a single group; the group now acting as an individual. The similarity matrix is recalculated so that the next closest pair may be grouped. The process continues, one grouping at a time, until all the individuals form a single group.

The similarity matrix, essential in all clustering procedures, involves the production of a triangular array of n x (n-1)/2 coefficients, such that each element of the matrix measures the similarity between two individuals (remembering that the similarity between an individual and itself must be perfect). Several measures of similarity exist, which have been divided, paradoxically, into those of dissimilarity and those of similarity. Geographers most frequently measure similarity with parametric statistics, particularly the Pearson product-moment correlation coefficient (Johnston, 1965). In the context of cluster analysis this is a similarity measure; the coefficient ranging from 0.0 (complete dissimilarity) to +/- 1.0 (exact similarity). This method gives results identical to those of the cosine θ coefficient (another common similarity measure) when the data are standardised (see below), as both methods are measures of the angle between samples in multi-dimensional space (Parks, 1966). Johnston (1976) and Mather (1976), however, both suggest that the use of correlation coefficients should be restricted, as there are problems in computing average correlations between, and among, groups at later stages in the clustering procedure.

An alternative measure, widely used in other disciplines (Johnston, 1965), is the index of dissimilarity or Squared Euclidean Distance coefficient, $D_{ij}$. This represents the shortest distance in the multi-dimensional space between two individuals, with smaller values representing the shorter distance and therefore greater similarity (Johnston, 1965). The distance is calculated using Pythagoras' Theorem from Euclidean geometry, which states that the square of the distance on the hypotenuse of a right angled triangle equals the sum of the squares of the distances on the two other sides. Where only two variables are considered, the Euclidean distance, in general terms, is calculated by:

$$D_{ij} = \sqrt{(i_x - j_x)^2 + (i_y - j_y)^2} \qquad (6)$$

where $i_x$, $j_x$ and $i_y$, $j_y$ are the values for i and j on variables x and y, respectively. $D_{ij}$ is the distance between i and j (fig. 9.2)(Johnston, 1976). In expanding this theorem to multi-dimensional space, necessitated by the increase in the number of variables, the equation for $D_{ij}$ is squared and divided by m to become the 'squared euclidean distance' calculated as:

$$D_{ij} = \Sigma (X_{ik} - X_{jk})^2/m \qquad (7)$$

where $X_{ik}$ and $X_{jk}$ denote the kth variable measured on objects i and j respectively, and m is the number of variables (Parks, 1966; Davis, 1973; Mather, 1976). The division by m becomes necessary because the distance is a function of m, increasing as m increases (Parks, 1966; Mather, 1976). Unlike the correlation coefficient, the distance coefficient is not constrained within the range +1 to -1 and, consequently, it may produce more effective clusters if a few of the objects are very dissimilar (Davis, 1973, p462). The problems encountered using the correlation coefficient (Johnston, 1976; Mather, 1976), and the advantage of the distance coefficient (Davis, 1973), suggest that the latter is more appropriate for most studies. This conclusion is reached by Khaiwka et al. (1981) who compare the results of both the distance and the correlation coefficient similarity matrices to those obtained by subjective appraisal. In all cases they conclude that:

> "The use of distance similarity coefficient . . . provides a better comparison than the use of the product-moment correlation coefficient."

In the application of either dissimilarity or similarity equations, problems can arise because of scale variations between variables. If, in the array of variables, some have a wider range of numerical values than others, then the distance between samples will be influenced most strongly by those variables (Davis, 1973). If the variables chosen for classification are of different types, as is the case with Parks (1966) and Khaiwka et al. (1981), and it is assumed that each should have equal importance in the discrimination process (Johnston, 1965; 1970), then any weighting must be removed and some standardisation process adopted. The convention most commonly used is to give each variable equal weight by transforming observed values so that each variable, incorporating all samples, has a mean of zero and unit variance (Davis, 1973; Johnston, 1976; Mather, 1976). This transformation produces a Z-score:

$$Z_{ik} = (X_{ik} - \bar{X}_k) / S_k \qquad (8)$$

where $Z_{ik}$ is the standard score,

$X_{ik}$ is the observed value of individual i on variable k,

$\bar{X}_k$ is the mean value of the n observations on variable k, and

$S_k$ is the standard deviation of variable k (Davis, 1973; Johnston, 1976; Mather, 1976).

In some situations, however, equal weight for each variable may not be desirable (Johnston, 1965; 1970):

> "Standardization of data to Z deviate scores is admirable as a method of bringing all values down to a common scale, but in some cases it may artificially inflate the amount of variability." (Johnston, 1970).

This, however, may be removed when dealing with a second, but related, problem encountered when using the distance similarity measure. The problem arises from the fact that the variables may not be independent - that is, they lack orthogonality (Mather, 1976). If two variables are intercorrelated then $D_{ij}$ will be weighted in favour of the related variables. To remove this discrepancy, a common procedure is to replace the original data set with a new set through the use of principal component analysis (for example, Parks, 1966; Khaiwka et al., 1981). Principal component analysis depends on the fact that at least some of the variables in the data set are intercorrelated. If none of the m variables is correlated with any other, there exists already a set of uncorrelated axes, and there is no point in performing a principal component analysis (Daultrey, 1976). Each variable measures an axis, or dimension, of variability, and describes differing amounts of the total variance (which is the sum of the individual variances). Principal component analysis transforms the data to describe the total variance, with the same number of axes as before (m) but in such a way that:

- the first axis accounts for as much of the total variance as possible,
- the second axis accounts for as much of the remaining

variance as possible, whilst being uncorrelated with the first,

- the third axis accounts for as much of the total variance remaining after the first two axes, whilst being uncorrelated with either,
- and so on until all the variance is explained (Daultrey, 1976).

The principal component axes, or dimensions, are known as eigenvectors. The length of each eigenvector, being proportional to the variance it explains, is given by the eigenvalue (or latent root) for that vector (Gould, 1967; Davis, 1973). Consequently, the greatest value is for the first vector since this explains the most variance. Each original variable is projected onto the principal component axes to produce the component scores for the observations on the new axes, such that each data point may be described by the vectors. These scores, or components, have a mean of 0.0 and a standard deviation of 1.0; that is, the data are standardised so that Pythagorean distances can be calculated immediately (Daultrey, 1976; Johnston, 1976). The standard scores on the principal components are then used in place of the observed data set for the cluster analysis (Mather, 1976).

Unless there is perfect correlation between two or more variables, then m principal components are required to account for the m-dimensional variable space. Hence all principal components are significant. However, due to the intercorrelation between many variables, the last few principal components (or eigenvector ) are frequently redundant (Johnston, 1976; Mather, 1976). To decide upon the number of principal components which are significant, a criterion frequently used is Kaiser's criterion (Child, 1970; Harman, 1976), where only the eigenvectors with eigenvalues greater than 1.0 are considered to be important. This will inevitably reduce the amount of data used in the cluster analysis, but Johnston (1976) states that this effectively removes redundancies in the original data set.

Cluster analyses, using both Q-mode (raw data matrix) and R-mode (principal component data matrix) analyses, have been compared (Khaiwka *et al.*, 1981) and have been found to give comparable sample groupings.

Hierarchical strategies available are reported to have properties which may render some techniques unsatisfactory for the task in hand (Lance and Williams, 1967; Mather, 1976). The most important of these is whether they are space-conserving or space-distorting. The original similarity matrix may be regarded as defining a space which contains all the points representing each individual. As groups form, the calculation of the new similarity matrix may not define a space with the original properties. If this occurs, the strategy is space-distorting and can result in the contraction, or dilation, of the space near the groups. In the former case, the result is that groups, or points, are more likely to join as they are drawn together. Such a situation may result in chaining. Strategies that produce space-dilating effects cause groups to recede on formation. This type will tend to produce small, compact, apparently well-separated groups.

The number of hierarchical clustering strategies is large (Johnston, 1976; Mather, 1976) and there is no single method which is superior in all circumstances. A brief description of the characteristics of the more common strategies is given so that the selection of the algorithm most appropriate for the present study can be made.

a) Single Linkage or Nearest Neighbour method.

The distance between two groups is defined here as the shortest distance between any pair of individuals (samples), one from each cluster. Groups are, therefore, established by the characteristics of one sample within a group; the characteristics of the group as a whole not being taken into account. The internal homogeneity of a group may, therefore, decrease with every additional linkage, and generally results in the production of 'straggling' clusters (Wishart, 1975). The method has space-contracting properties which often result in hierarchical structures in which chaining occurs. Consequently, Lance and Williams (1967)

> ". . . submit that nearest-neighbour sorting should be regarded as obsolete . . ."

b) Complete Linkage or Furthest Neighbour method.

This is the converse of the single linkage method, for the distance between pairs of groups is defined as the distance between the most dissimilar individuals. This will normally result in a hierarchical structure where group difference is emphasised. Such a technique is

> ". . . markedly space dilating." (Lance and Williams, 1967; Mather, 1976).

Although rather more applicable than a) above to the present study, problems are still apparent, in terms of the type of groups given. Johnston (1976) believes the groups resulting from the analysis will tend to be too numerous, while Wishart (1975) states that the method

> ". . . is liable to produce irregular results because the similarity criterion is determined for only two individuals and does not account for group structure."

c) Average Linkage or Group Average.

This method attempts to overcome the problems encountered in a) and b) above, where group structure is not taken into account. The similarity of the two groups

> ". . . is defined as the arithmetic average of the similarities between pairs of members of (i) and (j) . . ." (Mather, 1976);

that is, between pair of members of each group (Mather, 1976). The technique, therefore, produces more internally homogeneous clusters and

> ". . . is reasonably well behaved." (Wishart,1975).

A space-conserving quality is apparent (Mather, 1976), but chaining may still result.

d) Centroid method.

This attempts to refine further the clustering technique by incorporating the intra-cluster characteristics. The inter-group distance is defined as the distance between the centroids (variable means) of the two groups (Wishart, 1975; Mather, 1976). The method is space-conserving (Mather, 1976) but results often exhibit chaining (Wishart, 1975), although to a lesser extent than the above methods. This method may also, however, exhibit backward links in the dendrogram (see below; fig. 9.1), which are generally considered to be undesirable and are difficult to interpret (Mather, 1976).

e) Median method.

The distance between any cluster (X) and a previous cluster, resulting from the fusion of two groups i and j, is the distance from the centroid of X to the midpoint of the shortest line joining the centroids of i and j (Wishart, 1975; Mather, 1976). This method avoids the weighting that may occur if the centroid of the group ij lies close to (or within) the larger group, resulting in the loss of characteristics of the smaller group, by giving equal weight to both groups (Lance and Williams, 1967). This method can only be interpreted geometrically for distance-similarity coefficients (Lance and Williams, 1967). However, using distance, the median strategy tends to chain for large numbers of samples (Wishart, 1975), and backward links can occur (Mather, 1976).

f) Lance and William's Flexible Strategy.

After the fusion of two groups, i and j, to form a new group (k), the distance of k from a third group (h), needs to be calculated. This distance ($d_{hk}$) is found using a relationship between $d_{hi}$, $d_{hj}$ and $d_{ij}$ such that

$$d_{hk} = \alpha_i d_{hi} + \alpha_j d_{hj} + \beta d_{ij} + \gamma |d_{hi} - d_{hj}| \qquad (9)$$

where $\alpha_i$, $\alpha_j$, $\beta$ and $\gamma$ determine the nature of the strategy. $\gamma$ is usually 0, and $\alpha_i + \alpha_j + \beta = 1$. In most methods, the values of these parameters are specified by the strategy, but this method permits the user to define the characteristics of the strategy by specifying the Beta parameter. Given a Beta value between -1 and +1, the method can be made to range from space-dilating (Beta = -1) to space-contracting (Beta = +1). However, despite this flexibility, it is still not possible to specify a method that has space-conserving qualities. Lance and Williams (1967) suggest that a small, negative Beta value should be used (-0.25). This, however, gives results that behave much like Ward's method (see h below), and no advantage is obtained (Wishart, 1975). Sokal and Sneath (1973) claim the method seems too much like "cooking the results" to make them conform to the desired end product (Mather, 1976).

g) McQuitty's Similarity Analysis or Simple Average.

This method has an equivalent relationship to the Average Linkage method as Median has to Centroid. The two groups to be joined are given equal weight to help preserve the character of small groups (Mather, 1976). Subsequent relationships, however, will be biased in favour of the most recently formed group, which

> ". . . may tend to distort the space to make groups appear to be further apart than they do when the Group Average scheme is used." (Mather, 1976).

Similarity analysis can also be obtained with the Flexible strategy when Beta = 0. The method chains with large numbers of samples.

h) Ward's method or Minimum Variance method.

This, according to Wishart (1975), is

"Possibly the best of the hierarchical options . . .".

It is based on the assumption that groups produced by clustering should have maximum internal homogeneity - that is the distances of individual samples to group centroids are kept to a minimum. This means that the variance of the distance is kept to a minimum (Johnston, 1976; Mather, 1976). Ward terms this variance the "Error sum of squares" and it is defined as the sum of the distances from each individual to the sum of its parent cluster (Wishart, 1975). This is calculated as:

$$ESS = \sum_{i=1}^{n} (D_{ix})^2 / n \qquad (10)$$

where ESS is the Error sum of squares, D is the distance between place i and the group centroid x, assuming that i is a member of the group (X), and n is the number of members in group X (Johnston, 1976). Summation is over all variables.

The grouping proceeds so that

> ". . . the two groups to be combined at any given level are those whose fusion produces the least increase in the within-group sum of squares." (Mather, 1976).

This method, because the grouping is based on mean squared distance, magnifies the intra-group variation at later stages (Johnston, 1976) and results in the production of small, close, or tight clusters (Wishart, 1969). This method also has the advantage that backward links will not occur (Mather, 1976) and chaining is unlikely.

Of the above methods, Ward's method best meets the requirements set out above (p 197-8) and is, thus, used in the present study. It is available on the University of London Computing Centre package CLUSTAN, developed by D. Wishart (1975). The analysis which follows is, therefore, based on programs run using Ward's "Error sum of squares" method with the Squared Euclidean Distance as the similarity matrix.

Once the analysis is complete, the results have to be displayed in a form that is compatible with the methods used and easily understood by the user. The two most common forms are:

a) tabular, where the fusion of individuals, or groups, at each hierarchic level is printed, together with the similarity coefficient, and

b) graphical, where the same data are represented diagrammatically in the form of a dendrogram (fig. 9.1). The individuals are arranged in such a way that the stems of the dendrogram do not cross, and they link the individuals at the correct similarity coefficient level.

2. Data Type.

Two forms of lithological data are used in the present study: gross percentages and intercomponent ratios. In differentiating gravel units, each individual lithology may be important and the additional presence of one or more lithologies may be indicative of a change in the depositional environment and catchment change (McGregor and

Green, 1978). For this reason, gross percentages of each lithology are used (Appendix 1). This type of data has been used by Gibbard (1982) in a multivariate analysis (principal component analysis) of pebble count data on the Plateau Gravels south of the river Thames.

When using percentage data in cluster analysis, the data constitutes a closed array - that is, the variables sum to 100 percent for all observations. When this occurs, and if every lithology is used, the data matrix is overdetermined. If, for example, we know A, B, and C and the total, A + B + C, then one of the variables is superfluous (Davis, 1973; Fisher, 1982). In the present study, to avoid the mathematical complications caused by this, flint - the component present in all samples in relatively large proportions - is removed from the data matrix.

However,

> "It has been shown . . . that intercomponent ratios are more sensitive indicators of catchment change than gross percentages." (McGregor and Green, 1983a).

This is because

> "The use of a ratio rather than a direct percentage avoids the effect of an apparent decrease of one rock type, which may be due only to the addition of new material of another rock type as the stream [or ice stream] crosses an exposure of that new material." (Plumley, 1948).

The combination of the ratios used must be chosen with care so that catchment changes are evident. Changes in lithology between two gravel units may result from three processes.

a) Greater amounts of attrition and abrasion of one rock type against another downstream (Plumley, 1948).

b) Changes in catchment lithology (McGregor and Green, 1978). Different river deposits may have pronounced differences in their lithology as a result of dissimilar source rocks in areas which the rivers drain (Plumley, 1948).

c) Influxes into the basin of far-travelled material by external processes (for example, ice).

Because b and c are likely to cause the greatest ratio changes, both far-travelled and local material need to be considered. Changes in the local components will reflect within-basin differences, while changes in the far-travelled components will reflect external influences.

In the present study the lithologies are divided into durable and non-durable components, with the durable components reflecting, for the most part, the far-travelled constituents. The durable constituents are: quartzite, quartz, hard sandstone, chert, Rhaxella chert, cherty sandstone, igneous, schist, grit, flint and miscellaneous hard. The non-durable components are: soft sandstone, ferrous sandstone, limestone, ferrous limestone, chalk, calcareous sandstone, shells, phosphatic nodules, and mudstone. The non-durable components thought to be of most importance are ferrous sandstone, limestone and chalk; while of the durable components flint, quartzite, quartz, hard sandstone and Rhaxella chert are considered important. The combinations of these variables used are: percentage non-durable (nd); chalk as a percentage of nd; limestone as a percentage of nd; ferrous sandstone as a percentage of nd; percent flint; flint as a percentage of flint plus chalk; Rhaxella chert as a percentage of durable (d); percentage of quartzite and hard sandstone; quartzite and hard sandstone as a percentage of durable minus flint; quartz as a percentage of durable minus flint (Appendix II).

Each of the two data types (gross percentages and ratios) is analysed using the CLUSTAN program, with the data set always being standardised. A third analysis, combining the two data types, is also used. This, however, will weight those lithologies which are represented more than once in the analysis. To avoid the complications caused by the intercorrelation of variables (Mather, 1976; see B.1 above), the same three data sets are also processed after having first computed a principal component analysis data matrix. The major principal components, selected using Kaiser's criterion, are used in place of the raw data matrix.

One further adaption of the percentage data is used. The twenty lithologies identified are grouped into five major categories, based on the discussion of the lithologies in Chapter VIII :

Bunter-derived - hard sandstone and quartzite.

Cretaceous - chalk (and flint).

Jurassic - ferrous sandstone, limestone, ferrous limestone, shell, mudstone.

Local - miscellaneous hard, phosphatic nodules, chert, cherty sandstone, calcareous sandstone, soft sandstone, and quartz.

Other far-travelled - Rhaxella chert, igneous, schist and grit. Flint is again removed from the data matrix to avoid overdetermination.

To assist in the differentiation of samples from terrace deposits, from those of fluvioglacial origin, and to assist in the separation of different terrace deposits (for example, the separation of a first from a second terrace deposit), the height above the floodplain of the surface of the gravel deposit sampled is added to each of the data matrices presented above. The heights used are estimated from 1:25 000 O.S. maps (Chapter VII). The expectation here is that samples of a particular terrace level will be drawn closer together because they are within a restricted height range above the floodplain. Fluvioglacial samples, however, may be pulled further apart because these are scattered throughout the height range of the basin.

This gives a total of fourteen cluster analysis programs used in the analysis (table 9.2).

# Chapter X. Results.

## Introduction.

The results of the statistical analyses set out above are described and examined for within-basin relationships. The trend surface analysis, used to identify spatial patterns across the area, demonstrates that no simple patterns are present, and suggests that separate stratigraphic units, each with its own individual spatial pattern, are present. This is supported by the results of the cluster analyses which identify several lithologically distinct units. Each of these units, however, has both stratigraphic and spatial controls. Because the stratigraphic control appears to be dominant over any spatial control, the cluster analyses results are discussed in greater detail. The patterns identified by the cluster analyses can, however, in some instances, be identified weakly in the trend surfaces, but in none would the trend surface analyses alone have been sufficient for their determination.

## A. Trend Surface Analysis.

The trends observed in the present study are weak, suggesting that spatial patterns of the type demonstrated by Perrin et al. (1979) cannot be identified in the gravels of the Ouse basin. The statistical significance levels for the nine analyses are shown in tables 10.1 to 10.9, each table containing, a) the significance of each surface, and b) the improvement of each surface over the next lower surface. In all cases, except that of the phosphatic/quartzite and hard sandstone ratio, only the first four levels are shown, because the significance of the surfaces decreases further at the higher levels. The Nearest Neighbour statistic, generated as part of the SYMAP program, shows the forty-three sample points to be distributed randomly (R = .92), indicating that the data set is acceptable (Chapter IX.A; Norcliffe, 1969).

1. Limestone: With the major source of limestone lying to the north and northwest of the area (Chapter VIII.E), the expected trend is a linear, or possibly quadratic, progressive decrease in the proportion of limestone to the south and east of the area as the distance from outcrop increases. This trend may be produced by either fluvial, or fluvioglacial, agents moving away from the source geology.

None of the surfaces of limestone as a percent of non-durable (table 10.1), is significant at the 95 percent level and, therefore, the surfaces may not strictly be used for interpretative purposes. The quadratic surface, however, is significant at the 90 percent level, from which some insight may be drawn. This surface shows a 'col' between Newport Pagnell and Bedford, between 'peaks' to the northeast and southwest, with low values to the northwest and southeast (fig. 10.1). The surface may reflect transport away from the source area, by the Great Ouse, to Bedford. The 'high' near St. Neots is, perhaps, a function of the surface degree, as the residuals in this area are high and negative. The low explanation of the data by the surface (RSS% = 22%) strongly suggests that other geomorphological processes are active.

Similar results are obtained when gross percentages are analysed (table 10.2). The cubic surface, although significant at the 97.5 percent level, is not a significant improvement over the quadratic surface and may only be interpreted with reservations. This surface (fig. 10.2), like the quadratic surface described above, displays a 'high' to the southwest, with a 'ridge' following the general course of the Great Ouse. This 'ridge' is increased by the residuals which are all high and positive in this area (fig. 10.3). In this surface, the 'peak', previously displayed at St. Neots, is eliminated. Despite the significance of the surface, the explanation of the data remains low (RSS% = 41.5%).

2. Ferrous sandstone: With two potential sources of ferrous sandstone, in the northwest (Northampton Sands) and southeast (Lower Greensand) of the area (Chapter VIII.D), a trend, more complex than that for limestone, might be expected, with 'ridges' over both source areas and a decrease away from these areas, producing a cubic surface from northwest to southeast. Although this general trend is seen in the cubic surface of the ferrous sandstone as a percent of non-durable (fig. 10.4), the low significance levels of this surface (75%), and all the other surfaces of both analyses (tables 10.3; 10.4), suggest that they have little interpretative value.

3. Chalk: In the gravels being investigated, chalk has two possible source regions - the Lincolnshire Wolds and the adjoining areas of the North Sea, and the Chiltern escarpment to the south (Chapter VIII.F). The former source, if important, must involve glacial or fluvioglacial transport for incorporation of chalk into the gravels, while the latter need only require fluvial transport. The regional trends, from each of these sources, are expected to differ, the former with an increase to the northeast, the latter with an increase to the south and southeast. None of the surfaces of chalk as a percent of non-durable (table 10.5), provides a significant explanation of the data, indicating that the pattern may be more complex than that suggested. However, the analysis of chalk as a gross percent does provide one surface - the quadratic - which is significant at the 95% confidence level (table 10.6). The surface (fig. 10.5) shows a 'ridge' along the Chilterns, with a 'trough' along the Ouse-Nene watershed, indicating that absolute values do increase as the local outcrop is approached. As with the other analyses, however, the low explanation of the data by the surface (RSS% = 26.7%), and the complex residual pattern (fig. 10.6) suggest that the overall pattern is complex.

4. Quartzite/Hard sandstone: These lithologies are thought to be amongst the most durable of the far-travelled lithologies and a similar source for both has been suggested (Chapter VIII.B). This ratio should, therefore, remain constant throughout the area, if both components are equally resistant to abrasion, and a linear relationship

should be apparent. If, however, either one of the components is more susceptible to abrasion and attrition, then a decrease, or increase, will be apparent in the ratio, in the direction of further transport. The very low significance levels (table 10.7) of the trend surfaces, however, suggest that several processes, possibly glacial, fluvioglacial and fluvial, interact to disrupt any simple pattern of spatial redistribution.

5. Phosphatic Nodule/Quartzite and Hard sandstone: The number of possible sources of phosphatic nodules is large (Chapter VIII.I). This ratio is investigated to see if a single source area can be identified. The results (table 10.8) show that the trend surface is not significant until the quartic level. This surface is also a significant improvement over the cubic surface. The quintic surface, although significant, does not provide a significant improvement over the quartic and so is discarded. The quartic surface (fig. 10.7) shows a 'basin' surrounded in the northwest, northeast, southeast and southwest margins by high values. It shows, together with the residual surface (fig. 10.8), a complex situation, where low values on the trend are matched by high positive residuals, and high values are matched by high negative residuals. Interpretation, in terms of a single source area, is impossible. The diverse pattern may reflect multiple source areas, as already suggested, or it may reflect the number of sites (14) where no phosphatic nodules are present.

6. Quartz/Quartzite and Hard sandstone: The quadratic surface, significant at the 99 percent significance level, explains 33.5 percent of the data, and gives a significant improvement over the linear surface (table 10.9). Increasing the analysis to the cubic level, despite providing a significant fit to the data, does not give a significant improvment to the explanation of the quadratic surface. A similar relationship is apparent with the increase to the quartic level.

The quadratic surface shows a 'trough' trending north-northwest - south-southeast from Northampton to Leighton Buzzard, and slightly displaced to the north (fig. 10.9). The implication is a slight increase in quartz relative to quartzite and hard sandstone to the south, superimposed on a general decrease from the northeast. The residual plot (fig. 10.10) shows four high positive residuals (> 1sd). These are situated at Leighton Buzzard, St. Neots, between Hitchin and Biggleswade, and to the south of Northampton. These may be explained with reference to the solid geology (fig. 2.1). Trending northeast - southwest, from Biggleswade to Leighton Buzzard, is the outcrop of the Lower Greensand, which is reported to contain erratic pebbles, among which quartz is common (Kelly, 1877; Barrow, 1919; Kirkaldy, 1947; Nicholls, 1947; Wells and Gossling, 1947). This is, therefore, a potential source of quartz. Draining northwards, away from the Lower Greensand escarpment, are the rivers Ouzel and Ivel, the courses of which are followed closely by the residual patterns. This may be a function of the distribution of samples, but may also support the suggestion of a Lower Greensand source for the quartz. The southward tail of the residual at Hitchin may indicate movement of quartz, south from the Lower Greensand, through the Hitchin Gap; a direction which implies uphill transport. The high positive residual, south of Northampton, is caused by the samples from the Milton Sand, in which quartz is present, but quartzite and hard sandstones are infrequent.

The results of the trend surface analyses suggest that there are no simple spatial patterns discernible in the gravels of the upper Ouse basin. Two possible causes for this weak spatial pattern may be suggested.

(a) The ratios and percentages chosen do not represent the effects of a single pattern of spatial redistribution, but several patterns with dissimilar trends, superimposed on one another.

(b) Stratigraphical control is dominant, giving rise to stratigraphic units, each of which is characterised by distinctive spatial gradients. Separating these units to identify the trend of each unit, may be possible (see below), but the small number of sample points in each of the units may render trend surface analysis ineffective (Chapter IX.A).

## B. Cluster Analysis.

Because of the nature of the following sections, it is necessary, in the first instance, to define the terminology which is used in describing the results of the cluster analyses. Because more than one cluster analysis is used there are two stages in the interpretation. Firstly, there are the results of a single cluster analysis, and secondly, there are the results generated by analysis of several cluster analysis programs. To distinguish the results of each stage, the following terms are used:

Sample: individual gravel sample.

Data set: characteristics used in an single cluster analysis.

Link: the joining together of samples by a single cluster analysis.

Cluster: a number of samples brought together by a single cluster analysis.

Connection: the joining together of samples by a combination of several cluster analyses.

Group: a number of samples brought together by a combination of several cluster analyses.

Similarity level: the number of cluster analyses in which a link between particular samples exists.

Division: the natural (real world) cluster or group.

In addition, in discussing the characteristics of samples, clusters or groups, the type of data referred to needs to be identified. The following procedure is used:

63.25% : gross percentage of a variable of a sample.

Mean 63.25% : gross percentage of a variable of a group.

Subscript nd : percentage of the total non-durable.

Subscript d : percentage of the total durable.

The results of the fourteen cluster analyses are displayed in diagrammatic form in figures 10.11 to 10.24. The clusters they present are similar, though not identical, especially in detail. Because linking continues until one cluster contains every sample, for purposes of interpretation, a significant level of amalgamation must be selected. Unfortunately there is no simple selection procedure. In some investigations there may be *a priori* reasons for accepting a certain number of clusters. More usually, however, the number of natural divisions is unknown. Some statistical procedures are available for determining the level at which clustering should be discontinued, but

> "Conventional statistical tests of significance are difficult to apply to cluster . . . analysis . . ." (Parks, 1966, p713),

and objective methods are found to be more useful in practice (Mather, 1976). One approach is to accept the clusters formed when a predetermined distance, between clusters, is exceeded (Johnston, 1976); however, the distance still has to be determined. An alternative method is to stop when a significant drop, or discontinuity, in the similarity coefficient is observed. Ward's strategy, which magnifies the intra-cluster variation at later stages (Johnston, 1976), can aid this type of analysis by making natural breaks between clusters readily identifiable

(Parks, 1966). Often, however, it is possible to define two breakpoints and

> ". . . in the end, an arbitrary decision must be made." (Johnston, 1976).

Because, in the present analysis, the decrease in the similarity coefficient occurs gradually, and no simple break is evident, an arbitrary cut-off level is defined so that the number of clusters identified accords with a reasonable stratigraphic scheme for the region, and takes account of any 'special cases' among the samples. Nine clusters are chosen on the basis that at least this number may be encountered in the field:

i - iii) Ouse terraces; three are defined by Edmonds and Dinham (1965) and Horton (1970).

iv - v) Fluvioglacial gravels 1 and 2; related to Anglian and Wolstonian glacial advances.

vi) Nene terraces; the small number of samples from the basin prevents further differentiation.

vii) Thame basin.

viii) Pre-glacial deposits - Milton Sand; identified by Thompson (1930) and Castleden (1980c).

ix) Special cases.

The nine clusters identified for each analysis are indicated on the dendrograms (figs. 10.11 to 10.24). Although an ideally-clustered data set should produce the same result whichever method is applied, at least at the higher levels of amalgamation (Fisher, 1982; p157), the real data sets analysed here do not all produce the same result, although consistencies are apparent. In an attempt to identify the real divisions, the result of each analysis is compared to all others. The result of this comparison is displayed in matrix form (table 10.10). The matrix shows, for each sample, the samples with which it is clustered when nine clusters are identified, and which programs produce these clusters. For example, sample S16 (Moor End, Radwell) is clustered by method "d" with Great Barford (S13, S14), Great Linford (S24), Stoke Goldington (S26, S52), Bromham (S62) and Willington (S41). Overall, thirteen analyses cluster Radwell (S16) with Great Barford (S14) and Willington (S41), twelve cluster it with Great Barford (S13), Great Linford (S24), and eleven analyses cluster it with Stoke Goldington (S26, S52), Paxton (S34), Bromham (S62), and so on. The matrix, therefore, indicates which of the samples are always clustered together and are, thus, most similar (for example all fourteen analyses cluster the two Upper Sundon samples (S17, S73) together), and those samples which are most dissimilar (all the samples which are clustered together only once, or are never clustered together). It is obvious, therefore, that those samples forming the most probable divisions are clustered together by more analyses than those forming weaker divisions. The matrix also indicates, on the leading diagonal, samples which remain on their own in any particular cluster analysis.

The results indicated in the matrix, although apparently complex, can be simplified (fig. 10.25) to identify the number of analyses in which samples group together. As with the dendrogram results, to interpret this diagram it is necessary to select a significant similarity level. This may be achieved with reference to the original data sets (Appendices I and II) and the character of each group as it develops.

1. Similarity level eleven.

The results (fig. 10.25) indicate that at the highest similarity level (samples grouped together by 14 to 11 cluster analyses) three major groups emerge, together with eight smaller groups (table 10.11), accounting for fifty five of the sixty five samples. At these high similarity levels, each successively lower similarity level evaluated strengthens the connections already made at the next higher similarity level, while adding samples to each group. Between similarity levels 11 and 10 there appears to be a significant discontinuity. At lower similarity levels (samples grouped together by 10 to 7 cluster analyses), inter-group relationships begin to build up, making interpretation more complex, but allowing inferences to be made about the origin of some of the more obscure samples.

The samples grouped together by eleven or more cluster analyses (similarity level 11) are shown in table 10.11a. The mean composition of each group is displayed in tables 10.12a and 10.13a.

Group 1.

This group of thirteen samples is the largest formed at similarity level eleven. Within the group, however, only nine sites are represented with seven samples belonging to only three sites - those of Upper Sundon, Ippollitts and Ridgmont. The sites are distributed across the whole of the area under discussion - in both the Nene and Ouse basins (fig. 10.26), while the surface levels of the gravel deposit at each site vary throughout the height range of the basins (2.0 - 53.3m above river level) (table 10.14). Lithologically, the group consists predominantly of non-durable components (mean 65.52%), of which chalk forms the largest part (mean 60.81% nd). Limestone and ferrous sandstone play varying roles within each sample, but overall limestone is more prominent (mean 17.82% nd). Of the durable components, flint is dominant with quartzite, hard sandstone, and quartz poorly represented.

Group 2.

The ten samples in this group represent eight sites, with a restricted distribution along the course of the Great Ouse from Buckingham through to Paxton (fig. 10.26). The group consists mostly of durable lithologies (mean 67.98%) with flint dominant (mean 46.95%). Quartzite and hard sandstone form the bulk of the remainder. The non-durable component of the group, although relatively small (mean 32.02%), is significant in separating these samples from other groups. In this group, the dominant lithology is limestone (mean 74.76% nd); chalk and ferrous sandstone each comprising less than 10% of the non-durable component. The Paxton sample (S34) stands out in the group as a whole in terms of the proportion of durable material (91.95%). At Paxton, flint is dominant, with proportionally less quartzite and hard sandstone, while quartz is more prolific than in the group as a whole, both in terms of absolute percent and as a proportion of the durable components. The Paxton sample must be associated with this group because its non-durable component is dominantly limestone (66.71% nd). Buckingham (S44) has the weakest connection to the group at this similarity level. This may be for two reasons. Firstly, it contains more non-durable material than the other samples (59.97%), although limestone is still dominant (69.72% nd). Secondly, the site is at a higher altitude above the floodplain (16m) than the majority of the sites of the group (c.4m)(table 10.14).

Group 3.

Comparison of the mean characteristics of this group with the mean characteristics of group 2 shows them to be closely similar except in the nature of the non-durable component. Here dominance changes from limestone to ferrous sandstone (mean 49.68% nd), although limestone and chalk are present in relatively large proportions (mean 17.19% and 14.45% nd respectively). The samples in this group, like those of group 2, are also found within a few metres of the floodplain (table 10.14). However, the samples can be divided spatially into two regions - those in the Nene basin (Rushden, S33; Earls Barton, S32; Clifford Hill, S28), and those in the Ouse basin (Bow Brickhill, S57, S69; Broughton, S23, S68; Elstow, S64).

Studying more closely the lithology of the individual samples (Appendix 1), the two basins can be distinguished from one another in terms of two components - chalk and ferrous sandstone (table 10.15). The samples of the Nene basin contain large proportions of ferrous sandstone, as is indicated by the mean group characteristics, and have very little chalk. The Ouse samples, however, while displaying a dominance of ferrous sandstone, contain considerably less, and a proportionally larger amount of chalk.

Group 4.

This group comprises five samples. It has the largest proportion of flint (mean 68.59%), and the smallest proportion of non-durable material (mean 12.13%), of any group (table 10.12a). Group mean values for quartzite and hard sandstone are similar to those of other groups at similarity level eleven, but quartz is more frequent, both in gross percent (mean 3.5%) and as a percentage of durable (mean 17.8% d). Ferrous sandstone forms the major part of the non-durable material, with limestone and chalk absent in four of the five samples. Small amounts of limestone and chalk at Blunham (S12) give rise to the limited limestone and chalk content of the group as a whole. Other lithologies vary between samples. The sites of this group are altitudinally diverse, ranging from 0.5m to 61.0m above the floodplain, and no consistent spatial pattern can be recognised (fig. 10.26). The variability of this group explains its weaker structure, which is formed at similarity level eleven; unlike groups 2 and 3 above, which form tight groups at similarity levels twelve or thirteen (fig. 10.25a).

Group 5.

Overall, this group is similar to group 3, with ferrous sandstone comprising the major part (mean 83.38% nd) of the small non-durable content (mean 29.35%). Limestone and chalk are present in only one sample. Flint, quartzite and hard sandstone comprise the bulk of the material, but with quartzite and hard sandstone more important than in group 3. Apart from the more varied lithological nature of this group, the altitudinal range is also greater (2.0 to 41.0m above floodplain), than that of group 3 (table 10.14). Spatially, this group follows the course of the river Ouzel northwards from Leighton Buzzard (fig. 10.26).

Group 6.

The salient character of this group is the large proportion of non-durable material (mean 79.63%), dominated by ferrous sandstone (mean 86.08% nd). Flint forms most of the durable component (mean 64.76% d). Quartz, except at Milton Malsor (S61) where there is 0.43%, is absent. Spatially, the four samples are from both the Nene and Ouse basins. The Milton Malsor samples (S30, S61), in the Nene basin, are predominantly ferrous sandstone with minor amounts of flint, while Stewartby (S66) and Millbrook (S76), in the Ouse basin, contain more flint and substantially more phosphatic nodules (10 - 15%). The combination of the ferrous sandstone and phosphatic nodules in the Ouse samples, however, produces the high non-durable component which matches closely that produced by ferrous sandstone alone at Milton. This causes the connection between the two pairs to occur at the eleventh similarity level.

Group 7.

Lithologically, the three samples in this group contain a large proportion of chalk, similar to group 1 in terms of the proportion of the non-durable component (mean 57.89% nd), although in absolute terms the amount is much less (mean 24.91%). This is because the amount of non-durable material is significantly smaller than for group 1 (mean 43.81% as oppose to 65.52%). The deficiency is made up by an increase in flint, quartzite and hard sandstone.

Each of the remaining groups (groups 8 to 11), produced by eleven or more cluster analyses, consist of two samples. They will, therefore, be considered at a later stage - except to note that the duplicate samples at Lidlington (S77, S80) and Leighton Buzzard (S5, S7) (groups 8 and 9 respectively) are grouped together by all fourteen cluster programs (similarity level 14). With such strong within-site similarity, the lack of other samples connecting with these pairs suggests that the gravel suites they represent are distinctly different from other gravel suites in the basins.

It may also be pertinent to point out, here, that all groups formed at the 11 to 14 similarity level contain Rhaxella chert; a lithology believed to be rare in deposits earlier than the Anglian in other areas of southeast England (Bridgland, 1980; Green, McGregor and Evans, 1982).

2. Similarity level ten.

Grouping of samples by ten cluster analyses only produces changes to three groups - groups 2, 3 and 5 (table 10.11b). Other groups only tighten the internal relationships, apparent at higher similarity levels. The changed group means are shown in tables 10.12b and 10.13b.

### Group 2.

The addition of the Bromham (S37), Buckingham (S25), and Nether Heyford (S60) samples to this group does not significantly affect the mean proportion of durable components in the group, although a slight decrease does occur (mean 67.98% to 60.86%). The most significant change is in the limestone and chalk content of the new samples. Limestone remains the dominant, non-durable component (mean 70.16% nd), but, in the Bromham (S37) and Nether Heyford (S60) samples, the proportion of chalk is noticeably larger (47.6% nd and 30% nd respectively), at the expense of limestone. In fact, Bromham (S37) contains more chalk than limestone (24.5% and 19.9% respectively). Spatially, the Buckingham and Bromham samples continue the distribution along the course of the Great Ouse, but Nether Heyford is in the Nene basin. Altitudinally the Ouse samples are considerably higher above the floodplain (12.2m and 11.2m respectively) than is the norm for the group as a whole (table 10.14).

### Groups 3 and 5.

The lithological similarity between groups 3 and 5, described above (section X.8.1), causes their grouping at similarity level ten. Mean group content does not alter greatly with the amalgamation (tables 10.12b; 10.13b). Spatially, the two groups are closely related with four of the eight samples in group 3, and all the four samples in group 5, distributed along the river Ouzel (fig. 10.26).

The groups, at this similarity level account, for fifty eight of the sixty five samples and it is necessary to analyse the relationships at lower similarity levels before all the samples can be explained.

3. Similarity levels lower than ten.

Examining the inter-group relationships at the lower similarity levels is informative when interpreting the stratigraphic relations of the groups.

Group 1.

Inevitably, as the number of cluster programs producing a particular connection decreases, the number of intra- and inter-group connections increases. As this happens, group 1 becomes most closely related to the chalk-rich samples of group 7, together with the lower, chalky gravel at Clifton (S1) which is unattached at higher similarity levels. At lower similarity levels (similarity levels 8 and 7), the Clifton connection to group 1 is associated with connections to the Rushings (S21) and Aspley Guise (S38) samples, and of these to group 1. None of the three samples associate themselves with any other group at these similarity levels and it appears that it is their chalk and/or non-durable component which causes them to amalgamate with group 1. In addition, similarity level seven brings together the samples at Lodge Farm (S55) and Marsworth (S39), and connects the former to group 1. This is unexpected because the Lodge Farm sample contains no chalk. The Marsworth sample, containing 37.27% chalk, would be expected to be more similar to group 1 than Lodge Farm.

### Group 2.

It is not until similarity level eight that changes occur in this group - above this similarity level there is only a strengthening of the intra-group connections. At similarity level eight, however, while intra-group connections are further strengthened, the group becomes strongly attached to group 4. This connection is itself further strengthened at lower similarity levels, but the group becomes more heterogeneous with connections to groups 3 and 1.

### Group 3.

Apart from increasing the connections developed with group 5, group 3 becomes more diverse, with connections to groups 4 and 7. As described above, connections with group 2 also occur. At the weakest similarity level, a single connection is made with the Kempston (S50) and Elstow (S64) samples of group 10. This is the only external connection made with group 10 by more than six cluster analyses. The average composition of groups 3 and 10 (tables 10.12 and 10.13) again suggests that ferrous sandstone is the lithology determining the clustering, despite the reduction of the total non-durable component.

### Group 4.

This group is, apparently, related lithologically to most of the major groups, because at the lower similarity levels it connects with groups 2, 3, 5 and 7, its closest relation being with group 3/5. This again suggests that ferrous sandstone, the principal non-durable component, is the critical element. The connections with the Bromham (S62) and Paxton (S34) samples of group 2, however, suggest that flint and the small amount of non-durable material are significant at lower similarity levels.

Group 5.

Like group 3, with which it is most closely related, group 5 begins to increase its inter-group relationships, connecting with groups 4, 7 and 8. In addition, the only connection with Aspley Guise (S22), by more than six cluster analyses (similarity level six), is made, to the duplicate Fox Corner samples. The relationship with group 7 occurs via Fox Corner (S70), the only sample containing chalk. The link with group 8 is discussed below.

Group 6.

The separation of the four samples in this group, into Ouse and Nene sub-groups (see B.1 above), is emphasised, at similarity levels 8 and 9, by the manner in which the samples connect with group 11. Group 11, contains the Rowsham (S45) and Stewartby (S49) samples, and comprises mainly durable lithologies, flint, quartzite and hard sandstone (mean 65.75%) (table 10.12a). The non-durable component, is dominated by ferrous sandstone and phosphatic nodules, grouping with Stewartby (S66) and Millbrook (S76) in nine cluster analyses (similarity level nine). The Milton samples, devoid of phosphatic nodules, are connected more weakly to group 11 at similarity level eight.

Group 7.

The majority of connections made by this group at the lower similarity levels (with groups 1, 3, 4 and 5) are described above. The only noticeable exceptions are the connections with group 8, described below.

Group 8.

The two Lidlington samples (S77, S80), remain discrete until similarity level nine. From this similarity level to similarity level seven the samples connect with every sample in groups 5 and 7 - but nothing else. This suggests that the samples have characteristics of both groups. The samples are mostly durable (mean 59.05%), of which flint forms 47.71% d, and quartzite and hard sandstone the remainder (table 10.12a). Non-durable lithologies are all represented (limestone 37.18% nd; ferrous sandstone 27.86% nd; chalk 15.13% nd), with chalk more abundant than usual.

Group 9.

The only samples not attached to another group by similarity level seven are those in group 9 and Pitsford (S31). The two samples in group 9 are duplicate samples from Leighton Buzzard (S5, S7), which although grouped together closely, do not connect with the third sample from the site (S6) until similarity level six. The apparent lack of similarity may, however, reflect not differences in sediment type, but different sampling strategies. Samples S5 and S7 are sieved spot and bulk channel samples respectively (Chapter VI.A.2), while sample S6 conforms to the standard procedure used elsewhere. Although the difference between the samples suggests that the sampling techniques are not compatible, the closest similarity the samples have is with S6, indicating they are part of the same sedimentary unit.

The remaining, discrete sample is at Pitsford (S31) in the extreme northwest of the area. It contains a high proportion of quartzite and hard sandstone (38.17%). Ferrous sandstone is the principal non-durable lithology (88.79% nd); chalk and limestone being absent. Rhaxella chert is also abnormally frequent in this sample (3.93% d). The uniqueness of the sample, for whatever reason, is indicated by its isolation at similarity level seven.

4. Principal Component Analysis.

Despite the differences apparent in each of the fourteen cluster dendrograms (figs. 10.11 to 10.24), the consistencies in the above results suggest that individual statistical procedures may be informative. The most important of these is the principal component analysis on the gross percentage data (table 10.16). Of the six programs run, using a principal component analysis data matrix, the analysis on the gross percentage data matrix is investigated further, because each lithology is considered (the ratio matrix involves subjective selection of variables), and no over-representation, or weighting , of lithologies occurs by their presence in two or more forms (for example the combination of the ratio and gross percent matrices contains chalk, ferrous sandstone and limestone in more than one form).

The first seven eigenvectors, identified by Kaiser's criterion as the significant vectors and used for the data matrix, are investigated (table 10.16a). The seven vectors, or principal components, account for 69.45% of the total variance of the original variables, with the first vector accounting for 19.13%, the second 11.56%, the third 10.88% and the fourth 8.55%. This relatively low explanation of the data suggests that they may be of limited interpretative value. The loadings of every variable (lithology) on each eigenvector are presented in table 10.16b. Where a loading is positive, there is a positive correlation between the vector and that variable. Negative values indicate a negative correlation. High loadings, either negative or positive, indicate that a variable is either under- or over- represented in that particular vector. Values near to zero indicate that a lithology is averagely represented.

The results (table 10.16b) show that quartzite, hard sandstone, quartz, miscellaneous hard, and chert are over represented in vector one, while chalk, limestone and calcareous sandstone are under represented. This vector may be interpreted as representing the durable components.

Vector two, with large proportions of quartz, soft sandstone, cherty sandstone, miscellaneous hard and calcareous sandstone, and with small amounts of hard sandstone, Rhaxella chert and chert, obviously contains both durable and non-durable lithologies. If the weighting within a single vector may be interpreted as indicating a similar source area for each lithology, the presence of non-durable lithologies (soft sandstone and calcareous sandstone) indicates a local source. The only local geological stratum which contains soft sandstone and calcareous sandstone, and can be demonstrated to contain quartz and other 'hard erratics', is the Lower Greensand or

Cambridgeshire Greensand (see Chapter II). It is suggested, therefore, that this vector may represent the Lower Greensand.

Vector three comprises high positive weightings on ferrous sandstone and phosphatic nodules and high negative weightings on limestone, chert and calcareous sandstone. This suggests that limestone and ferrous sandstone are mutually exclusive, and that ferrous sandstone and phosphatic nodules may be derived from similar sources. Unfortunately, an examination of the lithologies present within the available strata (table 2.1) shows that the Northampton Sands and the Lower Greensand contain both lithologies. To identify a single source may, therefore, be impossible.

The fourth vector only explains 8.55% of the total variance and, therefore, despite being statistically significant, may not be particularly informative, interpretatively. This is evident from the variables which are heavily weighted - soft sandstone, schist, mudstone and igneous. All are lithologies which are only present in small quantities or are absent and, therefore, difficult to interpret meaningfully, especially as both far-travelled and local sources are represented. Similar arguments may be put forward for the last three statistically significant eigenvectors.

Under normal circumstances, by relating the eigenvectors to each sample, the main characteristics of that sample can be identified and the reasons for clustering may be more closely identified (those samples with similar weightings on each eigenvector being clustered together). However, due to the method employed here, where several cluster analyses programs are used, this part of the analysis may not be applicable; the principal component cluster analyses not producing the representative clusters identified above. Some useful information is, however, obtained. The weighting of each eigenvector (factor scores) on the samples in group 1 above, indicates which vector is most strongly represented in that sample (table 10.17). High positive scores indicate a good positive correlation between the vector and the sample, in the same manner as between eigenvector loadings and the respective variables. In the samples of group 1, vector one is negative and in all, except Winslow (S75) and Broughton Ground (S56), has the largest weighting. This vector, if positive, would indicate large proportions of the durable components (see above), and little chalk. The negative weighting, however, shows that the reverse is true and that chalk is dominant, with small proportions of the durable lithologies. The Winslow and Broughton Ground samples, however, have vector six (positive) and vector five (negative) dominating them respectively. The variable weightings in each of these shows that chalk is still dominant (table 10.16b), but that other lithologies vary in importance. It appears, therefore, that this group is a result of large amounts of chalk, as has already been suggested.

Comparing the samples of the other groups to the factor scores (table 10.17), however, does not give consistent results. Within any one group the dominant vector varies. This is not totally unexpected because, if the reasons for subdivision were clear, then a single cluster analysis using the principal component data matrix would produce the most probable division, and no further analysis would be required.

The separation of group 1 from the other groups, both in terms of this analysis, and in the analysis above (section B1 - B3), is supported by every dendrogram. One limb of each dendrogram always contains the chalk-rich samples - the other limb is always more heterogeneous.

### 5. Interpretation.

The results described above suggest that there is, within the gravels of the upper Ouse, and Nene basins, a basic division into two main suites, one of which may be subdivided. In addition, a number of smaller groups occur which provides some insight into the Quaternary development of the area.

#### a) Similarity level eleven.

1) The clearest suite defined by similarity level eleven is the non-durable, chalky gravel of group 1. Gravels with similar non-durable material, mainly chalk and Jurasic limestone pebbles, have been described, by Rose and Allen (1977), McGregor and Green (1978), and Green, McGregor and Evans (1982), in association with chalky till. The chalky till, itself, is demonstrated to contain relatively small proportions of durable stones; the most

prominent lithology being chalk (Rose, 1974). Perrin, Rose and Davies (1973) describe the components and confirm that chalk is dominant (56-84%), with flint and other (Jurassic) components equally abundant. Solomon (1932, p249) discussing the lithology of gravel deposits in the area states that

> "The frequent occurrence of chalk pebbles stamps the deposit at once as the product of a chalk-bearing ice sheet."

The fluvioglacial gravels described by McGregor and Green (1978) and Green, McGregor and Evans (1982), however, vary widely in the proportion of non-durable material they contain. Individual samples are shown to contain up to 30% non-durable while

> ". . . there are other samples in which non-durable material is lacking, but which in other respects are characteristic glacial gravels." (Green, McGregor and Evans, 1982).

It is this latter type of "chalky gravel" which is described by Rose and Allen (1977), in the southern part of East Anglia, containing only 1-2% non-durable. The explanation given for such differences in the amount of non-durable material by Green, McGregor and Evans (1982) is that the former gravels

> ". . . are evidently proximal elements of a suite of Anglian fluvioglacial sediments."

while the latter

> ". . . probably represent the distal portions of Anglian fluvioglacial sediment bodies, there being no evidence that non-durable material has been lost due to post-depositional solution."

The relationship of the present gravels to chalky till, together with their wide height range, support the interpretation that this suite is fluvioglacial in origin. Five of the samples underlie deposits of chalky till (Upper Sundon, S17, S73; Ippollitts, S58, S72; Winslow, S75) and three are from gravel pockets within till (Ridgmont, S48; Ippollitts, S71; St. Neots, S35). The large proportion of non-durable material (up to 80.77%) indicates the proximity of the ice margin at the time of deposition. Local incorporation of chalk is evident at Ippollitts and Upper Sundon where the Chiltern outcrop is crossed, and the amount of chalk is increased. The presence of the chalk elsewhere in the Ouse basin, and in the Nene basin (Weedon Bec, S59; Wootton, S29), indicates movement south or southwest from the Lincolnshire outcrop. Material of northern provenance is represented by the relatively large proportion of Rhaxella chert in the group (mean 2.51% d).

2) The decrease in the amount of non-durable material between group 1 and groups 2 and 3 (table 10.12a) indicates a change in the mode of deposition. In groups 2 and 3, similar amounts of non-durable material, and the similar nature of the durable components, suggests that the groups may be genetically related. The samples in group 2, distributed along the course of the Great Ouse (fig. 10.26) at a level below 4m above the floodplain, can be related to the terrace sequence of the river. A similar argument may be put forward for the samples in group 3. The only lithological difference between the groups, the non-durable component, may be explained in terms of the source geology. Upstream from Bedford, the river Great

Ouse is cut into the limestones of the Cornbrash and Great Oolite (fig. 2.1). Only rarely are strata containing ferrous sandstone encountered. This produces a preferential influx, into the river gravels, of Jurassic limestone. The influx is sufficiently large to ensure that, despite the non-durable nature of the limestone, it is not obviously affected by downstream transport, as in high level gravels of the river Thames (Higher Pebble Gravels, Westland Green Gravels, and Higher and Lower Gravel Trains), where

> ". . . no down-valley effects have been recognised which could be attributed to dilution, abrasion or selective entrainment." (McGregor and Green, 1978),

although here flint is more resistant to abrasion than limestone.

The presence, at similarity level eleven, of Buckingham (S44) and Bromham (S62), and the addition at later similarity levels of Buckingham (S25) and the duplicate Bromham sample (S37), which are at greater altitudes above the floodplain, may be a result of two processes.

i) They may be reworked terrace material, from lower terraces. Reworking by ice may be indicated by the increased proportion of chalk in the four samples affected. This is especially true of the Bromham (S37) sample where chalk is dominant over limestone.

ii) The higher level gravels may be part of a higher terrace deposit than the other samples in the group. Each terrace deposit has characteristics which make them difficult to separate lithologically. The increased proportion of chalk would, in this case, have to be derived from earlier glacial deposits; there being no direct link to a chalk outcrop.

3) In group 3, ferrous sandstone is more important than limestone (table 10.12a). The samples in the Nene basin, contain more ferrous sandstone than those in the Ouse basin (table 10.15), and presumably derive it from the Inferior Oolite; primarily the Northampton Sand and Ironstone. This, however, conflicts with Castleden's (1980b) description, of the terrace deposits of the Nene (table 4.3), in which he reports that limestone is the dominant non-durable lithology (31.4 - 41.8%) and chalk is more prolific than the present study suggests. In the Ouse basin, four of the group 3 samples are distributed along the river Ouzel (fig. 10.26). These samples, as noted above, contain less ferrous sandstone and more chalk than the Nene samples. A more limited source of ferrous sandstone is therefore indicated, together with a greater source of chalk. The river Ouzel has indirect access to both these lithologies. Upstream from Bletchley, the Ouzel flows across outcrops of the Lower Greensand, and in its headwaters, across the Chalk of the Chiltern escarpment. It is these strata which may have supplied the ferrous sandstone and chalk respectively. Chalk, however,

> ". . . never survives the ordinary process of erosion in pebble form." (Solomon, 1932, p249)

and its presence may therefore reflect, in part, derivation from chalky till.

Within the terrace gravels the presence of far-travelled lithologies, especially igneous and Rhaxella chert pebbles, and in the Nene basin, chalk, indicates that at some time prior to the deposition of the gravel, glacial incursion(s) into the area occurred.

4) Rather more difficult to explain is group 4 with its large flint component (table 10.12a). The durable nature of the group tends to suggest an origin by fluvial, rather than fluvioglacial, processes - an origin supported by the altitude of Leighton Buzzard (S6), Blunham (S12) and Clifton (S2). The Blunham and Leighton Buzzard samples are, also, from areas defined by the Geological Survey as first and second terrace. The other samples, however, vary widely. Toddington (S74) and Clifton (S2) are from areas reported to be covered by glacial gravels, while Buckingham (S43) is unclassified. Spatially, the samples are not related. Apart from flint, the samples in the group contain large proportions of quartz and their non-durable lithology is ferrous sandstone. Both lithologies may be related to the Lower Greensand (Chapter VIII, table 2.1), to which four of the five sample sites have direct access. The relationship at lower similarity levels with groups 3 and 5 supports this hypothesis.

5) Group 5, lithologically similar to group 3 and distributed along the course of the river Ouzel, might initially be regarded as a fluvial deposit. However, the altitude of the Fox Corner samples (S20, S70) (41.1m above floodplain) and the Bletchley sample (S42) (16m above floodplain) suggests that this interpretation may not be correct. There are two possible explanations for this

apparent difficulty:

i) the gravels may be fluvioglacial in origin, deriving their non-durable material locally (from the Lower Greensand). Limestone and chalk may have existed initially but have been removed by post-depositional decalcification.

ii) the gravels are redistributed terrace deposits; the terrace suite consisting of gravels similar to those of the Ouzel. The redistribution left intact the gross terrace characteristics, but caused sufficient modification to distinguish them from the terrace deposits sensu stricto.

Although distinct at similarity level eleven, connections at lower similarity levels with the terrace gravels of group 3 suggests that ii) is most likely. The situation at Fox Corner may be analogous with deposits overlying till in the Vale of St. Albans (McGregor and Green, 1978) where

> ". . . it seems likely that most of the material forming the gravels above the chalky till was derived locally from earlier gravels."

6) The samples of group 6 are derived from two sources. The samples in the Ouse basin are likely to be a product of material moving away from the Lower Greensand, from which the ferrous sandstone and phosphatic nodules are probably derived. The presence of Rhaxella chert and igneous pebbles in the Stewartby (S49) sample, with which this group is associated at lower similarity levels, and the stratigraphic relationships of the Millbrook and Stewartby sites (gravel overlying till) indicate post- or late-glacial formation. The Milton Malsor samples, are

part of the Milton Sand described by Thompson (1930), Dury (1949), Horton (1970), Horton et al. (1974) and Castleden (1980c). Locally derived material (Jurassic limestones and ironstone) is reported to be dominant, and although Horton (1970) reports quartz and quartzite of Bunter type occurring throughout, Thompson, Dury and Castleden disagree. Castleden (1980c) suggests that Horton

> ". . . has inadvertently included data from later gravels adjacent to the Milton Sand."

The present samples confirm the local composition and it is likely that the presence of flint in S30 (10%) is due to mixing of the surficial layers with later deposits. The origin of the deposit is discussed elsewhere (Thompson, 1930; Castleden, 1980c), and the small number of samples examined in the present study precludes further discussion.

7) Group 7, because of the large chalk content, may be related genetically to group 1. However, the origin of the large chalk content may differ between the samples of the group. The sample from Bletchley (S46), from a pocket within chalky till, may be expected to contain chalk derived from the till. At Broughton Ground a duplicate sample (S56) has 'glacial' characteristics (group 1), and therefore would support a fluvioglacial origin. The sample at Marsworth (S40), however, may not be explained in the same manner. The site lies on the chalk escarpment, and it is probable that the chalk is locally derived, thereby distorting the relationship. It may be significant to note that decalcification (see B.6 below) separates these samples. Below similarity level eleven, the relationship

of group 7 with groups 3 and 5 suggests that mixing with terrace deposits of the Ouzel may have occurred.

### b) Lower similarity levels.

The relationships developed by lower similarity levels explain the remaining samples and groups, although, at these levels, only tentative interpretations may be made. Group 8, comprising the Lidlington samples (S77, S80), resembles terrace deposits in terms of the proportion of durable lithologies. The non-durable component, with limestone dominant, would imply Great Ouse terrace. However, the large proportion of ferrous sandstone (mean 27.87% nd) and chalk (mean 15.13% nd), although small in absolute terms, may suggest Ouzel, or even fluvioglacial, origin. Altitude above the floodplain (92m) would support the latter. It is significant, therefore, that the samples become associated with every sample in groups 5 and 7, which have been interpreted as Ouzel terrace deposits disturbed by ice and as fluvioglacial deposits with some terrace characteristics respectively. Three interpretations of the Lidlington samples, and their relationship to groups, can be suggested:

i) the three groups are, in reality, distinct, but have one or two major lithologies which are similar and cause grouping as resolution falls.

ii) the Lidlington samples may have characteristics of both groups and lie in a zone of overlap.

iii) there is a gradation between the extremes of a single group, which, while distinct in detail, merge together as the level of resolution falls.

In the present situation, it is probable that the ferrous sandstone is derived from the underlying geology - the Lower Greensand. Limestone, the dominant non-durable lithology, is most likely to be derived from the Great Ouse, since no local outcrop occurs. This suggests derivation from a Great Ouse terrace. To find such a deposit in its present location suggests redistribution by glacial ice. Chalk may then be accounted for by inclusion during transportation by 'chalky till' ice. Interpretation ii) is therefore favoured.

At the lower similarity levels, other relationships can also be identified. The addition of Kempston (S50) and Elstow (S51) to the Ouzel terrace suite (group 3) suggests a similar tributary flowing northward away from the Lower Greensand, possibly associated with groups 6 and 11. The similarity of the two terrace suites (groups 2 and 3), despite the different non-durable components, is indicated by their grouping at similarity level seven and eight.

The connection of Clifton (S1), Rushings (S21), Aspley Guise (S38), Lodge Farm (S55) and Marsworth (S39) to group 1, and group 1 alone, suggests that, while different in detail, they are most closely related to fluvioglacial deposits. Aspley Guise (S38), in fact, lies stratigraphically within chalky till. The duplicate sample at this site (S22) may indicate, in its single connection with group 5, that the gravel also bears some resemblance to terrace deposits of the Ouzel, probably caused by the ferrous sandstone content. Rushings is also stratigraphically related to till. The Clifton sample

(S1), connected because of its chalk content, has been described previously as glacial gravel (Edmonds and Dinham, 1965). The Lodge Farm sample (S55) is more difficult to explain because it contains no chalk. It must therefore be similar in other ways (see X.B.6 below). The Marsworth sample, taken as a duplicate sample with S40, is probably similar to it and similarly characterised by its position on the Chalk outcrop. Overall, however, the numerous connections with group 1 made at the lower similarity levels may only reflect the wide variation in gravels related to glacial incursions described by McGregor and Green (1978).

Finally, there is evidence that the technique employed in the analysis has achieved what it set out to do, and that the different stages in the data analysis have not caused loss of significance. The position of the sample at Pitsford (S31), remaining distinct at similarity level seven, suggests that the requirement, that samples which are unusual should stand alone and not be forced into a group, is satisfied. The reason for the distinction is unknown; the lack of other samples of similar type making interpretation difficult.

### 6. Decalcified analysis.

The widespread distribution, in gravels, throughout the region described here, of chalk, and to a lesser extent limestone, suggests that there are few deposits which have not incorporated these lithologies, for one reason or another. In twelve samples, from six groups, both chalk and limestone are absent, although other samples in each of the groups contain both lithologies. This suggests that decalcification may have occurred. To examine this suggestion, decalcified, recalculated sample composition (Appendix III) are analysed with a single cluster analysis using gross percentages. Flint is again removed to prevent overdetermination (see Chapter IX.B.2). Three samples are removed from the analysis; the two Milton Malsor samples, which comprise the Milton Sand, and the single sample from the river Thame. The result of the cluster analysis is displayed in figure 10.27.

Identifying eight clusters in the analysis allows the groups identified above to be compared to the decalcified results. Although differences exist, it is possible that some of them are due, not to stratigraphically significant irregularities, but to cluster analysis irregularities which are not evident, because only one data set was analysed. Overall the decalcified analysis supports the majority of the interpretations described above. Two terrace suites can still be identified, together with the glacial suite, although the latter is modified. The Ouse terrace suite (group 2) is intact, including the Buckingham (S25) and Bromham (S37) samples. More closely associated with group 2 is group 4, supporting terrace derivation. The Lidlington samples, interpreted above as redistributed Ouse terrace material, are attached to group 2 supporting this interpretation.

The samples associated above with the Ouzel and Nene - either as terrace deposits or as redistributed terrace deposits (groups 3 and 5) - remain together, although Elstow (S64) and Bow Brickhill (S57) are removed. Samples with broadly similar characteristics are also linked to this group - Stewartby (S49), Aspley Guise (S22) and Broughton Grounds (S67); the last having already been described as Ouzel related. Nether Heyford (S60), previously part of group 2, also joins this 'ferrous sandstone' group.

The fluvioglacial suite (group 1) becomes split into two parts; one part with more ferrous sandstone, the other with more flint. The former, therefore, associates itself with the ferrous Ouzel samples, while the latter remains distinct. To this latter group, Lodge Farm (S55) is strongly attached, supporting the interpretation above. Three samples, previously described as having fluvioglacial affinities (Broughton Grounds, S56; Aspley Guise, S38; Rushings, S21), together with Pitsford (S31) are still, although not directly, related to the fluvioglacial suite. This may suggest that the Pitsford sample represents a decalcified, fluvioglacial gravel. Many of the samples previously distinct until low similarity levels, remain so with this analysis - Clifton (S1), Leighton Buzzard (S5 and S7), Marsworth (S39), Stewartby (S66) and Millbrook (S76).

The analysis indicates that although some decalcification may have occurred, it is not sufficient to create a serious interpretative problem. It is apparent, therefore, that suites are still distinct and dependent on their geographical source.

## Conclusions.

The results of the cluster analyses show that the gravel deposits of the Ouse basin are readily separable into two main groups - those forming part of the terrace system of the Ouse, and those of fluvioglacial origin (table 10.18). The gravels of fluvial origin have a greater proportion of durable clasts compared with those of fluvioglacial origin, but, despite this, it is the non-durable components which are significant in the identification and separation of the various fluvial gravels within the basin. This separation is dependent upon the catchment geology of each river system. The gravels of the Great Ouse are characterised by limestone, while those of the Nene and Ouzel are characterised by ferrous sandstone.

The fluvioglacial gravels of the basin show clear affinities with other fluvioglacial gravels in eastern England. They are characterised by high proportions of non-durable clasts, with chalk dominant; a distinction which is supported by the principal component analysis. The decalcified analysis, however, suggests that chalk is not the only distinctive component, because the separation of each suite is still apparent. In addition to the main suites of gravel, the complex mixing of rock types of widely different provenance as a result of glaciation, is demonstrated, including the redistribution of virtually intact terrace gravels, and the incorporation of terrace gravels into those of fluvioglacial origin (table 10.18).

The results of the principal component analysis, together with the trend surface of quartz/quartzite and hard sandstone, demonstrates that within the Ouse basin the Lower Greensand is a significant source of durable clasts - principally quartz, cherty sandstone and miscellaneous hard - together with the non-durable soft sandstone and calcareous sandstone. The remaining durable lithologies are believed to have a northern provenance.

# Chapter XI. Stoke Goldington.

## Introduction.

The discovery of a richly organic clay in association with gravels of two separate suites at Stoke Goldington (site 33), and the dating of associated material, provide important insights into the geomorphological environment of terrace formation and into the glacial succession in Midland England.

## A. Description.

The Stoke Goldington pit, worked by GFX Hartigan Limited, is situated on the northern bank of the Great Ouse (fig. 11.1) approximately five kilometres downstream from Newport Pagnell (SP854489). The adjacent floodplain is at 50.5m O.D., above which a terrace can be seen at 58.0 - 59.0m O.D. (plates 20, 21). The valley side above the pit is occupied by chalky till which has been found, in trial pits, to rest on limestone bedrock, the Great Oolite Limestone. The limestone bedrock can be traced to the edge of the pit, but the bench beneath the gravel deposit is cut in Upper Lias Clay. The till can be traced from its outcrop, to the north of the pit, to within 250m of the edge of the pit but nowhere has been seen in contact with the deposits exposed in the pit. Four exposures of an organic clay layer were available (figs. 11.1; 11.2) at points A, B, C and E.

At point A, a section was seen in the floor of the pit showing the lowest part of the lower gravel (j, see below) and underlying deposits, down to, and including, the unweathered Upper Lias Clay (plates 22, 23, 24). The overlying beds (j, k and l) are described from the nearby working face of the pit at A' (fig. 11.2; plate 25). The full sequence is as follows:

Surface

| | | | |
|---|---|---|---|
| A' | (l) | 1.8-4.4m | Upper chalky gravel, well involuted and alternating with 'loam' - it is finer than the lower gravel (j) with clasts mainly smaller than 16.0mm. |
| | (k) | 0.1-0.2m | Discontinuous light blue to grey tenaceous clay, grading downwards to a clayey sand and sandy clay. |
| | (j) | 1.9-3.7m | Horizontally bedded gravel, containing sand channels and layers of iron-staining. Clasts range up to 31.5mm in diameter. |
| A | (i) | 25cm | Pale grey and rust brown banded, sandy clay containing shells, although the upper layers become less shelly. Has a sharp basal boundary. |
| | (h-g) | 5-7cm | Grey clay with mottling, paling upwards to top where there is no mottling (h); Some shell debris present. |
| | (f) | 15-25cm | Grey clay with shells and darker grey mottling containing some sand, but free of stones. Variable texture due to sandy lenses. |
| | (e) | 6cm-1.10m | Dark greyish brown clay with ferrous |

| | |
|---|---|
| | mottling. Shell debris and few pebbles. Some wood fibre. |
| (d) 15cm | Inclined boundary between a sandy clay above and a clayey sand below. The lower clayey sand is more ferruginous and contains numerous shells, and gravel. |
| (c) 50-55cm | Free-running horizontally bedded brown gravel which is increasingly ferruginous upwards. The upper 10cm has three iron pans running through it. There is no sharp boundary between this gravel and the overlying sand. |
| (b) 10-20cm | Lag deposit one stone thick. Nodules and pebbles of limestone up to 20cm diameter. |
| (a) | Weathered Upper Lias. |
| | Upper Lias. |

In section B, the uneven surface of the basal gravel (c) was seen. In the hollows of this is the dark grey clay with darker mottling (f). The paler clay (g) again appeared above this, but with increased thickness. The basal gravel here contains lenses of slightly clayey sand with numerous shell fragments. Beneath the basal gravel (c) at point B a dark grey 'flaky' clay was exposed into which occasional pebbles had been impressed. This is the Upper Lias (a).

The third section, at point C, was a trench excavated into the top of the grey clay with shells (f). At this point the clay was found to be 1.25m thick before the basal gravel (c) was reached (fig. 11.3; plates 26, 27).

The maximum observed thickness of the clay (d - i) is 1.72m, seen in a trench (E) exposing a complete cross-section of the clay layer (plates 28, 29). The trench showed the clay to be in a channel-like depression underlying the lower gravel (j) and overlying the basal gravel (c); the depression having an approximate width of 20m. It is uncertain whether the trench exposes the true channel width. The surface of the clay (i) at 52.27m O.D. is 1.77m above the level of the floodplain, while the surface of the lower gravel (j), at approximately 54.07m O.D., is 3.57m above the floodplain.

In October 1983 the workings of the pit, having extended northward, exposed a further section (F) of the lower and upper gravel (j to l). The section (fig. 11.4; plates 30, 31) showed the horizontally bedded lower gravel (j) to be overlain by up to 1.5m of the grey, tenaceous clay (k). The surface of the lower gravel is 52.87m O.D. (2.37m above the floodplain). Within the clay (k) small pockets of shells were present. Overlying k, 1m of the upper gravel (l) is present; the upper part of the section being fill.

Samples were taken as follows. Three gravel samples were taken:

S26 from the basal metre of the lower gravel (j) from the working face of the pit (April 1981).

S27 from the upper metre of the upper gravel (l) from the working face of the pit (April 1981).

S52 from the basal gravel (c) at point A (October 1981).

Also at point A, samples were taken of the clay layers (d to i)(plates 22, 24):

R6 - From the upper half of the grey and brown banded sandy clay (i).

R5 - From the lower half of the grey and brown banded sandy clay (i).

R4 - From the upper part of the dark grey clay with darker mottling, together with the overlying paler clay (f, g, h).

R3 - From the lowest 10cm of the dark grey clay (f).

R2 - From the greyish brown clay with ferrous mottling (e).

R1 - From the lower clayey sand, which contained shell particulates (d).

At point B, S53 was taken from the lenses of clayey sand with shells, within the top of the basal gravel layer, for the analysis of the fauna. In the trench at point C, pollen samples were taken from the clay at 5cm intervals (November 1981); the first (No.1) taken from the top (0mm) of the grey clay with darker mottling (f)(plate 27). Twenty six samples were taken. Fifteen duplicate channel samples were taken from the uppermost 95cm of the same clay sequence for analysis of the fauna. The first sample was taken from the first 5cm, the next three at 10cm intervals. The last eleven were rather more uneven in their thickness. In the clay at point C a well-weathered bone fragment was collected.

In addition, a single sample (S25) was taken from the clay layer (k), at point D (November 1981). The sample is from the top of the sand and the bottom of the upper clay (fig. 11.5). Samples were also taken from the shelly pockets within this layer at F (October 1983).

The section (E) cut through the organic clay layer (November 1982) displayed the 1.72m clay section. A series of twenty nine pollen samples was taken - the upper twenty four at 5cm intervals, and the last five at 10cm intervals - together with seventeen duplicate channel samples (plate 29). Each sequence begins at 0cm; the boundary with the overlying gravel (i). These have not yet been fully analysed and are not described here. Fragments of wood were preserved in the clay in this section, while in the basal gravel (c) small fragments of bone were discovered. Investigation of the site is continuing as the working is extended northward.

### B. Fauna.

The fauna of the site is found mostly in the clay layers d to i, and consists of Mollusca, Ostracoda, Coleoptera and a Mammalian bone fragment. Two sequences have been analysed so far from point A and point C (fig. 11.2). The sample from the basal gravel (S53) at point B, and sample S25 at point D from bed k also contain molluscs.

For the analysis of the fauna I should like to express my deepest thanks to Dr. D.H. Keen (Mollusca), Dr. J.E. Robinson (Ostracoda), Dr. G.R. Coope (Coleoptera) and Dr.

A.P. Currant (Mammalia) for their time and effort spent in providing the following results, and their comments freely given for inclusion in the thesis.

1. Mollusca (D.H. Keen).

A total of forty six taxa have so far been recovered, which are dominated, at the base, by moving water forms, and, further up in the mud, by pond species (figs. 11.6, 11.7). A few land shells are present, mostly open grassland types, but a few shade-demanding (woodland) types also occur. Overall the fauna is of a large temperate river and its floodplain, in an open grassland area, with a few trees or shrubs, or possibly open woodland, scattered along the valley sides. The molluscs can be divided into four zones (fig. 11.6).

The basal zone (Zone I), represented in S53, is a zone dominated by Valvata piscinalis (40%), Bithynia tentaculata (10%) and Pisidium moitessieranum (7%), together with Pisidium amnicum (3%) and Corbicula fluminalis (0.5%); all of which are indicative of moving water conditions. Land molluscs are also present in small numbers, and are mostly shade demanding types.

Zone II comprises the main part of the organic clay (SGB15 to SGB5) and is dominated by the pond species Gyraulis leavis (up to 95%). The pond bivalves Pisidium nitidum, P. casertanum, Sphaerium corneum and S. lacustre are also present, suggesting a clear pond environment.

Zone III comprises the upper part of the organic clay (SGB4 to SGB1) to the base of the lower gravel (j). A pond fauna is present, but the values for G. laevis are reduced to c.10%, and the main species present are Armiger crista (up to 40%), Hippeutis complanatus (45%), Anisus vortex (10%) and Acroloxus lacustris (10%). This suggests that there was an increase in the silt content, a higher concentration of organic material and a lower oxygen level in this zone.

Zone IV comprises the intra-gravel clay lens (k; S25) and is, therefore, separated from the bulk of the organic deposits by a period of aggradation. A totally different fauna is present. At point D it is dominated by Pupilla muscorum (77.8%), Catinella arenaria (12%) and Limacid plates (10%), suggestive of a braid plain hollow under severe periglacial conditions. The sample from point F is also a restricted fauna, dominated by marsh/pond species (C. arenaria, L. trunculata, A. leucostona, Limax sp.) but with some drier land elements (P. muscorum). The environment here is suggestive of a damp hollow or muddy pool on a braid plain, under a severe climate.

a) Environmental indicators in the mollusca.

1) Zone I. This contains 43 taxa, of which 23 are aquatic, 4 are marsh and 16 are land taxa. The dominance of the aquatics points to an origin in moving water. The clearest indications of this are the zonal forms V. piscinalis and B. tentaculata, but the presence of C. fluminalis, Ancylus fluviatilis and the Pisidium sp. already mentioned, confirm this. Kerney (1971) states that

*V. piscinalis* is a characteristic lake species, but, where it occurs with *Ancylus*, it suggests a large river rather than a true lake. The near absence of the pond taxa *G. laevis*, *A. crista*, *H. complanatus*, *A. vortex* and *P. nitidum* confirm the general moving water aspect. The relatively small number of taxa present, compared with the number that might be expected in a river in the same area today, may be due to the selective destruction both before burial, and during sampling, of the absentees (large bivalves - *Unionidae*, and the large, more fragile *Lymnaea* sp.). The occurrence of *P. moitessieranum*, a southern species particularly characteristic of large rivers (Kerney, 1971) and *C. fluminalis*, a southern species now found in the Nile area and Asia west of India (West, 1977), is generally held to indicate interglacial conditions in British contexts, although these mollusca are not especially sensitive to the deterioration of climate which accompanies the interglacial / glacial transition (e.g. the instance of *C. fluminalis* at Wretton in the early Devensian layers - West *et al.*, 1974).

The marsh species are dominated by *Vallonia pulchella*, a snail of very damp grassland in riparian, and non-riparian situations alike. The occurrence of this species indicates damp grassland (suggestive of sedge fen - Kerney, 1971) on the river banks, but has few climatic implications as it is a member of mid-Devensian interstadial faunas as well as interglacial ones (Holyoak, 1982).

The presence of grassland on the areas surrounding the river is confirmed by the high values for the grassland species among the land mollusca. Most notable here are *P. muscorum* and *Vallonia costata*. The high values for *Helicella* sp. also indicate grassland, although in the absence of a confirmed specific identification, this taxon cannot be used as a firm indicator. The *Helicellids* are all juveniles, but the identification of *Helicella itala* in SGR1 (fig. 11.7) probably indicates that the *Helicellids* are this species, which supports a grassland environment.

The other elements of the land fauna are more difficult to interpret, in particular the *Clausilids*. *Clausilia pumila*, *Cochlodina laminata*, and *Azeca goodalli* (together with *Discus rotundatus* in SGR1) would normally be taken as indicators of deep shade (Kerney, 1971), usually woodland, or, at the very least, well developed scrub. It is possible that these taxa are relic populations, left behind after the retreat of the woods (cf. the population of *Clausilia bidentata* on the Durness Limestone in Sutherland left after the demise of the forest cover of the Northwest c.6000BP.), or that they indicate the actual presence of some woodland on the valley sides (there is no pollen or beetle evidence for this because the sandy nature of S53 prevents the preservation of these fossil types). The occurrence of *A. goodalli* is interesting as this is one of the most numerous land mollusca at Marsworth (Green *et al.*, in preparation) in a similar "treeless" context; substantiated at Marsworth by pollen and insects. *Azeca* is also present in some of the East German sites, for example

Weimar-Ehringsdorf (Jager and Heinrich, 1982), where the landscape is also one of a "treeless" interglacial. Although Jager and Heinrich only list Azeca menkeana at Ehringsdorf, this appears to be con-specific with A. goodalli, with the two grading into one another in Europe. The type of Azeca at Stoke Goldington, and Marsworth, is more like the current continental form, with a distinct pattern of parietal denticles inside the lip of the shell. The lack of a reliable study of the variation of the internal morphology of Azeca, however, prevents a close comparison, but a continental climate is also suggested by the occurrence of C. pumilla which has a current distribution in East Germany, Poland, Denmark and South Sweden (Kerney and Cameron, 1979).

As a whole, the environment of S53, as suggested by the land mollusca, is an open grassland, perhaps with scattered trees on the valley sides. The temperature was probably little different from now (C. pumilla, D. rotundatus, C. laminata are all interglacial indicators), but perhaps a more continental climate than is currently prevailing in Britain.

2) Zone II. The smaller numbers of mollusca in zones II - IV, and, especially, the smaller numbers of land mollusca, limit the interpretation, but the following changes from Zone I can be seen.

The numbers of moving water species are greatly reduced (e.g. V. piscinalis from c.40% to 10%, B. tentaculata from 10% to 3%) and the increase in pond species is correspondingly strong (G. laevis from c.4% in

S53 to 49% in SGB14). As a whole the fauna is typical of a clear, unsedimented pond. The dominant species, G. laevis, at present appears to prefer sand and gravel bottomed ponds with a fair degree of environmental stability (it is rare in the lowland parts of Britain and fairly common in Lake District and Pennine tarns). It is tolerant of cold (it is an early coloniser in the Late Devensian), but its presence here need not indicate any strong climatic deterioration.

The reason for the decline of the undoubted interglacial taxa C. fluminalis and P. moitessieranum is almost certainly ecological, and due to the decrease in moving water through the zone. The influence of the river becomes progressively less upwards, suggesting that the pond was a meander cut-off which became further and further removed from river action as the channel moved across the floodplain floor. However, occasional floods probably did occur, even high in Zone II, and one of these is probably shown in SGB7 where a temporary increase in the moving water species V. piscinalis, B. tentaculata, P. amnicum and P. moitessieranum occurs at the expense of G. laevis.

The land surrounding the pond probably changed little from Zone I to Zone II. The complete absence of shade demanding species suggests a lack of trees, but this may merely be due to the smaller counts of mollusca compared with Zone I. The grassland taxa P. muscorum and V. costata dominate, and with the marsh species V. pulchella, show a local environment of grassland and marsh. That the climate was still not rigorous is indicated by V. costata;

this species has a generally southern distribution at present, being absent from even the sub-arctic areas of Scandinavia, except at the coast of Norway, where it reaches seventy degrees north.

3) Zone III. The progressive silting of the pond in Zone II led to a change in the environmental conditions by the level of SGB4. The open, clear pond was replaced by more muddy, vegetation-rich and poorly oxygenated conditions. The replacement of *G. laevis* by *A. crista*, *H. complanatus*, *A. vortex* and *A. lacustris* clearly confirms this. The rise in the marsh species *Oxyloma pfeifferi* and *Lymnaea truncatula* also confirm the much more marshy aspect of Zone III. That the zone still had standing water bodies is, however, indicated by the occurrence of *A. vortex*, instead of the "slum" species *A. leucostoma* which tolerates the worst conditions of de-oxygenation. The total absence of *B. tentaculata*, *P. amnicum* and *P. moitessieranum* suggests the complete cessation of fluvial activity in the pond.

There is little in the fauna to indicate the climate of formation of Zone III. The small numbers of taxa would normally indicate rigorous, even interstadial, conditions, and the most numerous mollusca present, *A. crista*, *H. complanatus*, *A. vortex* and *A. lacustris*, are all tolerant of some degree of cold (Holyoak, 1982). However, the presence of *Sphaerium lacustre* and *S. corneum* shows that the climate was not cold. Both these species are regarded as thermophiles at present, and generally indicative of interglacial conditions. *Sphaerium corneum* is a late immigrant to Britain in the Flandrian, not arriving until shortly before the climatic optimum (it should be noted that this latter view is, however, based on a very imperfect knowledge of the Flandrian aquatic fauna) and it also occurs in the "warm" mid-Devensian at Kempton Park (Gibbard *et al.*, 1982)

The land fauna in Zone III is mostly similar to that in Zone II with only the lack of *V. costata*, perhaps suggesting a deterioration in the climate. The increase in the marsh forms *L. truncatula* and *O. pfeifferi* is a local effect due to the final stages of infill of the pond.

4) Zone IV. The gap between SGB1 and S25, filled as it is with coarse gravel, marks clearly the onset of much more severe climatic conditions than in Zone III. The fauna from the clay lens (k; S25) reflects this, only five taxa being present and two of these occurring at values below 0.5%. The bulk of the fauna is comprised of *P. muscorum*, *C. arenaria* and *Limax* sp. This is a typical cold climate fauna which could be found in the coldest parts of the Devensian. The small number of species even rules out any warm interstadial for this assemblage, and it must represent a very cold climate indeed. In terms of the environment, the usual problem of the juxtaposition of the marsh (*C. arenaria*) and the dry grassland (*P. muscorum*) species occurs. The usual explanation must be advanced to account for this occurrence. The association of these two ecologically dissimilar species must be due to either:

a) a change in the preferences of *P. muscorum* to allow it to live in more swampy conditions than it now prefers, or

b) the effects of the braiding river pulling together the *C. arenaria* from their marshes and the *P. muscorum* from their drier sites on the braid plain.
Both of these are possible explanations; the true answer may be in a combination of both (Green *et al.*, 1983). The occurrence of a similar faunal assemblage from the sample at point F, but with a change from dry land elements (*P. muscorum*) to the more marshy species, suggests that b) is more probable.

5) Summary. Zone I suggests an interglacial, with a slow-moving, well-oxygenated river. The river banks were largely covered by grassland, but scattered trees or scrub were almost certainly present on the valley sides. The climate was no colder than now, but may have been more continental.

Zone II is climatically uncertain, although the fine grained sediments suggest little change from the meandering river of Zone I; therefore suggesting no catastrophic climatic breakdown. The local environment is of a floodplain pond (?Meander cut-off) with clear, well oxygenated, weed-free water. Occasional inundation by the river still occurred.

Zone III is representative of a more muddy and organic-rich pond with, however, open water still present. The proportion of marsh is greater than Zone II. Grassland is dominant on the banks of the pond, but there is little indication of the climate, except that no great rigor can be suggested with the species of *Sphaerium* present.

Zone IV is fully periglacial. A marsh area in a wet hollow on the braid plain is suggested. It is probably not interstadial in type, but very cold indeed.

b) Stratigraphic implications.

It seems at present unlikely, from the molluscan fauna alone, that the attribution of the Stoke Goldington sequence to any particular episode in the Middle or Upper Pleistocene is possible. The deposits contain no species which are diagnostic of any particular phase. However, there are a few observations which might rule out some interglacials and suggest more strongly some others.

1) *Valvata piscinalis*. The form of *V. piscinalis* at Stoke Goldington is an unusual one (see plates 32, 33 which compare similar diameter examples from Stoke Goldington and the present Warwick Avon). It is very low in the spine and generally globose in form. This led to the initial identification of the mollusc as *Valvata naticina* Menke which is currently found in south and east Europe. Re-examination of the shells by M.P. Kerney, however, suggests that they are an extreme form of *V. piscinalis.* Stratigraphically this is important. *Valvata naticina* is not known after the Hoxnian in Britain, while *V. piscinalis* occurs in the Ipswichian and Flandrian. All other occurrences of *V. piscinalis* (except one) are of the modern form, although this is very variable. The exception is the shells from Stanton Harcourt which were also originally identified as *V. naticina* (D. Gilbertson, pers. comm.) but later revised to be an aberrant form of *V. piscinalis.* The close similarity of the forms of *V. piscinalis* from these two sites which have other (and

unique) similarities (insects, ostracods, pollen) cannot be an accident, and places Stoke Goldington with Stanton Harcourt, which Briggs, Gilbertson and Coope (pers. comm.) believe strongly to be post-Hoxnian, pre-Ipswichian, but of interglacial character.

2) *Gyraulus laevis.* Two species of *Gyraulus* are known in Middle and Upper Pleistocene deposits: *G. laevis* and *G. albus*. In the view of Kerney (in Shotton, 1977) the former typifies the Ipswichian, is rare in the Flandrian, and is absent in the Hoxnian. The latter is common in the Hoxnian and Flandrian, but absent in the Ipswichian. Thus there would appear to be a clear case for placing the Stoke Goldington deposit with others (of Ipswichian age) containing *G. laevis*. One set of "Hoxnian" sites do, however, contain *G. laevis*. These are the sites in the Hatfield area described by Sparks, West, Williams and Ransom (1969). These sites are in pond, silts and spring tufas with abundant *G. laevis*, but are regarded as Hoxnian on palynological grounds, and by their position in hollows on the chalky till sheet. The rest of the mollusca from these sites are, however, odd in Hoxnian terms. As a whole they appear to represent a molluscan spectrum which is rather continental and "warm" in appearance, much more like the Ipswichian than the general run of cool, oceanic Hoxnian faunas. It is possible, therefore, that the Hatfield sites are not Hoxnian, and thus the occurrence of *G. laevis* at Stoke Goldington may be evidence of a non-Hoxnian age.

3) *Sphaerium lacustre.* This species is regarded by Kerney (1977) as absent from the Hoxnian, but present in

the Ipswichian. This perhaps underlines the evidence of G. laevis above.

4) Corbicula fluminalis. This is very common in the Ipswichian, at most fluvial sites, and is less common in the Hoxnian, although frequently present. At Stoke Goldington it occurs only at the base of the sequence in Zone I, and the base of Zone II, in quantities below 0.5% . This is unlike its behaviour in the Ipswichian, but is certainly not a conclusive indicator of age.

5) Azeca goodalli. This is known in both the Hoxnian and Ipswichian in Britain, but is thought by Jager and Heinrich (1982) to be a significant indicator of their "Saalian interglacial" in East Germany.

### c) Conclusions.

The molluscan fauna allows a climatic and environmental reconstruction to be proposed for the site. In Zone I, fully interglacial conditions appear to have prevailed. The climate may have worsened in Zones II and III, but such changes as can be identified are, perhaps, at least as much due to ecological progression, as to regional climatic effects. Zone IV appears to mark the occurrence of full glacial conditions.

In terms of age, the molluscan evidence is inconclusive, due largely to the small number of previously described faunas. However, the fauna has aspects in keeping with an Ipswichian, rather than Hoxnian age. The strong similarities with Stanton Harcourt, and the several anomalous features of the fauna (section b), favour the attribution of the deposit to a phase which is of neither

Hoxnian nor Ipswichian age.

### 2. Ostracoda (J.E. Robinson).

Ostracods are present in the organic clay (d - i) and, therefore, are described from the SGB and SGR sample sets (figs. 11.8, 11.9). The sequence from SGR2 to 6 has less overall variation of species than the longer SGB sequence, although the species make-up is the same. The samples, forming Zones I and IV identified in the molluscan assemblage, do not contain ostracoda; therefore precluding comparison. Within the sequence SGB15 to 1, three divisions are apparent. Firstly, SGB15 to 11 are indicative of slightly stagnant, vegetated conditions. Secondly, SGB10 to 5 suggest fluctuating conditions, while thirdly, SGB4 to 1 indicate slacker flow.

#### a) Environmental indicators in the ostracoda.

1) In the basal part of the main sequence (SGB15 to 13) the large numbers of *Herpetocypris* and *Cypridopsis* would tend to suggest sluggish, if not stagnant, conditions. This is supported by the evidence of the small numbers of *Ilyocypris* and *Pelocypris*, both of which are poor- or non-swimming species which prefer to clamber upon water weeds. *Herpetocypris salina*, present in SGB15 and 14, is a species which is interesting in that it suggests saline/brackish water conditions. As such it can occur in coastal marshes where the saline increase is directly related to tidal spill. It can, however, also flourish in natural salt springs (as in the Cheshire basin - Worcester region), and in a fossil context, the species occurs in the Middle loam at Swanscombe. At Stoke Goldington, its

occurrence in SGB15 to 14 (and at the top of the profile, SGB5 to 2), could indicate slack water, allowing local build-up of the salt content from local sources (it need not be NaCl but other mineral salts), possibly from older tills.

2) Between SGB13 and 6, the lack of H. salina suggests that the flow of water was fluctuating, causing the dispersal of the saline conditions which created the brackishness in SGB15-14. The presence of Candona throughout the sequence would tend to support the presence of slack and fluctuating flow. The shorter sequence SGR, is thought to fit into the range of SGB13 to 11.

3) Sluggish flow, or ponded drainage, is again indicated for the upper part of the sequence (SGB3 to 1), although a slight increase in water flow is indicated in SGB5 and 4. Candona is a burrowing genus and, when in abundance, indicates the presence of soft substrates such as mud and silt. With this mode of life, and in the absence of other ostracods known to be free-swimming or benthic crawlers, moving waters can be considered likely. Both C. candida and C. neglecta are similar in their requirements, with two distinguishing ecological notes. Candona candida is referred to as "cold water stenothermal" (Klie, 1938; Absolon, 1973), while C. neglecta, also termed "cold water stenothermal" (Klie, 1938) has been noted as much commoner in Pleistocene deposits than recent deposits (Absolon, 1973). The peak of Candona, in SGB5 to 4, could, therefore, be considered to indicate an increase in water movement after the fluctuating flow of SGB6 (largely eliminating the above-surface species), and/or a

fall in water temperature, although no firm conclusions can be reached when C. candida is still extant in Britain. Such an occurrence at Stoke Goldington may support the molluscan evidence for the occasional flooding by the river (Zone II).

Following the Candona peak, quieter conditions are indicated. Herpetocypris reptans is a large ostracod (up to 3mm) with a fragile shell which prefers quiet, weed-rich bottoms. Its presence in SGB2 to 1 would, therefore, support quiet conditions. Herpetocypris salina in SGB5 to 2 would support the generally slack water conditions allowing the local build up of salt, in much the same way as earlier in the sequence. Confirming this, Cypridopsis vidua is an active swimming species, but in ostracod terms, this again signifies only slowly moving waters rather than normal river flow rates. Occurring in SGB3 to 2, Cypridopsis would confirm the Herpetocypris evidence for sluggish flow or ponded drainage.

4) Summary. Overall, the fauna is a limited one compared with a modern temperate lake (approximately twenty species rather than the seven or eight here), but greater than would occur in a river channel (perhaps three species). In these circumstances, the environment could be between the two and have produced the intermediate count of species, according to the environmental niches offered. This would support the evidence, given by the molluscan fauna, for a floodplain pond/meander cut-off environment. Alternatively, the low count could correspond with a low temperature environment, as temperature is another

significant cause for the curtailment of diversity. However, as most of the species are present in Britain today, this explanation seems less likely.

b) Stratigraphic implications.

All the common species are extant in Britain and so offer little in the way of age determination for the deposit. The one exception to this is the genus Pelocypris, which is not part of the current British fauna, but which has now been recorded from Stanton Harcourt, Oxfordshire (?Hoxnian, ?Ipswichian) and the Little Oakley site in East Anglia (Hoxnian). The record of the genus, and the species P. abatabulbosa is an interesting one. It is a species described by Delorme from the Prairie province of Canada; the species living in "permanent streams of east-central Saskatchewan" (Delorme, 1970) with the further information "collected from a permanent stream; substrate-water surface interface: depth 2.5ft.". Two points arise from this. First, it is a species which today inhabits a continental interior, sub-tundra environment, with generally treeless vegetation. Secondly, the fossil evidence from southern Britain seems to make this species, albeit a low-frequency element of the fauna, one of the few indicators of a time period which workers are consistently hesitating to call either Hoxnian or Ipswichian.

3. Coleoptera (G.R. Coope).

Insect remains are abundant in the organic clay and are obtained from all samples (SGB15-SGB1) (fig. 11.10). By far the most common are the fragments of coleoptera, but during the separation of insect fossils, remains of spiders, mites, leech cocoons, and fish bones were also recovered. Coleoptera nomenclature follows that of Kloet and Hinks check list of British insects (Coleoptera revised by R.D. Pope).

There are no important breaks in the faunal sequence that would justify any subdivision into zones or faunal units, though minor changes can be recognised and relate to the development of the local environment. The whole faunal assemblage will, therefore, be interpreted as if all species lived at the same time in the immediate neighbourhood of the sedimentary basin.

a) Environmental indicators in the Coleoptera.

There can be no doubt that the organic clay was deposited in either very slowly moving, or in places, stationary water. The caddis fly, *Hydropsyche*, has larvae that spin nets across the current to trap food items, but the speed of this water may have been very slow. There are none of the beetle species that are characterisic of rapidly flowing water. The presence of *Gasterosteus aculeatus* (stickleback) and the *Dytiscidae* (carniverous water beetle) in the lower half of the sequence also supports this interpretation. The increase of *Helophorus* and loss of *Dytiscidae* towards the top of the sequence, suggests that the aquatic environment became restricted to small puddles, as the hollow became filled with sediment.

Beside the water, the habitat was largely meadow, like the preferred environment of *Carabus granulatus*, *Loricera pilicornis*, *Bembidion obtusum*, *Pterostichus nigrita* and *Calathus melanocephalus*, all of which are abundant today in cultivated places. In the samples, *Bembidion obtusum* and *Bembidion properans* seem to be curiously exclusive of one another. Although both are species of damp clay soils, the former appears to need moderate shade from the ground vegetation, whilst the latter prefers sun-exposed patches with sparse vegetation. *Microlestes maurus* also requires sun-exposed localities. The larvae of *Agriotes* are the familiar "wire worms" that feed at the roots of plants in pasture land. The abundance of *Scarabaeidae* (dung beetles), particularly in the upper part of the sequence, is indicative of the presence of large herbivorous mammals, and the staphylinids *Platystethus* and *Anotylus* are predators that are often associated with dung. *Thanatophilus* and *Dermestes* are corpse beetles.

The phylophagous beetles provide information about the composition of the flora at the time. *Notaris bimaculatus* is recorded on tall, reed-like vegetation - in particular *Typha latifolia* and *Phalaris arundinacea*. The larvae of *Thryogenes festucae* live inside the stems of various *Cyperaceae*. The relative abundance of *Sitona* indicates the presence of *papilonaceae*, and the exotic weevil *Stomodes gyrosicollis* feeds on clovers; the larvae attacking the roots and the adult animal climbing the plants at night time to feed on the leaves. The two species of *Mecinus* have larvae that burrow into the roots and stems of *Plantago*, particularly *P. lanceolata*. *Liparus germanus* is one of the largest of European weevils and feeds upon the larger *Umbelliferae* such as *Heracleum*. The small weevil *Ceutorhynchus erysimi* lives on various *Cruciferae*, notably

*Capsila bursapauoris*. At the top of the sequence, the rise of *Donacia semicuprea* indicates the increase of its host plant, the sweet grass *Glyceria* which is also the food plant of *Notaris acridulus*. Of particular interest is the presence, at the base of the sequence, of *Heterhelus scutellaris*, which is seemingly dependent on *Sambucus racemosa*. Both beetle, and host plant, are not now native to the British Isles. The insects provide no evidence of trees in the neighbourhood, at the time.

Any interpretation of the climatic significance of Quaternary fossil remains is based on the present day geographical distributions of the organisms concerned. For the most part, the Stoke Goldington assemblage of Coleoptera is made up of species that could occur together in southern England today. However, six species (10%) are present in the fossil fauna that are not members of the modern fauna of the British Isles. All of them have geographical ranges to the south of these islands. *Aploderus caesus* is an eastern central European species that has its northern limit in Denmark. *Anotylus gibbulus* has a very disjunct distribution being found in the Caucasus mountains, though not necessarily at high altitudes. There is a record of a single specimen attributed to east Siberia north of Vladivostok (Hammond *et al.*, 1979). *Aphodius bonvouloiri* is restricted to the mountains of central and northern Spain (Corella, 1967). *Heterhelus scutellaris* is widespread in central and southern Europe where it occurs at moderate altitudes, but it is rarer in the north, reaching its northern limit at low altitudes in the extreme south of Sweden and southernmost Finland (Lindroth, 1960). *Stomodes gyrosicollis* is a southeastern and south central European weevil whose range extends as far west as the Cote d'Or, at Dijon. It also occurs in the neighbourhood of Paris, where it is said to have been an accidental importation brought from Herzgovena and Silesia in 1870 in fodder for the German army (Hoffmann, 1950, p153). *Cathormiocerus validiscapus* is found in Spain and the southern districts of France, as far northeast as Dijon.

The Coleoptera thus provide ample evidence that the climate at the time of deposition of the organic clay must have been warm temperate, with summer temperatures probably a degree or two warmer than those in southern England at the present day. There is no reason to believe that the winters were significantly colder than now. It is much more difficult to estimate precipitation levels at the time, but evidently there must have been adequate rainfall to maintain the pool and marshy meadow, and the presence of bones of *Gasterosteus aculeatus* (Stickleback) suggest that the water never entirely dried up during the summer.

### b) Stratigraphic implications.

It is not clear, from the evidence of the insect fauna above, whether the Stoke Goldington organic deposit was laid down during an interglacial or interstadial period. Definition of the term "interstadial" is notoriously difficult. Certainly in terms of climatic warmth, the deposit would seem to deserve interglacial status. However, mere thermal intensity is an inadequate criterion for defining an interglacial, since short but intense episodes of climatic warming are known during which biotal harmony is never achieved - such "failed interglacials" are, for the time being included under the umbrella term "interstadial".

However, the Stoke Goldington insect fauna does not stand alone. Two other insect faunas have recently been studied for which interglacial status can be convincingly claimed and which bear marked similarities to the Stoke Goldington insect assemblage. The first of these insect faunas was obtained from a channel in the Oxford Clay and overlain with marked discontinuity by terrace gravels at Stanton Harcourt, Oxfordshire. The second insect fauna came from the lower channel at Marsworth, Buckinghamshire, which is incised into the Lower Chalk, and in turn covered by solifluction deposits. The interglacial status of the Stanton Harcourt channel is beyond dispute since it has temperate insects, molluscs and plant fossils, including large oaktree trunks embedded in the sediments. The lower channel deposit at Marsworth contained a temperate insect and molluscan assemblage, but pollen analysis showed an absence of trees in the neighbourhood. At the base of the channel, however, there were large, angular pieces of travertine concentrated in such a manner as to suggest that they had been transported only a little way from their place of formation. Furthermore, the travertines contained the same molluscs that occurred in the channel sediments and bore the impressions of sticks and leaves of broad leaved trees. It seems likely, therefore, that the lower channel at Marsworth was filled during the closing stages of a true interglacial.

There are two main areas of similarity between the fossil insect assemblages from these three localities. Firstly, they contain a relatively high number of species in common, in spite of the fact that each assemblage must be a small sample of the actual insect fauna of the time; that is on the reasonable assumption that the insect faunas were then as diverse as temperate insect faunas are today. Stoke Goldington has half its species in common with the Stanton Harcourt and Marsworth assemblages. Comparison of the species recorded at Trafalgar Square (Ipswichian) with those at Nechells, Birmingham (Hoxnian), shows that they have less in common with one another, or with the Stanton Harcourt, Marsworth, Stoke Goldington group, than this latter group within itself. Here then, is the evidence to support the view that Stoke Goldington is truly interglacial in character but is markedly different from either the Ipswichian or Hoxnian Interglacials.

The second area of similarity between the insect assemblages grouped above, involves unusual species that they have in common. Most outstanding of these is the exotic staphylinid beetle, Anotylus gibbulus, which occurred in all but one of the samples at Stoke Goldington and was consistently the most common species recognised in the deposit. At Marsworth, this species is equally abundant and at Stanton Harcourt it was the most abundant staphylinid present (the staphylinidae are one of the largest families encountered in our fossil assemblages).

This species has never yet been obtained from any undoubted Ipswichian or Hoxnian deposit but it is found in very low numbers in deposits that date from the thermal maximum of the Upton Warren (Mid-Devensian) interstadial, and for a short period immediately afterwards. It must be emphasized that it is always very rare at this time. A further species of note is the conspicuous weevil, Stomodes gyrosicollis, which occurs in both the Stoke Goldington and the Marsworth deposits, but has not yet been found as a fossil elsewhere. Similarly Heterhelus scutellaris is found in the same two localities but, so far, nowhere else. These qualitative similarities also suggest that the Stoke Goldington, Stanton Harcourt, Marsworth group of insect assemblages date from the same interglacial, that differs, faunally, from either the Ipswichian or Hoxnian Interglacials.

### 4. Mammalia (A.P. Currant).

Vertebrate remains are rare, and are of little biostratigraphic significance, in the organic deposits at Stoke Goldington. However, two fragments of large bone have been recovered; a fragment of a thoracic vertebra of an indeterminate elephant from the organic clay (d to i) at point C, and the distal end of a left ulna belonging to a bovine, either Bos, or Bison sp., from the underlying gravel (c), at point E.

A limited quantity of small vertebrate material has also been obtained from the bulk samples taken at point C - SGB2, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14 and 15 all contained very small fish bones. At point A, SGR 3 contained very small fish bones and a fragment of the upper incisor of a microtine rodent cf. *Microtus* sp., while SGR 4 also contained small fish bones, together with *Anura* (frog or toad). The sample of the basal gravel, at point B (S53), contained a mesial fragment of the lower M1 of *Microtus oeconomus*, an upper M2 of *Microtus* sp., and numerous fragments of indeterminate rodent bones. Sample S25, from the clay layer (k) provided minute fragments of rodent tooth enamel, species unidentified.

The environmental and stratigraphical information obtained from this fauna is limited. However, the following comments can be made. *Microtus oeconomus*, the northern vole, has a long range in the Pleistocene of Eurasia, appearing in Britain during the Cromerian s.s. (*M. ratticepoides* of Hinton) and extending, with few interruptions, into the Holocene. It appears to have been absent during the warmest part of Stage 5 (Ipswichian s.s.). The preferred habitat of this rather catholic species is wet grasslands, but, in the absence of competition from other voles, it often extends to other regions. There is evidence to suggest that *Microtus oeconomus* enjoyed a period of almost total dominance of the small mammal fauna in Britain during the late Middle Pleistocene, but the stratigraphic position of most of the critical sites would be regarded by many as contentious.

C. Flora.

Samples of the organic clay (d - i) were taken for pollen analysis at section C. I should like to thank Dr. R.L. Jones for undertaking the analysis of the samples, which revealed the following pollen and spore flora, and for his comments gratefully received.

The pollen provides evidence of an open grassland vegetation with indications of climatic cooling towards the top of the sequence. Tree pollen values are low throughout (<20% of total land pollen - TLP). However, in the bottom part of the sequence, quite a number of tree taxa are recorded (20 - 30%) with a range of thermophilous taxa - *Pinus* (dominant), *Betula*, *Quercus*, *Alnus*, *Fagus*, *Tilia*, *Carpinus*, *Populus*, *Abies* and *Picea*. In the upper part of the sequence, the number of tree taxa declines, with *Pinus* still dominant, accompanied by *Picea*, *Betula*, *Alnus*, *Carpinus* and *Populus*.

Shrub and dwarf shrub pollen values are very low throughout (<5% of TLP) and occurrences are sporadic. *Corylus*, *Ilex*, *Salix*, *Ribes*, *Cornus*, and in the upper levels, *Juniperus* and *Rubus chamaemorus* are present. Occasional grains of *Empetrum* and other Ericales pollens are recorded.

Of the dominant herbaceous pollen, members of the *Gramineae*, *Cyperaceae*, *Compositae*, *Caryophyllaceae*, *Rosaceae*, *Ranunculaceae*, *Plantaginaceae* and *Polygonaceae* have the highest frequencies, although a wide range of taxa is recorded at all levels.

The spore flora is quite diverse, but its amount is small in proportion to TLP. Botrychium, Polypodium, Pteridium, Ophioglossum, Thelypteris, Osmunda, Adiantum, Lycopodium innundatum, L. selago, L. clavatum and Selaginella selaginoides are present; the latter three species in the upper levels.

Aquatic pollen values are also small in proportion to those of TLP, and are represented by numerous taxa, especially in the lower part of the sequence. Potamogeton dominates, with Alisma, Stratiotes, Hydrocharis, Myriophyllum spicatum, Nuphar, Typha latifolia, Callitriche, Lemna, Hydrocotyle and Nymphoides also present.

a) Environmental indicators.

The aquatic pollen flora indicates that the site at first contained shallow, still or slow-flowing water of medium to high base-status. There was a muddy substrate to the water, and a fringing swamp and fen. In the latter, Cyperaceae and a range of damp-loving herbs and ferns (Lythrum, Lycopus, Filipendula, F. innundatum, Thelypteris and Osmunda, for example) probably grew, together with Salix, Populus, Ribes, and Alnus. The majority of the aquatics have ranges which extend as far as southern Scandinavia today. Hence the environment, at this juncture, was, at worst, cool-temperate. The reduction in diversity of the aquatic flora in the upper levels was probably due to successional silting and swamp development, accompanied perhaps by deterioration in climate.

Regionally, the vegetation appears to have been largely open during the timespan represented. The tree and shrub pollen flora, while quite diverse, has low frequencies. There may, at first, have been areas of open woodland of both coniferous and deciduous type. This probably contained *Corylus*, *Ilex*, and later *Juniperus* as understory shrubs, together with a rich ground flora of herbs and ferns. The extent of woodland seems to have decreased later in the sequence, while its components were now mainly *Pinus*, *Picea*, *Betula*, *Carpinus* and *Alnus*. The majority of the landscape appears to have been covered by herb-rich grassland, with composites a notable component. As this grassland contained *Polygonum viviparum*, *L. selago*, *L. clavatum*, *S. selaginoids* and *R. chamaemorus* (present in the upper pollen spectra), then the inference is of a harsher climatic environment at this juncture, certainly of a boreal nature by the time of cessation of clay-mud deposition.

The overall pollen sequence may be comparable with that from the post-temperate stage of an interglacial (Turner and West, 1968). During such times, when the climate is deteriorating to glacial, the characteristic vegetation is that of open habitats with predominantly boreal trees accompanied by subdsidiary thermophiles.

b) Stratigraphic implications.

Given the palynological basis of the accepted working method for the zonation of the Quaternary in Britain, the low frequency of tree pollen at Stoke Goldington indicates a glacial episode. However, the character of the fossil assemblage as a whole suggests an episode climatically equivalent to an interstadial, or part of an interglacial.

In the established interglacial episodes with which comparison seems reasonable (the Hoxnian and Ipswichian), pollen evidence indicates that *Picea* was scarce in both, and that while *Abies* was present towards the end of the Hoxnian, it was rare or absent in the Ipswichian (West, 1980). The presence of *Picea* in the bottom part of the sequence, therefore, would suggest a non-Hoxnian age for the episode, while the presence of *Abies* suggests a non-Ipswichian age for the episode. *Tilia*, also appears to be present in small amounts in the Hoxnian, but is absent, or rare, in the Ipswichian. Its presence at Stoke Goldington, therefore, suggests a non-Ipswichian age.

Interstadial episodes which were forested are not well represented, but those of the early Devensian tend to have *Betula*, *Pinus* and *Picea* as their main components. *Abies* is not known. No clear affinities of interstadial floras with the Stoke Goldington flora are recognised.

## D. Gravel Deposits.

Two suites of gravel are identified at Stoke Goldington. The lower gravel suite (c and j) is horizontally bedded with some cross-bedding apparent (fig. 11.11; plates 34, 35, 36, 37, 38, 39). The lithological composition of the lower gravel suite (S26, S52) is mostly durable (c.60%) of which flint, quartzite and hard sandstone form the greater part. The non-durable component is principally Jurassic limestone, with only minor proportions of ferrous sandstone and chalk. The cluster analysis results (Chapter X) place both samples from this gravel into Group 2 - the suite defined as Great Ouse terrace gravel. The surface of this gravel is 3.57m above the floodplain; that is approximately 54.1m O.D. The fauna from the gravel sample (S53), and the fauna from the organic clays (SGB15 - 1), suggest a river environment and a floodplain environment respectively, both of which are consistent with a terrace origin for the lower gravels. The surface of the lower gravel is horizontal beneath the overlying clay and upper gravel, and is an erosion surface.

The upper gravel (1), which forms the terrace at c. 58 - 59m O.D., has a much greater proportion of non-durable material (71.78%) than the lower gravels. Chalk forms a much larger proportion (41.03% nd) than in the lower gravels, although limestone is still a major component (44.02% nd). The gravel is demonstrably a water laid deposit, as bedding is present in places, although the gravel is well involuted (fig. 11.11; plates 34, 35, 38), the amount of disturbance increasing to the surface. The presence of the involutions indicates strongly that either during deposition, or at some time after deposition, a cold climate prevailed. The upper gravel, separated from the fluvial gravel by a clay with a cool molluscan fauna (S25), is grouped by the cluster analysis in Group 1, a group which is defined as fluvioglacial in origin. No other connection is made with any other group. It is therefore suggested that a glacial event, which deposited a typical fluvioglacial gravel, occurred in the basin at some time after the deposition of the organic deposits.

## E. Uranium Series Dating.

A sample of 1.5g of Valvata piscinalis shells from the fully temperate Zone I (S53), was analysed radiometrically to provide a derived Uranium series date for the episode. The analysis was done at the Geophysical Tracer Studies unit, Harwell, by Dr. M. Ivanovich, who provided the following notes.

The derived age of 208Ka (table 11.1) is regarded as an upper limit only, because the low value of the 230Th/232Th activity ratio of 1.5 is indicative of the presence of detrital thorium in the sample. Corrections for the presence of detrital thorium could not be made because of the small sample size available. Dr. Ivanovich, however, was able to state that,

> ". . . from experience I can predict that the true age of this shell material is about 170Ka representing a correction due to detrital thorium of about 20%" (pers. comm.).

## F. Conclusions.

Within the lower part of a Great Ouse terrace gravel is a channel, up to 1.72m deep, filled with clay. The clay and parts of the terrace gravel beneath the clay are richly-organic, containing a wide range of fauna and flora.

The organic clay contains Mollusca, Ostracoda, Coleoptera, Mammalia and pollen. The gravel, beneath the clay, only contains Mollusca; these are indicative of a large, slow-moving, temperate river in an open grassland environment with a few trees, or shrubs, along the valley sides. The fauna and flora from the clay present a picture of a floodplain meander cut-off which becomes increasingly removed from the influence of the river. An initially clear, unsedimented, pond is replaced upwards by more muddy, vegetated, and marshy conditions. The molluscs and ostracods, however, indicate that periodic flooding by the river occurred.

Grassland species predominate in the faunal assemblages and, as Coope points out, there is "no evidence of trees in the neighbourhood". This is confirmed by the pollen, which has a low tree-count throughout.

The climate is indicated, by all the biological evidence, to be at least as warm as southern Britain today, and is considered, by R.L. Jones, to be, at worst, cool temperate. There does, however, appear to be some deterioration in the climate from the fully temperate conditions in the basal gravel, to the top of the clay stratum. The conclusion reached, from the mollusc, ostracod, coleoptera and pollen evidence, is that the clay represents interglacial, rather than interstadial, conditions - the pollen indicating the post-temperate stage of the interglacial. This is consistent with the fully temperate conditions at the base of the sequence - indicated by the molluscs (Zone I).

Climatic cooling, following the deposition of the clay (d - i), is indicated in the clay (k), which is separated from the temperate clay by the main part of the terrace gravel. Molluscs in the upper clay form a typical, cold climate fauna; indicative of a braid plain hollow, under severe periglacial conditions. The deterioration of the climate also appears to have heralded the advance of ice, as the clay (k) is overlain by strongly disturbed, typically fluvioglacial, outwash gravel. The evidence, therefore, supports an interglacial episode succeeded by a glacial episode; an episode which the molluscs (Zone IV) indicate to be at least as cold as the coldest part of the Devensian.

The age of the interglacial is problematical. All the groups of fossils represented have characteristics which are neither Hoxnian, nor Ipswichian. The Uranium series date, of the fully temperate mollusca, of 170Ka, is too young to be Hoxnian (c.245Ka; Nilsson, 1983) and too old to be Ipswichian (c.120Ka). A temperate episode between these episodes is therefore indicated.

Similar sites, both in terms of the fauna and flora, have been mentioned - namely Marsworth (Green et al., in preparation) and Stanton Harcourt. Coope, in fact, shows that the coleopteran assemblage from Stoke Goldington has more in common with these sites than with either Hoxnian or Ipswichian assemblages. Both these are demonstrably interglacial in character, and both are believed to represent an episode between the Hoxnian and the Ipswichian (Marsworth has Uranium series dates of a similar age to

Stoke Goldington - Green *et al.*, in preparation). It is also interesting to note that at Weimar-Ehringsdorf, in East Germany (Jager and Heinrich, 1982), a similar "Mid-Saalian" interglacial has also been reported, with a similar fauna, and a similar "treeless" vegetation.

# Chapter XII. Discussion.

## Introduction.

The results presented above indicate that, within the upper Ouse basin, gravel deposits are readily separable into two main groups, those forming parts of the terrace system of the Ouse, and those of fluvioglacial origin. Within the terrace gravels at Stoke Goldington a temperate deposit is described, which, together with evidence from the literature (Chapter V), suggests that deposits of several temperate episodes are preserved in the terrace deposits of the upper Ouse. In order to build up the stratigraphy of the area it is necessary to place the deposits in their relative chronological order, taking account of the lithological and/or biological constraints. The sequence may then be compared with the British regional standard succession for the Quaternary, either as it stands at present, or, if necessary, in modified form.

## A. Terrace Gravels.

Three suites of terrace gravels are identified, together with a fourth group which is probably also fluvial in origin (Chapter X.B). The suites are distinguished by their high proportion of durable clasts - the majority of which are far-travelled. Because the durable components, in each suite, are similar, differentiation is made through the non-durable clasts. This separates the limestone-rich gravels of the Great Ouse terraces (group 2) from the ferrous sandstone-rich gravels of the Ouzel and Nene terraces (group 3). The gravels of group 10, together with part of groups 6 and 11, may also represent the deposit of a south-bank tributary of the Great Ouse. The lithological differences are explained above by downstream changes in catchment geology and are, thus, spatial effects.

1. Great Ouse Gravels - Group 2.

Each site represented in group 2 contains lithologies which indicate that, at some time prior to deposition, a glacial event occurred. Durable lithologies predominate in the gravels in a basin which is composed principally of non-durable lithologies (Chapter II). The presence of igneous and Rhaxella chert pebbles within the group is strongly indicative of the existence of an earlier glacial event. Each sample also contains a small proportion of chalk which supports a previous glacial event. Chalk, in Ouse terrace deposits, may be derived from two sources:

a) from the Chilterns via the tributaries of the Ouzel and Ivel. However, the gravels at Buckingham (Site 44) and Great Linford (site 8) are upstream from the confluence with the Ouzel and the headwaters of the Ouse have no access to a Chalk outcrop.

b) from earlier chalk-rich gravels, or from chalk-rich till, both glacial in origin.

In the light of the sites at Buckingham and Great Linford, the second explanation is more probable; chalk-rich till being described at all altitudes in the basin (Horton, 1970; Horton <u>et al.</u>, 1974). This suggests that all terraces post-date a glacial event. Dury (1952) had previously suggested this, and, in support, Edmonds and

Dinham (1965) have described third terrace gravels at Great Barford overlying chalky till.

Within group 2, different terrace levels are indistinguishable on the basis of lithology. Although it is possible that all the samples are from a single aggradation, the variation of the terrace elevations above the floodplain tends to refute this. If several terraces are represented, as is suggested in this account, the few samples at the higher levels above floodplain may, in part, prevent their separation from the lower terrace deposits. The majority of the sites in group 2 have a gravel surface within five metres of the floodplain (table 10.14). The levels are within the ranges of the first and second terraces defined by Horton (1970; Horton _et al._, 1974; table 4.3), and Edmonds and Dinham (1965) describe gravel at Willington and Paxton as first and second terrace deposits. At Buckingham (site 26) and Bromham (site 30), the surfaces are at a greater elevation and may, therefore, represent higher, older terrace deposits. Gravels at similar levels above the floodplain, are described in the early literature in the Bedford area (Chapter V), but, for reasons stated below, may be younger in age (section G.2). Horton _et al._ (1974) believe that there are no high level terrace gravels along the Great Ouse above Bedford, only the low level first and second terraces. The terraces identified in this account do not, therefore, conform with Horton's interpretation. Clayton (in Straw and Clayton, 1979, p186), however, states that

> "Both the Ouse and the Ivel show wide terraces at heights of up to 18m above alluvium."

Alternatively, the more elevated gravels may represent glacially reworked terrace deposits as is suggested below (section C) for the duplicate Bromham sample (S37) and the similar Buckingham sample (S25).

If, as suggested, more than one terrace deposit is represented, catchment changes between stages are not readily identifiable, as they are in some of the early gravel deposits of the Thames (Green and McGregor, 1978; McGregor and Green, 1978). This suggests that the river at each stage had a similar source geology, with no major influxes of recognisably new, far-travelled material between each period of deposition.

As evidence is present in several forms within the basin (sections B and C) for a glacial event intercalated within the terrace succession, the lack of identifiable catchment changes requires explanation.

2. River Ouzel and Tributary Gravels - Group 3.

Group 3 is subdivided into Ouzel terrace and Nene terrace deposits on the assumption that there is no spatial connection between the two drainage systems, the similarity being due to bedrock geology. Arguments for the relative age of the deposits in this group are similar to those put forward in 1 above.

Far-travelled lithologies, including Rhaxella chert and igneous pebbles are again present, suggesting that the deposits post-date a glacial event(s). The presence of chalk in larger amounts in the Ouzel samples, compared with the other fluvial gravels, suggests that primary derivation is from the Chiltern outcrop. However, considering the presence of small amounts of chalk, which must be glacial in origin, in the fluvial deposits which have no access to the Chilterns, it is likely that the Ouzel also derived chalk from glacial sources.

Like the fluvial deposits of the Great Ouse, the Ouzel deposits cannot be subdivided into separate terrace levels. However, because the number of sites represented is small, and all are within five metres of the floodplain, this is not unexpected. The sites at Bow Brickhill and Broughton are both within the area mapped by Horton et al. (1974) and are defined as "sand and gravel of unknown age" and "second terrace gravel" respectively. The present analysis indicates that while Broughton (at 4.2m above the floodplain) is described accurately, the gravel at Bow Brickhill is similar in character and is fluvial in origin. The gravel surface at Bow Brickhill, however, is at 2.5m above the floodplain, and may therefore be a first terrace deposit, despite its lithological similarity to the deposits at Broughton.

The gravel at Elstow (S64) is also represented by sample S51 in group 10. The samples, therefore, should perhaps be closely related, as are other duplicate samples. The second Elstow sample (S51) connects with Kempston

(S50), which is itself connected to the samples from Stewartby and Millbrook (Group 6). If these samples are all part of a single fluvial system, flowing away from the Lower Greensand, as is suggested in Chapter X (the profile of the sites falls to the north from 32m above floodplain at Millbrook to 4.5m above floodplain at Elstow), then the presence of the Stewartby (S66) and Millbrook (S76) samples above chalky till confirms a glacial event before their deposition.

### 3. Nene Gravels.

The three samples of fluvial character from the Nene basin, like those of the Great Ouse basin, contain Rhaxella chert and igneous pebbles and therefore post-date a glacial event. The presence of chalk indicates that the glacial sediments were chalk-rich, because no Chalk outcrop occurs within the Nene watershed. Unfortunately, no lithological evidence can be put forward for the number of glacial events which preceded the terrace deposits and there is no lithological support for a subdivision of the deposits into different terrace levels. A difference in the surface level of approximately 2 to 2.5m between the sites at Rushden and Earls Barton and the site at Clifford Hill, may indicate that the latter is older, but no other supporting evidence can be given.

## B. Fluvioglacial Gravels - Group 1.

The gravel of group 1 shows clear affinities with other fluvioglacial gravels in eastern England (Chapter X), as do the samples from Rushings (S21), Aspley Guise (S38), Clifton (S1) and Lodge Farm (S55). Many of the samples are intimately associated with chalky till, and the high proportion of chalk, in all but the samples at Aspley Guise and Lodge Farm, shows that this glacial event introduced chalk. By analogy with chalky gravels in eastern England, the gravels of group 1 appear to have been deposited close to the ice front. The distribution of the fluvioglacial gravels across both the Ouse and the Nene basins, and the samples interbedded with chalky till at Upper Sundon and Ippollitts, show that ice reached as far south as the Chilterns, probably entering the Vale of St. Albans at Stevenage. The lithological composition of the gravel indicates a mainly northern or, less certainly, a northeastern provenance. But as Beaumont (1971) notes for northeastern England

> "Although indicator erratic boulder studies reveal the general directions of ice movement over large areas they give no indication of the detailed pattern of movements within a small region." (Beaumont, 1971, p344).

The far-travelled components, therefore, only indicate the overall resultant direction of ice movement. However, most tell the same story. Quartzite and hard sandstone are both considered to be from the Triassic strata due north of the study area, while Rhaxella chert is considered to be from the Corallian of Yorkshire (Chapter VIII.H.2; figs. 8.1, 8.4). The occasional presence of red chalk, a lithology peculiar to the Lincolnshire strata (Casey, 1961; Kent, 1967; Greensmith, 1978), and the presence of large amounts of chalk in the fluvioglacial samples of the Nene suggest that the Lincolnshire Chalk strata, due north of the study area, are the source outcrop. Lithologies of undoubted, western provenance are not found in the gravels. Igneous pebbles of Welsh provenance, described in the Thames gravels (Green, Hey and McGregor, 1980) have not been identified in the present study (Chapter VIII.I.2), and as demonstrated in Chapter VIII.A quartz is relatively much less common than in Thames gravels.

The decalcified analysis (Chapter X.B.6; fig. 10.27) provides some indication of a northerly source. The analysis divides the fluvioglacial gravels into flint and ferrous subgroups. The dividing line is not clear-cut but samples in the flint subgroup are mostly in the eastern part of the study area, while those of the ferrous subgroup are mostly in the west (fig. 10.26). The division may be explained by two adjacent, contemporaneous ice streams: one flowing south from the Lincolnshire Chalk outcrop in the east, and the other along the strike of the ferrous Jurassic strata in the west. Although the separation is not complete, its occurrence, in conjunction with the other forms of evidence, indicates a northern provenance. Perrin et al. (1979, Fig. 10) suggest that ice of the chalky till glaciation moved southwestward into the basins of the Ouse and Nene, but the Jurassic components (especially limestone) in the southern and eastern parts of the Ouse basin do not support this. The possibility that two glacial episodes occurred, with slightly different routes south, cannot be entirely dismissed, but the uniformity of the group in other respects does not support a lithological subdivision into two fluvioglacial suites. However, at least two glacial events, within the basin, are supported for other reasons.

For the lithological reasons discussed above (1), at least one glacial event must pre-date the development of all the surviving fluvial deposits in the basin. This is supported by the fact that the terraces must post-date the infilling of the deep channels, which are described beneath the courses of the major rivers in both the Nene and Ouse basins. The channels are filled with lacustrine clay, sand, gravel and chalky till (Horton, 1970; Horton et al., 1974).

At some individual sites, fluvioglacial gravels are seen beneath terrace gravels. It is not possible, however, at the sites in question, to determine the age of the fluvioglacial gravels - i.e. whether they pre-date all elements of the surviving terrace system, or whether they are intercalated within it and therefore represent evidence of a later glacial event. An example of this can be seen at Clifton (site 28) where a chalky fluvioglacial gravel (S1) underlies a gravel which has fluvial affinities (S2). Edmonds and Dinham (1965) have previously described the site as showing well-bedded chalky gravel overlain by brown decalcified flint gravel. The two were believed to represent a single deposit of glacial origin, although Edmonds and Dinham suggest that, in the Biggleswade area, some of the gravels mapped as glacial deposits

> ". . . are probably terrace deposits . . ."

The decalcified analysis does not support Edmonds and

Dinham's suggestion that the upper gravel is decalcified, because the samples remain distinct. The evidence, therefore, points to Edmonds and Dinham's alternative suggestion. Horton (1970, p10) provides similar evidence from the gravels in the area around Tempsford, where he separated

> ". . . the brown river gravels . . . from the chalk-rich glacial sands and gravels (at least 15ft thick) upon which they rest in places."

The occurrence of a glacial event other than the one pre-dating the terrace system is indicated by two forms of evidence:

i) (a) At Stoke Goldington (site 33, Chapter XI), a gravel which is strongly fluvioglacial in character, is underlain by a clay with a cool molluscan fauna, both of which overlie Ouse terrace gravel which contains Rhaxella chert, igneous and chalk pebbles. Temperate sediments, contained in the terrace gravel, show that glacial events preceding the terrace gravel deposition and those post-dating the terrace formation cannot be the same event. The surface of the Ouse terrace gravel is 3.57m above the level of the floodplain, which is within the height range of the second terrace defined by Horton <u>et al.</u> (1974). Using the arguments presented above, the terrace gravel must post-date chalky glacial sediments to account for the incorporation of the far-travelled lithologies. The lithological similarity of the upper gravel (S27) to the other fluvioglacial gravels in the basin precludes other modes of formation, and another glacial event, characterised by chalky sediments, is proposed. If terrace deposits post-dating this later glacial event exist, and have been sampled, they are indistinguishable from the older terraces. The later glacial event, therefore, did not bring any recognisably new far-travelled material into the basin, which, by inference, suggests that two glacial events deposited lithologically similar glacial sediments.

(b) Support for glacial deposits overlying terrace deposits is provided by Horton (1970, p20) at Hail Weston (TL175615) where gravel, which lies on the profile of the third terrace, is overlain by a clay deposit, believed to be a remanié till. Horton suggests the gravel may be glacial in origin, following Edmonds and Dinham (1965), but is inclined more towards a fluvial origin. This evidence cannot, however, be used as positive proof of a second glacial event, because the till may have been soliflucted from higher levels.

ii) Terrace gravels, of both the Great Ouse and Ouzel rivers, appear to have been reworked and redistributed, virtually intact, to higher elevations within the basin (section C). However, because it is impossible to identify lithologically which terrace level has been affected, it is impossible on this basis to place the later glacial event(s) in the succession. Ice is the only possible agent that could cause such redistribution.

Whether the glacial event identified in the upper gravel at Stoke Goldington and the event which redistributed the terrace gravels of the Ouse and Ouzel, are the same, or separate also cannot be determined on the basis of gravel characteristics alone. Both forms of evidence suggest that the later glacial event(s) introduced chalk into the Ouse catchment. The upper gravel at Stoke Goldington contains abundant chalk; and the reworked terrace deposits are apparently enriched in chalk (e.g. Lidlington. See Chapter X).

The evidence, therefore, supports at least two chalky glacial episodes; one pre-dating the development of the present terrace system and infilling the deep channels, the second post-dating some of the identifiable terrace deposits of the present drainage system. The fluvioglacial gravels identified (Group 1) could represent either one, or more than one, event. If only one is represented, then the strong association with the upper gravel at Stoke Goldington suggests that they represent the second episode. If, however, more than one is represented then they cannot be distinguished lithologically, which suggests similar source areas.

## C. Redistributed Gravels.

The samples which form groups 4, 5, 7 and 8, together with the samples from Nether Heyford (S60), Buckingham (S25) and Bromham (S37), are thought to represent gravels which have been redistributed or reworked by glacial ice (Chapter X).

Groups 4, 5 and 8 are lithologically similar to the terrace gravels of the Ouse and Ouzel. The altitude above the floodplain of many of the samples, (e.g. Lidlington is 92m above the floodplain), however, suggests that they have been redistributed by ice which caused some lithological modification, but not sufficient to obscure the fluvial characteristics. The gravel at Simpson (S54) is described by Horton et al. (1974) as 'sand and gravel of unknown age', which suggests that they were unsure whether it was glacial or fluvial in origin. The evidence, here, suggests that this is because the gravel has characteristics of both types. Group 7 is believed to represent fluvioglacial gravel which has incorporated some terrace material. Some of the ferrous sandstone in the group, however, may be derived locally from the Lower Greensand.

The samples which remain distinct, until similarity level 10, from Buckingham (S25) and Bromham (S37) may represent glacially redistributed terrace gravels, similar to groups 4, 5 and 8. Alternatively, the other sample at Bromham (S62) and the similar gravel at Buckingham (S44) may indicate that the Buckingham (S25) and Bromham (S37) samples are terrace gravels, similar to group 2, as it is to this group that they are most closely related. Horton et al. (1974), however, suggest that in the Buckingham area only low level first and second terraces exist. If this is accepted, the gravels cannot be anything but redistributed.

Both explanations of the redistributed gravels require the existence of terrace sediments deposited before, or possibly during, the early stages of a glacial event. But, because the available evidence does not allow the separation of the terrace levels, it is impossible to identify when the glacial incursion occurred. For example, if two terraces existed, T1 and T2 (fig. 12.1), and both had a similar lithological content, then the redistributed gravel (Rg), having a similar original lithology to both T1 and T2, must post-date the earlier terrace (T2), but could also post-date the later terrace (T1). In any event, the ice, which caused the redistribution, incorporated the chalk contained in many of the samples. The association of the gravels at Fox Corner (S20, S70) and Lidlington with chalky till, and at Clifton with chalky gravel (S1), supports this hypothesis, as does the association of group 7 with group 1. The event may be that which deposited the fluvioglacial gravel at Stoke Goldington (S27), but such a correlation cannot be proven on the basis of gravel characteristics.

The lithological similarity of the terrace gravels forming after the redistribution to those forming prior to the event, suggests that no recognisable new influx of far-travelled material occurred, supporting the suggestion that, if two glacial incursions occurred, they had a similar provenance.

## D. Milton Sand.

Although forming part of group 6, it is evident that the samples from Milton Malsor (S30, S61) are neither stratigraphically nor spatially related to the samples in the Ouse Basin. They are considered to be part of the Milton Sand, described by Thompson (1930), Dury (1949), Horton (1970) and Castleden (1980c).

Assuming that the presence of flint in S30 is caused by mixing with overlying deposits, the composition of the deposit suggests that it is of entirely local provenance, and that the Sand is entirely pre-glacial. At Milton Malsor, its presence, beneath chalky till, suggests that it was deposited prior to an ice incursion, as suggested by all previous writers. However, the descriptions by Hollingworth and Taylor (1946) and Castleden (1980c) of similar deposits overlying a lower till (Chapter V) suggests that the Sand also post-dates a glacial incursion. If a local, periglacial origin is put forward (Dury, 1949; Castleden, 1980c), post-dating the lower till, the lack of erratic material from the earlier glacial event needs to be explained. Castleden realises this because he states that

> "In places the sand overlies the Lower Boulder Clay yet, curiously, contains no erratic material derived from it."

although he does not provide an explanation.

Thompson (1930) describes the Sand as lying in a channel which falls in height to the southeast from Nether Heyford, at a height of approximately nine metres above the floodplain. This falls within the height range of the second terrace deposits of the Nene (Taylor, 1963) and would, therefore, suggest that it has to post-date the higher, third terrace deposits described by Taylor between 10.6 and 16.8m above the floodplain. If the Milton Sand is pre-glacial, then the third terrace would probably also have to be pre-glacial. The presence within the third terrace deposits, described by Taylor (1963) and Castleden

(1980b), of far-travelled material (Bunter quartzite, quartz, quartzose granite, gritstone and chalk - table 4.3), precludes such an interpretation and, therefore, an entirely pre-glacial age for the Sand would also have to be dismissed. That it pre-dates one glacial event is certain, but why it contains no erratic material from a glacial event which may precede it, is unclear. By analogy with other gravels in southern and eastern England, the complete absence of far-travelled lithologies from the Sand indicates a pre-glacial age because, once a basin has been invaded by ice, erratics are present. The report of the underlying till may, therefore, be erroneous and the clay may be Liassic in origin.

## E. Pitsford.

The single sample from Pitsford (S31) cannot be related stratigraphically to any of the other gravel suites identified in the study area. The gravel deposit lies within till which infills a wedge, or gull, let down into the Northampton Sands. The gravel must therefore post-date, or be similar in age, to the till.

By analogy with the other gravel suites, the high durable content of the sample would suggest a fluvial deposit. However, it is entirely dissimilar to the terrace deposits identified in the Nene and is at a much higher level. The decalcified analysis associates the sample with three samples considered to be fluvioglacial. The association, however, is weak.

Whatever the origin of the deposit, it contains a large proportion of Rhaxella chert, quartzite and hard sandstone, which indicate a northern provenance. One possibility is that the deposit is part of a terrace gravel, from a river basin to the north of the Nene, which has been transported south and reworked by ice, but this cannot be proven with the evidence available.

## F. Conclusions from the Gravels.

Seven conclusions can be made from the discussion above.

i) Terrace gravels cannot be subdivided into different terrace levels on the basis of lithology.

ii) All terrace deposits contain far-travelled material, therefore, at least one glacial event, prior to the formation of all the surviving terrace deposits, must be acknowledged.

iii) The presence of chalk in all the terrace deposits suggests that at least one previous glacial event introduced chalk.

iv) The fluvioglacial deposit overlying the terrace gravel at Stoke Goldington, and the redistribution of terrace material by ice indicate the occurrence of at least one other, and later, glacial event.

v) The presence of chalk in the fluvioglacial gravel at Stoke Goldington indicates that a second glacial event introduced chalk.

vi) The fluvioglacial gravels cannot be subdivided lithologically, despite the evidence in the area for at least two glacial events.

vii) A northern provenance for all the fluvioglacial gravels is indicated, whether they represent one, or more, events.

## G. Fossil Evidence.

Two forms of evidence are used to define the number of temperate episodes which can be recognised in the upper Ouse basin.

1. The fossil and stratigraphical evidence at Stoke Goldington.
2. The descriptions of faunas in the early literature, and the positions of these faunas in the terrace succession.

1. The evidence from Stoke Goldington, presented in Chapter XI, shows that two phases of terrace gravel deposition are separated by organic clays and muds, which have a temperate fauna. In addition to the lithological evidence presented in A and B above, the two phases of gravel deposition may be used to confirm the cold episodes both before, and after the deposition of the organic sediments.

Models of terrace formation put forward by Wymer (1968), Castleden (1980a) and Green and McGregor (1980), although different in detail, suggest that gravel aggradation occurs during periods of increased discharge associated with periglacial conditions. The occurrence of gravel both below, and above the organic sediments, therefore, indicates periglacial conditions both before, and after their deposition. These periglacial conditions may represent evidence of the final and initial stages respectively, of two glacial episodes. The restricted fauna (largely *Pupilla muscorum* or *Catinella arenaria*) in the clay (k) overlying the terrace gravels supports a return to cold conditions following the temperate episode. During the end of the temperate stage, decreased discharge and more stable conditions gave rise to the deposition of the finer sediments (clays, silts and muds) in quiet, backwater situations.

2. The early literature, describing the deposits near Bedford and those further downstream at Willington, Great Barford and Little Paxton (Chapters IV and V), indicates that faunas of temperate aspect occur at three separate levels above the floodplain. Unfortunately, the terminology used in the identification of the fauna from many of the sites is now antiquated, rendering modern re-interpretation difficult. However, assuming that there is a decrease in age with height, as there is for example in the Thames basin (Chapter V), then relative ages may be suggested.

At Biddenham, up to 18m above the floodplain, a fauna is described which includes *Pisidium*, *Bythinia*, *Valvata*, *Hydrobia marginata* (now known as *Belgrandia marginata*) and *Palaeoloxodon antiquus* (Straight tusked elephant) (table 4.1). This is taken to antedate the deposits at Kempston, Harrowden and the Bedford Railway Cutting (9.1 to 12.2m above the floodplain) where other fossiliferous deposits of temperate aspect are described. Hippopotamus is recorded at the Bedford Railway Cutting site which, by analogy with the accepted stratigraphical criteria, would suggest an Ipswichian age. A Hippopotamus fauna is also described in second terrace deposits, 3.5 to 5m above the floodplain, at Brampton, near Huntingdon (Tebbutt, 1927; Paterson and Tebbutt, 1947) suggesting a possible correlation downstream. The altitude of the Bedford Railway Cutting site, however, is above the range given by Horton (1970) for second terrace deposits (table 4.3), and therefore may represent an older terrace. An Ipswichian age for the third terrace of the Cam, however, has been proposed at Barrington (Gibbard and Stuart, 1975), a terrace which Edmonds and Dinham (1965) correlated to the third terrace of the Ouse. Straw (in Straw and Clayton, 1979) follows this correlation. It is this terrace, therefore, with which the Bedford Railway Cutting may be correlated.

Deposits which, by virtue of their lower elevation (1.5 to 3m above the floodplain), appear to be younger are described at Summerhouse Hill, Willington, Great Barford, St. Neots and Little Paxton. At the Summerhouse Hill site (Wyatt, 1864), a fauna with Hippopotamus is described, although at the other sites early Devensian ages have been put forward (Renfrew, 1974; Chapter IV). It is possible that two terrace deposits are represented at these sites, because they are at an altitude above the floodplain which is within the range of the first AND second terraces defined by Horton (1970). If two terraces are present, however, the higher deposits at the Kempston level, with their apparently temperate faunas, seem to represent a third terrace, while the deposits at Biddenham could represent an older, fourth terrace.

Horton (1970; Horton et al., 1974) has correlated the low first and second terraces of the Ouse with the low terraces of the Cam, and suggests that they are early- and late-Devensian respectively. This may be correct and thus they may be separate from the deposits containing Hippopotamus at the Bedford Railway Cutting. However, if the report of Hippopotamus at the Summerhouse Hill site is reliable, that site also includes material of Ipswichian age, therefore implying aggradation from below the Summerhouse Hill level up to the Railway Cutting level during the Ipswichian, followed by a complex post-Ipswichian history of terrace development. This interpretation would avoid conflict with Horton's correlation of the lower terraces with Devensian deposits downstream, and would account for the higher level of the Hippopotamus fauna at the Bedford Railway Cutting.

The evidence from the literature indicates a complex sequence of terraces. The highest, and presumably the oldest, terrace deposit at Biddenham is of uncertain age (although the presence of flint implements, of apparently Acheulian character, may suggest a Hoxnian age). Below this are the deposits at Kempston and the Bedford Railway Cutting which have apparently temperate faunas, and may be Ipswichian in age. Below this, one or two terraces may exist which may be Devensian in age but which are underlain by both Devensian and Ipswichian deposits.

When both lines of evidence are examined, inconsistencies are apparent. If the terraces decrease in age with decreasing height above the floodplain and are, by implication, parallel to the floodplain, the gravels at Bromham (site 30) are similar in age to the deposits at Kempston and the Bedford Railway Cutting, being at a similar level above the floodplain (11m). The report of Hippopotamus at the Bedford Railway Cutting suggests an Ipswichian age. However, upstream at a much lower level above the floodplain (3.57m), are the pre-Ipswichian deposits at Stoke Goldington, while the apparently pre-Ipswichian deposits at Biddenham are 18m above the floodplain. If an attempt is made to correlate the deposits at Biddenham with those at Stoke Goldington, then the terrace has a gentler gradient than the present river. If this correlation is incorrect, then a reverse terrace sequence has to be suggested (whereby an older terrace is at a lower elevation above the floodplain than a younger terrace) and/or another terrace level has to be put forward. Alternatively, the Summerhouse Hill deposits may be the Ipswichian level, therefore allowing the slightly higher deposits at Stoke Goldington to fit into a normal terrace sequence. The gravel deposits at Kempston and Biddenham then have to represent two further terraces, both older than Stoke Goldington. The reports of Hippopotamus at the Bedford Railway Cutting then have to be explained.

A correlation of the Stoke Goldington terrace with a level above that of the Kempston, and related sites, possibly with the Biddenham deposits, would indicate a gradual steepening of the river gradient through time. Such an occurrence may partially explain the changes in the profile of the Great Ouse surveyed by Dury (1952). Dury identified three knickpoints along the Ouse; at Bedford, Stafford Bridge and Newport Pagnell (Chapter III; fig. 3.3), to which he associated three terraces at 50' (15.2m), 20' (6.1m) and 10' (3.1m) above the alluvium. Each of the terraces converge with the present profile upstream to meet their respective knickpoints. The three levels of gravel described in the Bedford area may be related to, and explain, the knickpoints. The low level deposits at Willington and the related sites, may represent the first terrace and converge with the knickpoint at Bedford. The intermediate deposits at Kempston and the Bedford Railway Cutting, and possibly the gravels at Bromham, may represent the next higher terrace, and converge with the knickpoint at Stafford Bridge. The gravels at Bletsoe and Radwell, upstream from Stafford Bridge, and believed to be the same deposit as at Kempston, may be similar to the gravels at Biddenham and may represent the third terrace which converges from 18m above the floodplain at Biddenham, to 9.1m at Bletsoe and Radwell, to 3.57m at Stoke Goldington, with the knickpoint at Newport Pagnell. Such an interpretation allows the pre-Ipswichian deposits at Stoke Goldington to lie at a lower elevation above the floodplain than the supposed Ipswichian deposits at the Bedford Railway Cutting. The hypothesis has been put forward previously by Dury (1952) but was dismissed by him because

> "The profiles of terraces and alluvium below Bedford are steeper than those in the Buckingham-Olney reach;

> No. 3 Terrace, has a profile rising well above the alluvium towards Olney, where it curves noticeably headwards; and in this terrace, as recognised and mapped, there is a knickpoint near Bedford." (Dury, 1952, p137).

In the present analysis further complications arise.

i) Horton (1970; Horton et al., 1974) suggests that the third terrace converges DOWNSTREAM with the floodplain, while the first and second terraces are parallel to the floodplain. The model presented here would require all terraces to converge UPSTREAM with the floodplain.

ii) Horton (1970) suggests that the third terrace is present only downstream from Bedford, while the terraces upstream are the low-level first and second terraces. The knickpoint model presented here would imply that the first terrace is only present downstream from Bedford and that upstream, only terraces two and three exist.

iii) The low level terrace gravels at Great Linford and the high level terrace gravels at Buckingham (S25, S44) cannot be explained, unless they represent higher and older terraces than that at Stoke Goldington.

iv) The essentially climatic models of terrace formation put forward by Wymer (1968), Castleden (1980a) and Green and McGregor (1980) call for changes in the regime of the whole river, therefore the whole profile would be affected, discouraging the formation of knickpoints. The present interpretation would require other processes to be in operation, such as glacial isostacy or glacio-eustatic effects - processes which have not generally been invoked in the surrounding areas of eastern England.

v) At Stoke Goldington the presence of the fluvioglacial gravel, overlying the pre-Ipswichian terrace, to a height of approximately 8m above the floodplain, suggests that the subsequent fluvial activity began development at this level. At Bedford, the evidence at the Railway Cutting site suggests that aggradation and the formation of the supposed Ipswichian deposits occurred, followed by downcutting to the lower terraces and the floodplain. At Stoke Goldington, however, no terrace is visible below the level of the pre-Ipswichian terrace (Plates 20, 21). Therefore, either downcutting occurred continually to the present floodplain or, if subsequent terrace formation did occur, no evidence for it has been identified in the present study.

If the faunal record from the Bedford Railway Cutting is inaccurate and the sediments are part of a terrace deposit older than that at Stoke Goldington, then there are far more terraces in the Ouse basin than have previously been identified. The Summerhouse Hill deposits may then be Ipswichian in age, with Stoke Goldington, the Railway Cutting and Biddenham levels representing three older terrace deposits.

## H. Sequence of Events.

Using the evidence presented above (XII.A-G) a stratigraphic succession for the upper Ouse basin is suggested (table 12.1). For simplicity, the succession will be discussed in reverse order (youngest to oldest), because the events most clearly represented, and those which provide an understanding of the early events, are those which are most recent.

The youngest deposit present is that of the modern floodplain alluvium which exists along the present course of the river (Edmonds and Dinham, 1965; Horton, 1970; Horton et al., 1974) and is Flandrian in age. At a low level above the floodplain (c.1.5m) is a terrace (Terrace I) which is underlain by deposits containing artifacts and a fauna which are believed to be early Devensian in age. The deposits concerned are those described at St. Neots and Little Paxton (De la Condamine, 1853; Tebbutt, 1927; Paterson and Tebbutt, 1947; Chapter IV.E.1), Willington (Banton, 1924; Bate, 1926; Mantle, 1926) and Great Barford (Mantle, 1926). The terrace at Summerhouse Hill, however, at a similar elevation above the floodplain (1.5m) is apparently cut into deposits containing an Ipswichian (Hippopotamus) fauna. A possible explanation of this apparent discrepancy may be that the first terrace is cut into the remnants of an Ipswichian deposit which was not removed during the post-Ipswichian period of downcutting.

The deposits which contain apparently Ipswichian faunas appear to range in height from the Summerhouse Hill level (1.5m) to the terrace at approximately 9m above the floodplain at Kempston, Harrowden and the Bedford Railway Cutting (Prestwich, 1861; 1864; Wyatt, 1861; 1862). If the gravel aggradation occurred in a cool environment (see model above), the terrace deposits probably accumulated at a late stage of the Ipswichian, incorporating the contained fauna from Ipswichian deposits on the valley sides. The terrace (Terrace 2), therefore, would be late Ipswichian in age.

Prior to the deposition of the supposed Ipswichian deposits, and post-dating the terrace gravels at Stoke Goldington, the chalky fluvioglacial gravel (l) at Stoke Goldington suggests that glacial ice entered the Ouse basin. The ice of this episode (Glacial Event III), however, did not obscure the terrace deposits at Stoke Goldington, nor the apparently earlier terrace deposits at Biddenham. At neither of these sites is till seen overlying the terrace, suggesting that neither has been overrun by ice. It is suggested, therefore, that the upper gravel at Stoke Goldington is the proximal outwash of an ice sheet which only just crossed the Ouse-Nene watershed. The ice of this event, if it crossed the Ouse-Nene watershed, must have covered the Nene river valley. The lack of till overlying the terrace gravels sampled in the Nene basin implies that these gravels post-date Glacial Event III, and therefore suggests that they correlate with terraces 1 and/or 2 in the Ouse basin.

The organic deposits at Stoke Goldington, overlain as they are by fluvial gravels (j) and the clay with the cold molluscan fauna (k), support deterioration of the climate and the formation of the terrace (Terrace 3) prior to the advance of the ice, but after the warmest period of the Interglacial (Zone I of the molluscan zonation). The terrace development therefore, appears to have followed the same pattern as the younger terraces. The deposition of the Stoke Goldington organic sediments and the terrace sediments, as indicated above (A), must post-date the deep channels and their infilling with chalky till. Equally, however, the relatively high-level gravels, with the apparently temperate fauna, at Biddenham (c.18m above floodplain) must also post-date the deep channels. The Biddenham deposits are the highest recorded terrace deposits in the basin and are, therefore, considered to be older than the temperate deposits at Stoke Goldington. A correlation of the Biddenham terrace with Stoke Goldington terrace is considered unlikely because the gradient between the two sites would be unreasonably low. The record of the fauna and the flint implements, within the basal layers of the gravel at Biddenham, indicates that a similar pattern of development occurred as is suggested for the second and third terraces. Archaeological remains and faunal material deposited on the valley sides and floodplain during a temperate period, were incorporated into the base of the terrace deposits during aggradation. By analogy with the other periods of aggradation in the basin, and following the model of terrace development, the aggradation probably occurred in a cold environment. The lack of evidence for till or fluvioglacial gravel overlying the Biddenham terrace (Terrace 4), however, suggests that glacial ice either did not reach the basin at this time, or it only just reached the basin. No subsequent glaciation appears to have overrun the site. Following the formation of the Biddenham terrace, downcutting to the Stoke Goldington cycle occurred.

Before the aggradation of Terrace 4, the next event for which there is evidence in the Ouse basin is the formation and infilling of the deep channels, proved beneath the modern floodplain. Horton (1970) and Horton et al. (1974) describe chalky till, glacial sand and gravel, and lacustrine clays infilling the channels, therefore indicating a glacial incursion into the basin (Glacial Event II). The main part of the chalky till appears to have been deposited during this stage. The distribution of the chalky till within the Ouse basin indicates that the ice reached the Chiltern escarpment to the south and southeast, and the Ouse - Thame watershed to the west and southwest. No outwash from the maximum extent of this ice sheet appears to have crossed the watershed into either the Thame basin or the Vale of St. Albans, except at Hitchin. Here a deep channel crosses the Chiltern escarpment and is reported to be filled with chalky till and gravel (Hill, 1908; Woodland, 1970). Outwash from this glacial advance must, therefore, have found another outlet. There are two possible courses along which outwash could flow. Firstly, the flow could be ice-marginal, following a course between the ice and the Chiltern scarp slope. Secondly, subglacial drainage may have occurred. There is little, if any, evidence either of an erosional or depositional nature, for flow along the Chiltern scarp. It is suggested, therefore, that outwash flowed back under the ice, probably enhancing a pre-existing drainage pattern, and developing the deep channels. The presence of lacustrine clays, containing drop-stones and interdigitated with till and gravel, is seen by Horton (1970; Horton et al., 1974) to indicate a series of proglacial ribbon lakes (Chapter V.E). He proposes three advances, each followed by a retreat stage and the formation of a lake. Within the present study, the gravels associated with the chalky till are those of fluvioglacial character (group 1), and those of fluvial character which appear to have been glacially reworked and redistributed (groups 4, 5, 7 and 8), although some of the former may be associated with Glacial Event III. If the interpretation suggested above, for the limited extent of the ice which deposited the fluvioglacial gravel at Stoke Goldington, is correct, then the redistribution of Ouse terrace gravels (together with the presence of chalky till) to the top of the Lower Greensand escarpment at Lidlington, and along the Ouzel valley, for example, cannot have occurred during Glacial Event III. Only an advance which reached the Chilterns could have caused the redistribution. Such a hypothesis has two implications.

1) If the glacial advance incorporated within its deposits river gravels lithologically similar to later river gravels, it indicates the presence of river deposits before glaciation. This would lend support to the suggestion that the subglacial drainage enhanced a pre-existing drainage pattern.

2) The river gravels which are found incorporated within the chalky till of Glacial Event II are composed largely of durable, far-travelled lithologies of glacial origin. This shows that one (or more) glacial incursions occurred in the basin before the development of the river system described in 1).

A third glacial incursion (Glacial Event I) is, therefore, proposed within the Ouse basin. The lower till described by Horton (1970) and Horton et al. (1974) in the Towcester region (Chapter IV.C.1) and further north in the Nene basin (Hollingworth and Taylor, 1946a; 1951; Kellaway and Taylor, 1952; Taylor, 1963) may be the surviving remnants of a till from this episode.

The lithological evidence presented for the Milton Sand, with its distinct lack of far-travelled material must place the deposit before the first glacial incursion into the area since, as stated above (section D), once a basin has been invaded by ice, erratics are present. However, the position of the Milton Sand within the Nene basin (section D above) suggests that the succession may be more complex.

## I. Correlation.

The sequence of events presented above (table 12.1) supports at least three glacial episodes (excluding the Devensian), separated by at least three temperate periods (excluding the Flandrian). Although this sequence may be incomplete, with further episodes unidentified, two possible correlations may be made with the British regional standard succession for the Quaternary (table 12.1), although in modified form.

1. There are two points at which the sequence presented may be correlated with the stratigraphy of Mitchell et al. (1973):

a) The early Devensian terrace deposits and

b) the supposed Ipswichian terrace deposits and associated terraces.
Correlation of events prior to the supposed Ipswichian deposits, however, is dependent on evidence drawn from surrounding areas (Chapter V). The earliest event(s) (Glacial Event I) is identified by the erratic material in the terrace deposits which have been disturbed by, or incorporated within, the till of Glacial Event II (groups 4, 5, 7 and 8). Significantly, each group contains Rhaxella chert (tables 10.12a, 10.13a), although in smaller proportions than the apparently later fluvioglacial sediments (group 1) and fluvial sediments (groups 2 and 3). From this it can be inferred that Glacial Event I brought Rhaxella chert into the basin. In the Thames basin Rhaxella chert is reported to be rare or absent in sediments earlier than the Anglian (Bridgland, 1980; Green et al., 1982). The presence of Rhaxella chert in the disturbed samples could, therefore, suggest that Glacial Event I is Anglian or later.

If an Anglian age is accepted then the subsequent warm period, between Glacial Events I and II, could be Hoxnian. This correlation would indicate that Glacial Event II and Glacial Event III, each of which brought chalk south, post-date the Hoxnian. This, however, conflicts with the accepted stratigraphies in both East Anglia and the Midlands.

In East Anglia, Bristow and Cox (1973), Perrin *et al.* (1973) and Perrin *et al.* (1979) have not only suggested, that only one chalky till exists, but that it is Anglian in age because it underlies Hoxnian deposits; at Hoxne for example (Chapter V.A). In addition, the only glacial event which is believed to have reached the Chiltern escarpment, is that depositing the chalky till in the study area. This is the event, therefore, which must have entered the Vale of St. Albans via the Hitchin - Stevenage Gap. The evidence presented by Gibbard (1977), however, indicates that only one incursion of chalk-rich ice occurred into the Vale; this ice being Anglian in age because it underlies Hoxnian deposits at Hatfield and Fishers Green (Chapter V.D). The correlation of the chalky till in the present study area with the early Wolstonian therefore conflicts with the accepted stratigraphy in the Vale of St. Albans.

In the Midlands, although a post-Hoxnian chalky till is believed to exist (Shotton, 1976; and others), there is no record of the two episodes which would be required by this interpretation of the Ouse evidence.

2. An alternative correlation is set out in table 12.1. The supposed Ipswichian and post-Ipswichian correlation remains as in 1 above. The pre-Ipswichian stratigraphy may, however, be interpreted differently.

The earliest glacial event (Glacial Event I) is suggested above to be Anglian in age on the basis that Rhaxella chert was first brought as far south as the middle and lower Thames valley in significant proportions during the Anglian. However, Rhaxella chert is reported to have been brought south in earlier stages. Hey (1980), for example, suggests that Rhaxella chert was introduced into north Norfolk by a North Sea glacier during the Pre-Pastonian. It is possible, therefore, that Rhaxella chert-rich, pre-Anglian tills existed in the Midlands and in the Ouse basin, thus allowing Glacial Event I to be pre-Anglian. The ice advances which caused the influx, however, did not extend far enough south to introduce Rhaxella chert into the Thames system. The number of ice incursions that entered the Ouse basin cannot be identified.

Following the development of the Ouse drainage pattern after Glacial Event I, the main incursion of ice into the Ouse basin occurred (Glacial Event II). The ice at this stage reached the Chiltern escarpment, allowing the formation of the deep channels and the deposition of the chalky till across the basin. As stated above, it is this advance which is considered to have entered the Vale of St. Albans through the Hitchin - Stevenage Gap. Several arguments can be presented as to the age of this episode.

Firstly, only one incursion of ice which deposited chalky till is considered to have occurred into the Vale of St. Albans (Gibbard, 1977). The age of the incursion is believed to be Anglian because it underlies Hoxnian deposits at Fishers Green (Gibbard and Aalto, 1977) and Hatfield (Sparks _et al._, 1969), and because it pre-dates the Boyn Hill Terrace which is considered to be Hoxnian (Kellaway _et al._, 1973). The incursion from the Ouse basin, if it is the same incursion, is therefore Anglian in age.

Secondly, the correlation, of the chalky till in the Thames basin with the Anglian episode, conforms with the recently accepted stratigraphy in East Anglia of a single chalky till (Bristow and Cox, 1973; Perrin et al., 1973; Rose and Allen, 1977; Perrin et al., 1979) which underlies Hoxnian deposits at Hoxne (West, 1956) and Marks Tey (Turner, 1970). In both the Thames and East Anglia, therefore, the maximum incursion of ice appears to have occurred in the Anglian. It seems reasonable, therefore, to correlate the maximum incursion of ice in the Ouse basin with those of East Anglia and the Thames. The increase in the proportion of Rhaxella chert in the Ouse fluvioglacial gravels (table 10.12), from the proportion in the earlier reworked terrace gravels, would support an influx of Rhaxella chert into the Thames system at this time. The river gravels incorporated into the chalky till are therefore pre-Anglian in age.

An additional, although more indirect line of reasoning, may support the correlation. In Essex, a series of buried "tunnel valleys" has been identified by Woodland (1970). Woodland suggests that

> ". . . the channels are in general, . . . genetically related to the Great Chalky (Gipping) Boulder Clay." (Woodland, 1970, p521).

Although the correlation, by Woodland, of the chalky till with the Gipping, would infer a Wolstonian age, the more recent interpretation of the chalky till in East Anglia as

Anglian (Perrin et al., 1979) would support an Anglian age for the development of the buried valleys. This is the interpretation advanced by Straw (in Straw and Clayton, 1979). It is possible, therefore, that the deep channels in the Ouse basin are similar in age to those beneath the chalky till in Essex and East Anglia.

The correlation of Glacial Event II in the Ouse basin with the Anglian suggests that the apparently temperate episode recorded at Biddenham may be Hoxnian. This is followed by a cold episode in which no ice incursion is recognised. This episode, and the following episodes (both cold and temperate), through to the Ipswichian, would normally be considered as Wolstonian.

The temperate episode at Stoke Goldington, as discussed in Chapter XI, is similar to the interglacial episode at Stanton Harcourt and Marsworth, both of which are considered to be post-Hoxnian and pre-Ipswichian in age. A correlation with other apparently post-Hoxnian, pre-Ipswichian deposits at Aveley and Ilford (Sutcliffe, 1976), Stoke Tunnel (Turner, 1977), Sutton, Harkstead, Maidenhall and Brundon (Shotton, 1983a; Chapter V.D) may, therefore, be possible. This correlation, and the stratigraphic position in the Ouse basin, is supported by the Uranium series date (170Ka) for the fully temperate sediments at Stoke Goldington. Unlike the other sites, however, Stoke Goldington has evidence of an ice advance (Glacial Event III) after the deposition of the interglacial sediments. This advance is not believed to have spread far into the basin. Support for this episode can be presented from the surrounding regions.

In East Anglia, no reliable evidence has yet been presented which would support an ice incursion after the Anglian. Straw (1979; 1982), however, believes that a Wolstonian ice advance did extend as far south as north Norfolk. This would conform with a limited ice advance into the Ouse basin. Secondly, in the Midlands the Wolston series, believed by Shotton (1953; 1976; 1983b), Bishop (1958), Rice (1968; 1981), Bridger (1975; 1981) and Douglas (1980), to post-date the Hoxnian deposits at Nechells and Quinton, is defined as the Wolstonian type series (Chapter V.B). The ice margin during this stage fluctuated in its extent, but at its maximum a chalk-rich ice sheet reached the Jurassic escarpment at Morton-in-Marsh (Bishop, 1958), BUT DID NOT CROSS IT. This could indicate that the advance at this stage was not very powerful. This, therefore, could be correlated with the chalk-rich Glacial Event III in the Ouse basin.

Thirdly, the evidence presented by Wymer (1974), and Shephard-Thorn and Wymer (1977), at Swanscombe in the Thames valley, at Hoxne, Suffolk (Wymer, 1974; Turner, 1977) and at Marsworth, Buckinghamshire (Green et al., in preparation) supports the existence of two cold episodes separated by a temperate episode following the Hoxnian (Chapter V.D). At none of these sites, however, are glacial sediments present either after the Hoxnian, or after the post-Hoxnian temperate period. This implies that during neither of the cold stages did glacial ice extend to the Chilterns, or into East Anglia and the Thames.

The limited extent of the post-Hoxnian ice advance is apparently supported, albeit indirectly, in all the areas surrounding the present study area. The southern limit of this "late-Wolstonian" ice advance may possibly be traced from the limit described by Shotton (1976) and others in the Midlands, across the northern margin of the Ouse basin to the limit proposed by Straw (1979; 1982) in Norfolk (fig. 12.2).

Following this glacial episode the Ipswichian and post-Ipswichian succession completes the sequence. Although, in the discussion above (H) questions were raised about the relationships of the sites in the Bedford area which apparently contain Hippopotamus, and therefore the apparently large aggradation which would have to have occurred during the Ipswichian, this can be accounted for by reference to the terrace development of the Avon (Chapter V.B). Shotton (1953; 1983b) argues that the deposits of the third and fourth terraces are part of a continuous aggradational sequence, with the third terrace formed during downcutting. The third terrace deposits, at the base of the sequence, contain a fauna indicative of an Ipswichian age. The fourth terrace gravels, overlying the third terrace gravels, contain a cold fauna. It appears, therefore, that at the end of the Ipswichian period in the Avon, there was a long period of aggradation into the beginning of the Devensian. This may be correlated with the apparent aggradation in the Ouse basin.

Of the two possible correlations, therefore, there appears to be more supporting evidence for the latter than the former. It must be remembered, however, that neither need be complete. Hiatuses may be present which have not been identified. In neither of the sequences is the Milton Sand fitted into the stratigraphy, and without more detailed analysis of the deposit, it remains an enigma.

## Conclusions.

The lithological evidence presented here from the gravel deposits of the upper Ouse basin, together with the biological evidence from Stoke Goldington and that described in the literature, allows the development of a sequence of events which may be correlated with the stratigraphic successions of the surrounding regions.

Three glacial events are recognised within the basin, intercalated within the terrace succession. Four terraces are identified. Unfortunately, the apparent lithological similarity of the gravels of each glacial event and the lithological similarity of the terrace gravels of a particular river, precludes the identification of each event in terms of gravel composition alone. However, the fossil evidence contained within the terrace deposits and the stratigraphic superposition of fluvioglacial gravels over terrace gravels at Stoke Goldington, permits a correlation of the proposed succession with the British regional standard succession for the Quaternary. The correlation, however, requires that the standard succession is modified to include a mid-Wolstonian interglacial; an event which has previously been suggested, but which is not yet accepted by the majority of investigators.

The glacial stratigraphy proposed here is consistent with the evidence presented in all the surrounding regions, with the maximum ice incursion extending into East Anglia and into the Thames basin during the Anglian. Nowhere is the following cold episode, separating the Hoxnian from the mid-Wolstonian temperate period, identified by glacial sediments, although at several sites - Hoxne, and Swanscombe for example - a cold episode is recorded.

The glacial advance, after the formation of the terrace deposits which contain the mid-Wolstonian interglacial sediments at Stoke Goldington, is believed to have had a limited extent. This event is also supported by the evidence in the surrounding regions. In the Midlands, the Wolstonian advance did not extend over the Jurassic escarpment, while in eastern England, Straw (1979) claims that Wolstonian ice did not extend further south than north Norfolk. The logical link between these areas is across the northern edge of the Ouse basin, as is suggested by the interpretation of the Ouse evidence. There is no evidence further south of glacial deposition, although a cold episode, which is not the Devensian, is recorded after the pre-Ipswichian interglacial at Marsworth, Hoxne and Swanscombe.

Ipswichian and Devensian deposits are recorded in the Ouse basin following the Wolstonian ice advance, in the deposits of the first and second terraces.

# Chapter XIII. Conclusion.

The lithological examination of gravel deposits of the upper Ouse basin, and the statistical analysis of the results, are shown to have great potential for unravelling the Quaternary development of an area which has been overrun by glacial ice. Two statistical analyses - trend surface analysis and cluster analysis - were performed on the results of the lithological determination to identify both spatial trends and stratigraphic divisions among the samples.

The results of the trend surface analysis suggests that no simple overall spatial pattern is discernible in the gravels of the upper Ouse basin, and it is concluded, from this analysis, that stratigraphic control is dominant, giving rise to a number of stratigraphic units each characterised by a distinctive spatial gradient.

The lithostratigraphic units are identified using a total of fourteen cluster analyses, each having a different data matrix. Gross percentages and intercomponent ratios are used, both individually, and in combination. All types of data set are analysed in their raw form and, also, having first computed a principal component data matrix. The clusters that the analyses produce are similar, though not identical, and, therefore, to identify the most probable divisions, the result of each analysis is compared to all others. The similarity of the results, however, is in itself significant. Firstly, the consistencies apparent between the results of the gross percentage analyses and the intercomponent ratio analyses suggest that in the Ouse basin intercomponent ratios are no more sensitive to changes in catchment than are gross percentages; a finding which does not concur with McGregor and Green's (1978) analysis in the Thames basin, where they show that intercomponent ratios are more sensitive. It is also interesting to note that the similarity of the gross percentage and intercomponent ratio results also indicates that the ratios chosen are representative of the whole sample.

Secondly, the slight loss of information involved when using the principal component data matrices, rather than the raw data matrices, does not appear to have a significant detrimental effect on the results. Both analyses, therefore, may be used to good purpose on pebble count data. It is possible to conclude that for a preliminary investigation of a lithological data set the analysis of any data matrix type by cluster analysis appears to have satisfactory results. The differences in detail between these analyses does, however, suggest that a combination of analyses are necessary to identify the real divisions.

The result of the combined cluster analyses shows that the gravel deposits sampled in the Ouse basin are readily separable into those of fluvial origin and those of fluvioglacial origin, each dendrogram clearly separating the suites. The significant distinction is that the gravels of fluvial origin are characterised by a greater proportion of durable clasts than those of fluvioglacial origin. However, it is the non-durable components which are significant in the identification and separation of the fluvial gravels within the basin. The separation is not in terms of different terraces, but it is spatial, rather than stratigraphical, changes which are identified. The spatial relationships show that the non-durable component of any river in the study area is dependent upon the source geology of that river. Downstream changes in gravel lithology, therefore, reflect downstream changes in catchment geology. The results show that the non-durable component of Ouse terrace gravels is predominantly limestone, originating from the Cornbrash, Great Oolite and Inferior Oolite strata. The Ouzel non-durable components are mainly ferrous sandstone from the Lower Greensand, and chalk from the Chiltern Chalk outcrop. The Nene non-durable component is mainly ferrous sandstone from the Northampton Sand of the Inferior Oolite.

The combination of the results of the fourteen cluster analyses, however, also allows the separation of gravels which have characteristics of both the fluvial and the fluvioglacial suites. These appear to be the product of redistribution and mixing of terrace gravels with fluvioglacial gravels, as a result of glaciation. The ability of the technique to distinguish the samples which occupy this zone of overlap, rather than forcing them into the group they are most closely related to, demonstrates the particular suitability of cluster analysis in this type of study.

Examination of the groups identified by the cluster analyses allows, on the basis of gravel lithology alone, a simple succession to be suggested, in which at least two glacial incursions are intercalated within the terrace succession. Both glacial incursions brought chalk south into the basin. However, the lithological similarity of all the fluvioglacial gravels, and the uniformity of all terrace gravels from any one river, prevent the clear identification of each stratigraphical unit. This conflicts with the view of Perrin *et al.* (1979) that deposits with uniform lithology are of the same stratigraphical unit; a view which had previously been disputed by Shotton *et al.* (1977).

The discovery of a richly organic clay at Stoke Goldington, associated with gravels of both fluvial and fluvioglacial origin, enables a more complete stratigraphy to be described. The faunal evidence, especially the Mollusca, indicates that the episode is fully temperate in character and represents the latter part of an interglacial. This, together with the uranium series date on *Valvata piscinalis* from the fully temperate sample (of 170Ka) shows that there is a temperate period which is mid-Wolstonian in age. Similar temperate sites have been described at Stanton Harcourt (Lynch Hill), and at Marsworth, where a similar age has been determined. Although such an episode has previously been suggested by Sutcliffe (1975; 1976) on mammalian evidence in the Thames basin, it has not generally been recognised. However, the recent abundance of evidence, both in Britain and on the continent (Jager and Heinrich, 1982), makes it difficult to avoid the conclusion that a mid-Wolstonian temperate episode does exist.

At a number of sites around Bedford, other temperate deposits are also described (Prestwich, 1861; 1864; Wyatt, 1861; 1864). Three levels appear to be of significance: at Biddenham (18m above the floodplain), the Bedford Railway Cutting (9.1m above the floodplain) and at Summerhouse Hill and Willington (1.5m above the floodplain), none of which can be correlated to the Stoke Goldington terrace.

The relationship between the lithological and biological evidence indicates that at least four terraces are present within the basin, with at least three glacial episodes represented. A fourth cold period, for which there are no glacial deposits recognised in the area, is also suggested. The identification of four terraces in the basin conflicts with the reports by Edmonds and Dinham (1965) and Horton (1970; Horton et al., 1974), that only three terraces exist, and requires that the correlations of the Ouse terraces with those of the Cam and Nene, made by previous authors, be modified.

The succession and correlations suggested for the Ouse basin here, conforms with the evidence presented from the surrounding areas. The maximum ice advance, depositing the chalky till, occurred in the Anglian, which agrees with the evidence in the Thames basin and in East Anglia (Gibbard, 1977; Perrin et al., 1979). This, however, conflicts with

Horton's report (1970; Horton et al., 1974) that the chalky till in the area is Wolstonian. The Hoxnian and the mid-Wolstonian interglacial episodes are separated by the cold episode with no recognisable deposits, while the mid-Wolstonian temperate episode is succeeded by the last glacial advance to reach the basin. The correlation of this event with the Wolstonian advances, suggested to the east and west of the area, suggests that this glacial advance is late-Wolstonian in age. Lithological evidence suggests that prior to the Anglian advance, river deposits, similar in nature to the river deposits post-dating the Anglian, were present. A previous glacial advance(s) is also recognised on the basis of erratics present in these river deposits.

The evidence, therefore, demonstrates the existence of the present drainage pattern in the Middle Pleistocene and throughout the Upper Pleistocene. It also demonstrates that glaciation has not obscured the depositional record of river development. However, it is apparent that it is not as easy, in areas which have been glacially disturbed, to identify glacial influxes of far-travelled material as it is in areas which have remained pro-glacial - the Thames, for example (Green and McGregor, 1978). It is also apparent that a combination of both lithological and biological evidence is necessary to identify the full succession.

The complexity of the succession in the upper Ouse basin is apparent and further work is still needed before the stratigraphical history of the area is fully understood. A number of alternative studies could usefully be undertaken.

Firstly, a more detailed analysis of the terrace gravels may allow the lithological differentiation of separate terrace levels in individual sub-catchments. The present study is not able to identify separate terraces because there are not enough samples from any single sub-catchment. A detailed mapping and levelling programme, within a particular sub-catchment, to identify terraces and an analysis of the order of fifteen samples from each terrace deposit, may allow lithological differences between terraces to be identified.

Secondly, analysis of other characteristics of the terrace deposits, may aid in their separation; for example, an examination of the heavy mineral content, or the chemical composition or the grain size distribution of the sediments.

The description of the deposits in the Bedford area shows that several terraces are present in a small area, each containing biological material. Both sedimentological and biological investigations of the deposits may usefully be employed, since no analysis of the deposits has been undertaken since the end of the last century.

Dury (1952), in fact, states that

> "Thus although the record of intermittent downcutting and of the formation of terraces is one of considerable detail, it cannot yet be regarded as fully interpreted or understood. In particular, the evidence in the twenty miles of valley from Bedford upstream calls for close examination; it appears likely that the solution to problems of correlation will ultimately be found here." (Dury, 1952, p137).

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# ASPECTS OF THE MIDDLE AND UPPER PLEISTOCENE OF THE UPPER OUSE BASIN.

By

Robert Christopher Young.

A thesis presented for the degree of
Doctor of Philosophy
at the
University of London.

Volume II.

Department of Geography, May 1984.
Bedford College. N.W.1.

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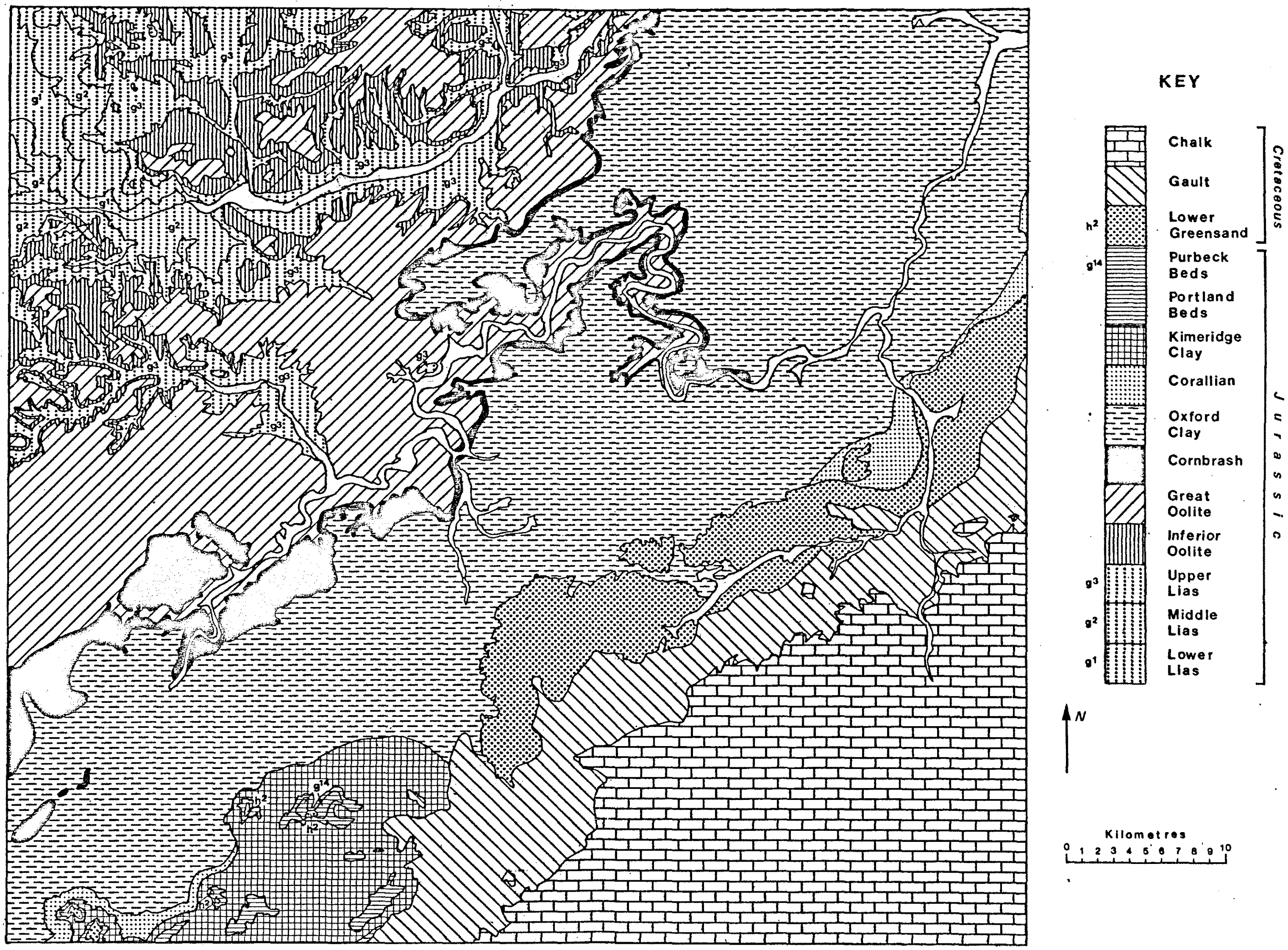


Figure 2.1 Solid Geology of the study area.

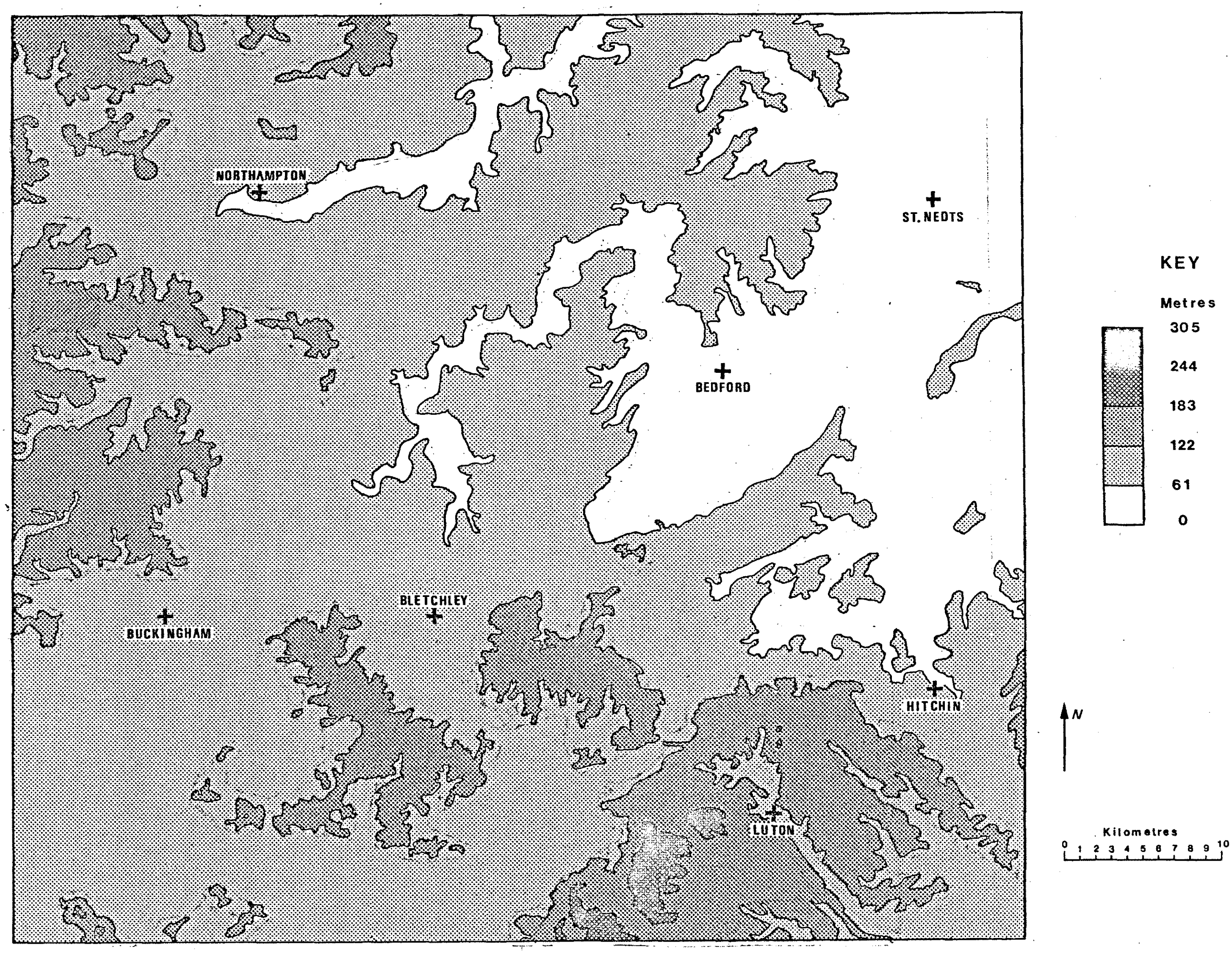


Figure 3.1 Relief of the study area.

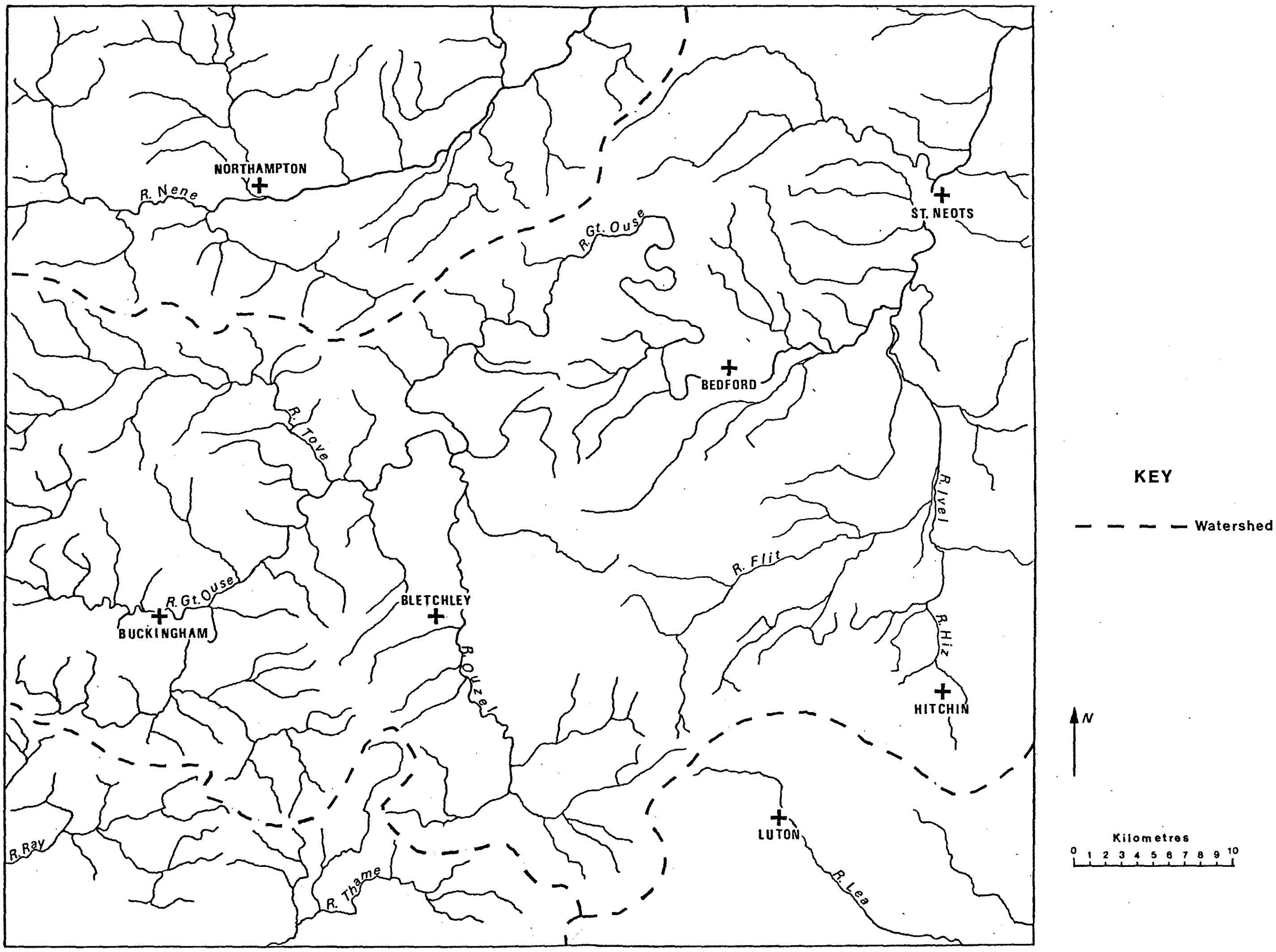


Figure 3.2 Drainage of the study area.

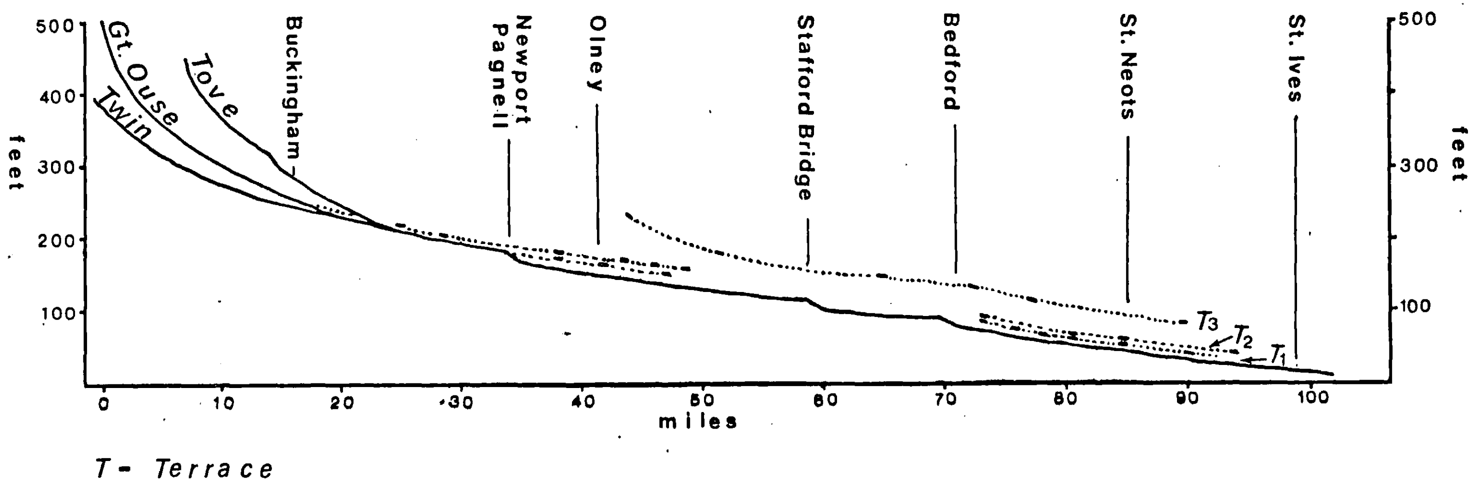
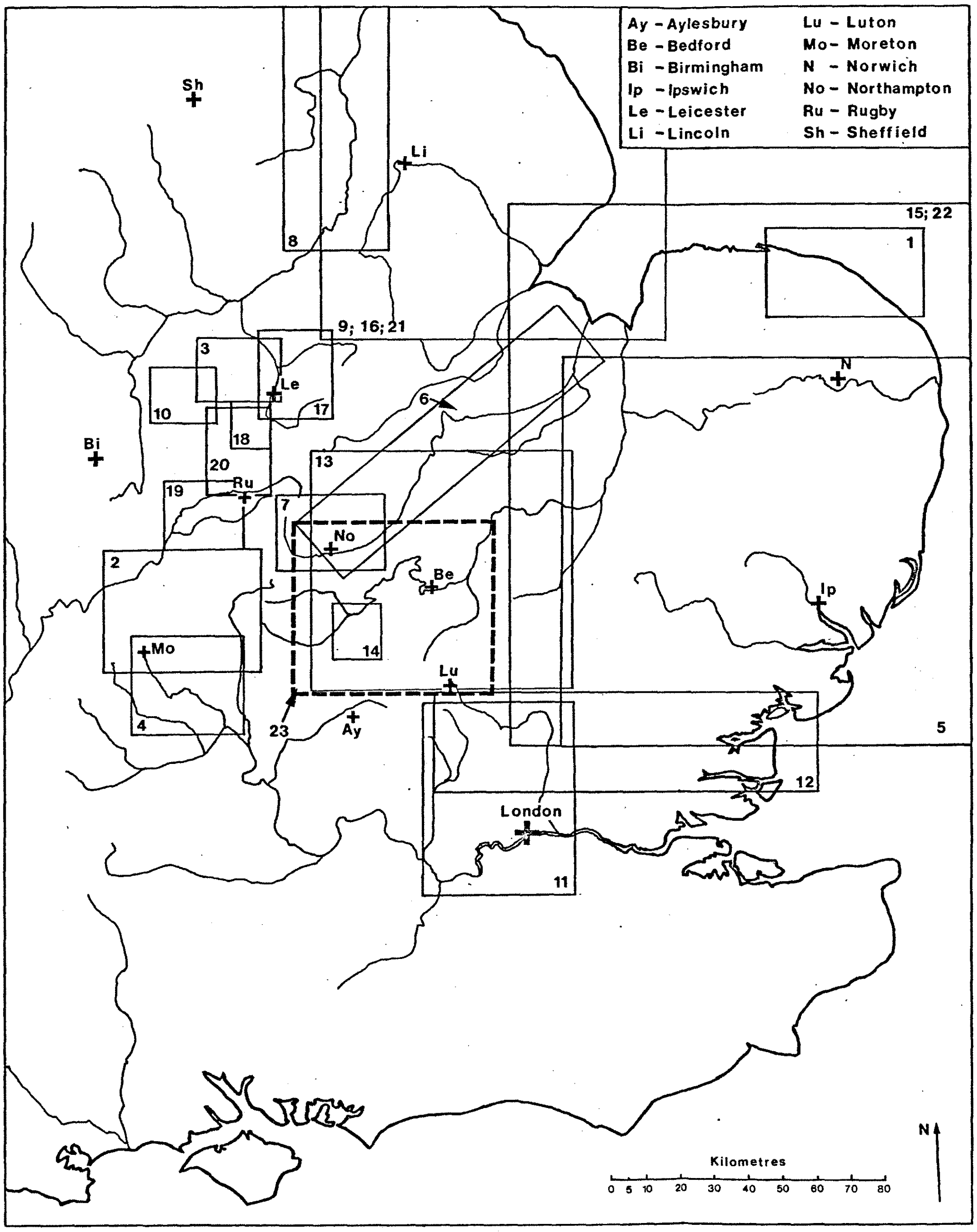


Figure 3.3 Profile of the Great Ouse and tributaries. (After Dury, 1952).



## KEY

| | |
|---|---|
| 1 | Banham, 1975 |
| 2 | Bishop, 1958 |
| 3 | Bridger, 1975 |
| 4 | Briggs & Gilbertson, 1973; 1980 |
| 5 | Bristow & Cox, 1973 |
| 6 | Castleden, 1976 |
| 7 | Castleden, 1980c |
| 8 | Clayton, 1953 |
| 9 | Clayton, 1957 |
| 10 | Douglas. 1980 |
| 11 | Gibbard, 1977; 1979 |
| 12 | Green & McGregor, 1978<br>McGregor & Green, 1978<br>Green, McGregor & Evans, 1982 |
| 13 | Horton, 1970 |
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| 16 | Posnansky, 1960 |
| 17 | Rice, 1968 |
| 18 | Rice, 1980 |
| 19 | Shotton, 1953 |
| 20 | Shotton, 1976 |
| 21 | Straw, 1979; 1982 |
| 22 | West & Donner, 1956 |
| 23 | Present Study |

Figure 5.1

Research areas of previous workers.

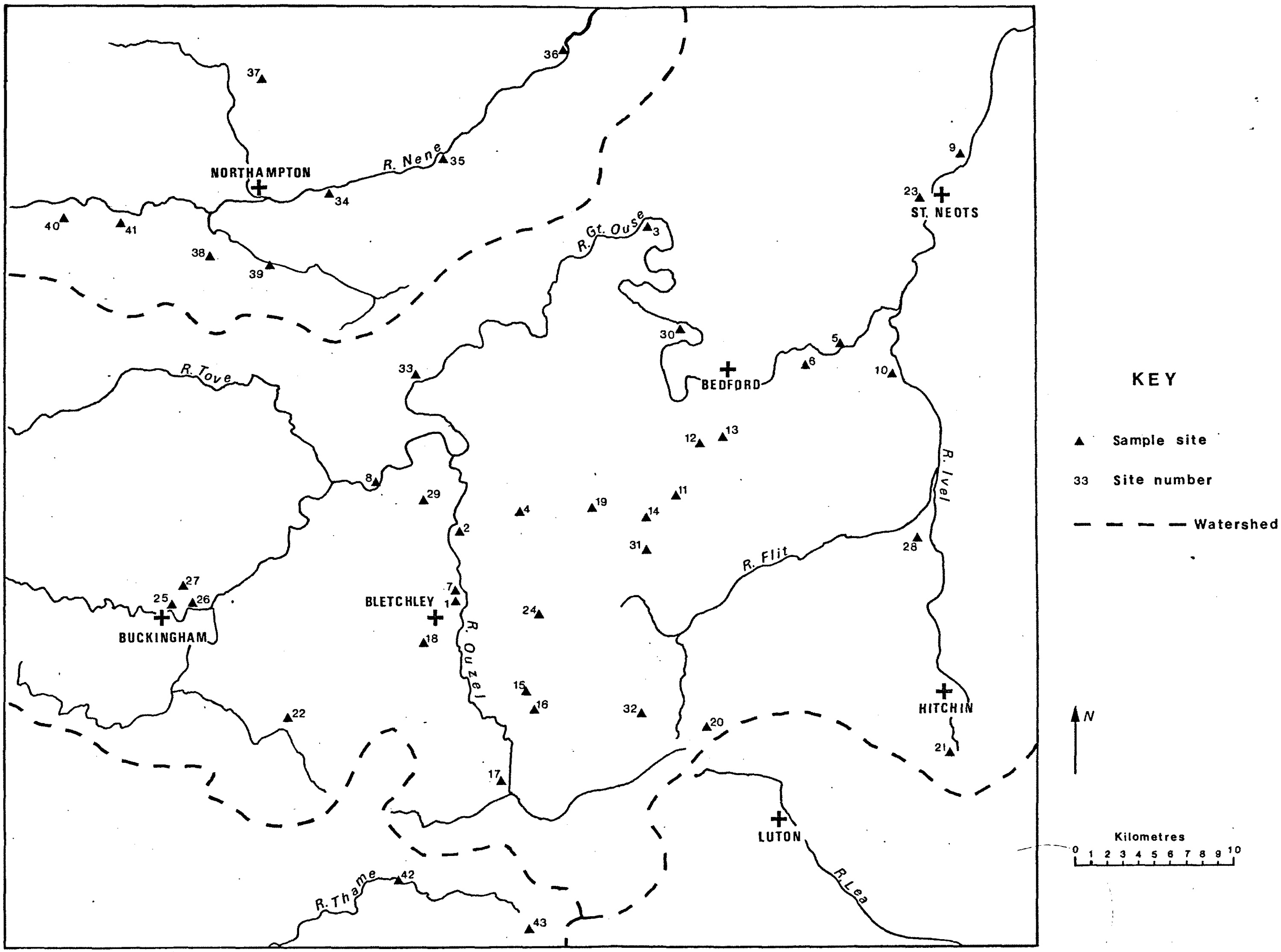


Figure 6.1 Location of sample sites.

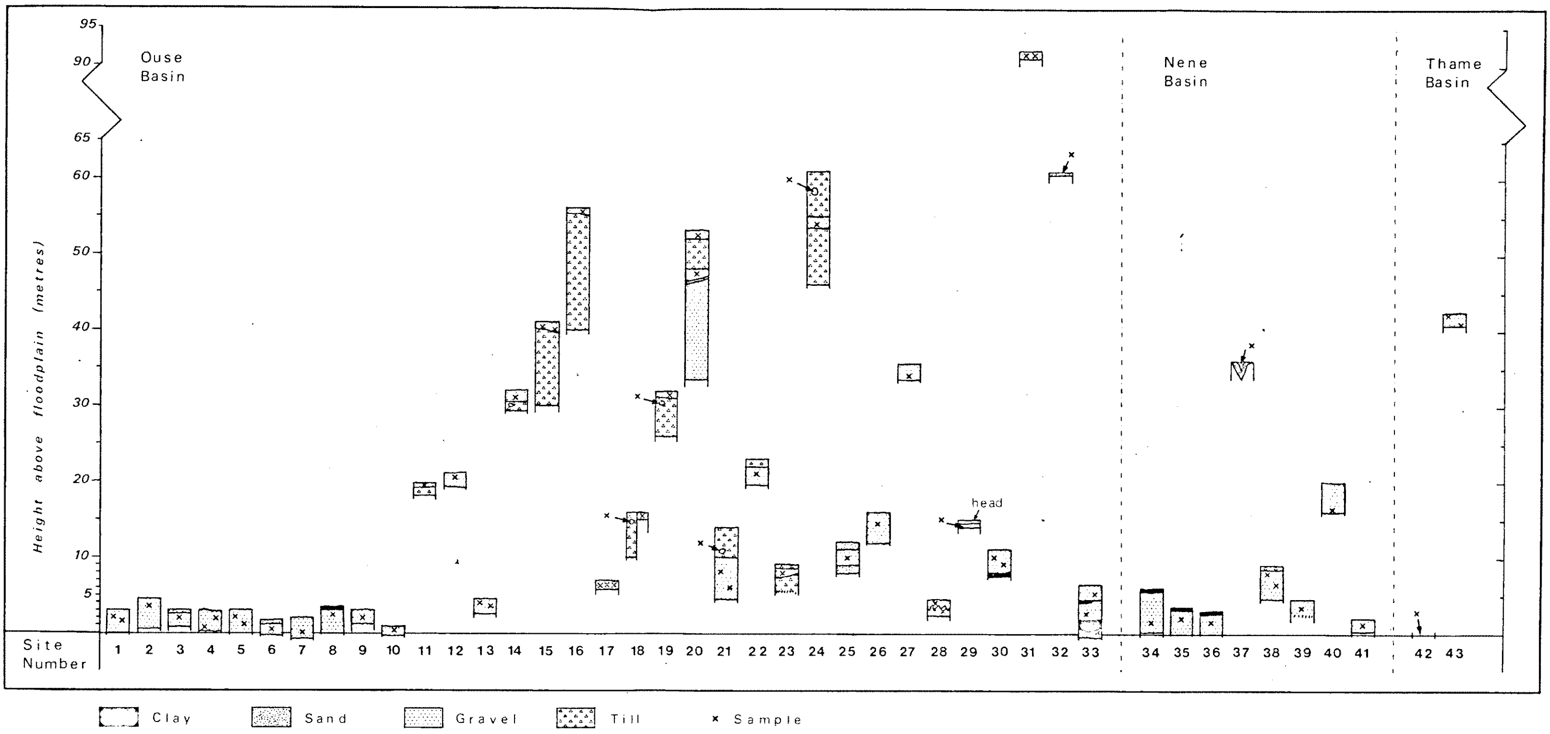


Figure 6.2 Individual site stratigraphies.

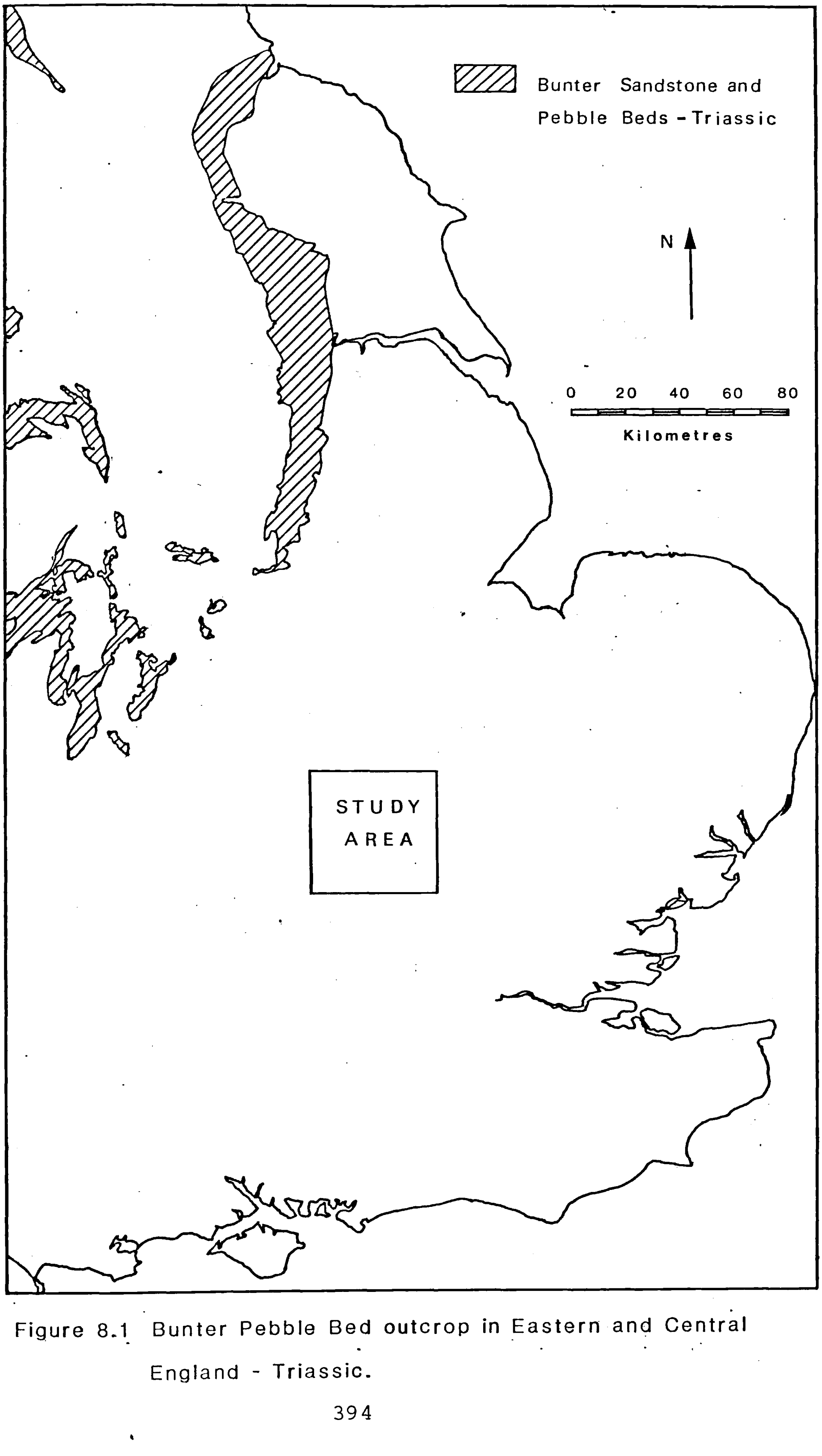


Figure 8.1 Bunter Pebble Bed outcrop in Eastern and Central England - Triassic.

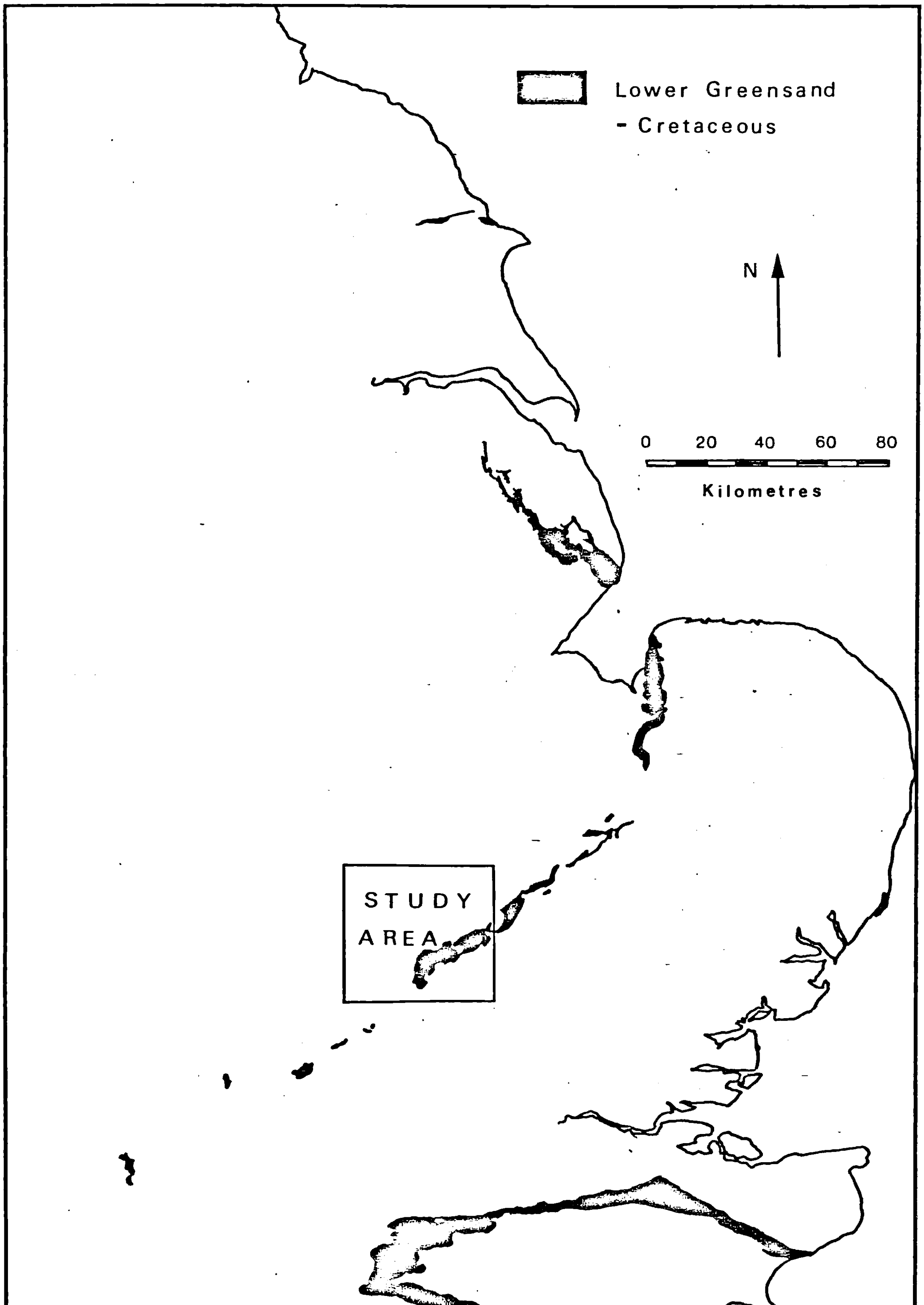


Figure 8.2 Lower Greensand outcrop - Cretaceous.

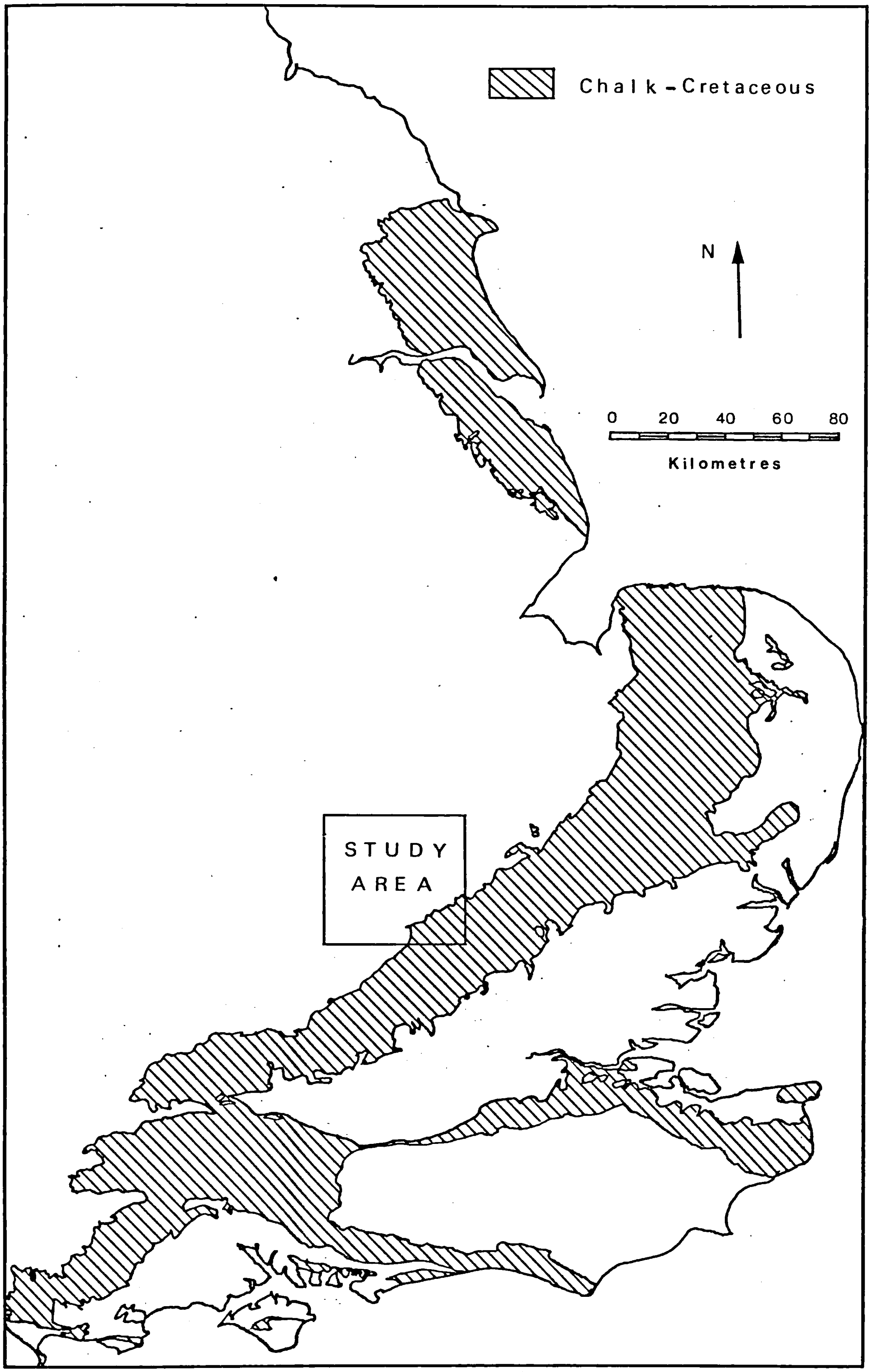


Figure 8.3 Chalk outcrop - Cretaceous.

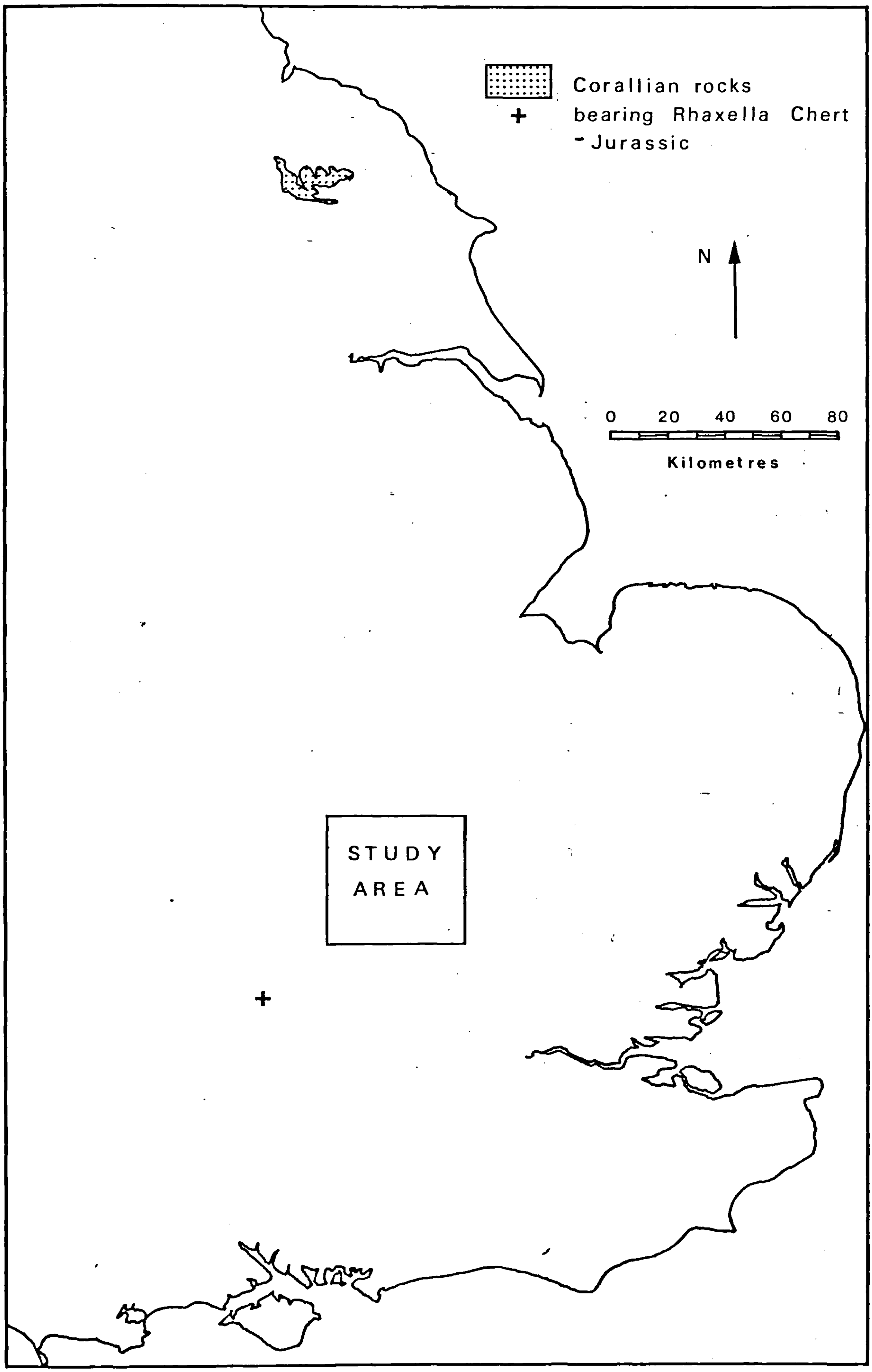


Figure 8.4 Corallian rocks containing Rhaxella chert - Jurassic.

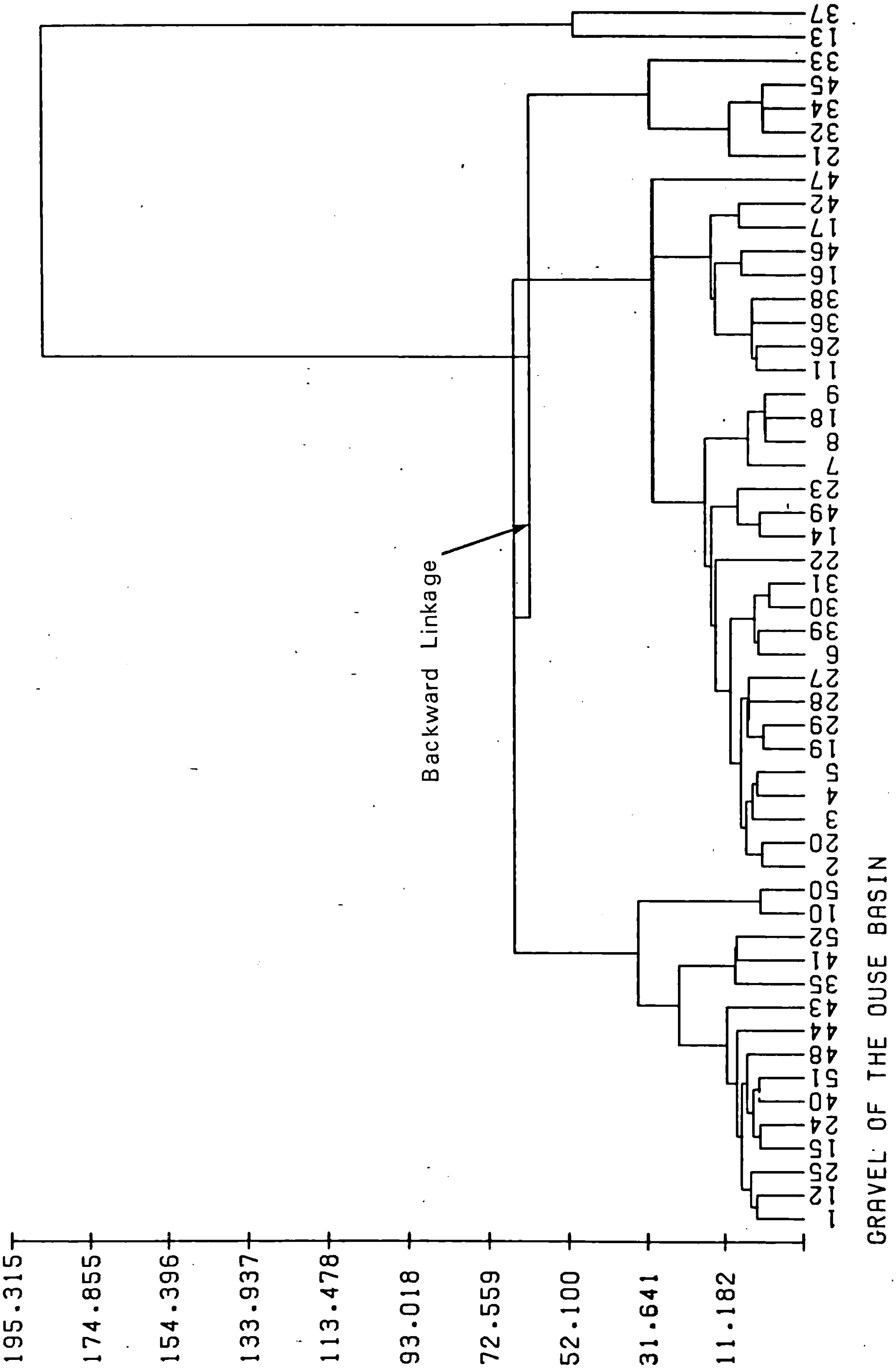


Figure 9.1 Dendrogram - with a backward linkage.

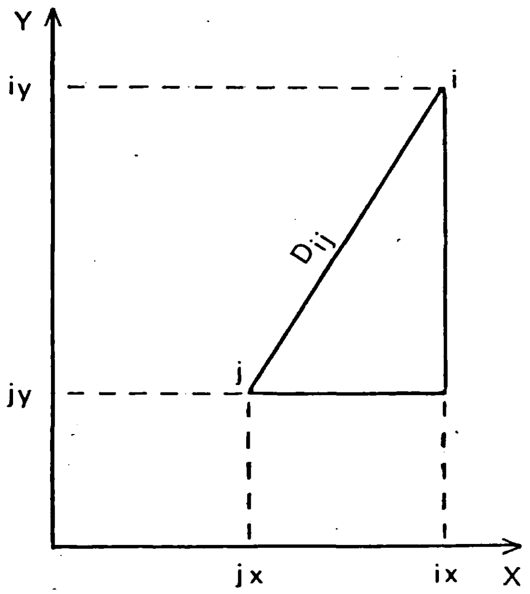
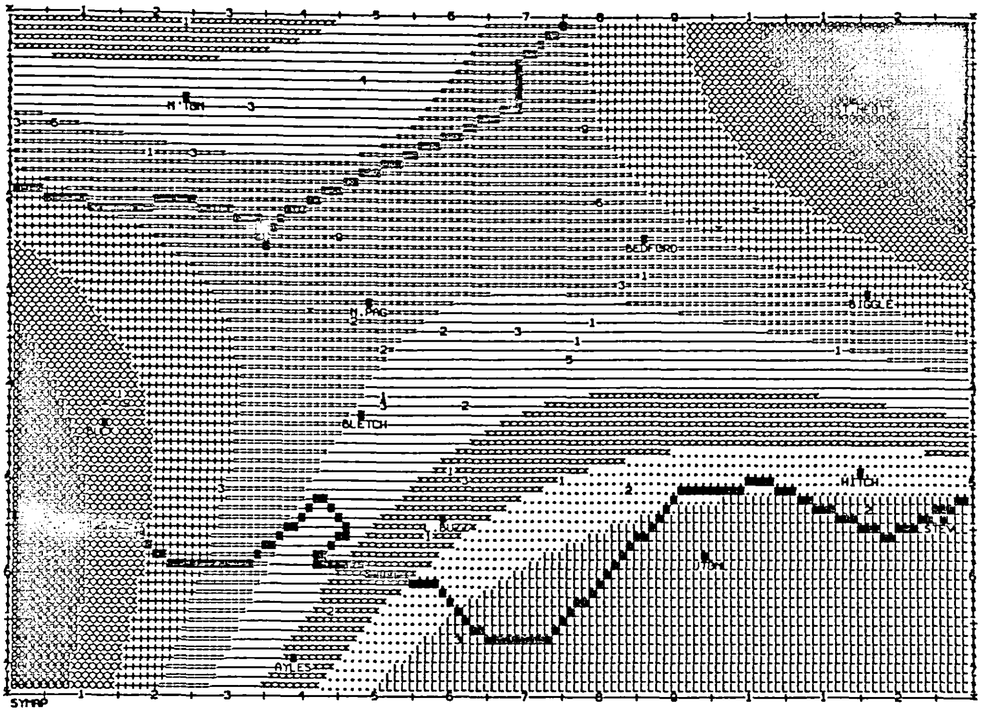


Figure 9.2 Euclidean Distance from Pythagoras' theorem. (see text for explanation).



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TREND SURFACE ANALYSIS OF LIMESTONE AS A PERCENTAGE
OF NON DURABLE RATIO USING 2 LEVELS FOR ALL SAMPLES
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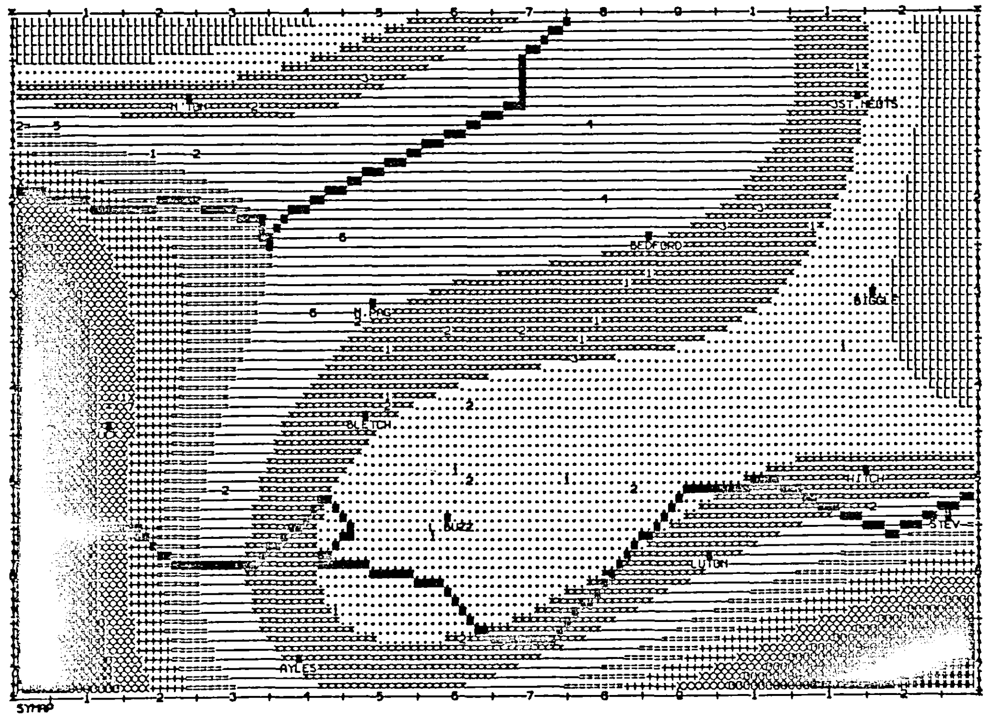
Figure 10.1 Limestone as a percentage of non-durable - quadratic trend surface.



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PERCENTAGE USING 3 LEVELS FOR ALL SAMPLES OF THE
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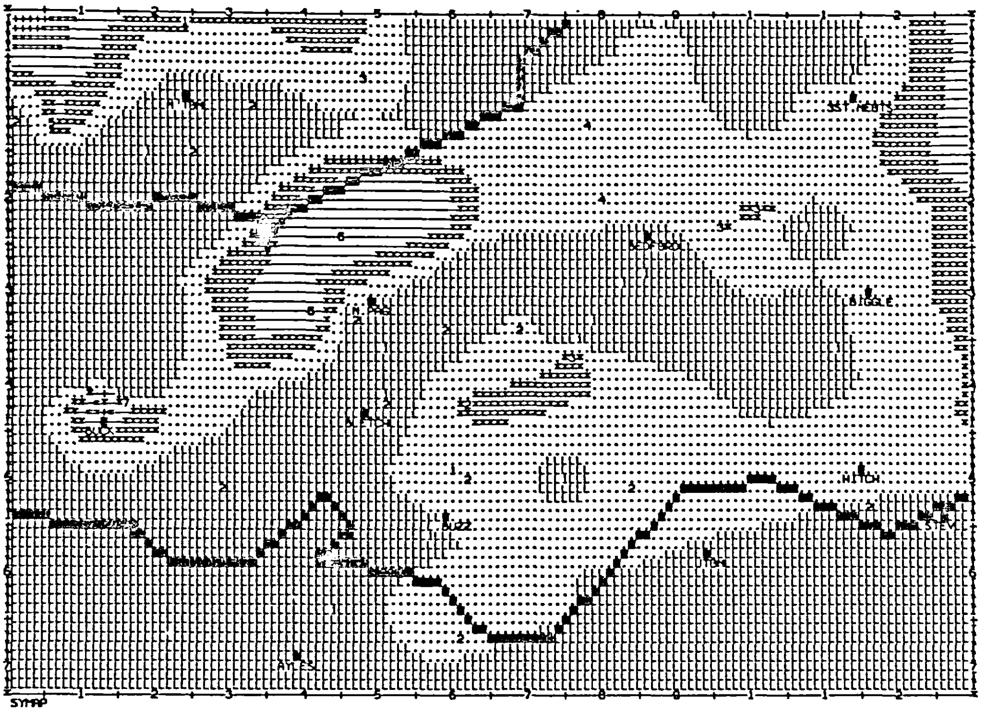
Figure 10.2 Limestone as a gross percentage - cubic trend surface.



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PERCENTAGE USING 3 LEVELS FOR ALL SAMPLES OF THE
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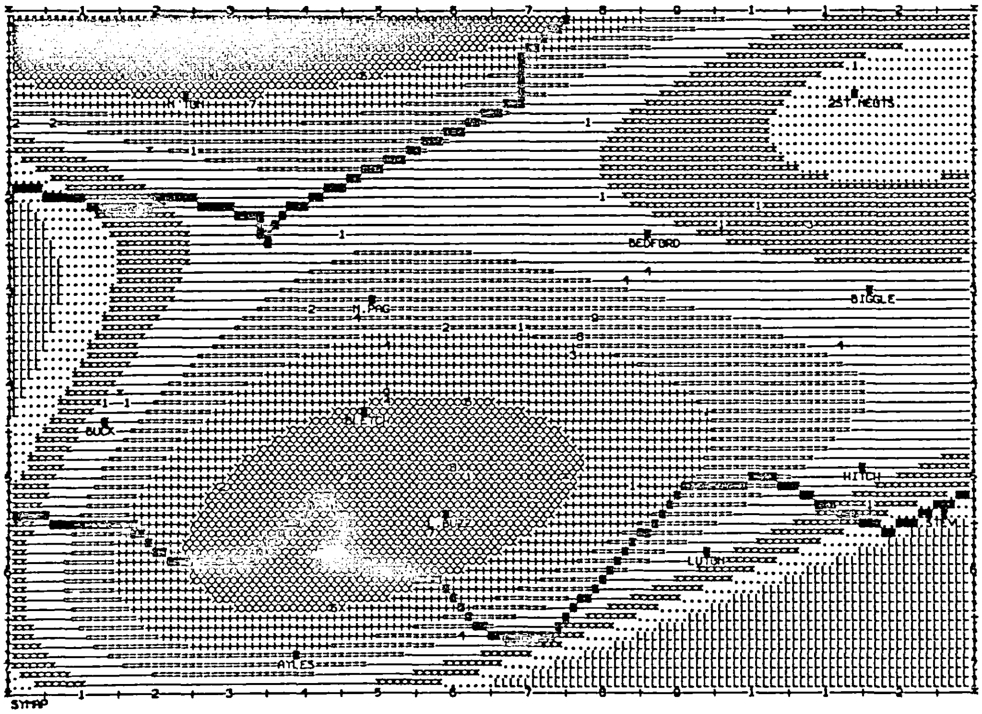
Figure 10.3 Limestone as a gross percentage - cubic residual surface.



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TREND SURFACE ANALYSIS OF FERROUS SANDSTONE AS A
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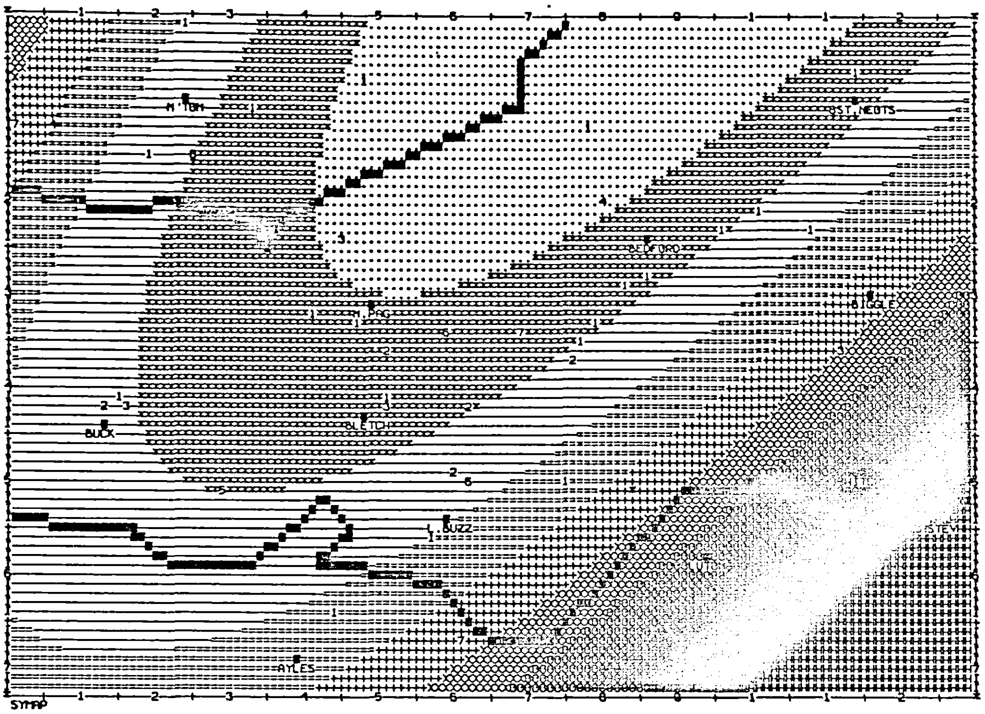
Figure 10.4 Ferrous sandstone as a percentage of non-durable - cubic trend surface.



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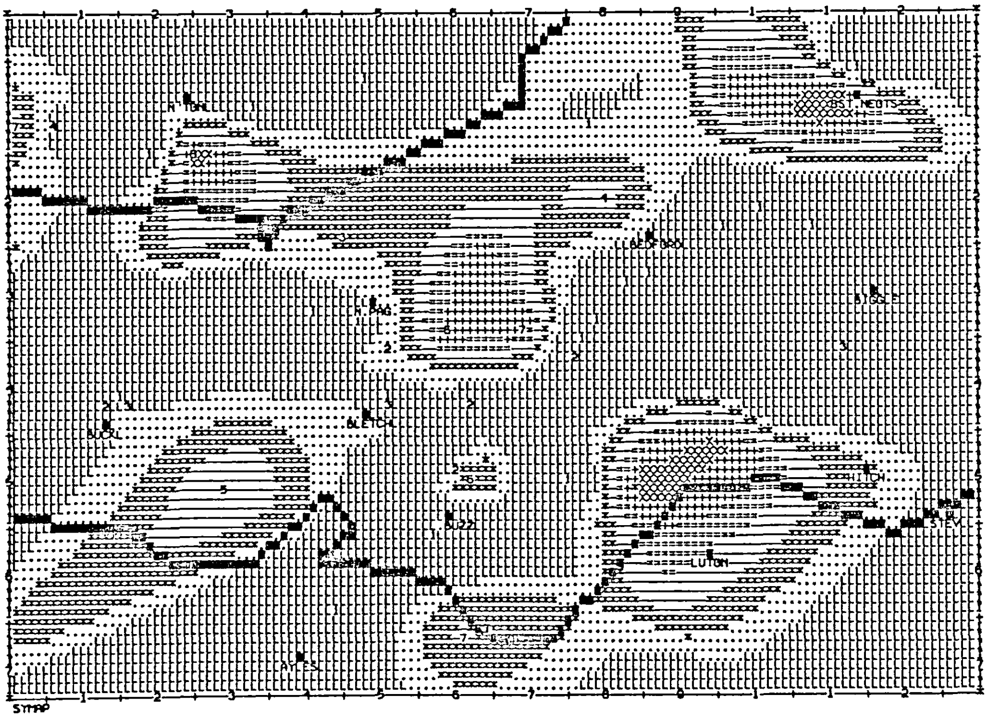
TREND SURFACE ANALYSIS OF CHALK AS A PERCENTAGE
USING 2 LEVELS FOR ALL SAMPLES OF THE OUSE BASIN

Figure 10.5 Chalk as a gross percentage - quadratic trend surface.



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TREND SURFACE ANALYSIS OF CHALK AS A PERCENTAGE
USING 2 LEVELS FOR ALL SAMPLES OF THE OUSE BASIN

Figure 10.6 Chalk as a gross percentage - quadratic residual surface.

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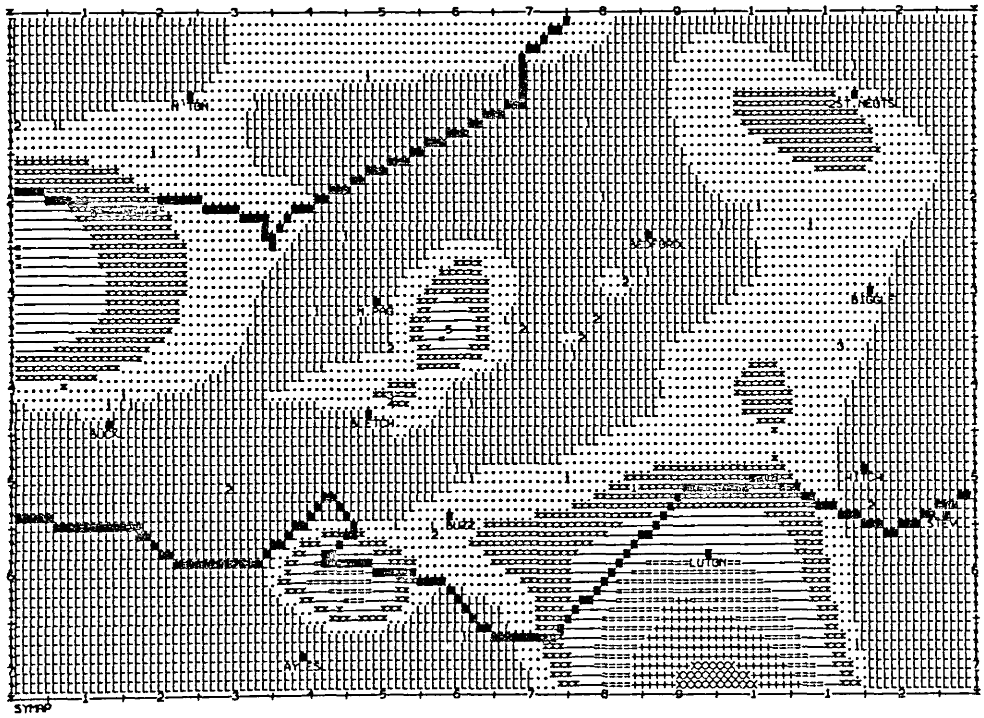
TREND SURFACE ANALYSIS OF THE PHOSPHATIC NODULE/QUARTZITE
& HARD SANDSTONE RATIO USING 4 LEVELS FOR ALL SAMPLES OF

Figure 10.7 Phosphatic Nodules/Quartzite and Hard sandstone - quartic trend surface.



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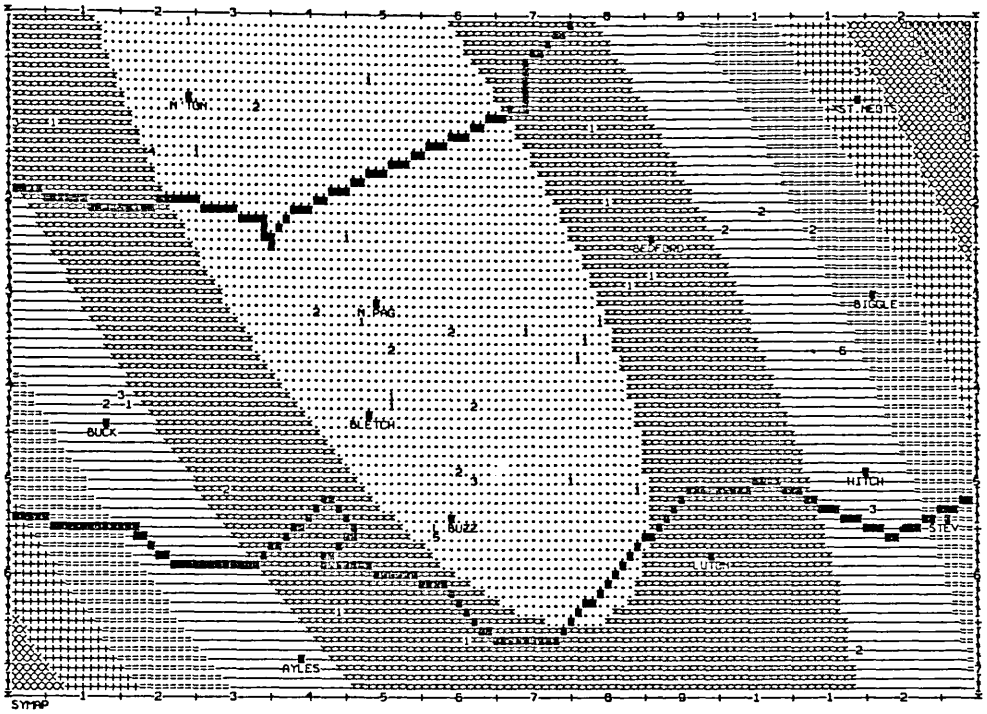
TREND SURFACE ANALYSIS OF THE PHOSPHATIC NODULE/QUARTZITE
& HARD SANDSTONE RATIO USING 4 LEVELS FOR ALL SAMPLES

Figure 10.8 Phosphatic Nodules/Quartzite and Hard sandstone - quartic residual surface.



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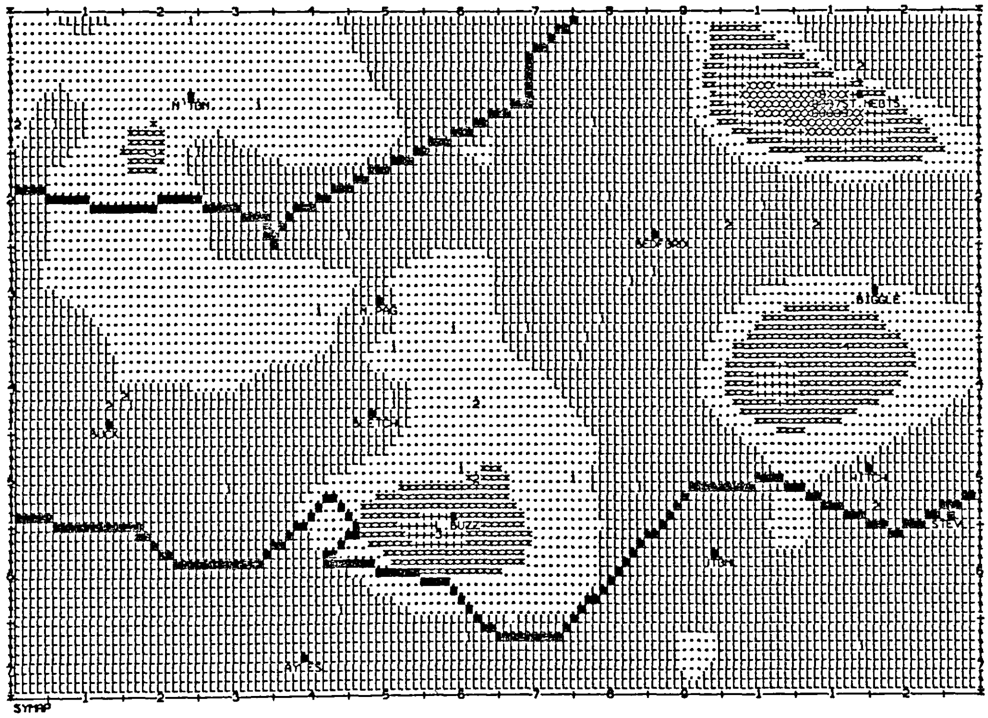
TREND SURFACE ANALYSIS OF THE QUARTZ / QUARTZITE &
HARD SANDSTONE RATIO USING 2 LEVELS FOR ALL SAMPLES

Figure 10.9 Quartz/Quartzite and Hard sandstone - quadratic trend surface.



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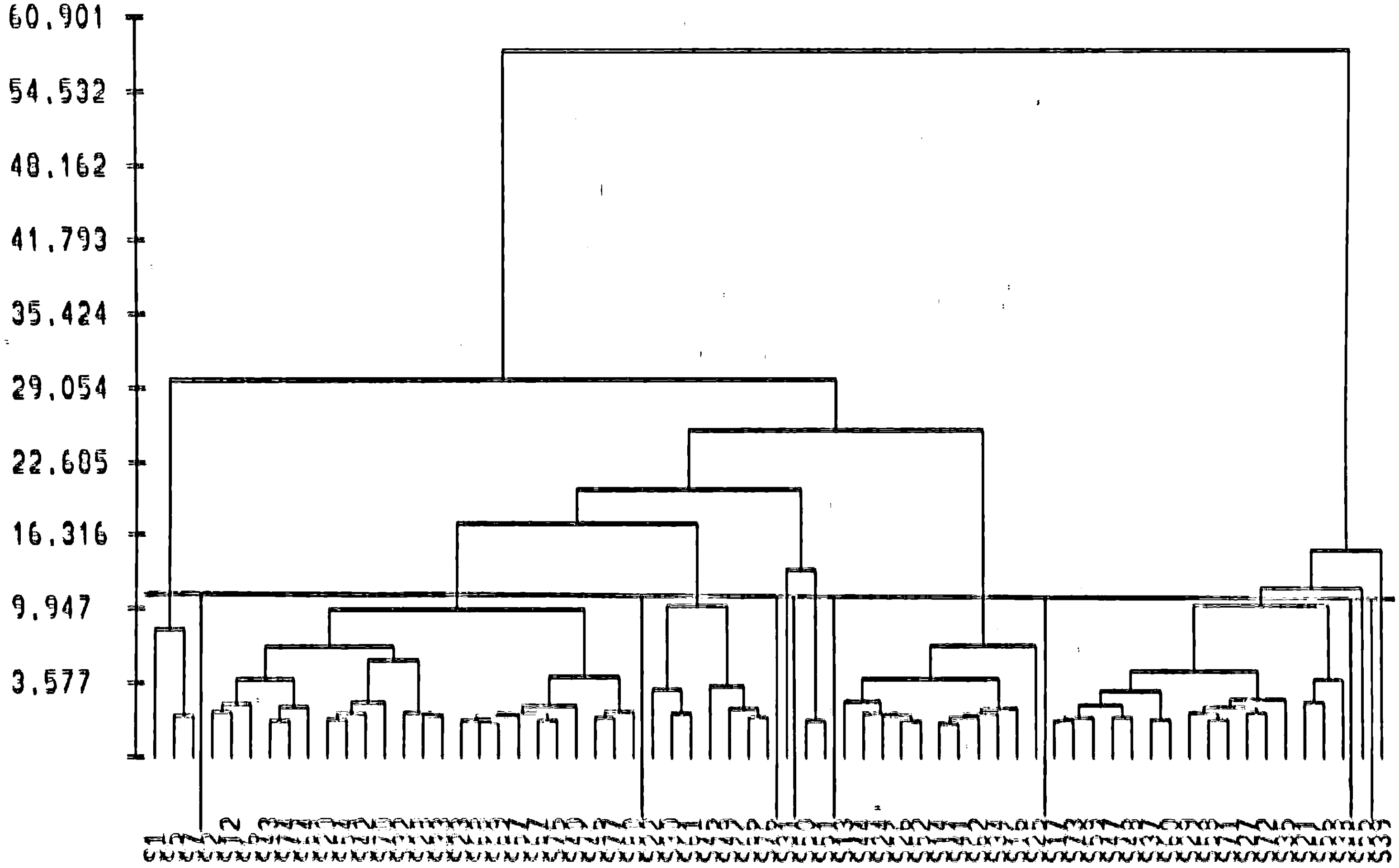
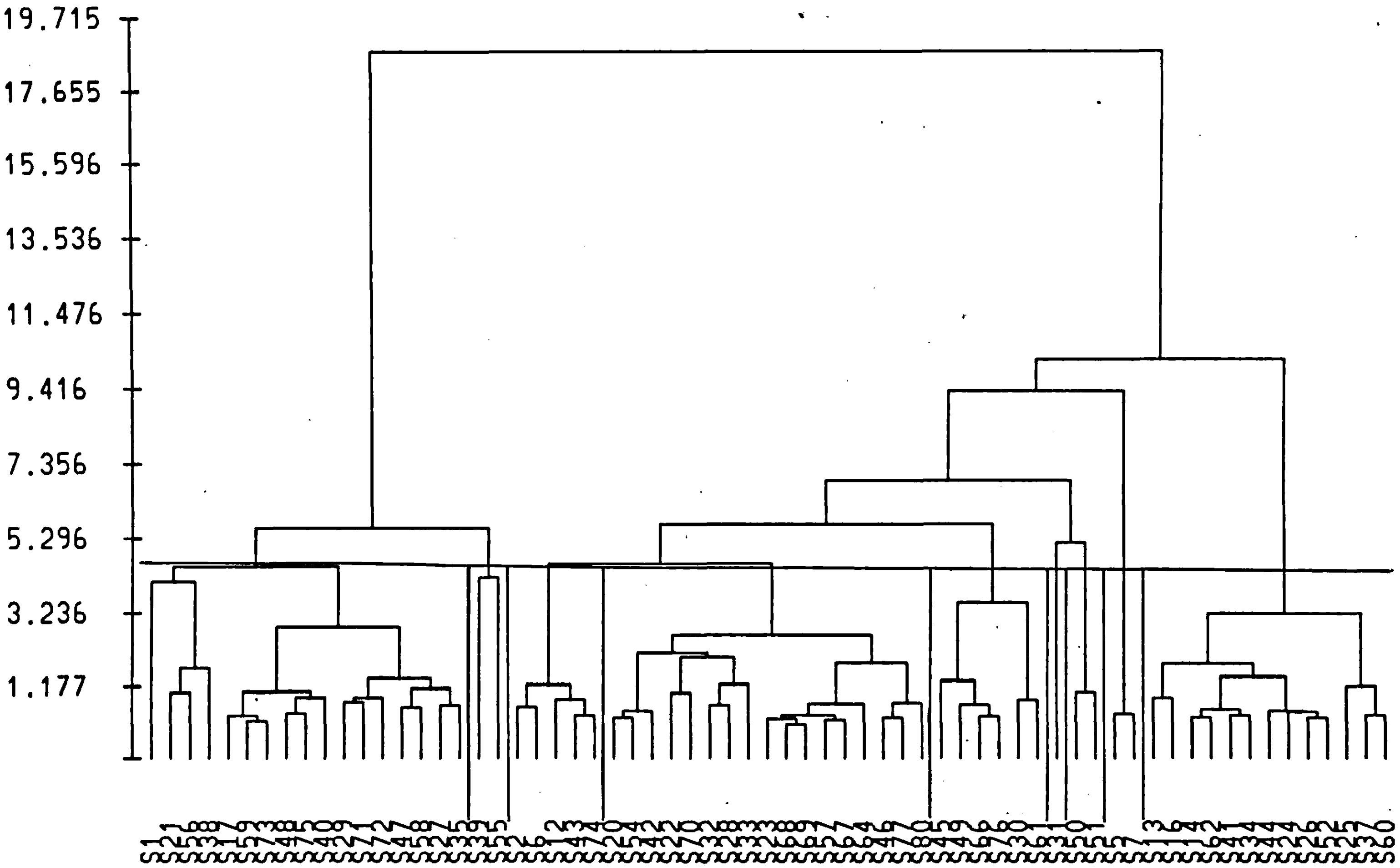
TREND SURFACE ANALYSIS OF THE QUARTZ / QUARTZITE &
HARD SANDSTONE RATIO USING 2 LEVELS FOR ALL SAMPLES

Figure 10.10 Quartz/Quartzite and Hard sandstone - quadratic residual surface.



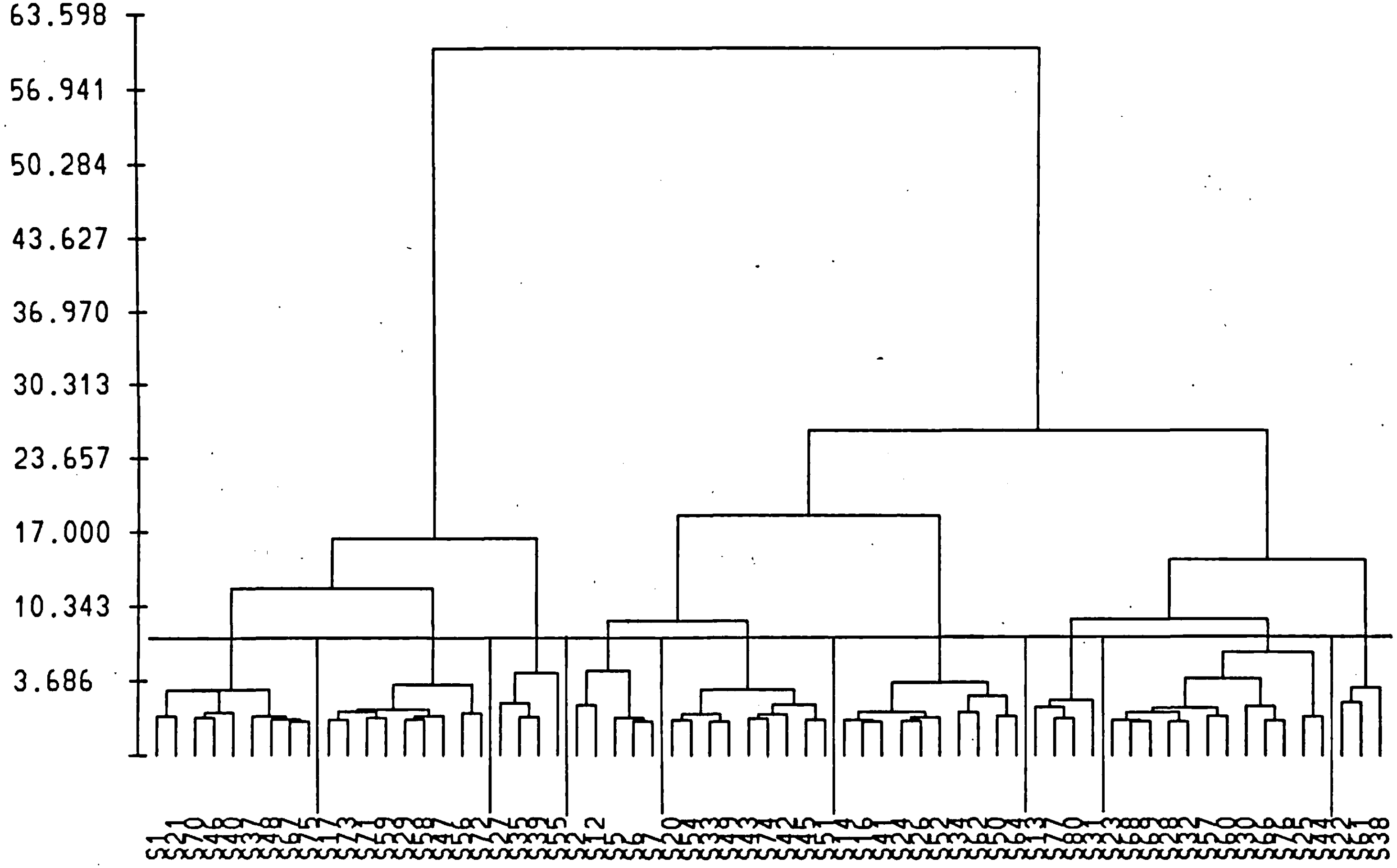
GRAVEL OF THE OUSE BASIN (A)

Figure 10.11 Cluster Dendrogram a.



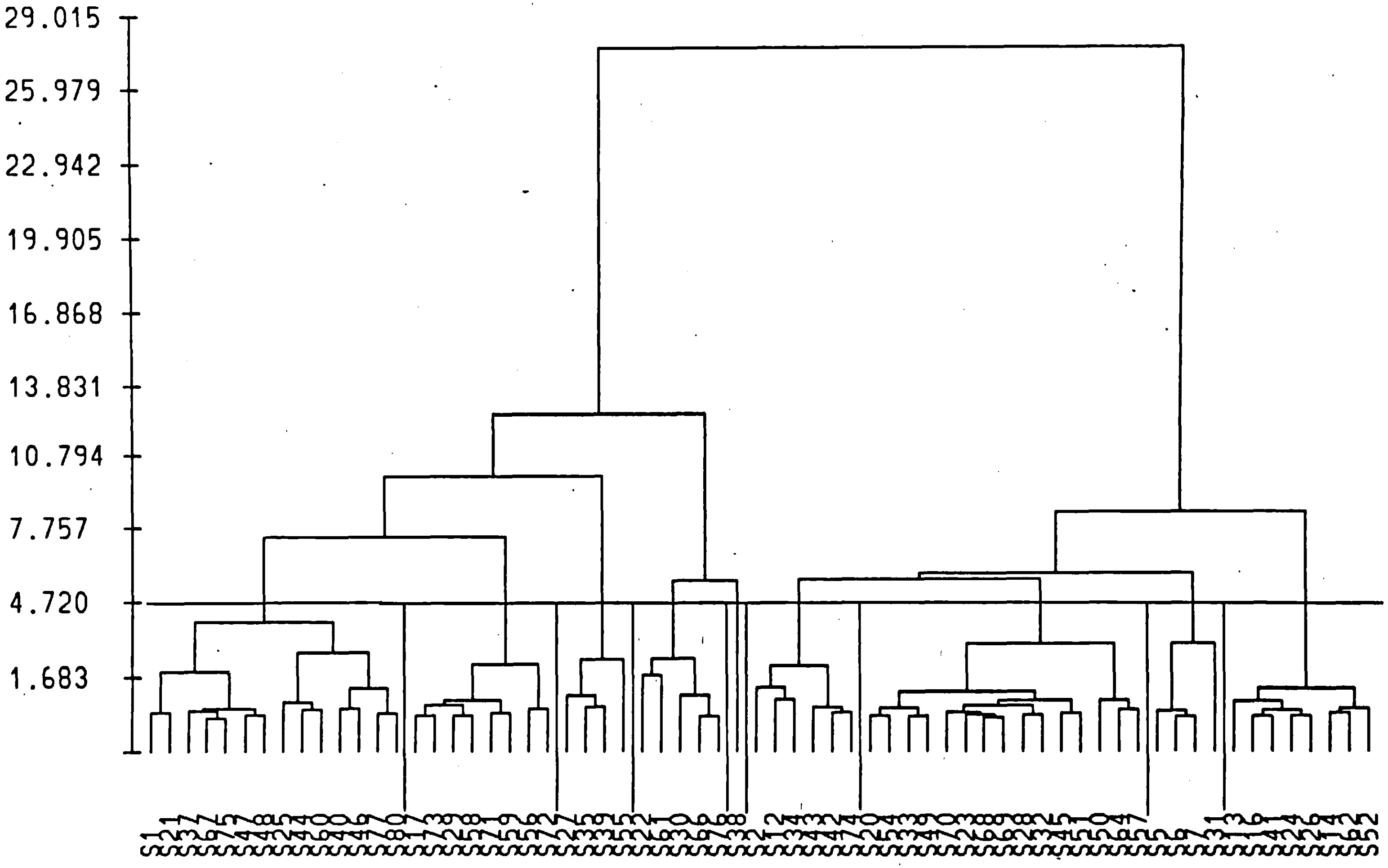
GRAVEL OF THE OUSE BASIN (B)

Figure 10.12  Cluster Dendrogram b.



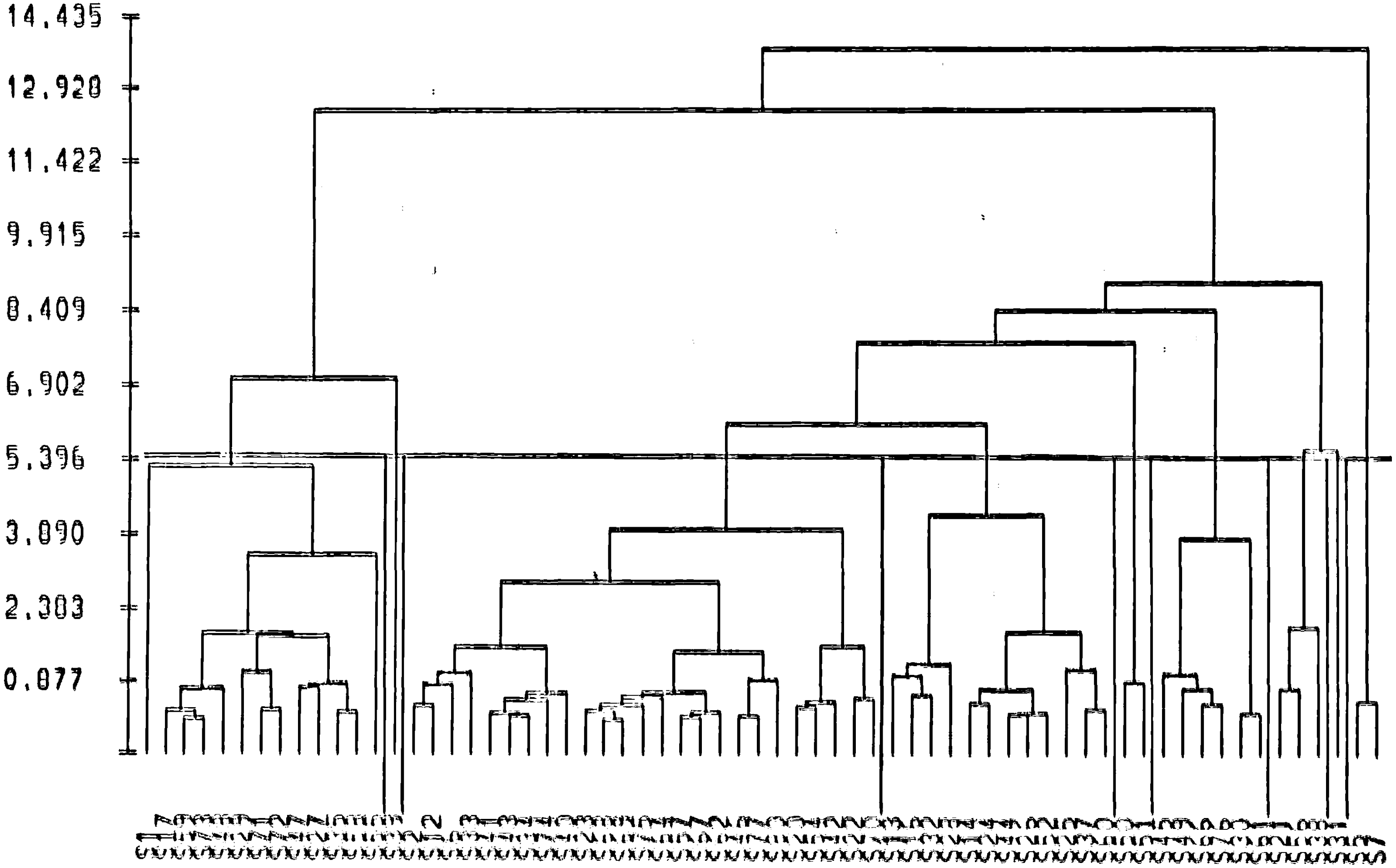
GRAVEL OF THE OUSE BASIN (C)

Figure 10.13 Cluster Dendrogram c.



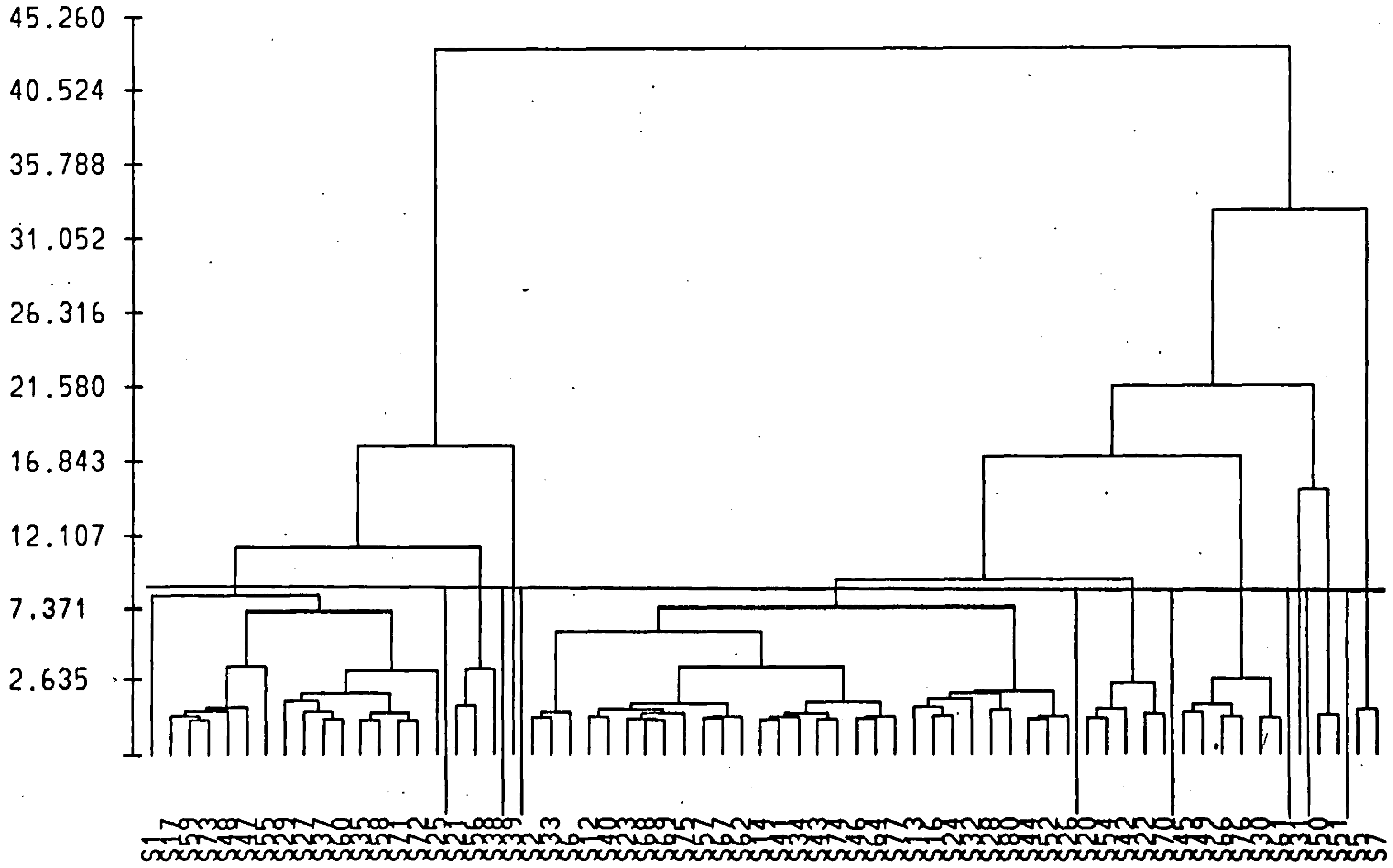
GRAVEL OF THE OUSE BASIN (D)

Figure 10.14 Cluster Dendrogram d.



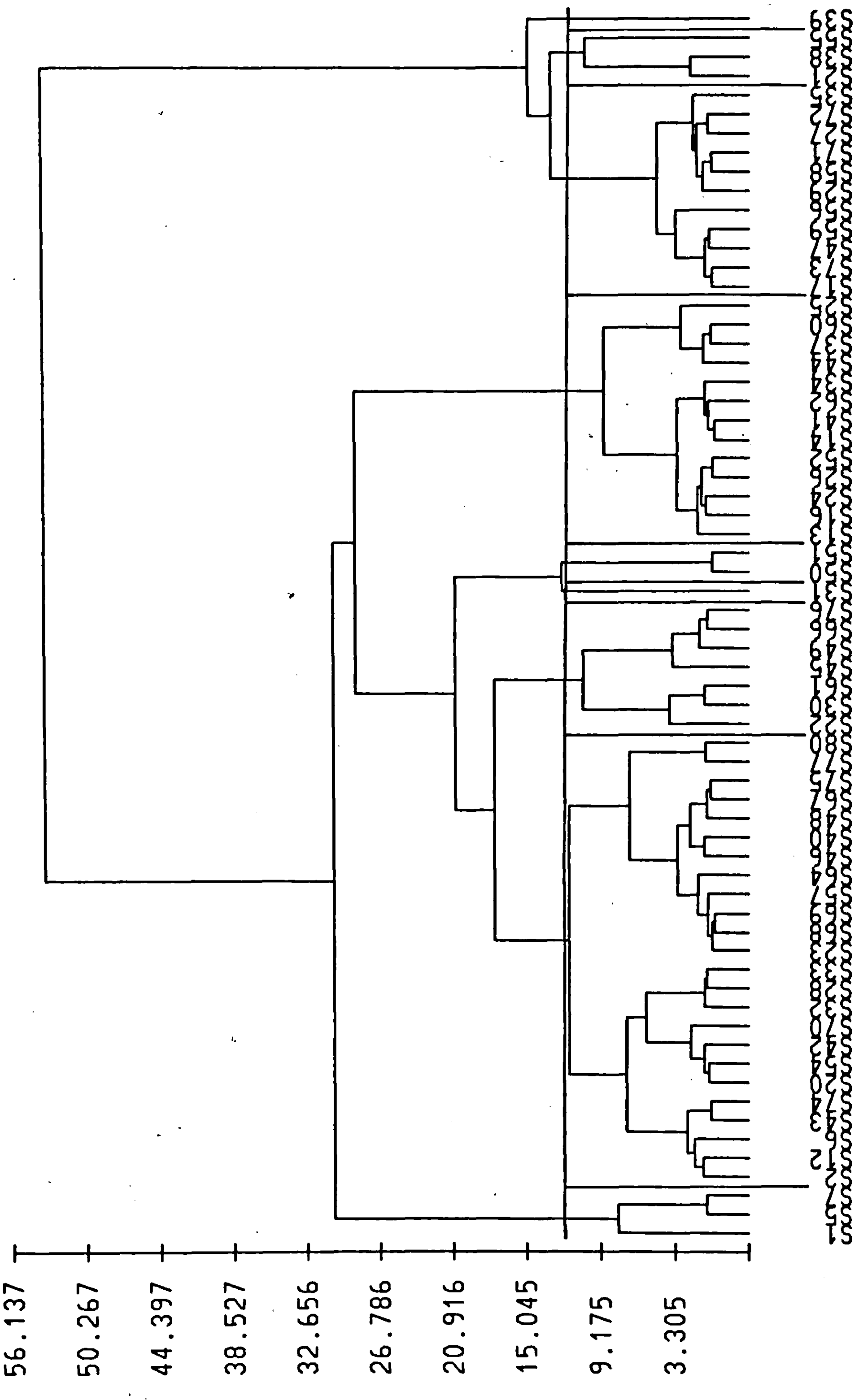
GRAVEL OF THE OUSE BASIN (E)

Figure 10.15 Cluster Dendrogram e.



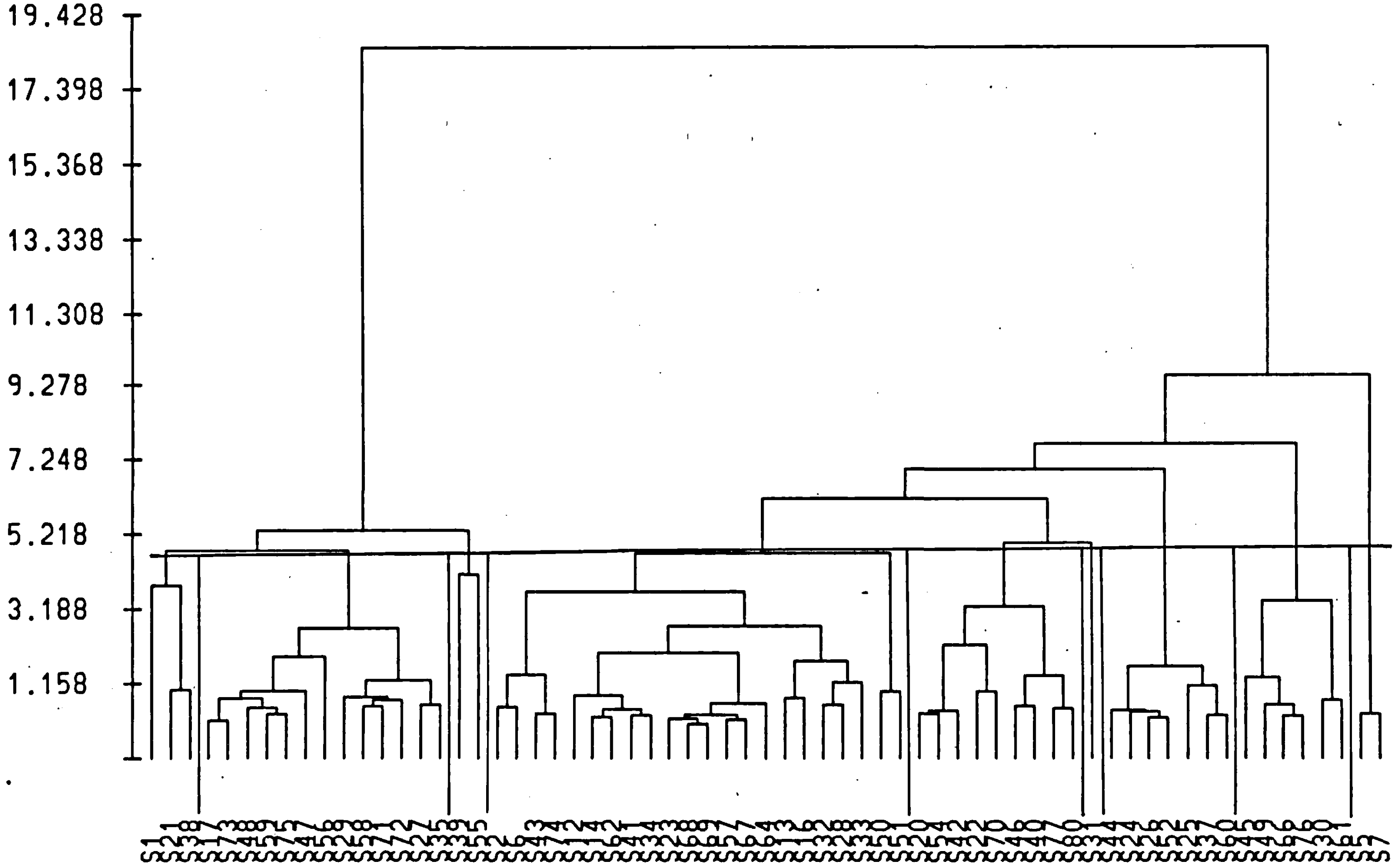
GRAVEL OF THE OUSE BASIN (F)

Figure 10.16 Cluster Dendrogram f.



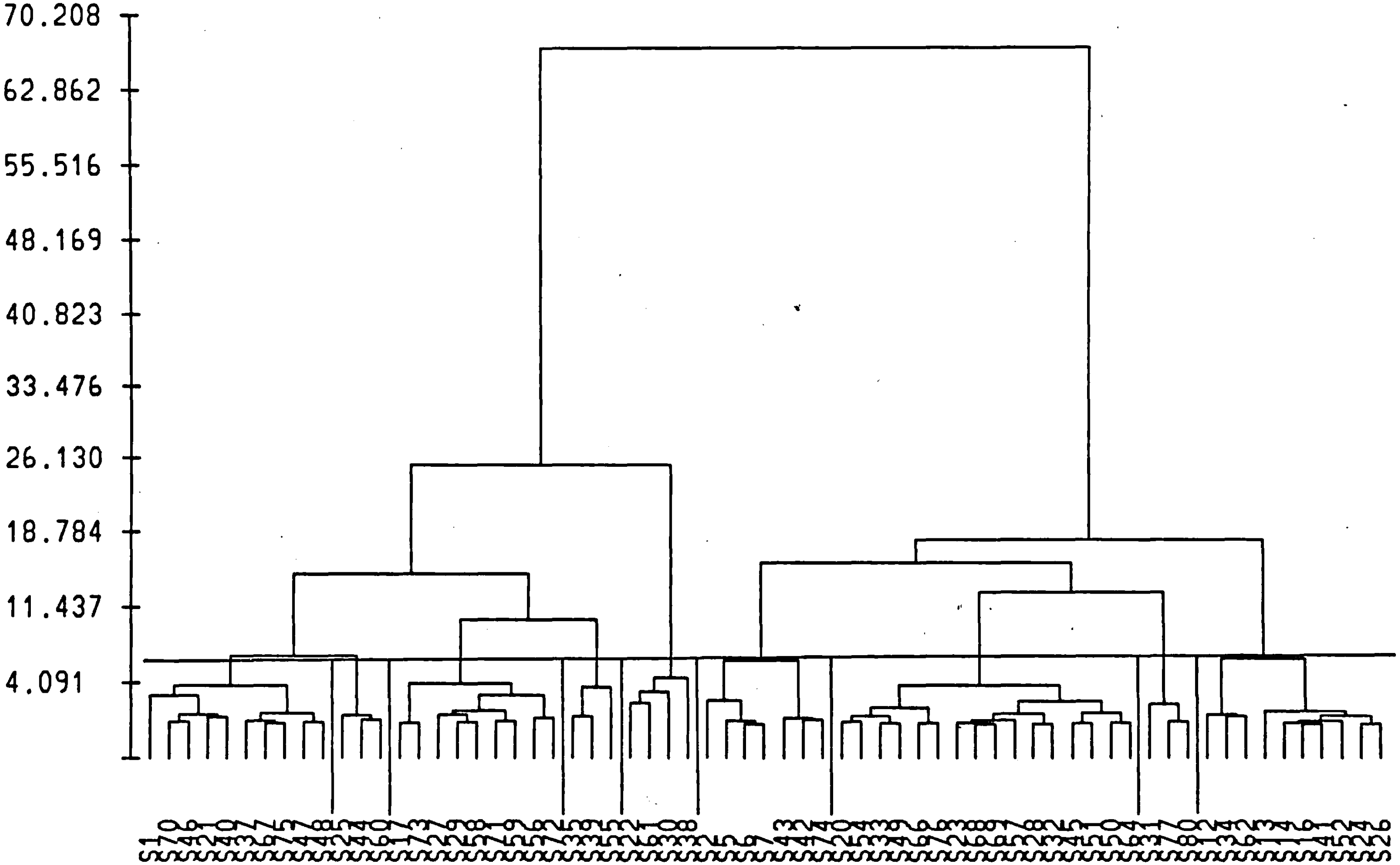
GRAVEL OF THE OUSE BASIN (G)

Figure 10.17 Cluster Dendrogram g.



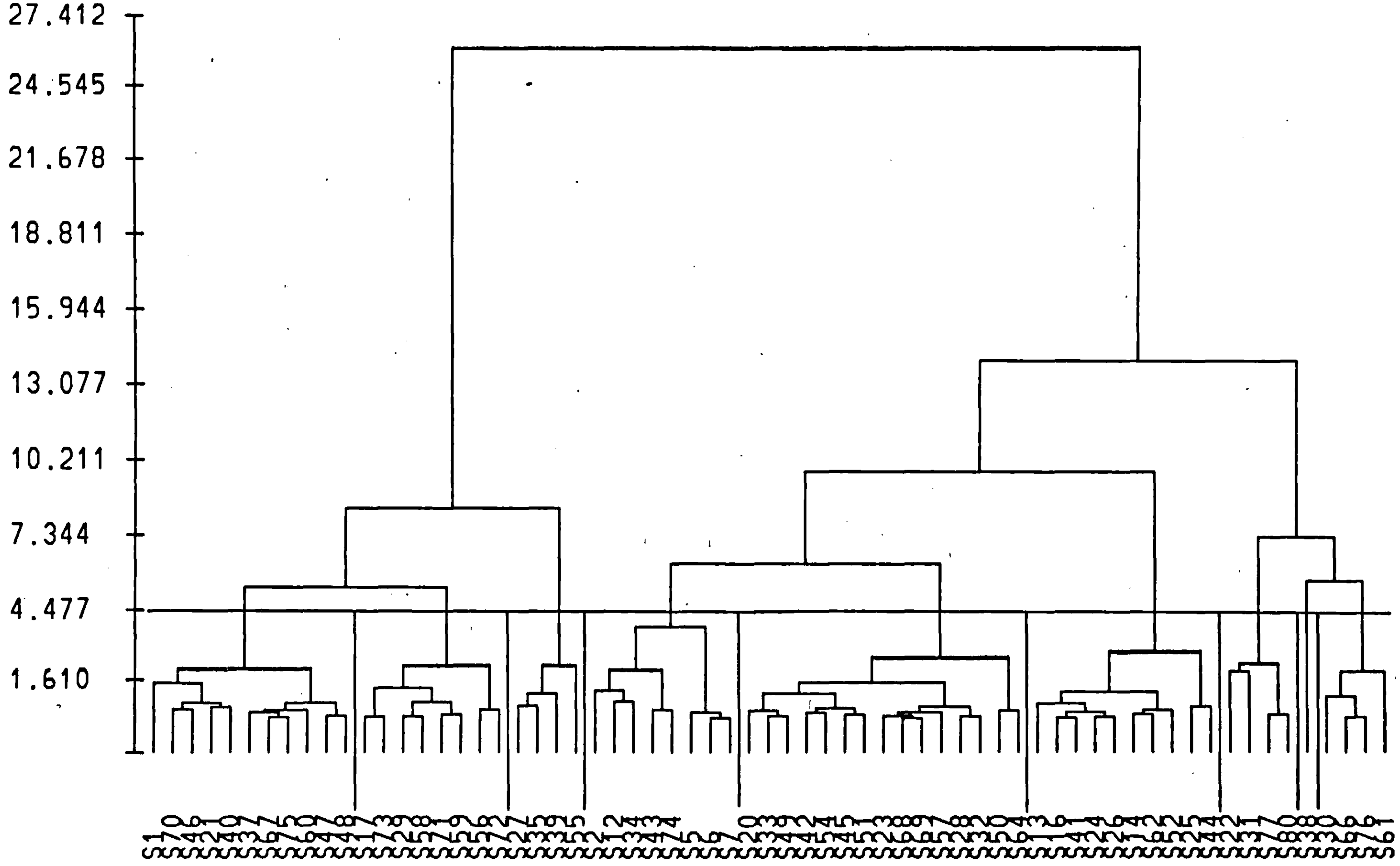
GRAVEL OF THE OUSE BASIN (H)

Figure 10.18 Cluster Dendrogram h.



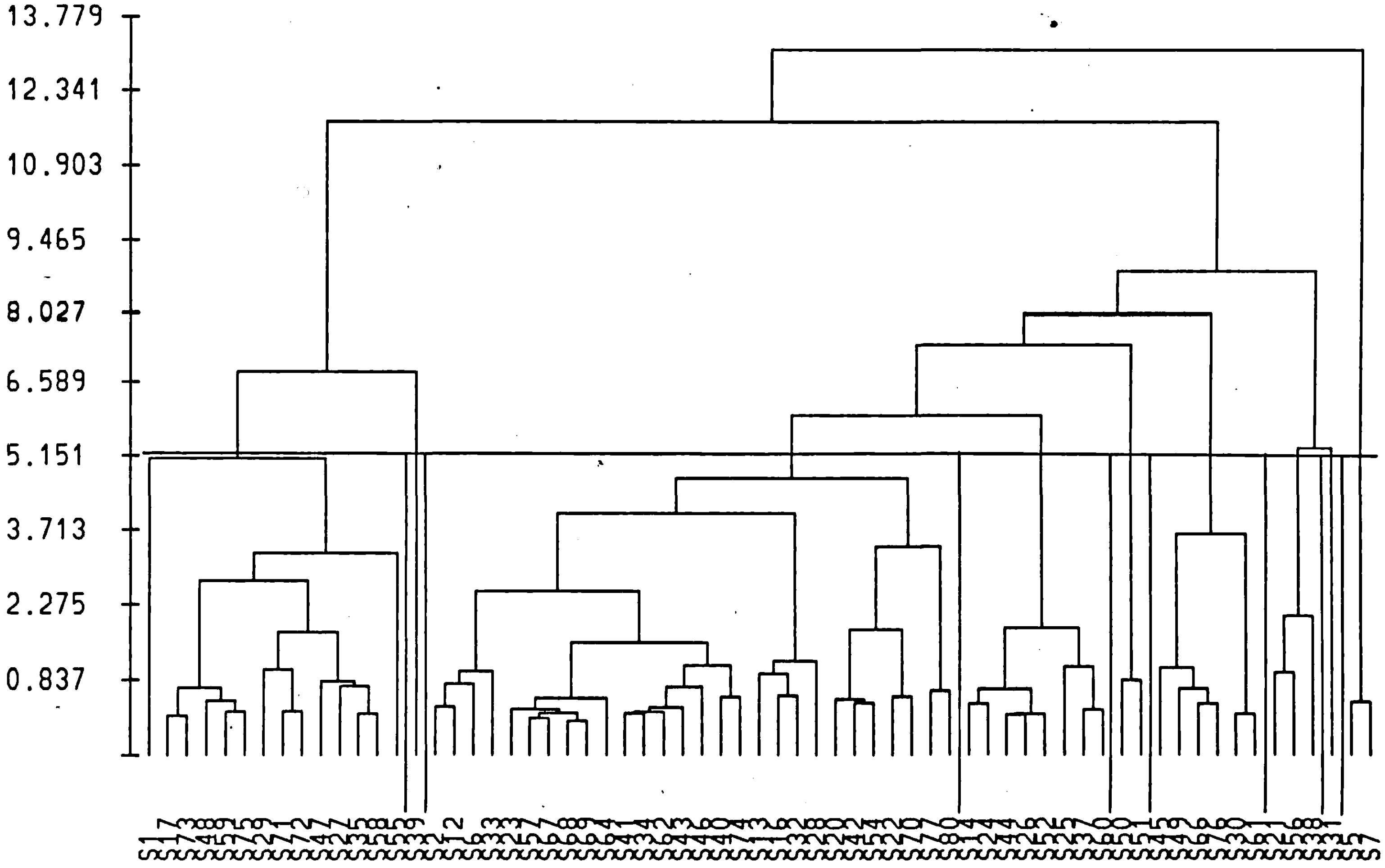
GRAVEL OF THE OUSE BASIN (I)

Figure 10.19 Cluster Dendrogram i.



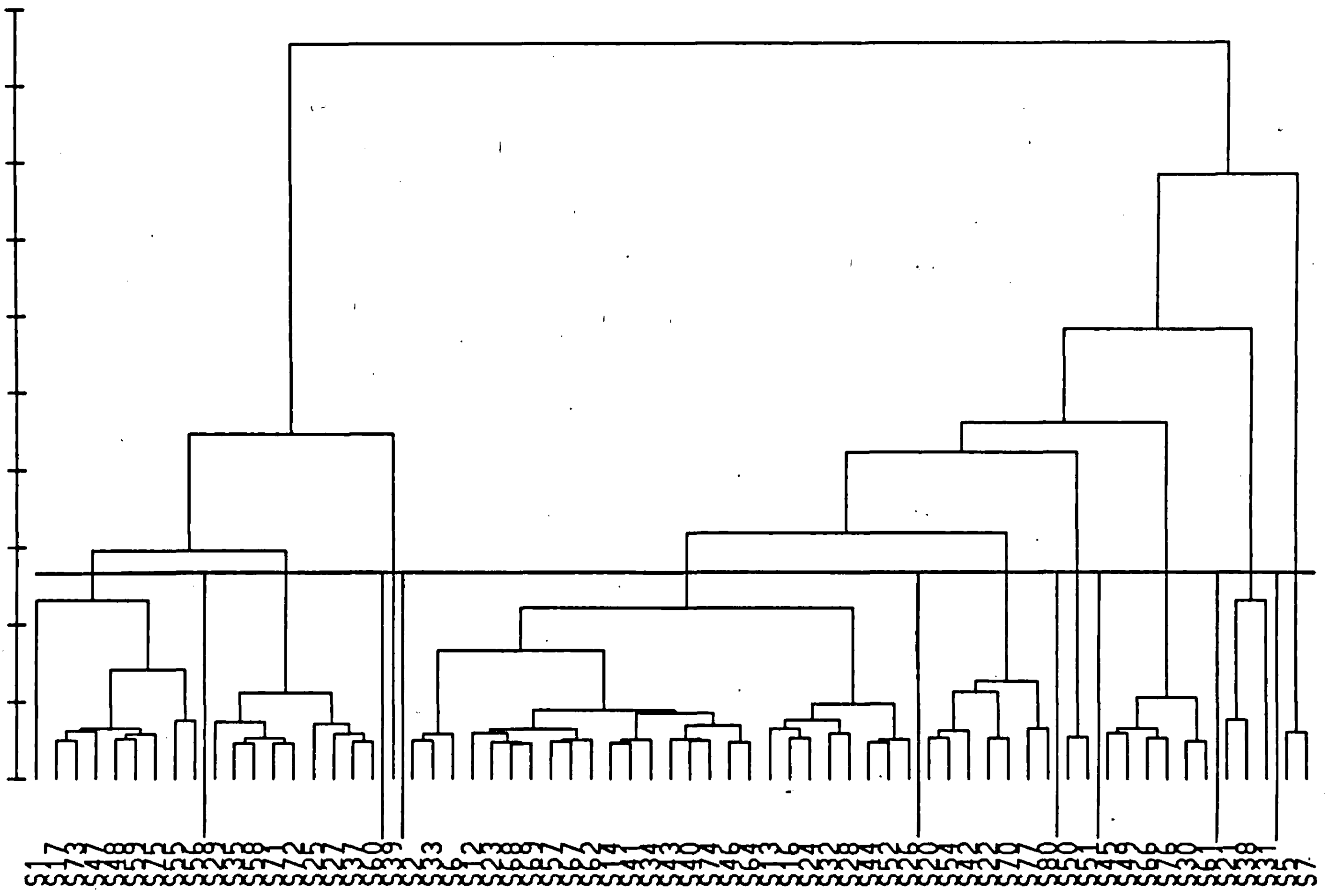
GRAVEL OF THE OUSE BASIN (J)

Figure 10.20 Cluster Dendrogram j.



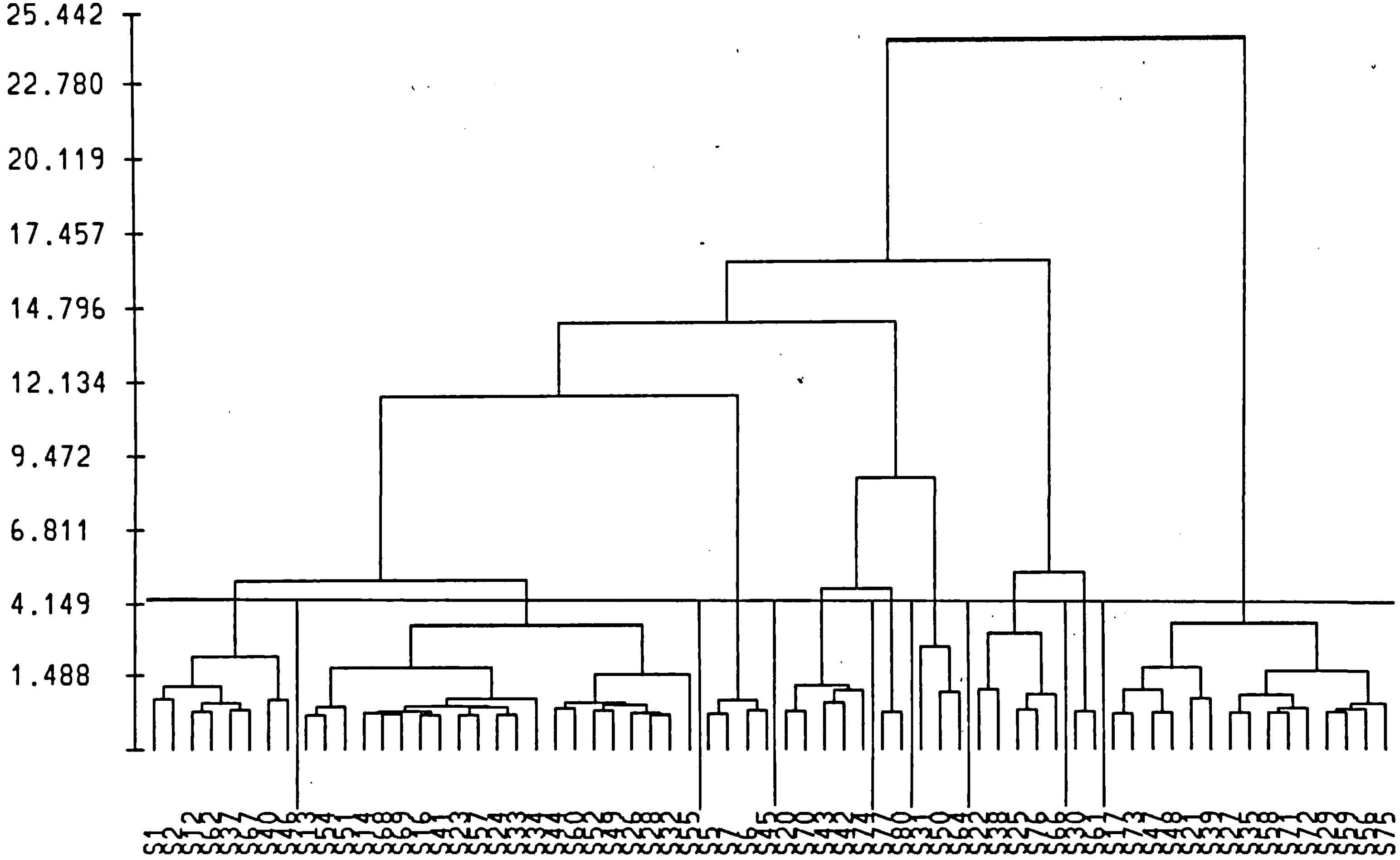
GRAVEL OF THE OUSE BASIN (K)

Figure 10.21 Cluster Dendrogram k.



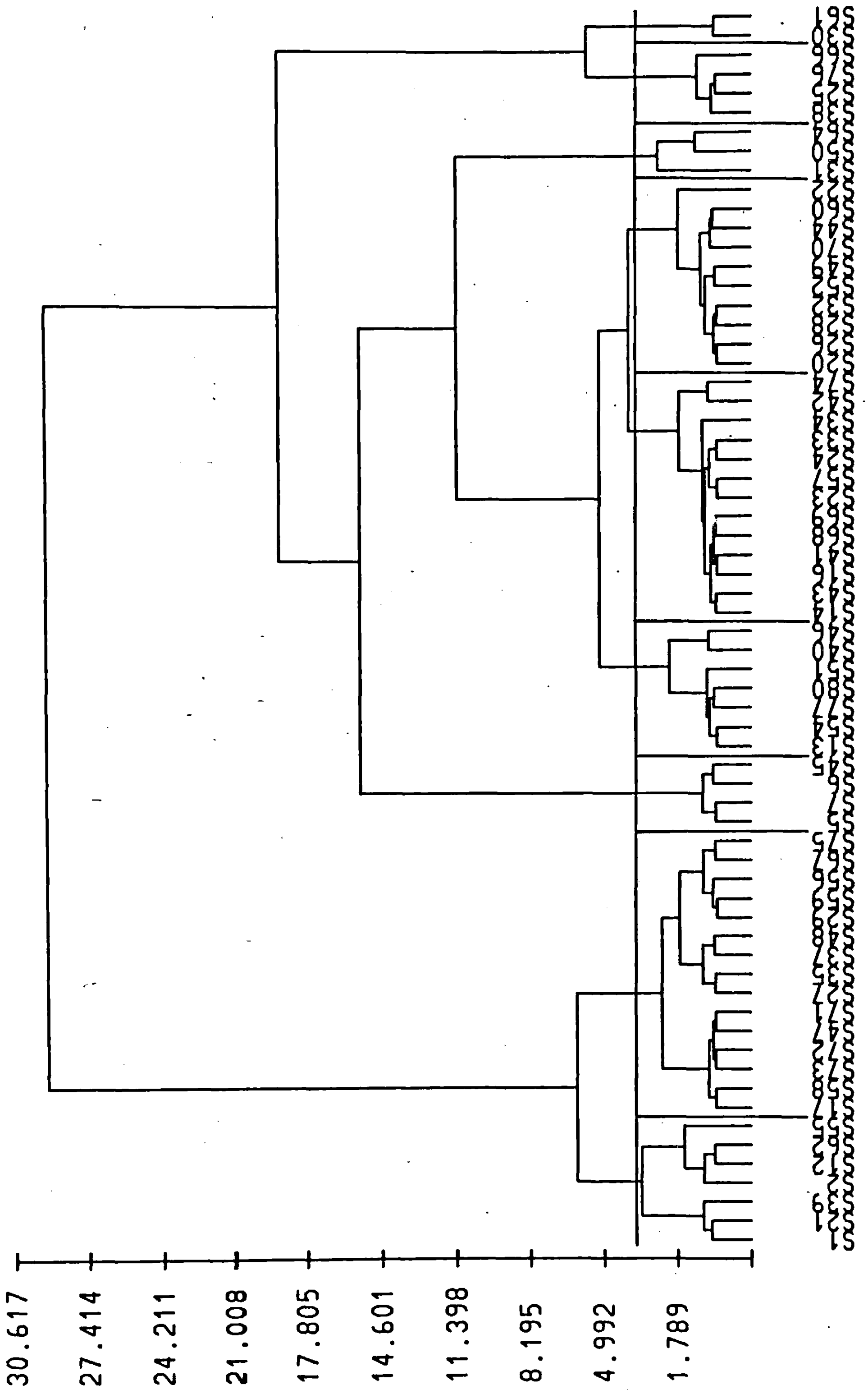
GRAVEL OF THE OUSE BASIN (L)

Figure 10.22 Cluster Dendrogram I.



GRAVEL OF THE OUSE BASIN (M)

Figure 10.23 Cluster Dendrogram m.



GRAVEL OF THE OUSE BASIN (N)

Figure 10.24 Cluster Dendrogram n.

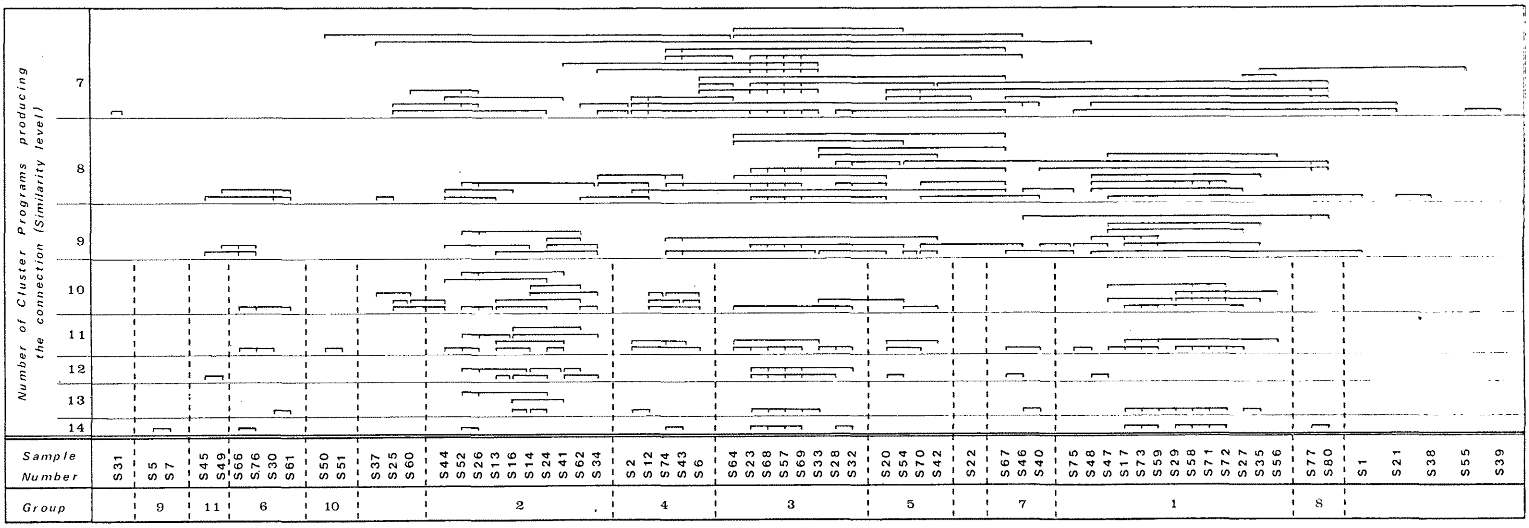


Figure 10.25a Groups indicated by Table 10.10.

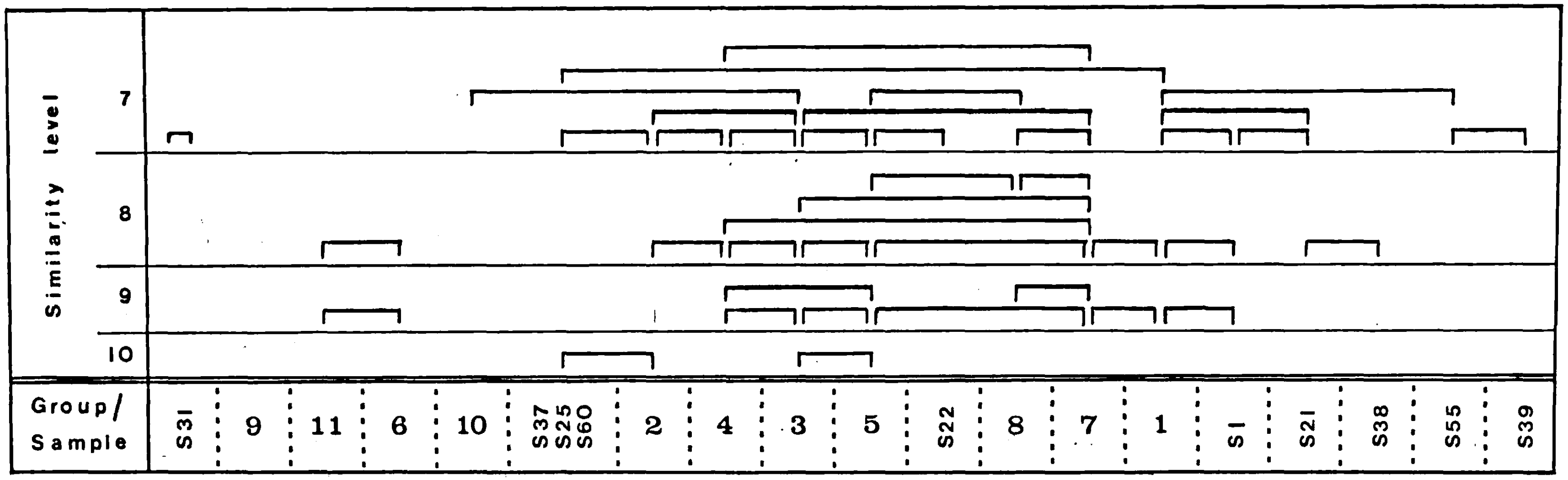


Figure 10.25b  Group linkages from similarity level eleven.

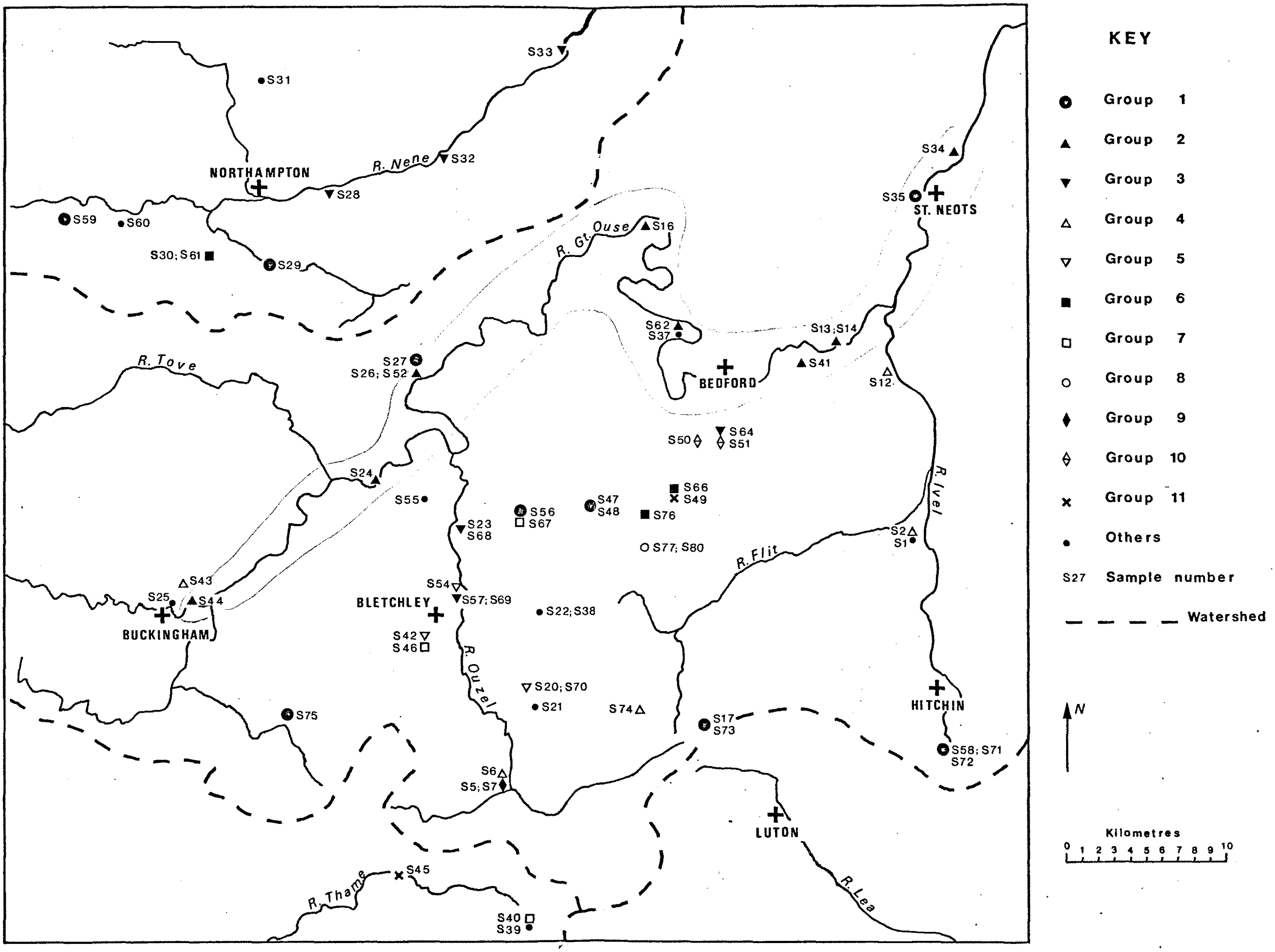
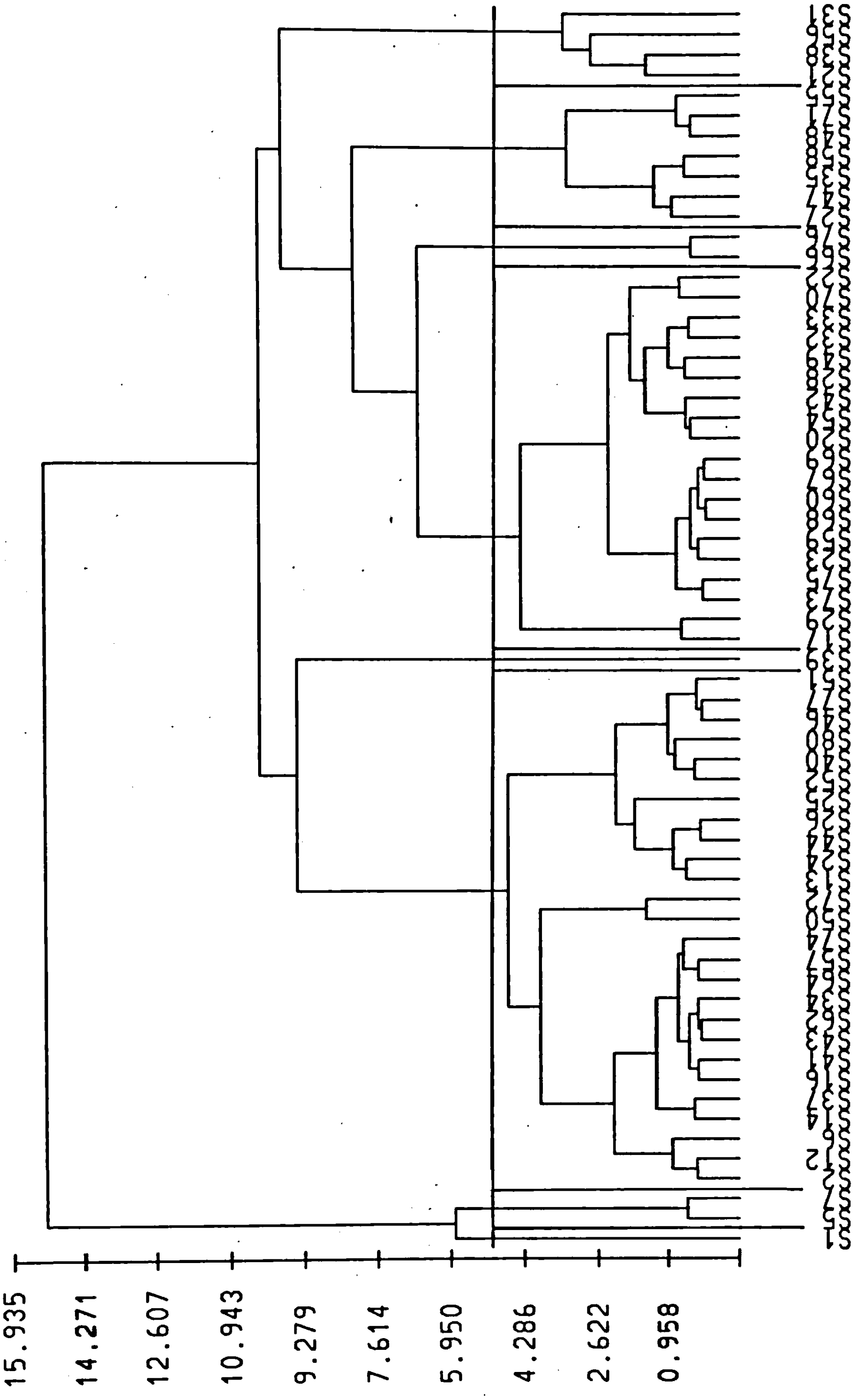


Figure 10.26 Distribution of Groups formed at similarity level eleven.



DECALCIFIED GRAVEL OF THE OUSE BASIN

Figure 10.27 Decalcified analysis dendrogram.

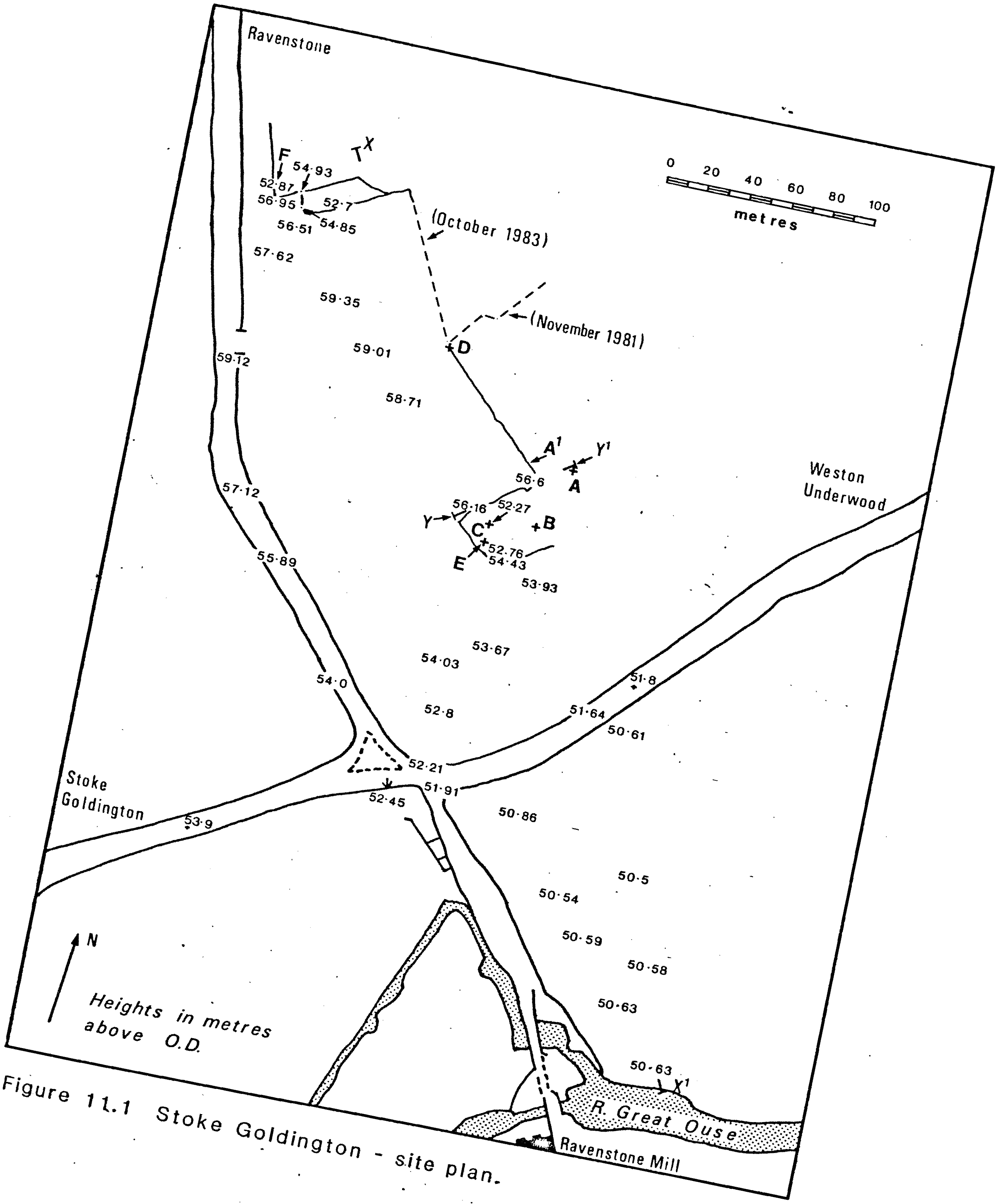


Figure 11.1 Stoke Goldington - site plan.

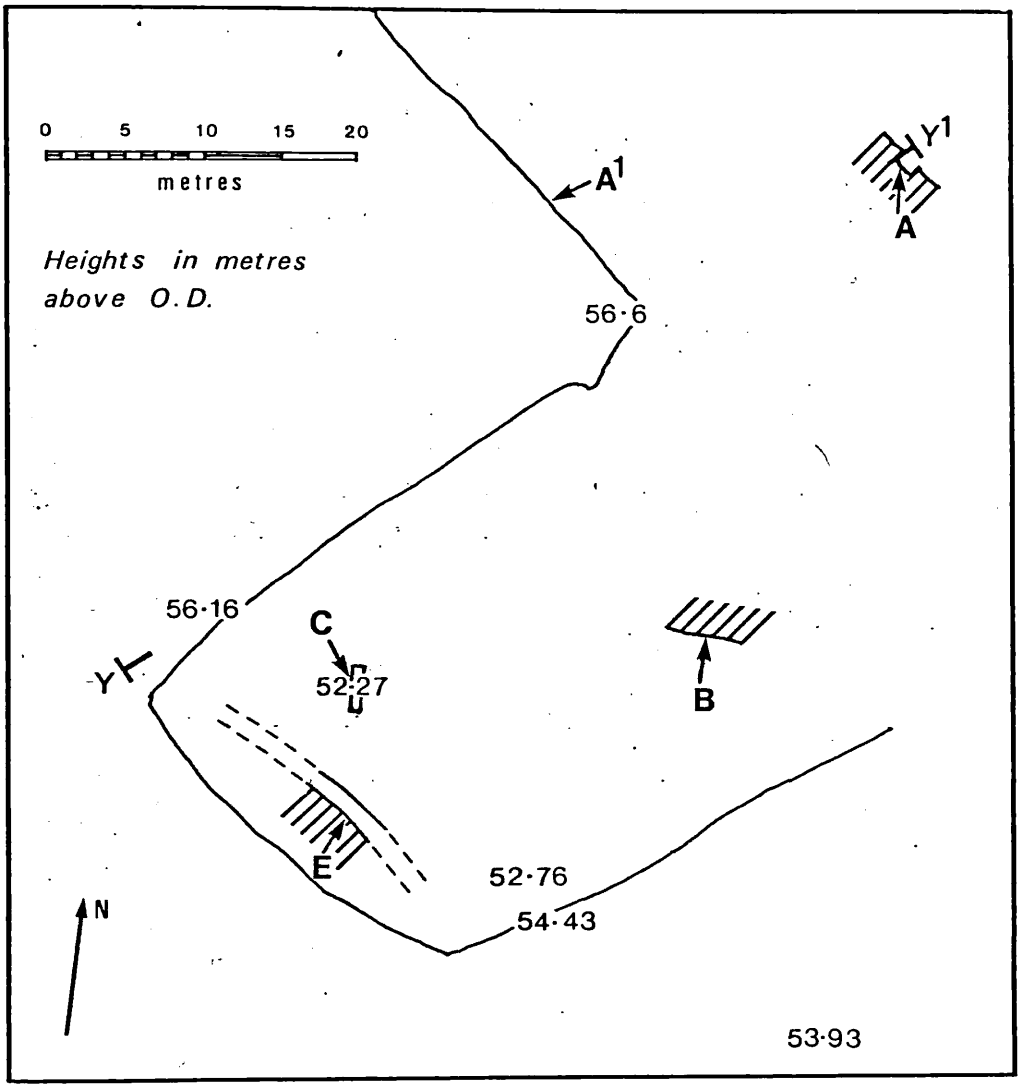


Figure 11.2 Stoke Goldington
- site plan of organic sections.

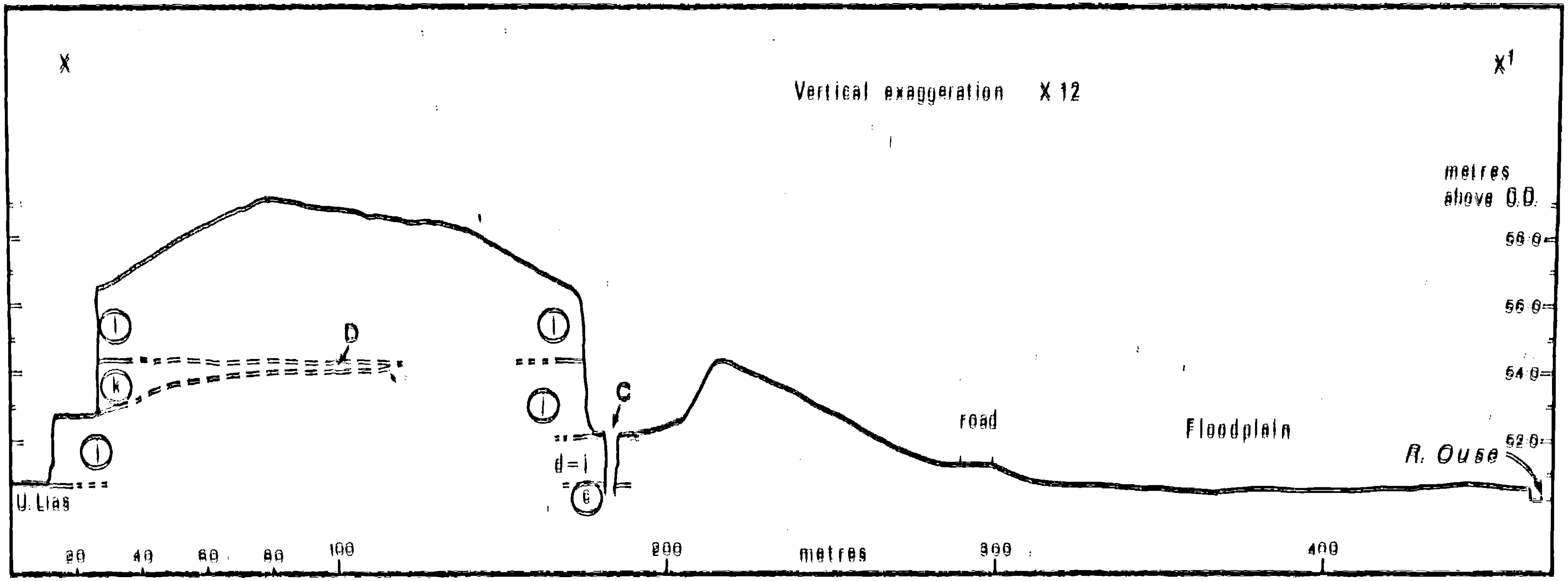


Figure 11.3 Stoke Goldington - cross-section X - X'.

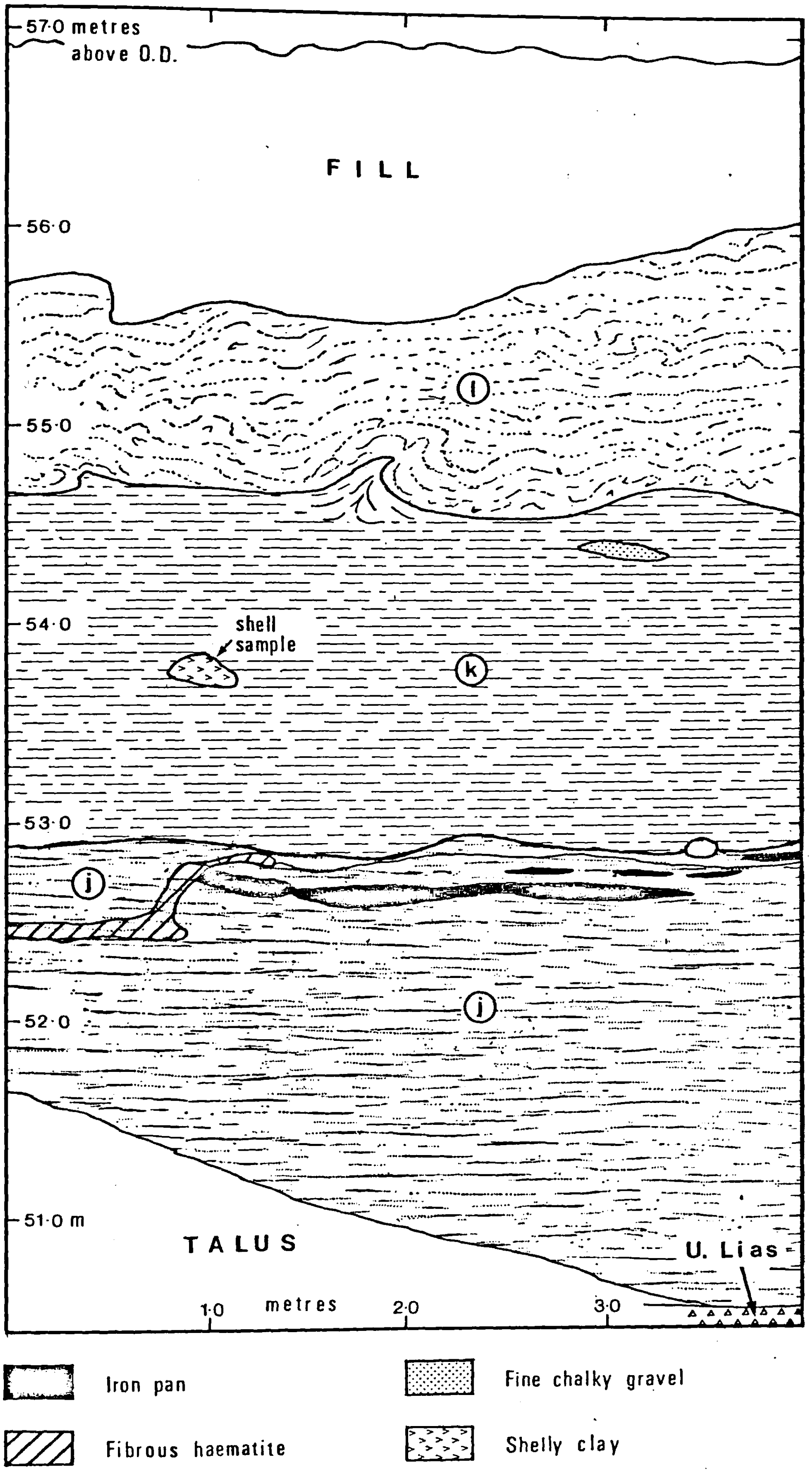
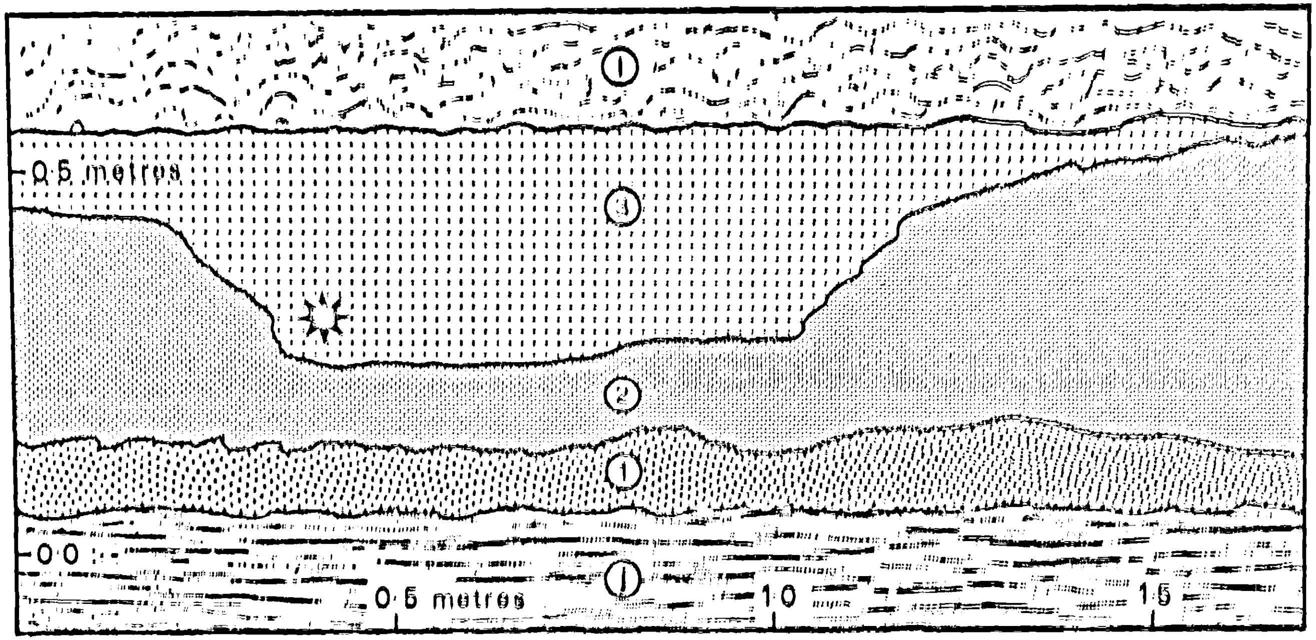


Figure 11.4 Stoke Goldington - section at point F.



|  |  |  |
|---|---|---|
| I | Upper involuted gravel. |  |
| 3 | Tenaceous clay (70-80% clay). |  |
| 2 | Clayey sand grading into 1. | k |
| 1 | Sandy clay. |  |
| j | Lower horizontally bedded gravel. |  |
| ✲ | Sample. |  |

Figure 11.5 Section at point D.

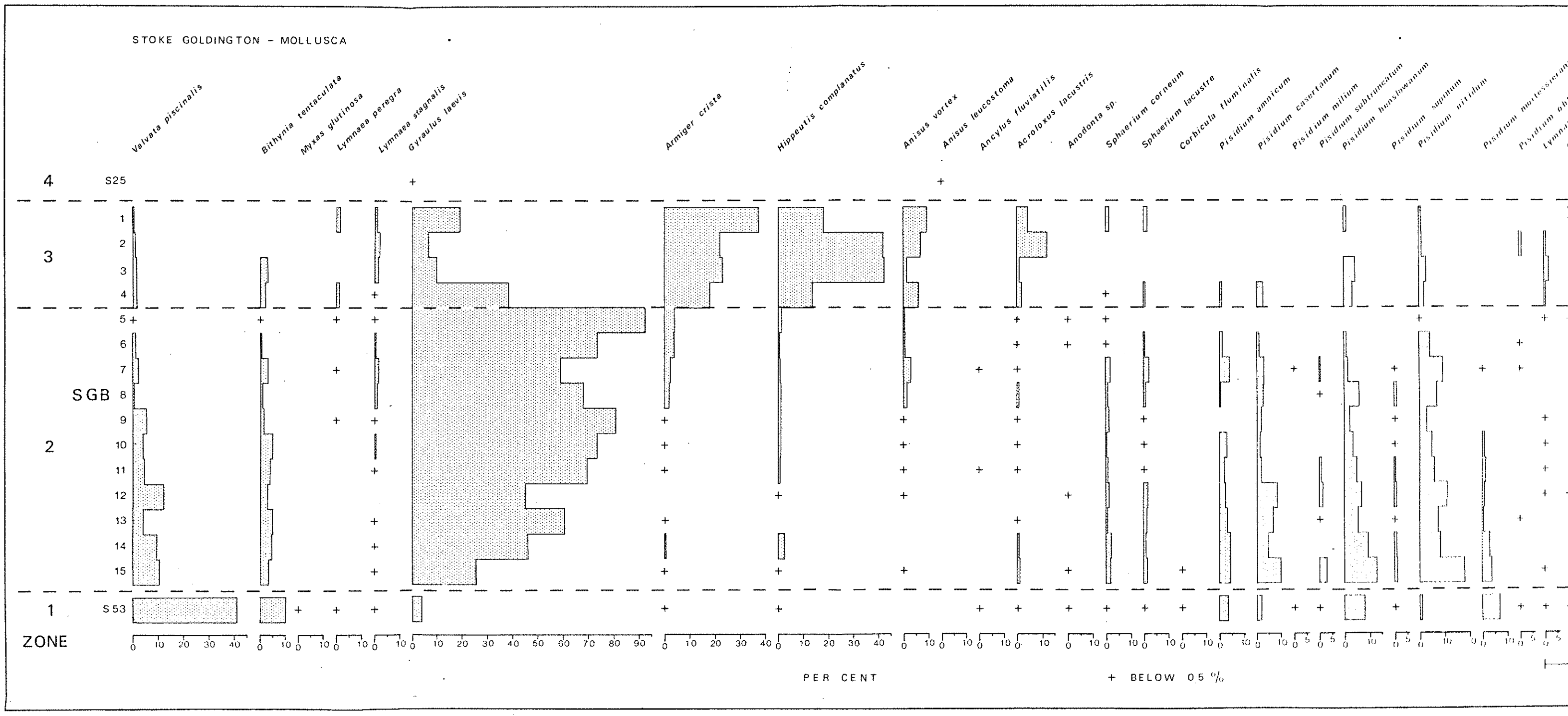
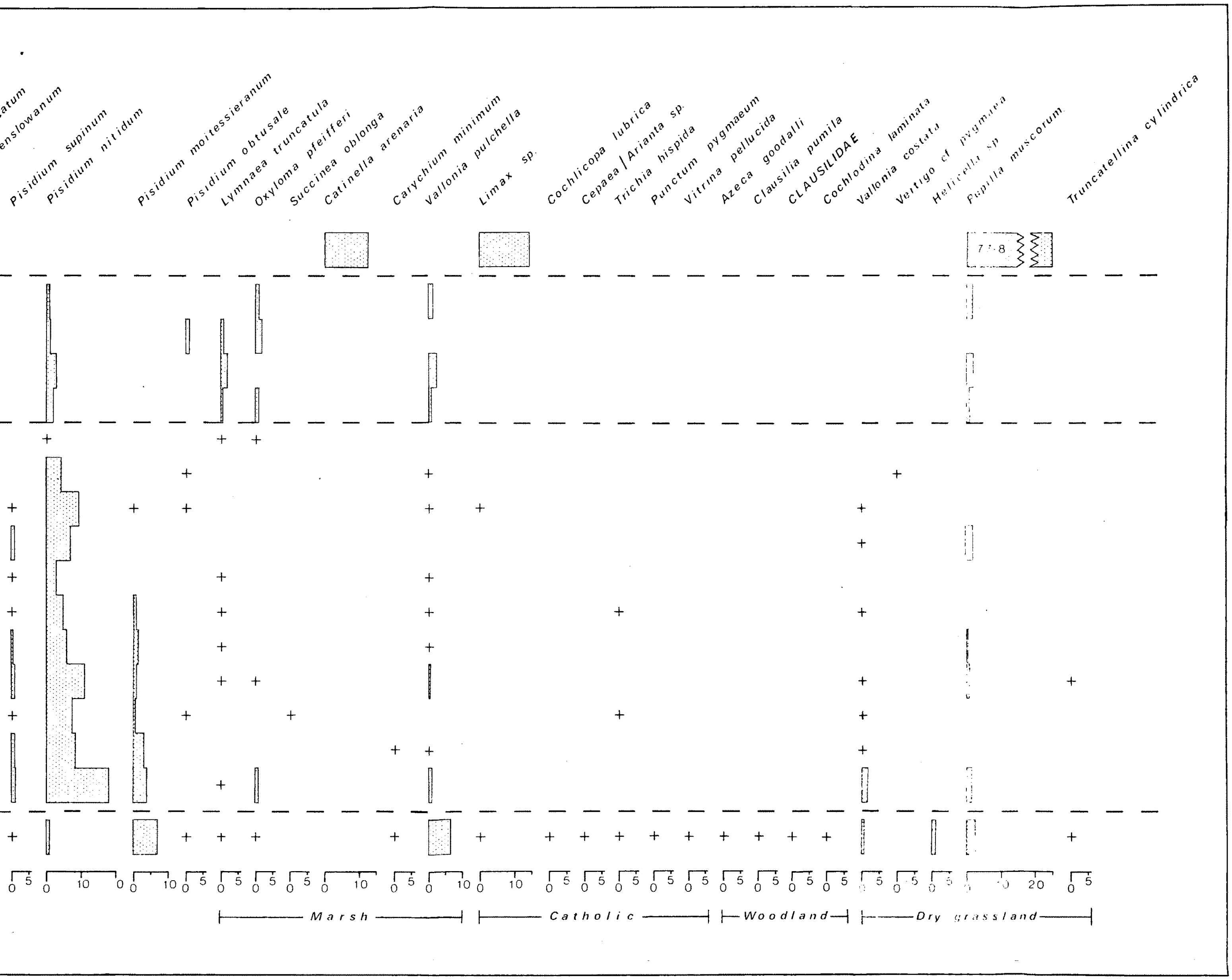


Figure 11.6 Stoke Goldington - Mollusca SGB15-SGB1.

428


...atum
...enslowanum
Pisidium supinum
Pisidium nitidum
Pisidium moitessieranum
Pisidium obtusale
Lymnaea truncatula
Oxyloma pfeifferi
Succinea oblonga
Catinella arenaria
Carychium minimum
Vallonia pulchella
Limax sp.
Cochlicopa lubrica
Cepaea / Arianta sp.
Trichia hispida
Punctum pygmaeum
Vitrina pellucida
Azeca goodalli
Clausilia pumila
CLAUSILIDAE
Cochlodina laminata
Vallonia costata
Vertigo cf pygmaea
Helicella sp
Pupilla muscorum
Truncatellina cylindrica
77·8
0 5
0 10
0 10
0 5
0 10
0 20
Marsh
Catholic
Woodland
Dry grassland

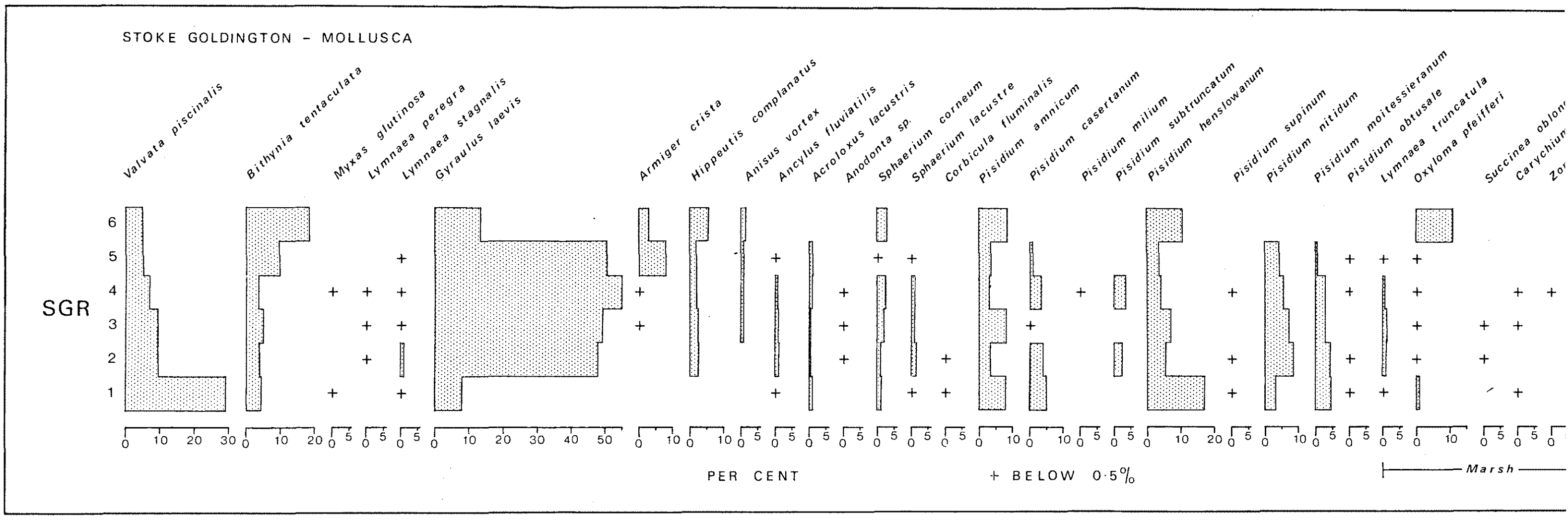
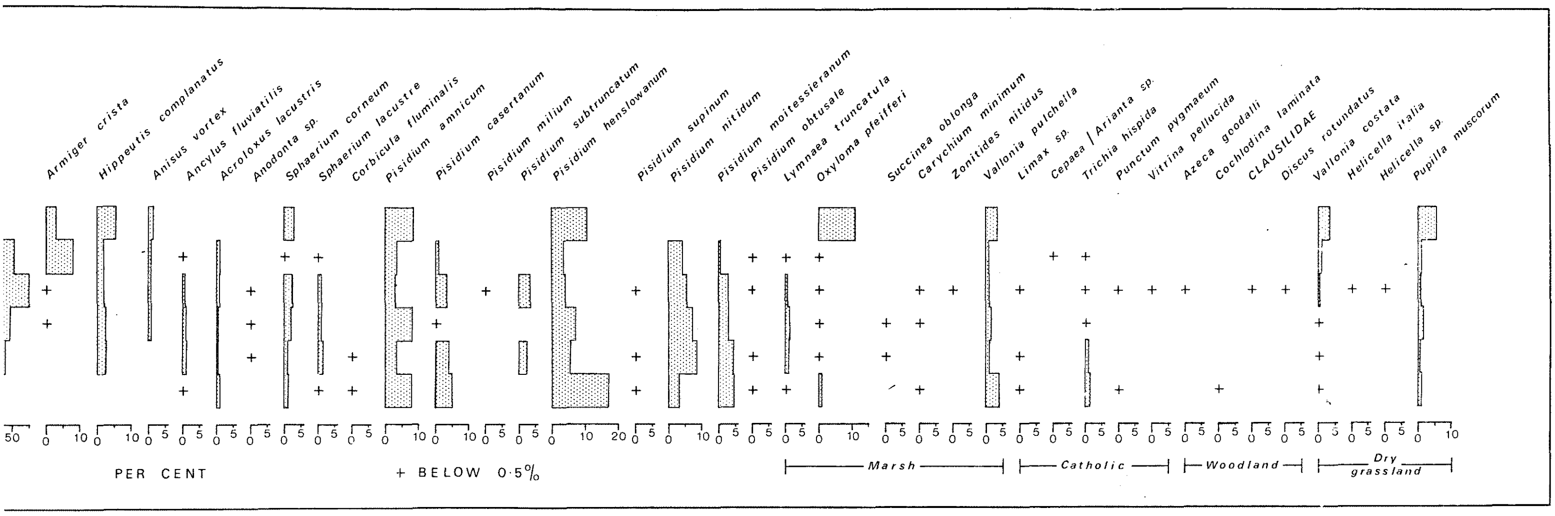


Figure 11.7 Stoke Goldington - Mollusca SGR1-SGR6.


Armiger crista
Hippeutis complanatus
Anisus vortex
Ancylus fluviatilis
Acroloxus lacustris
Anodonta sp.
Sphaerium corneum
Sphaerium lacustre
Corbicula fluminalis
Pisidium amnicum
Pisidium casertanum
Pisidium milium
Pisidium subtruncatum
Pisidium henslowanum
Pisidium supinum
Pisidium nitidum
Pisidium moitessieranum
Pisidium obtusale
Lymnaea truncatula
Oxyloma pfeifferi
Succinea oblonga
Carychium minimum
Zonitides nitidus
Vallonia pulchella
Limax sp.
Cepaea / Arianta sp.
Trichia hispida
Punctum pygmaeum
Vitrina pellucida
Azeca goodalli
Cochlodina laminata
CLAUSILIDAE
Discus rotundatus
Vallonia costata
Helicella italia
Helicella sp.
Pupilla muscorum
50
0 10
0 10
0 5
0 10
0 10 20
PER CENT
+ BELOW 0·5%
Marsh
Catholic
Woodland
Dry grassland

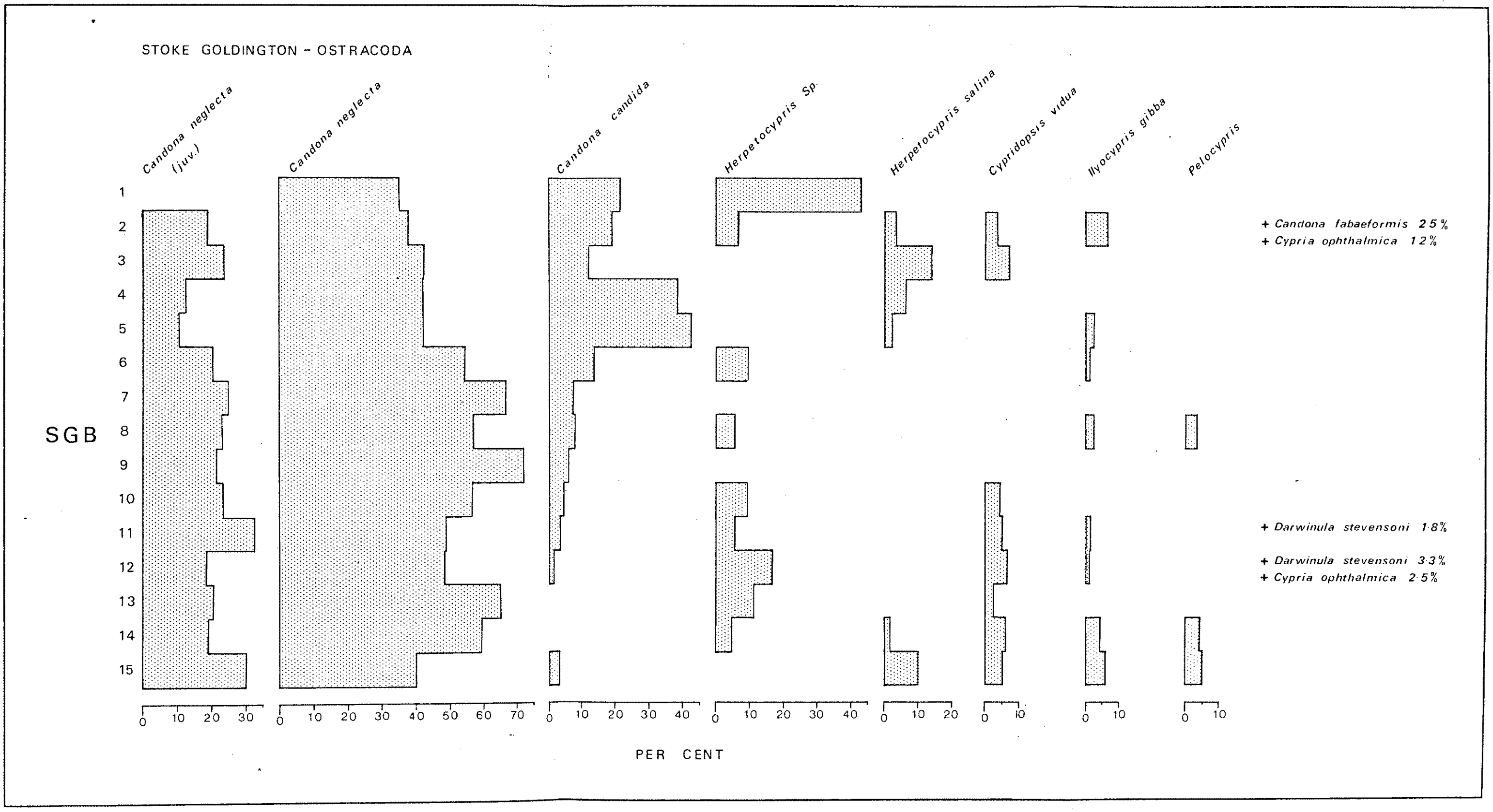


Figure 11.8 Stoke Goldington - Ostracoda SGB15-SGB1.

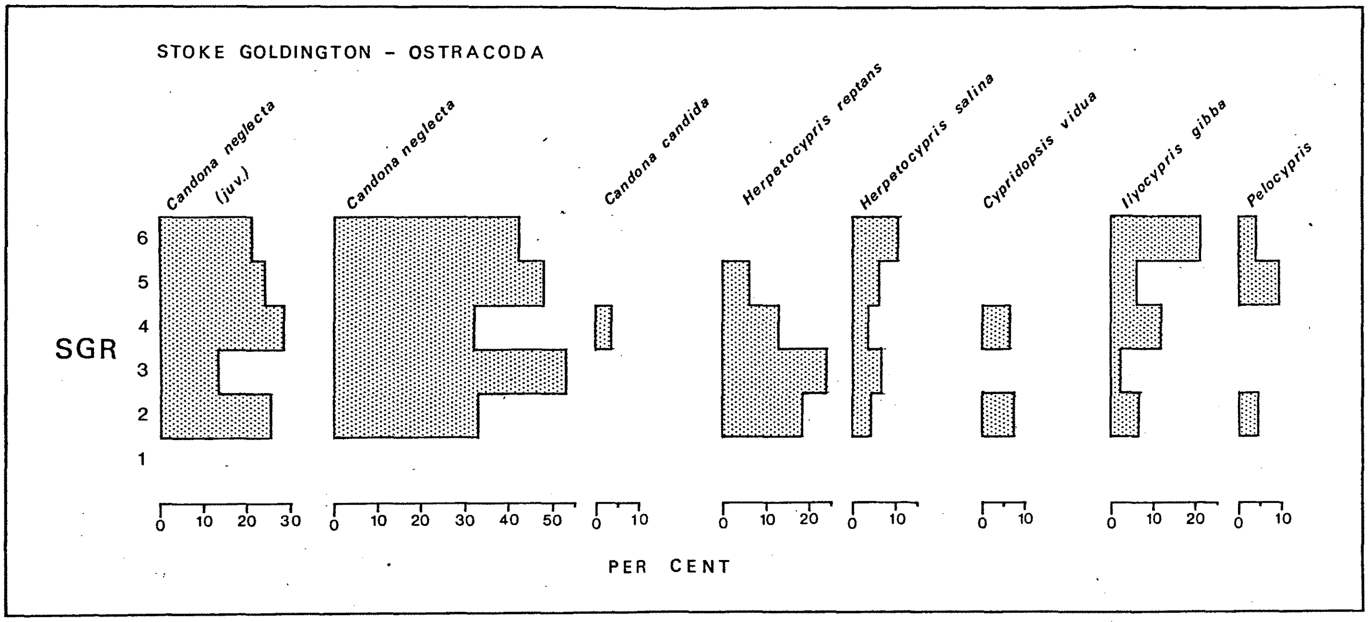


Figure 11.9 Stoke Goldington - Ostracoda SGR1-6

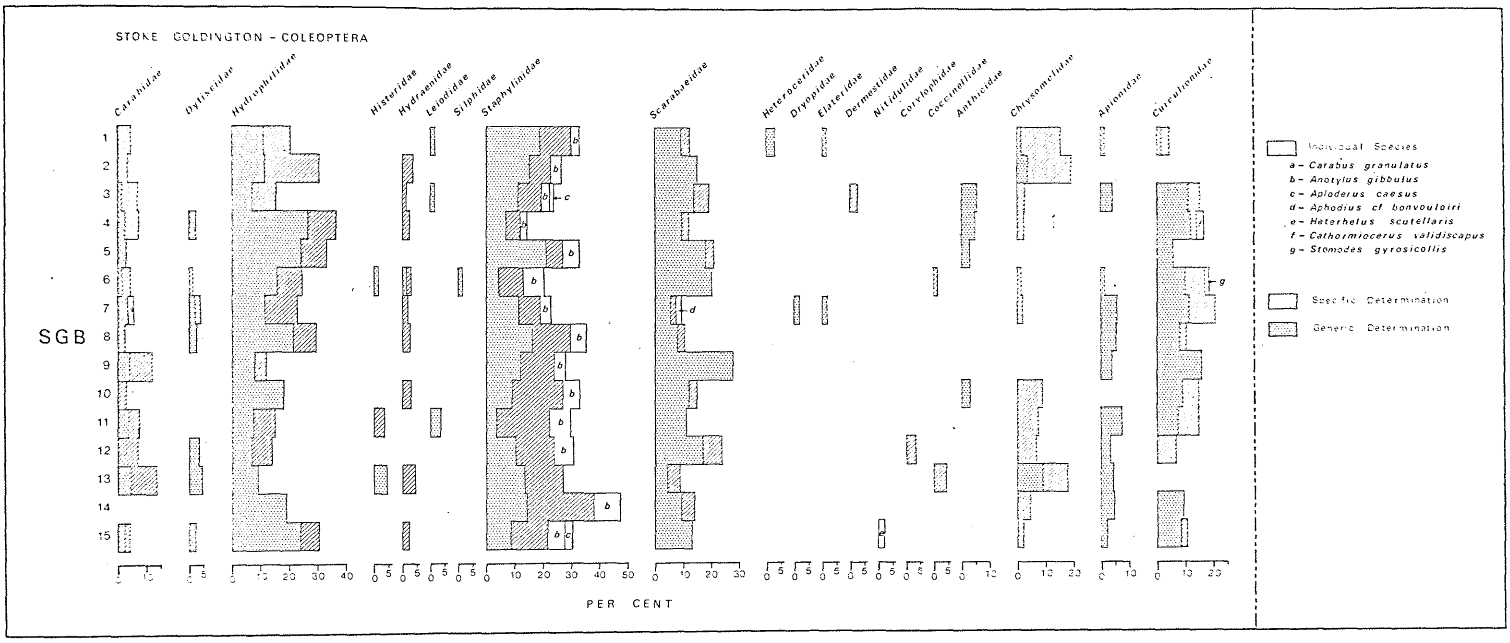


Figure 11.10 Stoke Goldington - Coleoptera SGB15-SGB1.

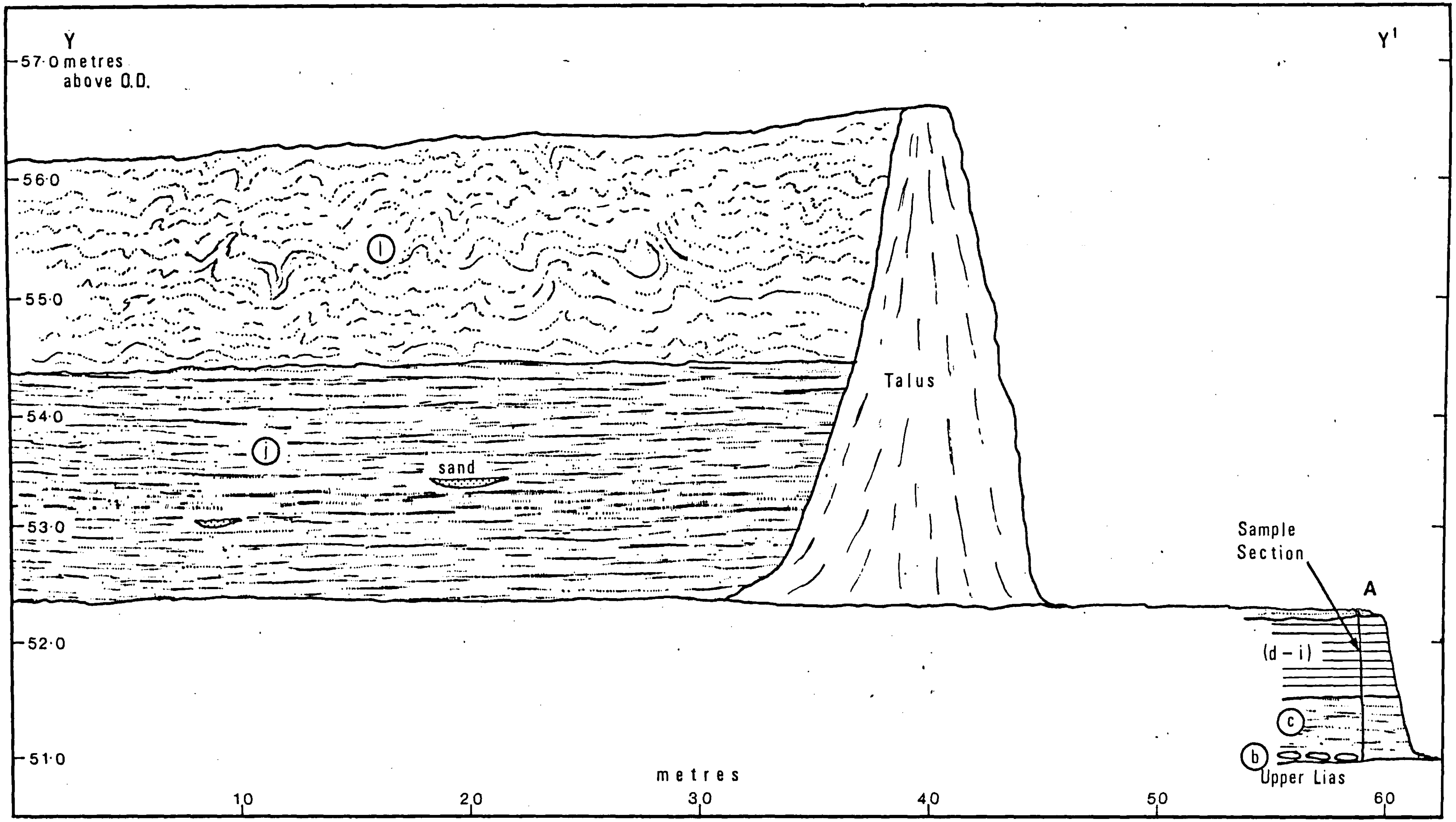


Figure 11.11 Stoke Goldington - cross-section Y - Y'.

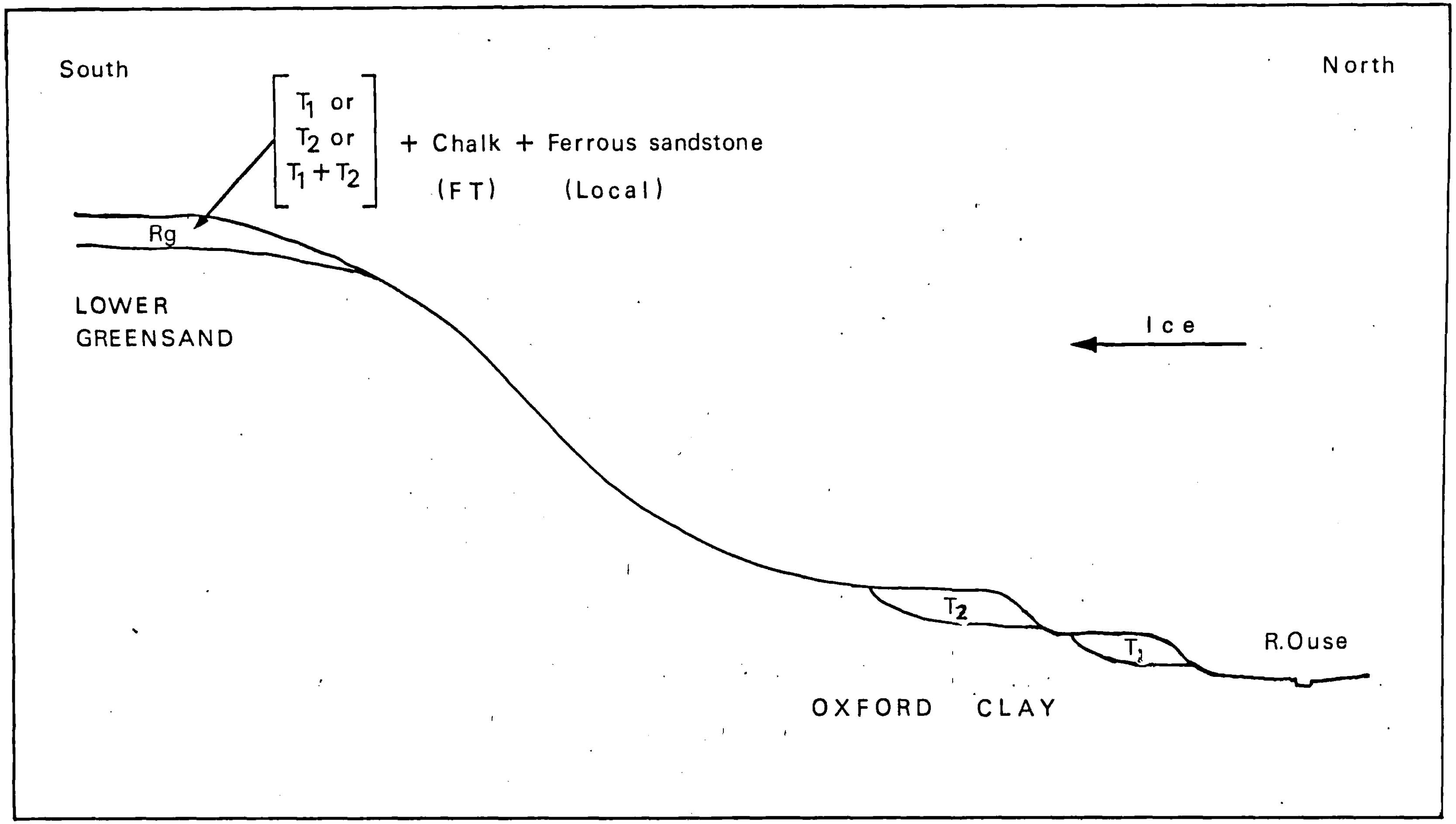


Figure 12.1 Redistributed gravels and terraces.

(see text for explanation).

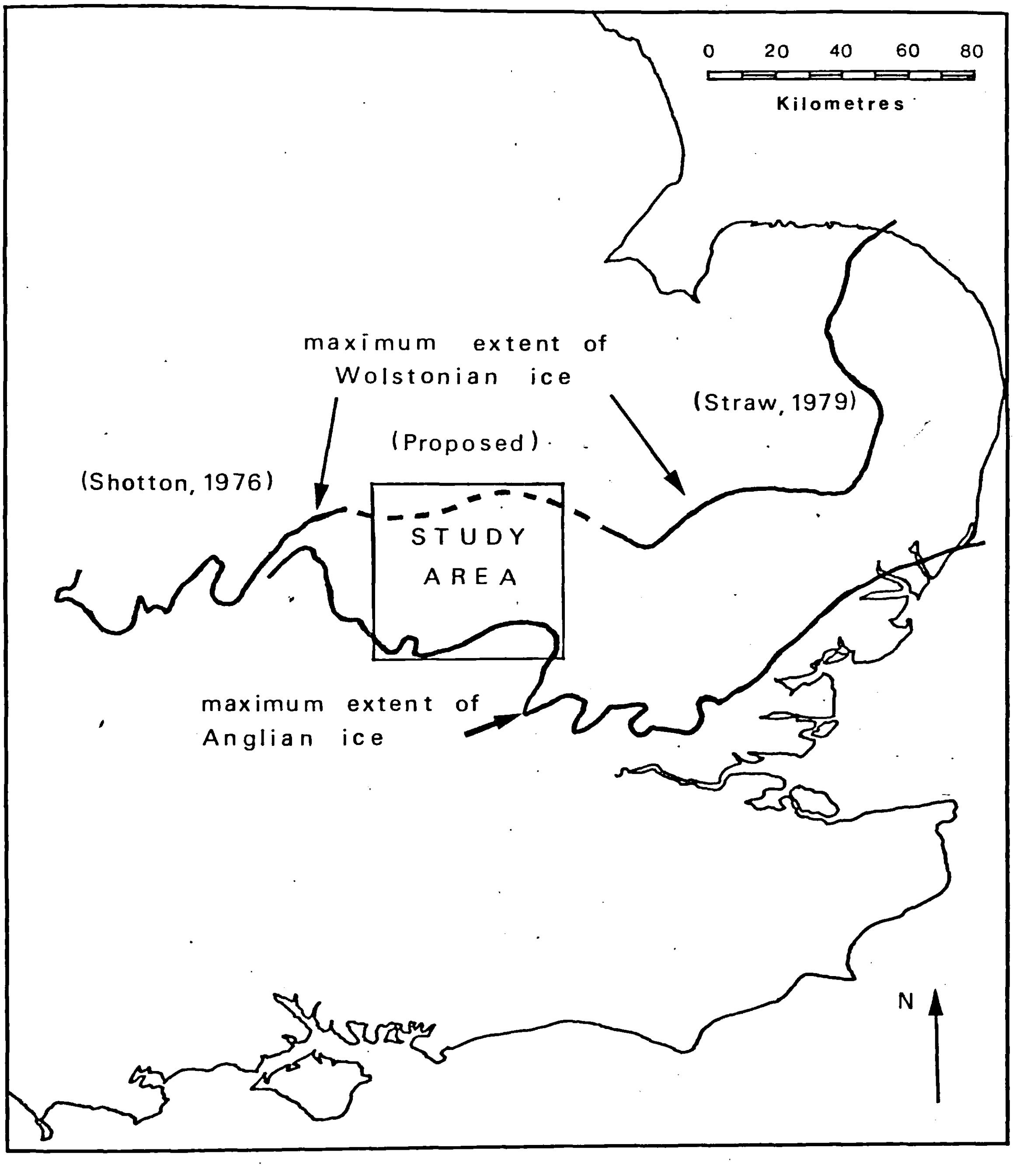


Figure 12.2 Proposed ice margins in southern Britain.

Table 2.1 Summary of geological stratum and their lithologies.

| Stratum | Main Characteristics | Lithologies available |
|---|---|---|
| Lias: | | |
| Lower | Blue grey clays, with nodules of clay ironstone; includes the Frodingham Ironstone - a ferrous oolitic limestone. | 5;6a;b. |
| Middle | Clay and silt with quartz grains grading upwards into Marl stone - a sandy oolitic limestone with iron. | 6b. |
| Upper | Fissile limestone and paper shales. Top is a rubbly limestone, commonly shelly and frequently with "false ooliths" of calcite. Contains phosphatic lumps. | 6a;8. |
| Inferior Oolite: | | |
| Northampton Ironstone | Ooliths of chamosite and limonite in a siderite and calcite matrix. It is sandy and passes down into green ferruginous sandstone. Oxidisation results in Ironstone "box" structures. Base includes phosphatic nodules. | 4;5;8. |
| Lower Estuarine Series | Dark grey fine sands, silts and clays. To north it becomes a flaggy limestone, passing through many gradations to calcareous sandstone and sand. | (3;6a). |

Table 2.1 cont.

| | | |
|---|---|---|
| Lincolnshire Limestone | Not present at the surface in the study area. It is mainly an oolitic limestone in a very fine calcitic matrix. May have up to 30% quartz. Remainder is broken shell and skeletal debris. | (6a). |
| Great Oolite: | | |
| Upper Estuarine Series | Clay, silts and sands with some rubbly and massive limestone. | 6a. |
| Blisworth Limestone | Termed "White Limestone", it is usually creamy or pale buff, rubbly and flaggy, composed of rolled shell fragments, occasionally associated with superficial ooliths and pellets. Absence of ooliths may lead to difficulty in distinguishing from Cornbrash. Compares to Lincolnshire Limestone, although latter has less skeletal debris. Proportion of shells and ooliths vary. Upper part may be ferruginous. | 6a;b. |
| Blisworth Clay | Variegated, bluish, greenish or purplish grey, black or yellow clay with impersistent sandy bands and ironstone nodules. | 5. |
| Cornbrash: | Hard detrital shelly limestone, brown to grey in colour with much fine to medium, well-rolled shell debris. Ooliths may be present and locally the limestone may be ferrous. Upper Cornbrash has more coarser shell debris and is more massive. It contains scattered phosphatic pebbles. | 6a;b;8. |

Table 2.1 cont.

| | | |
|---|---|---|
| Kellaways Beds: | Medium to dark grey, shaley mudstone, sands and silts. Partly calcareous. | |
| Oxford Clay: | Black, grey or bluish grey clay, richly fossiliferous with ammonites, lamellibranchs and belemnites. | |
| Corallian: | Iron shot oolitic limestone with dark grey or black tenaceous clay containing thin bands of hard, nodular and argillaceous limestone. | 6a;(10). |
| Kimmeridge Clay: | Marine muds and shales - highly fossiliferous. Some argillaceous limestones present. | (6a;8). |
| Portland and Purbeck: | Limestones and sands, containing quartz and 'lydian' stone (chert) pebbles. Limestone is hard, frequently rubbly and glauconitic. These are not found in the study area. | (1;8;9). |
| Lower Greensand: | Coarse, poorly-cemented, yellow glauconitic sands with iron-staining and frequent iron pans along joints. In places it is replaced by the variable Shenley Limestone. It contians "erratic" pebbles. | 1;2;3;4;6a;<br>8;9;10;11. |

Table 2.1 cont.

| | | |
|---|---|---|
| Gault Clay: | Dark to light grey, stiff and tenaceous clay becoming calcareous upwards. | 8. |
| Cambridge Greensand: | A glauconitic sandy marl containing erratics. | 1;2;3;8;9;11. |
| Chalk: | Soft, white to grey, fine-grained limestone with three hard grounds caused by increased shell and foraminiferal components. Contains at its base, erratics and in the Middle and Upper Chalk increasing amounts of flint. | 1;3;7;8;9; 11. |

---

| Lithologies: | | | Hardness |
|---|---|---|---|
| 1) | Quartz | (Qtz) | VH |
| 2) | Quartzite | (Q'ite) | VH |
| 3) | Sandstone | (S'stn) | VS - VH |
| 4) | Ferrous Sandstone | (FeS) | S - H |
| 5) | Ironstone | (Is) | H |
| 6a) | Limestone | (Ls) | S - H |
| b) | Ferrous Limestone | (FeLs) | S - H |
| 7) | Chalk; Flint | (Ch; Fl) | S - H; VH |
| 8) | Phosphatic nodules | (Pn) | H - VH |
| 9) | Chert and/or Cherty sandstone | (C / Cs) | VH |
| 10) | "Rhaxella" Chert | (RC) | VH |
| 11) | Igneous pebbles | (Ig) | VH |

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Where lithologies are in brackets, they are not found within the study area but can be found in strata to the north.
VS=Very Soft; S=Soft; H=Hard; VH=Very Hard.

Table 4.1 Fauna described in pits around Bedford.

| | Biddenham | Kempston | Harrowden | Summerhouse Hill | Willington | Railway Cutting |
|---|---|---|---|---|---|---|
| Land and Freshwater shells (using Wyatt's and Prestwich's terminology). | | | | | | |
| Sphaerium | | | | 4 | | |
| Pisidium | 1;2 | | | 4 | | |
| Bythinia | 1;2 | 3 | | 4 | | |
| Valvata | 1;2 | | | 4 | | |
| Succinea | 2 | 3 | | 4 | | |
| Helix | 1;2 | 3 | | 4 | | |
| Pupa | | 3 | | 4 | | |
| Planorbis | 1;2 | 3 | | 4 | | |
| Limnaea | 1;2 | | | 4 | | |
| Ancylus | | | | 4 | | |
| Zua | | | | 4 | | |
| Unio | | | | 4 | | |
| Valletia | 2 | | | | | |
| Cyclas | 1;2 | | | | | |
| Paludina | 2 | | | | | |
| Hydrobia | 3;9 | | | | | |

Table 4.1 cont.

| | Biddenham | Kempston | Harrowden | Summerhouse Hill | Willington | Railway Cutting |
|---|---|---|---|---|---|---|
| Mammals * | | | | | | |
| Mammuthus primigenius (Mammoth) | 1;2 | | 2 | | 6;7;8; | |
| Palaeoloxodon antiquus (Straight tusked elephant) | 2;5 | | | 4 | | 1 |
| Bos primigenius (aurochs) | 2;5 | | | 4 | 8 | |
| Cervus elaphus (Red Deer) | 1;5 | | 2 | 4 | | 1 |
| Rangifer tarandus (Reindeer) | 2 | | | 4 | 8 | |
| Ursus (Bear) | | | | 4 | | |
| Equus (Horse) | 1;2;5 | | 2 | | | 1 |
| Hippopotamus (Hippopotamus) | | | | 4;5 | | 1 |
| Coelodonta antiquitatis (Woolly Rhinoceros) | 1;2;5 | | 2 | | 8 | 1 |
| Ox | 1;5 | | 2 | | | 1 |

Table 4.1 cont.

| | Biddenham | Kempston | Harrowden | Summerhouse Hill | Willington | Railway Cutting |
|---|---|---|---|---|---|---|
| Flint Implements | | | | | | |
| Unspecified type | 1;2;4 | 3;4 | 2;4 | 4 | | |
| Chellian | 6 | | | | 6 | |
| Late Acheulian/ Mousterian | | | 6 | | | |
| Acheulian | 6 | | | | | |
| Mousterian | 6 | | | | | |
| Comments | 1 High-level g. (18m above flood-plain, (a fp)) | 3 9.1m a fp. | 3 Similar fauna to Biddenham.<br>6 Lower than Biddenham. (9.1m a fp) | 4 Low-level (1.4-1.5m a fp) | 6 low-level 1.4-1.5m a fp) | 1 (9.1m a fp) |

* Due to the inconsistent use of terminology in the literature, and the change in terminology through time, all the mammalian species have been referred to the modern terminology of Stuart (1982).
1=Prestwich (1861); 2=Wyatt (1861); 3=Wyatt (1862); 4=Wyatt (1864);
5=Doubleday and Page (1904); 6=Banton (1924); 7=Mantle (1926); 8=Bate (1926).
9=Harrison (1877).

Table 4.2 Second terrace gravel samples (% wt) (after Castleden, 1980b).

| Sample No. and Nat.Grid.Ref. | Q'tz | F'spar | Q'ite | Ch | Fl | Ls | Is | S'stn | F.T. | Local |
|---|---|---|---|---|---|---|---|---|---|---|
| 5: Billing SP808621. | 1.4 | | 25.7 | | 31.5 | 31.4 | 2.9 | 7.1 | 58.6 | 41.4 |
| 6: Grendon SP880618. | | 0.4 | 9.2 | 15.0 | 26.8 | 37.6 | 9.8 | 1.2 | 51.4 | 48.6 |
| 7: Grendon | | | 8.9 | 8.5 | 35.0 | 41.8 | 5.8 | | 52.4 | 47.6 |

Q'tz=Quartz; F'spar=Feldspar; Q'ite=Quartzite; Ch=Chalk; Fl=Flint;
Ls=Limestone; Is=Ironstone; S'stn=Sandstone; F.T.=Far-travelled.

Table 4.3 Summary of Terrace Characteristics.

Ouse Terraces

| Terrace No. | Height above floodplain | Gravel constituents | Comments | Reference |
|---|---|---|---|---|
| Third Terrace: | | | | |
| | 15.2m | | | Dury (1952) |
| Ouse below Bedford and R.Ivel. | 14.6-17.6m | | | Edmonds and Dinham (1965) |
| | 16.1-17.6m at St.Neots; 8.5m at Holywell. | | Converges with alluvium downstream. | Horton (1970) |
| Second Terrace: Above Bedford. Ouse: | 3.1-4.6m | Local:Jur Ls, Is.<br>Erratic: Fl, Ch, Bu pebbles. | | Horton (1970) |
| | 2.0-4.5m | | | Horton et al. (1974) |

Table 4.3 cont.

| | | | | |
|---|---|---|---|---|
| Ouzel: | 3.0-5.5m | Fl, Ch, Jur Ls, Is, Belemnites, Gryphaea, Phosphatic casts of Ammonites. | Terraces are parallel to each other and the the alluvium. Terraces are thought to relate to those below Bedford | Horton *et al.* (1974) |
| Below Bedford. | Where separate 2.7-4.8m | | First and second terraces merge. | Horton (1970) |
| First Terrace: Above Bedford. | 0.6-2.0m | Bu-derived pebbles, "with minor amounts of Ch, Jur. and other rocks" | | Horton *et al.* (1974) |
| Below Bedford. | 1.2-1.5m | | | Horton (1970) |
| Nene Terraces | | | | |
| Third Terrace: | 10.6-16.8m | Fl, Bu-Q'ite, Is, Ls, brown S'stn, Q'tz grit, silicified S'stn, gneissose granite. | | Taylor (1963) |
| | | Bu-Q'ite, gritstone, Fl, Ch, granite, shelly and oolitic Ls, sideritic Is and S'stn. | Terrace is well dissected. Gravel is positively skewed. | Castleden (1980b) |

Table 4.3 cont.

| | | | | |
|---|---|---|---|---|
| Second Terrace: | | | | |
| | 4.6-9.1m (mean 7.6m) | Local: shelly and oolitic Ls, Sideritic Is and S'stn, Erratic: Bu-Q'ite, white Q'tz, Fl, Ch, Feldspar. | | Taylor (1963) |
| | 4.0m | | | Castleden (1977) |
| First Terrace: | | | | |
| | 1.2-2.4m | | Least dissected of the terraces | Taylor (1963) |
| | | Fl, Shelly Ls. | | Morgan (1969) |
| | | Fl, Ch, Q'ite, Ls, Hornblende, gneiss. | | Castleden (1976) |

Jur=Jurassic; Fl=Flint; Ch=Chalk; Q'tz=Quartz; Q'ite=Quartzite; S'stn=Sandstone
Ls=Limestone; Is=Ironstone; Bu=Bunter.

Table 5.1 East Anglian correlations.

| Boswell (1931)<br>Solomon (1932)<br>Baden-Powell (1948) | | West and Donner (1956) | | | | Perrin *et al.* (1973)<br>Bristow and Cox (1973)<br>Perrin *et al.* (1979) | |
|---|---|---|---|---|---|---|---|
| Hunstanton Till | 4 | | | | | Hunstanton Till | 2 |
| March Gravels | | | | | | Ipswichian lake clays | |
| Gipping Till | 3 | Gipping Till | | | 2 | Cold | |
| Hoxne Interglacial | | | | | | Hoxnian lake clays | |
| Lowestoft Till | 2 | Lowestoft II | (retreat) ] | l | | Main Chalky Till (Anglian) | 1 |
| | | Lowestoft I | ] ] | ot | | (Norwich Brickearth) | |
| Corton Beds | | | ]advance] | wo | 1 | | |
| Norwich Brickearth ] | N.S.D. | Norwich Brickearth | ] ] | ef | | | |
| Cromer Till ] | 1 | Cromer Till | ] ] | st | | | |

1, 2, 3, 4. Number of Glacial events; N.S.D. = North Sea Drift.

Table 5.2 Midlands correlations.

| Coventry (Shotton, 1953) | N. Leicestershire (Rice, 1968) | S. Leicestershire (Shotton, 1976; Rice, 1981) | W. Leicestershire (Douglas, 1980) | (Sumbler, 1983) |
|---|---|---|---|---|
| Dunsmore Gravel | | Dunsmore Gravel | Flint Gravel | Dunsmore Gravel |
| Upper Wolston Clay ] | Oadby Till | Upper Oadby Till<br>Lower Oadby Till | Pennine Till /<br>Chalk Till | Upper Wolston Clay |
| Wolston Sand ] | Wigston S. and G. | Wolston S. and G. | Cadeby S. and G. | Wolston S. and G. |
| Lower Wolston Clay ] | Glen Parva Clay<br>Thrussington Till | Bosworth silts and clays<br>Thrussington Till | Basal Till | Lower Wolston Clay<br>Thrussington Till |
| Baginton Sand<br>Baginton-Lillington G. | Thurmaston S. and G. | Baginton Sand<br>Baginton-Lillington G. | | Baginton S. and G. |
| Bubbenhall Clay | | | | |

S=Sand; G=Gravel.

Table 5.3 Terrace succession of the Upper Thames.

| | Bishop (1958); Mitchell *et al.* (1973). | Shotton *et al.* (1980); Briggs and Gilbertson (1973); Briggs *et al.* (1975); Shotton (1980). |
|---|---|---|
| Northern Drift | Anglian | Pre-Pastonian/Anglian |
| Hanborough Terrace | Hoxnian | Late Anglian/Early Wolstonian |
| Wolvercote Terrace | Late Wolstonian | Late Wolstonian |
| Summertown-Radley Terrace - Lower | Late Wolstonian/ early Ipswichian | Late Wolstonian |
| - Upper | Ipswichian | Ipswichian |
| Wolvercote Channel | Late Ipswichian | Late Ipswichian |
| Floodplain | Devensian | Devensian |

Table 5.4 Terraces of the Upper Thames and the Trent.

| Avon | Soar | Trent | Evenlode | Age |
|---|---|---|---|---|
| 1 | Quardon | | | |
| 2 | Syston | Floodplain terrace | Floodplain | Devensian |
| 4 | Wanlip | | | |
| 3 | Birstal | Beeston | Upper Summertown-Radley | Ipswichian |
| 5 | Knighton Surface | Hilton | Lower Summertown-Radley | late Wolstonian |
| Dunsmore Gravel | | | Wolvercote | Wolstonian |
| | | | Hanborough terrace | early Wolstonian |
| | | | Sugworth terrace | |

Table 5.5 Terraces of the Lower Thames

| Stage | Reference | Age |
|---|---|---|
| 500' Pebble Gravel ] | Wooldridge, 1927 | |
| 400' Pebble Gravel ] | | |
| Westland Green Gravel | Hey, 1965 | |
| CHILTERN DRIFT | Wooldridge, 1938 | |
| Higher Gravel Train ] | Wooldridge, 1938 | |
| Lower Gravel Train ] | | |
| Upper Winter Hill Terrace ] | Soner and Wooldridge, 1929; Wooldridge, 1938; Sealy and Sealy, 1956 | Late Cromerian |
| Lower Winter Hill Terrace ] | | |
| CHALKY TILL | | Anglian |
| Black Park Terrace | Hare, 1947 | Late Anglian |
| Boyn Hill Terrace | | Hoxnian |
| Lynch Hill Terrace | Hare, 1947 | Hoxnian / Wolstonian |
| Upper Taplow Terrace ] | Sealy and Sealy, 1956 | Ipswichian / |
| Lower Taplow Terrace ] | | Ilfordian |
| Upper Floodplain | | Ipswichian |
| Lower Floodplain | | Devensian |

Table 7.1 Sample numbers and sample sites.

| Sample Number | Site Number | Site Name |
|---|---|---|
| S1 | 28 | Clifton |
| S2 | 28 | Clifton |
| S5 | 17 | Leighton Buzzard |
| S6 | 17 | Leighton Buzzard |
| S7 | 17 | Leighton Buzzard |
| S12 | 10 | Blunham |
| S13 | 5 | Great Barford |
| S14 | 5 | Great Barford |
| S16 | 3 | Radwell |
| S17 | 20 | Upper Sundon |
| S20 | 15 | Fox Corner |
| S21 | 16 | Rushings |
| S22 | 24 | Aspley Guise |
| S23 | 2 | Broughton |
| S24 | 8 | Great Linford |
| S25 | 25 | Buckingham |
| S26 | 33 | Stoke Goldington |
| S27 | 33 | Stoke Goldington |
| S28 | 34 | Clifford Hill |
| S29 | 39 | Wootton |
| S30 | 38 | Milton Malsor |
| S31 | 37 | Pitsford |
| S32 | 35 | Earls Barton |
| S33 | 36 | Rushden |
| S34 | 9 | Little Paxton |
| S35 | 23 | St. Neots |
| S37 | 30 | Bromham |
| S38 | 24 | Aspley Guise |
| S39 | 43 | Marsworth |
| S40 | 43 | Marsworth |
| S41 | 6 | Willington |
| S42 | 18 | Bletchley |
| S43 | 27 | Buckingham |
| S44 | 26 | Buckingham |
| S45 | 42 | Rowsham |
| S46 | 18 | Bletchley |
| S47 | 19 | Ridgmont |
| S48 | 19 | Ridgmont |
| S49 | 11 | Stewartby |
| S50 | 12 | Kempston |
| S51 | 13 | Elstow |
| S52 | 33 | Stoke Goldington |
| S54 | 7 | Simpson |
| S55 | 29 | Lodge Farm |
| S56 | 4 | Broughton Ground |
| S57 | 1 | Bow Brickhill |
| S58 | 21 | Ippollitts |
| S59 | 40 | Weedon Bec |
| S60 | 41 | Nether Heyford |
| S61 | 38 | Milton Malsor |
| S62 | 30 | Bromham |
| S64 | 13 | Elstow |

Table 7.1 cont.

| Sample Number | Site Number | Site Name |
|---|---|---|
| S66 | 11 | Stewartby |
| S67 | 4 | Broughton Ground |
| S68 | 2 | Broughton |
| S69 | 1 | Bow Brickhill |
| S70 | 15 | Fox Corner |
| S71 | 21 | Ippollitts |
| S72 | 21 | Ippollitts |
| S73 | 20 | Upper Sundon |
| S74 | 32 | Toddington |
| S75 | 22 | Winslow |
| S76 | 14 | Millbrook |
| S77 | 31 | Lidlington |
| S80 | 31 | Lidlington |

Table 8.1 Abundance of quartz in Thames and Ouse gravels. (after Green and McGregor, 1978).

| | Mean Quartz % | S.D. | Mean Qtz./ Qite and Hs | S.D. | No. of samples |
|---|---|---|---|---|---|
| Higher pebble Gravel | 5.5 | | 4.2 | | 1 |
| Westland Green | 27.8 | 1.27 | 1.43 | .45 | 3 |
| Higher Gravel Train | 14.8 | 5.2 | .92 | .26 | 5 |
| Leavesden Gravel Train | 10.6 | 6.74 | .91 | .3 | 10 |
| Lower Gravel Train | 21.3 | 5.75 | 1.24 | .37 | 11 |
| Total Thames | 16.0 | | 1.74 | | 30 |
| Nene | 1.02 | 1.14 | .1 | 1.11 | 9 |
| Ouse | 1.64 | 2.26 | .13 | .18 | 53 |

Qtz=Quartz; Qite=Quartzite; Hs=Hard sandstone; S.D.=Standard Deviation.

Table 9.1 Comparison of Cluster analyses strategies.

| Strategy | % score | Type |
|---|---|---|
| AXOR | 97.6 | Polythetic Divisive. |
| MONIT | 90.5 | |
| DISMA | 73.8 | |
| GOWER | 42.9 | |
| MONO | 59.5 | Monothetic divisive. |
| AGGLOM | 83.3 | Polythetic agglomerative. |

% score calculated as the percentage attainment of the perfect answer over 42 tests (After Lambert et al., 1973).

Table 9.2 Cluster programs used in the present study.

| Program | data type | No. of variables |
|---|---|---|
| a | %age and ratio PCA | 30 (10) |
| b | %age and ratio Raw | 30 |
| c | Ratio PCA | 11 (5) |
| d | ratio Raw | 11 |
| e | %age Raw | 19 |
| f | %age PCA | 19 (7) |
| g | a with height added | 31 (10) |
| h | b " " " | 31 |
| i | c " " " | 12 (5) |
| j | d " " " | 12 |
| k | e " " " | 20 |
| l | f " " " | 20 |
| m | n with height added | 6 |
| n | %age major lithologies | 5 |

Figures in parenthesis are the number of principal components used in the data matrix, defined using Kaisers criterion.

Table 10.1 Significance of trend surfaces - Limestone as a percentage of non-durable

10.1a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 4.8076 | 1.01 | 2 | 40 | 3.2317 | 5.1785 | 50% |
| 2 | 21.969 | 2.0834 | 5 | 37 | 2.4495 | 3.5138 | 90% |
| 3 | 36.0885 | 2.0704 | 9 | 33 | 2.2107 | 3.0665 | 90% |
| 4 | 41.5551 | 1.422 | 14 | 28 | 2.0148 | 2.7002 | 75% |

10.1b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 4.8076 | 1.01 | 2 | 40 | 3.2317 | 5.1785 | 50% |
| 2 | 17.1614 | 2.7125 | 3 | 37 | 2.8387 | 4.3126 | 90% |
| 3 | 14.1194 | 1.8226 | 4 | 33 | 2.6896 | 4.0179 | 75% |
| 4 | 5.4665 | .5237 | 5 | 28 | 2.5336 | 3.699 | 10% |

For tables 10.1 to 10.9 Df1, Df2 and Df3 = Degrees of freedom as specified in Chapter IX.A. F95 = F-Value at the 95% confidence level. F99 = F-Value at the 99% confidence level. * Significant at 95% cl. ** Significant at >97.5% cl.

Table 10.2 Significance of trend surfaces - Limestone as a gross percentage

10.2a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 8.5204 | 2.2869 | 2 | 40 | 3.2317 | 5.1785 | 75% | |
| 2 | 24.7406 | 2.4326 | 5 | 37 | 2.4495 | 3.5138 | 90% | |
| 3 | 41.4286 | 2.5934 | 9 | 33 | 2.2107 | 3.0665 | 97.5% | ** |
| 4 | 47.6369 | 1.8194 | 14 | 28 | 2.0148 | 2.7002 | 90% | |

10.2b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 8.5204 | 2.2869 | 2 | 40 | 3.2317 | 5.1785 | 75% |
| 2 | 16.2202 | 2.6581 | 3 | 37 | 2.8387 | 4.3126 | 90% |
| 3 | 16.6879 | 2.3505 | 4 | 33 | 2.6896 | 4.0179 | 90% |
| 4 | 6.2083 | .6639 | 5 | 28 | 2.5336 | 3.699 | 25% |

Table 10.3 Significance of trend surfaces - Ferrous sandstone as a percentage of non-durable

10.3a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 3.9911 | .8314 | 2 | 40 | 3.2317 | 5.1785 | 50% |
| 2 | 17.7073 | 1.5922 | 5 | 37 | 2.4495 | 3.5138 | 75% |
| 3 | 29.2033 | 1.5124 | 9 | 33 | 2.2107 | 3.0665 | 75% |
| 4 | 36.8461 | 1.1668 | 14 | 28 | 2.0148 | 2.7002 | 50% |

10.3b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 3.9911 | .8314 | 2 | 40 | 3.2317 | 5.1785 | 50% |
| 2 | 13.7162 | 2.0556 | 3 | 37 | 2.8387 | 4.3126 | 75% |
| 3 | 11.496 | 1.3396 | 4 | 33 | 2.6896 | 4.0179 | 50% |
| 4 | 7.6427 | .6777 | 5 | 28 | 2.5336 | 3.699 | 25% |

Table 10.4 Significance of trend surfaces - Ferrous sandstone as a gross percentage

10.4a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 6.9825 | 1.5013 | 2 | 40 | 3.2317 | 5.1785 | 75% |
| 2 | 17.3544 | 1.5538 | 5 | 37 | 2.4495 | 3.5138 | 75% |
| 3 | 20.505 | .9457 | 9 | 33 | 2.2107 | 3.0665 | 50% |
| 4 | 28.3695 | .7921 | 14 | 28 | 2.0148 | 2.7002 | 25% |

10.4b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 6.9825 | 1.5013 | 2 | 40 | 3.2317 | 5.1785 | 75% |
| 2 | 10.3718 | 1.5478 | 3 | 37 | 2.8387 | 4.3126 | 75% |
| 3 | 3.1506 | .3269 | 4 | 33 | 2.6896 | 4.0179 | 10% |
| 4 | 7.8644 | .6148 | 5 | 28 | 2.5336 | 3.699 | 25% |

Table 10.5 Significance of trend surfaces - Chalk as a percentage of non-durable

10.5a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 7.3625 | 1.5895 | 2 | 40 | 3.2317 | 5.1785 | 75% |
| 2 | 23.5837 | 2.2837 | 5 | 37 | 2.4495 | 3.5138 | 90% |
| 3 | 31.0465 | 1.6509 | 9 | 33 | 2.2107 | 3.0665 | 75% |
| 4 | 33.297 | .9983 | 14 | 28 | 2.0148 | 2.7002 | 50% |

10.5b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 7.3625 | 1.5895 | 2 | 40 | 3.2317 | 5.1785 | 75% |
| 2 | 16.2211 | 2.618 | 3 | 37 | 2.8387 | 4.3126 | 90% |
| 3 | 7.4628 | .8929 | 4 | 33 | 2.6896 | 4.0179 | 50% |
| 4 | 2.2504 | .1889 | 5 | 28 | 2.5336 | 3.699 | 2.5% |

Table 10.6 Significance of trend surfaces - Chalk as a gross percentage

10.6a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 4.5936 | .9629 | 2 | 40 | 3.2317 | 5.1785 | 50% | |
| 2 | 26.6979 | 2.6952 | 5 | 37 | 2.4495 | 3.5138 | 95% | * |
| 3 | 37.3962 | 2.1902 | 9 | 33 | 2.2107 | 3.0665 | 90% | |
| 4 | 39.179 | 1.2883 | 14 | 28 | 2.0148 | 2.7002 | 50% | |

10.6b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 4.5936 | .9629 | 2 | 40 | 3.2317 | 5.1785 | 50% | |
| 2 | 22.1042 | 3.7191 | 3 | 37 | 2.8387 | 4.3126 | 97.5% | ** |
| 3 | 10.6982 | 1.4098 | 4 | 33 | 2.6896 | 4.0179 | 50% | |
| 4 | 1.7828 | .1641 | 5 | 28 | 2.5336 | 3.699 | 2.5% | |

Table 10.7 Significance of trend surfaces - Quartzite/ Hard sandstone

10.7a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 4.1697 | .8919 | 2 | 41 | 3.2317 | 5.1785 | 50% |
| 2 | 6.4422 | .5233 | 5 | 38 | 2.4495 | 3.5138 | 10% |
| 3 | 18.2122 | .8412 | 9 | 34 | 2.2107 | 3.0665 | 25% |
| 4 | 30.9644 | .9291 | 14 | 29 | 2.0148 | 2.7002 | 25% |

10.7b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level |
|---|---|---|---|---|---|---|---|
| 1 | 4.1697 | .8919 | 2 | 41 | 3.2317 | 5.1785 | 50% |
| 2 | 2.2725 | .3076 | 3 | 38 | 2.8387 | 4.3126 | 10% |
| 3 | 11.77 | 1.2232 | 4 | 34 | 2.6896 | 4.0179 | 50% |
| 4 | 12.4821 | 1.0486 | 5 | 29 | 2.5336 | 3.699 | 50% |

Table 10.8 Significance of trend surfaces - Phosphatic nodule/ Quartzite and Hard sandstone

10.8a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 9.4427 | 2.1376 | 2 | 41 | 3.2317 | 5.1785 | 75% | |
| 2 | 14.9269 | 1.3334 | 5 | 38 | 2.4495 | 3.5138 | 50% | |
| 3 | 31.4054 | 1.7296 | 9 | 34 | 2.2107 | 3.0665 | 75% | |
| 4 | 62.5831 | 3.4646 | 14 | 29 | 2.0148 | 2.7002 | 99.5% | ** |
| 5 | 71.0679 | 2.8248 | 20 | 21 | 2.1242 | 2.9377 | 97.5% | ** |
| 6 | 75.1218 | 1.7893 | 27 | 16 | 2.2468 | 3.2141 | 75% | |

10.8b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 9.4427 | 2.1376 | 2 | 41 | 3.2317 | 5.1785 | 75% | |
| 2 | 5.4841 | .8165 | 3 | 38 | 2.8387 | 4.3126 | 50% | |
| 3 | 16.4785 | 2.0419 | 4 | 34 | 2.6896 | 4.0179 | 75% | |
| 4 | 31.1776 | 4.8328 | 5 | 29 | 2.5336 | 3.699 | 99.5% | ** |
| 5 | 8.4848 | 1.1242 | 6 | 21 | 2.599 | 3.8714 | 50% | |
| 6 | 4.0538 | .3724 | 7 | 16 | 2.7066 | 4.1415 | 5% | |

## Table 10.9 Significance of trend surfaces - Quartz/Quartzite and Hard sandstone

### 10.9a Goodness of fit of surface to data

| Order | %RSS | F-values | Df1 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 8.6448 | 1.9399 | 2 | 41 | 3.2317 | 5.1785 | 75% | |
| 2 | 33.5062 | 3.8296 | 5 | 38 | 2.4495 | 3.5138 | 99% | ** |
| 3 | 42.3748 | 2.778 | 9 | 34 | 2.2107 | 3.0665 | 95% | * |
| 4 | 50.9075 | 2.148 | 14 | 29 | 2.0148 | 2.7002 | 95% | * |

### 10.9b Improvement of higher order surface over next lower

| Order | Improved %RSS | F-values | Df3 | Df2 | F95 | F99 | Confidence level | |
|---|---|---|---|---|---|---|---|---|
| 1 | 8.6448 | 1.9399 | 2 | 41 | 3.2317 | 5.1785 | 75% | |
| 2 | 24.8614 | 4.7359 | 3 | 38 | 2.8387 | 4.3126 | 99% | ** |
| 3 | 8.8685 | 1.3081 | 4 | 34 | 2.6896 | 4.0179 | 50% | |
| 4 | 8.5327 | 1.008 | 5 | 29 | 2.5336 | 3.699 | 50% | |

Table 10.10 Comparison of each cluster analysis to every other.

| | S1 | S2 | S5 | S6 | S7 | S12 | S13 | S14 | S16 | S17 | S73 | S20 | S70 | S21 | S22 | S38 | S23 | S68 | S24 | S25 | S43 | S44 | S52 | S26 | S27 | S28 | S29 | S30 | S61 | S31 | S32 | S33 | S34 | S35 | S37 | S62 | S39 | S40 | S41 | S42 | S46 | S45 | S47 | S48 | S49 | S66 | S50 | S51 | S64 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Clifton S1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Clifton S2 | mn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Leighton Buzzard S5 | ag | cij | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Leighton Buzzard S6 | | abcefghijkl | cdijmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Leighton Buzzard S7 | ag | cij | abcdefghijklmn | cdijmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Blunham S12 | mn | [illegible] | cj | abcefghjkl | cj | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Great Barford S13 | | fhkl | | fhkl | | fhikl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Great Barford S14 | | fhl | | fhl | | fhil | abdefghijlm | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Radwell S16 | | fhkl | | fhkl | | fhikl | [illegible] | [illegible] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Upper Sundon S17 | befkl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Upper Sundon S73 | befkl | | | | | | | | | abcdefghijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Fox Corner S20 | | aegk | | aegk | | aegk | k | | k | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Fox Corner S70 | cij | aegk | | aegk | | aegk | k | | k | | | abdefghklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Rushings S21 | bcdhijn | n | | | | n | | | | abm | abm | | cij | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aspley Guise S22 | | ek | | ek | | ek | k | | k | | | befhkin | befhkin | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Aspley Guise S38 | bh | | | | | | | | | ab | ab | | | abefghkl | cim | ej | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Broughton S23 | | aefghkl | | aefghkl | | aefghkl | fhkim | fhlmn | fhklmn | | | abdegijk | abdegk | | bek | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Broughton S68 | | aefghkl | | aefghkl | | aefghkl | fhklm | fhlmn | fhklmn | | | abdegijk | abdegk | | bek | | abcdefghijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Great Linford S24 | | fl | | fl | | fil | abdefgijlm | [illegible] | [illegible] | | | | | | | | flmn | flmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Buckingham S25 | dl | | | | | | abegj | abegjk | abegj | f | f | | | d | m | mn | c | c | abeghjk | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Buckingham S43 | | abdefghijkl | ij | abefghijkl | ij | abdefghjkl | fhkl | fhln | fhklm | | | acegkm | aegkm | | ek | | aefghkln | aefghkln | fln | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Buckingham S44 | d | fl | | fl | | fl | abefgjlm | abefgjklm | abefgjlm | | | n | n | d | n | | cflm | cflm | abefghjklm | abcdeghijk | fl | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Stoke Goldington S52 | | fl | | fl | | fil | abdefgijlm | abcdefgijklm | abcdefgijlm | | | n | n | | n | | flm | flm | abcdefghijklm | abeghjk | fl | abefghijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Stoke Goldington S26 | | fl | | fl | | fil | abdefgijlm | [illegible] | abcdefgijlm | | | n | n | | n | | flm | flm | abcdefghijklm | abeghk | fl | abefghijkmn | [illegible] | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Stoke Goldington S27 | befk | | | | | | | | | abefghikmn | abefghikmn | | | abm | | ab | | | | fl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Clifford Hill S28 | | afghkl | | afghkl | | afghkl | efhklm | efhlm | efhklm | | | abdgijkn | abdgkn | | bkn | | abcdfghijklm | abcdfghijklm | eflm | ce | afghkl | ceflm | eflmn | eflmn | | | | | | | | | | | | | | | | | | | | | | | | | |
| Wootton S29 | befk | | | | | | | | | [illegible] | abcdefghijkmn | | | abm | | ab | | | | fl | | | | | abefghijklmn | | | | | | | | | | | | | | | | | | | | | | | | |
| Milton Malsor S30 | | | | | | | | | | | | | | | aegi | i | c | c | | | | c | | | | c | | | | | | | | | | | | | | | | | | | | | | | |
| Milton Malsor S61 | | | | | | | | | | | | | | | acdgi | ci | | | | | | | | | | | | abdefghijklmn | | | | | | | | | | | | | | | | | | | | | |
| Pitsford S31 | | | d | d | d | | c | | | | | | | l | j | l | | | | | | | | | | | | | | bdfge | | | | | | | | | | | | | | | | | | | |
| Earls Barton S32 | | afghkl | | afghkl | | afgkl | efhklm | efhlm | efhklm | | | abdgijkn | abdgkn | | bkn | | abcdfghijklm | abcdfghijklm | eflm | ce | afghkl | ceflmn | eflmn | eflmn | | [illegible] | | c | | | | | | | | | | | | | | | | | | | | | |
| Rushden S33 | | aefghkl | | aefghkl | | aefghkl | fhklm | fhlmn | fhklmn | | | abcdegijk | abdegk | | bek | | abdefghijklmn | abdefghijklmn | flmn | | acefghkln | flm | flm | flm | | [illegible] | | | | | abdfghjklm | | | | | | | | | | | | | | | | | | |
| Little Paxton S34 | | defhjkl | j | efhjkl | j | defhijkl | abfghiklm | abcfghilmn | abcfghiklmn | | | ek | ek | | ek | | efhklmn | efhklmn | abefgilmn | abg | defhjkln | abfglm | abcfgilm | abcfgilm | | fhklm | | | | | fhklm | efhklmn | | | | | | | | | | | | | | | | | |
| St. Neots S35 | befk | | | | | | | | | abefghkmn | abefghkmn | | | abm | | ab | | | | fl | | | | | abcdefghijklmn | | abefghklmn | | | | | | | | | | | | | | | | | | | | | | |
| Bromham S37 | cdfijm | m | | | | m | beg | begk | beg | afn | afn | | cij | acdij | | a | | | beghk | bdefghkl | | bdeghk | beghk | beghk | afln | e | afln | | | | e | | bg | afln | | | | | | | | | | | | | | | |
| Bromham S62 | mn | efhklmn | | efhkl | | efhiklmn | abdfghijkl | abcdfghijl | abcdfghijkl | | | ek | ek | n | ek | | efhkl | efhkl | abcdfgijl | abgj | efhkl | abfgjl | abcdfgijl | abcdfgijl | | fhkl | | | | | fhkl | efhkl | abcefghikl | | bgm | | | | | | | | | | | | | | |
| Marsworth S39 | n | n | | | | n | | | | m | m | | | mn | | | | | | | | | | | cdjm | | m | | | | | | | cdijm | | n | abijkl | | | | | | | | | | | | |
| Marsworth S40 | bcdijm | aefgklm | | aefgkl | | aefgklm | fkln | fl | fkl | b | b | aeghk | aceghijk | bcdij | ehk | b | aefgkl | aefgkl | fl | d | aefgkl | dfl | fl | fl | b | afgkl | b | | | | afgkl | aefgkl | efkl | b | cdijm | efkm | | | | | | | | | | | | | |
| Willington S41 | | efhkl | | efhkl | | efhikl | abdfghijklm | abcdfghijlmn | abcdfghijklmn | | | ek | ek | | ek | | efhklmn | efhklmn | abcdfgijmn | abgj | efhkln | abfgjlm | abcdfgijlm | abcdfgijlm | | fhklm | | | | | fhklm | efhklmn | [illegible] | | bg | [illegible] | | efkl | | | | | | | | | | | |
| Bletchley S42 | | adegik | i | aegik | i | adegk | k | n | kn | | | abcefghjklm | abefghklm | | befhkl | | abegjkn | abegjkn | n | | acdegikmn | | | | | abgjk | | | | | abgjk | abcegjkn | dekm | | | ek | | aeghk | ekn | | | | | | | | | | |
| Bletchley S46 | cdijm | aefgklm | | aefgkl | | aefgklm | ikln | fl | fkl | | | abeghk | abceghijk | cdij | behk | | abefgkl | abefgkl | fl | d | aefgkl | dfl | fl | fl | | abfgkl | | | | | abfgkl | abefgkl | efkl | | cdijm | efklm | | [illegible] | efkl | abeghk | | | | | | | | | |
| Rowsham S45 | | | mn | mn | mn | | | | | | | cdij | d | | ag | | dij | dij | | | c | | | | | dij | | abefghkl | abefghkl | | dij | cdij | | | | | | | | cj | | | | | | | | | |
| Ridgmont S47 | bdefijkl | | | | | | | | | abcefghklmn | abcefghklmn | | ij | abdijm | | ab | | | | df | | d | | | abefghkmn | | abcefghkmn | | | | | | | abefghkmn | adfijn | | m | bdij | | | dij | | | | | | | | |
| Ridgmont S48 | bcdefijkl | g | | g | | g | | | | abefhklmn | abefhklmn | g | cgij | abcdijm | | ab | g | g | | df | g | d | | | abefhkmn | g | abefhkmn | | | | g | g | | abefhkmn | acdfijn | | m | bdegij | | g | cdgij | | [illegible] | | | | | | |
| Stewartby S49 | | | | | | | m | m | m | | | cdijn | dn | | agn | | dijm | dijm | m | | c | mn | mn | mn | | dijmn | | abefghkl | abefghkl | | dijmn | cdijm | m | | | | | | m | cj | | [illegible] | | | | | | | |
| Stewartby S66 | | | | | | | | | | | | i | | | adgm | mn | ci | ci | | cmn | | c | | | | ci | | abcdefghijkl | abdefghjkl | | ci | i | | | | | | | | | | abefghkl | | | abefghjkl | | | | |
| Kempston S50 | | h | | h | | h | h | ch | ch | | | dij | d | | | | dhij | dhij | c | | h | | c | c | | dhij | | | | mn | dhij | dhij | ch | | | ch | | | ch | i | | dij | | | dij | i | | | |
| Elstow S51 | | h | | h | | h | hmn | hm | hm | | | cdij | d | | | | dhijm | dhijm | m | | ch | m | m | m | | dhijm | | | | | dhijm | cdhijm | mh | | | h | | n | hm | cj | n | cdij | | | cdijm | i | [illegible] | | |
| Elstow S64 | | aefghkl | | aefghkl | | aefghkl | fhkl | cfhl | cfhkl | | | abdegijk | abdegk | | bek | | abdefghijkl | abdefghijkl | cfl | | aefghkl | fl | cfl | cfl | | abdfghjkl | | | | mn | abdfghjkl | abdefghijkl | cefhkl | | | cefhkl | | aefgkl | cefhkl | abegjk | abefgkl | dij | | g | dij | i | cdijmn | dhij | |
| Simpson S54 | | aegk | | aegk | | aegk | kmn | m | km | | | [illegible] | abdefghkl | | befhkl | | abdegijkm | abdegijkm | m | | acegk | m | m | m | | abdgijkm | | | | | abdgijkm | abcdegijkm | ekm | | | ek | | aeghkn | ekm | abcefghjkl | abeghkn | cdij | | g | cdijm | i | dij | cdijmn | abdegijk |
| Lodge Farm S55 | efklm | n | | | | n | m | m | m | efkl | efkl | | | gn | | g | m | m | m | f | | m | m | m | cdefjk | m | efk | | | | m | m | m | cdefijk | f | n | bcdhijn | | m | | | | efkl | efkl | m | | | m | |
| Broughton Ground S56 | hl | | | | | | | | | [illegible] | [illegible] | | | abefkm | | abefk | | | | | | | | | abghimn | | abcdghijmn | | | | | | | abghmn | an | | m | b | | | | | abcghlmn | abhlmn | | | | | |
| Broughton Ground S67 | cdijm | aefghklm | | aefghkl | | aefghklm | fhkl | fhl | fhkl | n | n | aegk | abcegijk | cdij | bek | | abefghkl | abefghkl | fl | d | aefghkl | dfl | fl | fl | n | abfghkl | n | | | | abfghkl | abefghkl | efhkl | n | cdijmn | efhklm | | [illegible] | efhkl | abegk | [illegible] | | dijn | cdgijn | | | h | i | abefghkl |
| Bow Brickhill S57 | | aefghkl | | aefghkl | | aefghkl | fhklm | fhlmn | fhklmn | | | abdegijk | abdegk | | bek | | [illegible] | [illegible] | flmn | c | aefghkln | cflm | flm | flm | | abcdfghijklm | | c | | | [illegible] | [illegible] | efhklmn | | | efhkl | | aefgkl | efhklmn | abegjkm | abefgkl | dij | | g | dijm | ci | dhij | dhijm | [illegible] |
| Bow Brickhill S69 | | aefghkl | | aefghkl | | aefghkl | fhklm | fhlmn | fhklmn | | | abdegijk | abdegk | | bek | | [illegible] | [illegible] | flmn | c | aefghkln | cflm | flm | flm | | abcdfghijklm | | c | | | [illegible] | [illegible] | efhklmn | | | efhkl | | aefgkl | efhklmn | abegjkm | abefgkl | dij | | g | dijm | ci | dhij | dhijm | [illegible] |
| Ippollitts S58 | befk | | | | | | | | | [illegible] | [illegible] | | | abm | | ab | | | | fl | | | | | abefghiklmn | | [illegible] | | | | | | | abefghklmn | afln | | m | b | | | | | abcefghkmn | abefhkmn | | | | | |
| Ippollitts S71 | befk | | | | | | | | | [illegible] | [illegible] | | | abm | | ab | | | | fl | | | | | abcfghiklmn | | [illegible] | | | | | | | abefghklmn | afln | | m | b | | | | | abcefghkmn | abefhkmn | | | | | |
| Ippollitts S72 | befk | | | | | | | | | [illegible] | [illegible] | | | abm | | ab | | | | fl | | | | | abefghiklmn | | [illegible] | | | | | | | abefghklmn | afln | | m | b | | | | | abcefghkmn | abefhkmn | | | | | |
| Weedon Bec S59 | befkl | | | | | | | | | [illegible] | [illegible] | | | abm | | ab | | | | f | | | | | abefghikmn | | [illegible] | | | | | | | abefghkmn | afln | | m | b | | | | | [illegible] | abefhklmn | | | | | |
| Nether Heyford S60 | dfj | | | | | | begm | begkm | begm | af | af | n | jn | adj | n | a | cm | cm | beghkm | bcdefghikl | | bcdeghikmn | beghkmn | beghkmn | afl | cemn | afl | c | | | cemn | m | bgm | afl | abdefghjkl | bg | | dj | bgm | | dj | | afj | afj | mn | c | | m | |
| Toddington S74 | | [illegible] | ij | abefghijkl | ij | abdefghjkl | fhkl | fhln | fhkln | | | acegkm | aegkm | | ek | | aefghkln | aefghkln | fln | | [illegible] | fl | fl | fl | | afghkl | | | | | afghkl | acefghkln | defhjkln | | | efhkl | | aefgkl | efhkln | acdegikmn | aefgkl | c | | g | c | | h | ch | aefghkl |
| Winslow S75 | bcdijkl | aefg | | aefg | | afg | f | f | f | bhklmn | bhklmn | aeg | acegij | bcdijm | e | b | aefg | aefg | f | d | aefg | df | f | f | bhkmn | afg | bhkmn | | | | afl | aefg | ef | bhkmn | cdijn | ef | m | abcdefgil | ef | aeg | acdefgil | | bdhijklmn | [illegible] | | | | | aefg |
| Millbrook S76 | | | | | | | | | | | | i | | | adgm | mn | ci | ci | | cmn | | c | | | | ci | | abcdefghijkl | abdefghjkl | | ci | i | | | | | | | | | | abefghkl | | | abefghkl | [illegible] | i | i | i |
| Lidlington S77 | d | aefgk | | aefgk | | aefgk | cfkn | f | fk | | | abeghkl | abeghkl | d | behjkl | | abefgk | abefgk | f | d | aefgk | df | f | f | | abfgk | | | | cij | abfgk | abefgk | efk | | d | efk | | adefghkn | efk | abeghkl | abdefghkn | | d | dg | | | | n | abefgk |
| Lidlington S80 | d | aefgk | | aefgk | | aefgk | cfkn | f | fk | | | abeghkl | abeghkl | d | behjkl | | abefgk | abefgk | f | d | aefgk | df | f | f | | abfgk | | | | cij | abfgk | abefgk | efk | | d | efk | | adefghkn | efk | abeghkl | abdefghkn | | d | dg | | | | n | abefgk |

| 21 | S22 | S38 | S23 | S68 | S24 | S25 | S43 | S44 | S52 | S26 | S27 | S28 | S29 | S30 | S61 | S31 | S32 | S33 | S34 | S35 | S37 | S62 | S39 | S40 | S41 | S42 | S46 | S45 | S47 | S48 | S49 | S66 | S50 | S51 | S64 | S54 | S55 | S56 | S67 | S57 | S69 | S58 | S71 | S72 | S53 | S60 | S74 | S75 | S76 | S77 | S80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| fghk | cim | c j | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | bek | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | bek | | abcdefg hijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | flmn | flmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | m | mn | c | c | abeghjk | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | ek | | aefghkl n | aefghkl n | fln | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | n | | cflm | cflm | abefghj klm | abcdeghi jk | fl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | n | | flm | flm | abcdefg hijklm | abeghjk | fl | abefgh ijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | n | | flm | flm | abcdefg hijklm | abeghk | fl | abefgh ijklmn | abcdefj hijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ) | | ab | | | | fl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | bkn | | abcdefg hijklm | abcdefg hijklm | eflm | ce | afghkl | ceflm | eflmn | eflmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | ab | | | | fl | | | | | abefgh ijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | aegi | i | c | c | | | | c | | | | c | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | acdgi | ci | | | | | | | | | | | | abdefgh ijklmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | j | j | | | | | | | | | | | | | | [illegible] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | bkn | | abcdfg hijklm | abcdfg hijklm | eflm | ce | afghkl | ceflmn | eflmn | eflmn | | [illegible] | | c | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | bek | | abdefgh ijklmn | abdefgh ijklmn | flmn | | acefgh kln | flm | flm | flm | | abdfghi jklm | | | | | abdfghi jklm | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | ek | | efhklmn | efhklmn | abefgil mn | abg | defhjk ln | abfglm | abcfgil m | abcfgil m | | fhklm | | | | | fhklm | efhklm n | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | ab | | | | fl | | | | | abcdefg hijklmn | | abefghk lmn | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ij | | a | | | beghk | bdefgh kl | | bdeghk | beghk | beghk | afln | e | afln | | | | e | | bg | afln | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | ek | | efhkl | efhkl | abcdfgi jl | abgj | efhkl | abfgjl | abcdfgi jl | abcdfgi jl | | fhkl | | | | | fhkl | efhkl | abcefgh kl | | bgm | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | cdjm | | m | | | | | | | cdijm | | n | [illegible] | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ij | ehk | b | aefgkl | aefgkl | fl | d | aefgkl | dfl | fl | fl | b | afgkl | b | | | | afgkl | aefgkl | efkl | b | cdijm | efkm | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | ek | | efhklmn | efhklmn | abcdfgi jlmn | abgj | efhkln | abfgjl m | abcdfg ijlm | abcdfgi jlm | | fhklm | | | | | fhklm | efhklm n | [illegible] | | bg | [illegible] | | efkl | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | befhkl | | abegjkn | abegjkn | n | | acdegi kmn | | | | | abgjk | | | | | abgjk | abcegjk n | dekm | | | ek | | aeghk | ekn | | | | | | | | | | | | | | | | | | | | | | | | | | |
| l | behk | | abefgkl | abefgkl | fl | d | aefgkl | dfl | fl | fl | | abfgkl | | | | | abfgkl | abefgkl | efkl | | cdijm | efklm | | acdefgh ijklmn | efkl | abeghk | | | | | | | | | | | | | | | | | | | | | | | | | |
| | ag | | dij | dij | | | c | | | | | dij | | abefghk l | abefghk l | | dij | cdij | | | | | | | | cj | | | | | | | | | | | | | | | | | | | | | | | | | |
| ijm | | ab | | | | df | | d | | | abefghk mn | | abcefgh kmn | | | | | | | abefgh kmn | adfijn | | m | bdij | | | dij | | | | | | | | | | | | | | | | | | | | | | | | |
| dijm | | ab | g | g | | df | g | d | | | abefhk mn | g | abefhk mn | | | | g | g | | abefhk mn | acdfijn | | m | bdegij | | g | cdgij | | abdefgh ijklmn | | | | | | | | | | | | | | | | | | | | | | |
| | agn | | dijm | dijm | m | | c | mn | mn | mn | | dijmn | | abefgh kl | abefgh kl | | dijmn | cdijm | m | | | | | | m | cj | | abcdefg hijkl | | | | | | | | | | | | | | | | | | | | | | | |
| | adgm | mn | ci | ci | | cmn | | c | | | | ci | | abcdefg hijkl | abdefghj kl | | ci | i | | | | | | | | | | abefghi kl | | | abefgh ijkl | | | | | | | | | | | | | | | | | | | | |
| | | | dhij | dhij | c | | h | | c | c | | dhij | | | | mn | dhij | dhij | ch | | | ch | | | ch | j | | dij | | | dij | i | | | | | | | | | | | | | | | | | | | |
| | | | dhijm | dhijm | m | | ch | m | m | m | | dhijm | | | | | dhijm | cdhijm | mh | | | h | | n | hm | cj | n | cdij | | | cdijm | i | abdefg ijkl | | | | | | | | | | | | | | | | | | |
| | bek | | abdefgh ijkl | abdefgh ijkl | cfl | | aefghk l | fl | cfl | cfl | | abdfghi jkl | | | | mn | abdfghi jkl | abdefgh ijkl | cefhkl | | | cefhkl | | aefgkl | cefhkl | abegjk | abefgk l | dij | | g | dij | i | cdhijmn | dhij | | | | | | | | | | | | | | | | | |
| | befhkl | | abdegij km | abdegij km | m | | acegk | m | m | m | | abdgijk m | | | | | abdgijk m | abcdegi jkm | ekm | | | ek | | aeghkn | ekm | abcefgh jkl | abeghk n | cdij | | g | cdijm | i | dij | cdijmn | abdegi jk | | | | | | | | | | | | | | | | |
| | | g | m | m | m | f | | m | m | m | cdefjk | m | efk | | | | m | m | m | cdefijk | f | n | bcdhijn | | m | | | | efkl | efkl | m | | | m | | m | a | | | | | | | | | | | | | | |
| fkm | | abefk | | | | | | | | | abghim n | | abcdghi jmn | | | | | | | abghmn | an | | m | b | | | | | abcghl mn | abhlmn | | | | | | | i | | | | | | | | | | | | | | |
| | bek | | abefgh kl | abefgh kl | fl | d | aefghk l | dfl | fl | fl | n | abfghk l | n | | | | abfghkl | abefgh kl | efhkl | n | cdijmn | efhklm | | acdefgh ijklm | efhkl | abegk | abcdefg ijklm | | dijn | cdgijn | | | h | i | abefgh kl | abegk | | n | | | | | | | | | | | | | |
| | bek | | [illegible] | [illegible] | flmn | c | aefghk ln | cflm | flm | flm | | abcdfgh ijklm | | c | | | [illegible] | [illegible] | efhklm n | | | efhkl | | aefgkl | efhklm n | abegjk m | abefgkl | dij | | g | dijm | ci | dhij | dhijm | [illegible] | [illegible] | m | | abefgh kl | | | | | | | | | | | | |
| | [illegible] | | [illegible] | [illegible] | flmn | c | aefghk ln | cflm | flm | flm | | abcdfgh ijklm | | c | | | [illegible] | [illegible] | efhklm n | | | efhkl | | aefgkl | efhklm n | abegjk m | abefgkl | dij | | g | dijm | ci | dhij | dhijm | [illegible] | [illegible] | m | | [illegible] | | | | | | | | | | | | |
| | | [illegible] | | | | [illegible] | | | | | abefghi klmn | | [illegible] | | | | | | | abefghk lmn | afln | | m | b | | | | | [illegible] | [illegible] | | | | | | | [illegible] | [illegible] | | | | | | | | | | | | | |
| | | [illegible] | | | | [illegible] | | | | | [illegible] | | [illegible] | | | | | | | abefghk lmn | afln | | m | b | | | | | [illegible] | [illegible] | | | | | | | [illegible] | [illegible] | | | | | | | | | | | | | |
| | | [illegible] | | | | [illegible] | | | | | [illegible] | | [illegible] | | | | | | | abefghk lmn | afln | | m | b | | | | | [illegible] | [illegible] | | | | | | | [illegible] | [illegible] | | | | | | | | | | | | | |
| | | [illegible] | | | | | | | | | [illegible] | | [illegible] | | | | | | | abefghk mn | afln | | m | b | | | | | [illegible] | [illegible] | | | | | | | [illegible] | | | | | | | | | | | | | | |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | cemn | afl | c | | | cemn | m | bgm | afl | abdefg hjkl | bg | | di | bgm | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [illegible] | | | [illegible] | [illegible] | [illegible] | | [illegible] | | | | | [illegible] | | | | | afghkl | acefgh kln | defhkl n | | | efhkl | | [illegible] | [illegible] | [illegible] | [illegible] | | | | | | | | | | | | | | | | | | | | | | | | |
| [illegible] | | | [illegible] | [illegible] | | [illegible] | | | | | [illegible] | | | | | | afl | aefg | ef | bdkmn | cdijn | ef | m | [illegible] | | [illegible] | [illegible] | | | | | | | | | | | | | | | | | | | | | aefg | | | |
| [illegible] | [illegible] | | [illegible] | [illegible] | | | | | | | | | | | | | ci | i | | | | | | | | | [illegible] | | | | | | | | | | | | | | | | | | | | | | | | |
| [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | | | | | | | | | ij | abfgk | abefgk | efk | | d | efk | | | | | | | | | | | | | | | | | | | | | | | | | | aefgk | aefg | | |
| [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | | | | | | | | | ij | abfgk | abefgk | efk | | d | efk | | | | | | | | | | | | | | | | | | | | | | | | | | aefgk | aefg | [illegible] | |

a – Cluster Analysis a
b – Cluster Analysis b
c – Cluster Analysis c
d – Cluster Analysis d
e – Cluster Analysis e
f – Cluster Analysis f
g – Cluster Analysis g
h – Cluster Analysis h
i – Cluster Analysis i
j – Cluster Analysis j
k – Cluster Analysis k
l – Cluster Analysis l
m – Cluster Analysis m
n – Cluster Analysis n

Number of Cluster Analyses

▭ 14
▭ 13
▭ 12
▭ 11

Table 10.11a Samples grouped together at similarity level eleven.

| | |
|---|---|
| Group 1 | Winslow (S75) |
| | Ridgmont (S47) |
| | Ridgmont (S48) |
| | Upper Sundon (S17) |
| | Upper Sundon (S73) |
| | Weedon (S59) |
| | Wootton (S29) |
| | Ippollitts (S58) |
| | Ippollitts (S71) |
| | Ippollitts (S72) |
| | Stoke Goldington (S27) |
| | St. Neots (S35) |
| | Broughton Ground (S56) |
| Group 2 | Buckingham (S44) |
| | Stoke Goldington (S26) |
| | Stoke Goldington (S52) |
| | Great Barford (S13) |
| | Great Barford (S14) |
| | Radwell (S16) |
| | Great Linford (S24) |
| | Willington (S41) |
| | Bromham (S62) |
| | Paxton (S34) |
| Group 3 | Elstow (S64) |
| | Broughton (S23) |
| | Broughton (S68) |
| | Bow Brickhill (S57) |
| | Bow Brickhill (S69) |
| | Clifford Hill (S28) |
| | Earls Barton (S32) |
| | Rushden (S33) |
| Group 4 | Clifton (S2) |
| | Blunham (S12) |
| | Toddington (S74) |
| | Buckingham (S43) |
| | Leighton Buzzard (S6) |

Table 10.11a cont.

| | | | |
|---|---|---|---|
| Group 5 | Fox Corner (S20)<br>Fox Corner (S70)<br>Simpson (S54)<br>Bletchley (S42) | Group 6 | Milton Malsor (S30)<br>Milton Malsor (S61)<br>Millbrook (S76)<br>Stewartby (S66) |
| Group 7 | Broughton Ground (S67)<br>Bletchley (S46)<br>Marsworth (S40) | Group 8 | Lidlington (S77)<br>Lidlington (S80) |
| Group 9 | Leighton Buzzard (S5)<br>Leighton Buzzard (S7) | Group 10 | Kempston (S50)<br>Elstow (S51) |
| Group 11 | Rowsham (S45)<br>Stewartby (S49) | Others | Pitsford (S31)<br>Aspley Guise (S22)<br>Bromham (S37)<br>Buckingham (S25)<br>Nether Heyford (S60)<br>Clifton (S1)<br>Rushings (S21)<br>Aspley Guise (S38)<br>Lodge Farm (S55)<br>Marsworth (S39) |

This accounts for 55 of the 65 samples.

Table 10.11b Samples grouped together at similarity level ten.

| | |
|---|---|
| Group 1 | Winslow (S75) |
| | Ridgmont (S47) |
| | Ridgmont (S48) |
| | Upper Sundon (S17) |
| | Upper Sundon (S73) |
| | Weedon (S59) |
| | Wootton (S29) |
| | Ippollitts (S58) |
| | Ippollitts (S71) |
| | Ippollitts (S72) |
| | Stoke Goldington (S27) |
| | St. Neots (S35) |
| | Broughton Ground (S56) |
| Group 2 | Buckingham (S44) |
| | Stoke Goldington (S26) |
| | Stoke Goldington (S52) |
| | Great Barford (S13) |
| | Great Barford (S14) |
| | Radwell (S16) |
| | Great Linford (S24) |
| | Willington (S41) |
| | Bromham (S62) |
| | Paxton (S34) |
| | Bromham (S37) |
| | Buckingham (S25) |
| | Nether Heyford (S60) |
| Group 3 | Elstow (S64) |
| | Broughton (S23) |
| | Broughton (S68) |
| | Bow Brickhill (S57) |
| | Bow Brickhill (S69) |
| | Clifford Hill (S28) |
| | Earls Barton (S32) |
| | Rushden (S33) |
| | Fox Corner (S20) |
| | Fox Corner (S70) |
| | Simpson (S54) |
| | Bletchley (S42) |
| Group 4 | Clifton (S2) |
| | Blunham (S12) |
| | Toddington (S74) |
| | Buckingham (S43) |
| | Leighton Buzzard (S6) |
| Group 6 | Milton Malsor (S30) |
| | Milton Malsor (S61) |
| | Millbrook (S76) |
| | Stewartby (S66) |

Table 10.11b cont.

| | | | |
|---|---|---|---|
| Group 7 | Broughton Ground (S67)<br>Bletchley (S46)<br>Marsworth (S40) | Group 8 | Lidlington (S77)<br>Lidlington (S80) |
| Group 9 | Leighton Buzzard (S5)<br>Leighton Buzzard (S7) | Group 10 | Kempston (S50)<br>Elstow (S51) |
| Group 11 | Rowsham (S45)<br>Stewartby (S49) | Others | Pitsford (S31)<br>Aspley Guise (S22)<br>Clifton (S1)<br>Rushings (S21)<br>Aspley Guise (S38)<br>Lodge Farm (S55)<br>Marsworth (S39) |

This accounts for 58 of the 65 samples.

Table 10.12a Mean ratio composition of groups formed at similarity level eleven

| Group | %nd | Ch%nd | Ls%nd | FeS%nd | %Fl | Fl%d | Fl%Fl + Ch | RC%d | Qite + Hs | Qite+Hs% d-Fl | Qtz% d-Fl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 65.52 | 60.81 | 17.82 | 7.97 | 26.6 | 77.51 | 40.22 | 2.51 | 5.43 | 64.26 | 4.81 |
| 2 | 32.02 | 9.41 | 74.76 | 7.0 | 46.95 | 68.0 | 92.72 | 1.78 | 15.16 | 71.37 | 6.84 |
| 3 | 37.78 | 17.19 | 14.45 | 49.68 | 42.12 | 67.43 | 87.62 | 2.15 | 15.13 | 75.57 | 4.87 |
| 4 | 12.13 | 7.48 | 4.21 | 72.64 | 68.59 | 77.92 | 98.73 | .33 | 13.75 | 71.25 | 17.8 |
| 5 | 29.35 | 7.76 | 3.45 | 83.38 | 45.99 | 64.9 | 92.5 | .59 | 20.34 | 82.51 | 4.06 |
| 6 | 79.63 | .29 | 1.27 | 86.08 | 13.53 | 64.76 | 98.24 | .85 | 5.81 | 80.6 | 6.07 |
| 7 | 43.81 | 57.89 | 13.67 | 19.06 | 35.29 | 62.5 | 58.59 | .59 | 16.62 | 78.66 | 6.46 |
| 8 | 40.95 | 15.13 | 37.18 | 27.86 | 28.59 | 47.71 | 82.6 | .75 | 25.21 | 82.93 | 4.2 |
| 9 | 20.07 |  |  | 69.96 | 42.48 | 53.2 | 100.0 | .81 | 22.1 | 59.37 | 26.98 |
| 10 | 13.65 | 6.52 | 13.75 | 36.26 | 57.2 | 66.09 | 97.46 | 3.51 | 17.41 | 59.94 | 5.01 |
| 11 | 34.25 | 7.45 | 5.32 | 45.77 | 47.77 | 72.84 | 97.13 | .82 | 15.62 | 86.42 | 4.28 |

Table 10.12b Mean ratio composition of groups formed at similarity level ten

| Group | %nd | Ch%nd | Ls%nd | FeS%nd | %Fl | Fl%d | Fl%Fl + Ch | RC%d | Qite + Hs | Qite+Hs% d-Fl | Qtz% d-Fl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 39.14 | 14.06 | 70.16 | 6.68 | 42.18 | 67.86 | 85.17 | 1.45 | 13.42 | 71.06 | 7.29 |
| 3 | 34.97 | 14.05 | 10.78 | 60.91 | 43.41 | 66.59 | 89.25 | 1.63 | 16.87 | 77.88 | 4.6 |

nd=non-durable; d=durable; Fl=Flint; For others see Table 10.13

Table 10.13a Mean percentage composition of groups formed at similarity level eleven

| Group | Qite | Qtz | Hs | Ss | FeS | Ls | Ch | RC | C | Calc Sst | Cs | Ig | Sh | Misc H | PhN | Mstn | FeLs | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.09 | .42 | 3.32 | .69 | 5.16 | 11.79 | 40.14 | .78 | .73 | 1.42 | .01 | .4 | 4.75 | | .8 | .14 | .58 | .02 | |
| 2 | 8.01 | 1.48 | 7.15 | .56 | 2.37 | 23.87 | 3.27 | 1.19 | 2.68 | .65 | .03 | .27 | .58 | .03 | .22 | .03 | .47 | | .05 |
| 3 | 6.77 | .99 | 8.35 | .94 | 19.16 | 5.99 | 6.26 | 1.39 | 2.05 | .67 | | .47 | 2.54 | .03 | 1.43 | .07 | .63 | | |
| 4 | 6.02 | 3.5 | 7.72 | 1.31 | 8.12 | .57 | 1.01 | .78 | 1.04 | | .06 | .6 | .12 | | .99 | | | | |
| 5 | 7.44 | .93 | 12.89 | .12 | 22.76 | 1.63 | 3.68 | .45 | 1.23 | | .39 | 1.12 | | .13 | 1.13 | | | | |
| 6 | 2.48 | .1 | 3.32 | .48 | 69.89 | 1.0 | .23 | .12 | .66 | | | .11 | 1.41 | | 6.49 | | | | |
| 7 | 7.41 | 1.3 | 9.2 | | 8.58 | 6.08 | 24.91 | .33 | 2.44 | .26 | | .13 | 2.37 | | 1.58 | | | | |
| 8 | 10.33 | 1.28 | 14.87 | .23 | 11.37 | 14.86 | 5.8 | .46 | 3.25 | 1.15 | | .23 | 5.91 | | 1.5 | .11 | | | |
| 9 | 13.91 | 10.22 | 8.18 | 2.9 | 13.98 | | | .65 | 2.29 | | .83 | | | 1.25 | 3.19 | | | | |
| 10 | 4.48 | 1.45 | 12.92 | | 5.16 | 1.67 | 1.35 | 3.19 | 7.01 | .22 | | | 3.26 | | 2.0 | | | | |
| 11 | 6.42 | .86 | 9.19 | .27 | 20.48 | 1.2 | 1.69 | .51 | .79 | | | .13 | .24 | | 10.22 | .13 | | | |

Table 10.13b Mean percentage composition of groups formed at similarity level ten

| Group | Qite | Qtz | Hs | Ss | FeS | Ls | Ch | RC | C | Calc Sst | Cs | Ig | Sh | Misc H | PhN | Mstn | FeLs | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 7.24 | 1.29 | 6.17 | .5 | 2.57 | 26.77 | 6.43 | .95 | 2.53 | 1.4 | .02 | .26 | .71 | .02 | .22 | .02 | .49 | | .03 |
| 3 | 7.0 | .97 | 9.86 | .67 | 20.36 | 4.54 | 5.4 | 1.08 | 1.78 | .45 | .13 | .68 | 1.69 | .06 | 1.33 | .05 | .42 | | |

Qite=Quartzite; Qtz=Quartz; Hs=Hard sandstone; Ss=Soft sandstone; FeS=Ferrous sandstone; Ls=Limestone; Ch=Chalk; RC=Rhaxella chert; C=Chert; Calc Sst=Calcareous sandstone; Cs=Cherty sandstone; Ig=Igneous; Sh=Shells; Misc H=Miscellaneous hard; PhN=Phosphatic nodule; Mstn=Mudstone; FeLs=Ferrous limestone; Sch=Schist; Grt=Grit.

Table 10.14 Groups at similarity level eleven and their height above floodplain (All heights are estimated from 1:25000 OS Maps).

| | | | | | |
|---|---|---|---|---|---|
| Group 1 | Winslow (S75) | 23.0m | Group 2 | Buckingham (S44) | 16.0m |
| | Ridgmont (S47) | 32.0m | | Stoke Goldington (S26) | 3.6m |
| | Ridgmont (S48) | 32.0m | | Stoke Goldington (S52) | 3.6m |
| | Upper Sundon (S17) | 53.3m | | Great Barford (S13) | 2.5m |
| | Upper Sundon (S73) | 53.3m | | Great Barford (S14) | 2.5m |
| | Weedon (S59) | 20.0m | | Radwell (S16) | 3.0m |
| | Wootton (S29) | 4.5m | | Great Linford (S24) | 3.0m |
| | Ippollitts (S58) | 14.0m | | Willington (S41) | 1.5m |
| | Ippollitts (S71) | 14.0m | | Bromham (S62) | 11.2m |
| | Ippollitts (S72) | 14.0m | | Paxton (S34) | 3.0m |
| | Stoke Goldington (S27) | 6.0m | | | |
| | St. Neots (S35) | 9.1m | | Bromham (S37) | 11.2m |
| | Broughton Ground (S56) | 2.0m | | | |
| | | | | Buckingham (S25) | 12.2m |
| | | | | Nether Heyford (S60) | 1.5m |
| Group 3 | Elstow (S64) | 4.5m | Group 4 | Clifton (S2) | 4.5m |
| | Broughton (S23) | 4.2m | | Blunham (S12) | 0.5m |
| | Broughton (S68) | 4.2m | | Toddington (S74) | 61.0m |
| | Bow Brickhill (S57) | 2.5m | | Buckingham (S43) | 35.5m |
| | Bow Brickhill (S69) | 2.5m | | Leighton Buzzard (S6) | 7.0m |
| | Clifford Hill (S28) | 6.0m | | | |
| | Earls Barton (S32) | 3.5m | | | |
| | Rushden (S33) | 3.0m | | | |

Table 10.14 cont.

| | | |
|---|---|---|
| Group 5 | Fox Corner (S20) | 41.1m |
| | Fox Corner (S70) | 41.1m |
| | Simpson (S54) | 2.0m |
| | Bletchley (S42) | 16.0m |
| Group 7 | Broughton Ground (S67) | 2.0m |
| | Bletchley (S46) | 16.0m |
| | Marsworth (S40) | 42.6m |
| Others | Pitsford (S31) | 36.5m |
| | Aspley Guise (S22) | 61.0m |
| | Clifton (S1) | 4.5m |
| | Rushings (S21) | 56.0m |
| | Aspley Guise (S38) | 61.0m |
| | Lodge Farm (S55) | 15.0m |
| | Marsworth (S39) | 42.6m |
| Group 6 | Milton Malsor (S30) | 9.0m |
| | Milton Malsor (S61) | 9.0m |
| | Millbrook (S76) | 32.0m |
| | Stewartby (S66) | 19.8m |
| Group 8 | Lidlington (S77) | 92.0m |
| | Lidlington (S80) | 92.0m |
| Group 9 | Leighton Buzzard (S5) | 7.0m |
| | Leighton Buzzard (S7) | 7.0m |
| Group 10 | Kempston (S50) | 16.0m |
| | Elstow (S51) | 4.5m |
| Group 11 | Rowsham (S45) | 0.0m |
| | Stewartby (S49) | 19.8m |

Table 10.15 Separation of group 3 into Ouzel and Nene samples.

| | Ch % | Ch % nd. | FeS% | FeS % nd. |
|---|---|---|---|---|
| River Ouzel. | | | | |
| S23 Broughton | 9.6 | 25.44 | 13.33 | 37.43 |
| S68 Broughton | 10.61 | 29.49 | 15.35 | 42.66 |
| S57 Bow Brickhill | 11.48 | 28.28 | 12.6 | 31.03 |
| S69 Bow Brickhill | 10.2 | 23.37 | 18.77 | 43.0 |
| S64 Elstow | 3.27 | 20.02 | 6.53 | 39.99 |
| River Nene. | | | | |
| S28 Clifford Hill | 2.09 | 4.61 | 31.58 | 69.62 |
| S33 Rushden | .54 | 1.47 | 29.8 | 80.91 |
| S32 Earls Barton | 2.33 | 4.86 | 25.32 | 52.81 |

Ch = Chalk; FeS = Ferrous sandstone; nd = Non-durable.

Table 10.16 Principal component analysis of gross percentages.

a) Eigenvalues

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Eigenvalues | 3.65 | 2.2 | 2.07 | 1.62 | 1.35 | 1.19 | 1.13 | .99 | .87 | .78 | .64 | .6 | .53 | .35 |
| | .28 | .25 | .21 | .16 | .12 | | | | | | | | | |
| Percent Variance | 19.13 | 11.56 | 10.88 | 8.55 | 7.11 | 6.28 | 5.94 | 5.2 | 4.57 | 4.12 | 3.36 | 3.17 | 2.8 | 1.87 |
| | 1.49 | 1.33 | 1.12 | .86 | .66 | | | | | | | | | |
| Cumulative Variance | 19.13 | 30.69 | 41.57 | 50.12 | 57.23 | 63.51 | 69.45 | 74.65 | 79.22 | 83.35 | 86.71 | 89.88 | 92.67 | 94.54 |
| | 96.03 | 97.36 | 98.48 | 99.34 | 100.0 | | | | | | | | | |

b) Vector Loadings

| Vector | Qite | Qtz | Hs | Ss | FeS | Ls | Ch | RC | C | Calc Stn | Cs | Ig | Sh | Misc H | PhN | Mstn | FeLs | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .407 | .36 | .376 | .104 | .049 | -.225 | -.352 | .156 | .241 | -.284 | .187 | -.026 | -.189 | .312 | .11 | .027 | -.134 | .062 | -.097 |
| 2 | .073 | .385 | -.267 | .374 | -.065 | .09 | .157 | -.341 | -.258 | .259 | .371 | -.057 | -.035 | .397 | -.155 | -.066 | .137 | .015 | .038 |
| 3 | -.179 | -.06 | -.138 | .014 | .466 | -.402 | -.08 | -.295 | -.403 | -.318 | .003 | .091 | .004 | .05 | .338 | -.186 | -.182 | -.112 | .065 |
| 4 | .159 | -.076 | .1 | .367 | .245 | -.072 | .005 | -.075 | -.189 | .018 | -.244 | .251 | .072 | -.146 | -.086 | .457 | .171 | .55 | -.17 |
| 5 | .236 | -.122 | .091 | -.059 | .142 | .336 | -.275 | -.238 | -.114 | .032 | -.117 | .388 | -.489 | -.076 | -.151 | -.107 | .252 | -.36 | -.044 |
| 6 | .074 | .022 | .262 | -.351 | -.251 | -.146 | .327 | -.147 | -.155 | -.011 | .305 | .548 | .066 | -.01 | -.147 | .184 | -.325 | -.001 | .081 |
| 7 | -.022 | .059 | -.043 | .082 | -.042 | .004 | .092 | .024 | -.018 | -.232 | -.206 | -.126 | -.382 | -0.0 | -.203 | .139 | -.111 | .147 | .79 |

Table 10.17 First seven factor scores for all samples

| Sample Number | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| S1 | .294 | 3.612 | -.857 | -2.215 | -1.953 | 2.401 | -1.906 |
| S2 | .902 | 1.128 | .955 | .028 | -.192 | -1.298 | .653 |
| S5 | 6.426 | 5.731 | .185 | -1.518 | -1.002 | -.113 | .098 |
| S6 | 2.547 | .951 | .704 | .137 | -.028 | -.567 | .499 |
| S7 | 5.084 | 4.09 | .744 | -1.127 | -.815 | -.382 | -.082 |
| S12 | .045 | .775 | 1.021 | -.33 | .237 | .293 | .176 |
| S13 | 1.866 | .092 | -1.464 | .496 | 2.1 | -.024 | .16 |
| S14 | .864 | -.073 | -.881 | -.673 | .651 | -.594 | .271 |
| S16 | .357 | .166 | -1.949 | -.183 | 1.843 | -1.442 | -.387 |
| S17 | -2.273 | .799 | .863 | .402 | -.268 | 1.463 | .223 |
| S20 | 1.11 | -.599 | 1.369 | .332 | 1.41 | 1.548 | -.37 |
| S21 | -.004 | .923 | -1.026 | 2.589 | -2.327 | .017 | .596 |
| S22 | -.43 | .062 | 1.596 | 1.041 | 1.586 | .953 | .396 |
| S23 | .477 | -.445 | -.028 | .122 | .4 | .399 | -.422 |
| S29 | -2.864 | 2.023 | -.362 | 1.465 | .472 | -.328 | -.651 |
| S31 | 4.338 | -1.649 | -2.444 | 5.907 | -.999 | 1.79 | 1.642 |
| S32 | -.206 | .771 | -.082 | 1.154 | 2.089 | -1.619 | -.221 |
| S41 | .933 | -.651 | -.764 | -.928 | .334 | -.437 | .436 |
| S42 | 2.405 | .362 | .269 | -.627 | .956 | 2.246 | -.508 |
| S43 | 1.075 | -.619 | .14 | -.788 | -.051 | -.381 | .488 |
| S44 | -.983 | -.023 | -1.688 | -.563 | 1.475 | .218 | -.101 |
| S45 | 1.339 | -1.253 | 2.039 | -.848 | -.363 | -.443 | -.634 |
| S46 | .916 | -1.329 | -.469 | -.775 | -.42 | .083 | -.064 |
| S47 | -2.073 | -.085 | -.421 | 1.284 | -1.398 | 1.522 | .1 |
| S48 | -1.713 | -.376 | .505 | -.483 | -1.421 | .794 | -.812 |
| S49 | .461 | -1.121 | 1.935 | .574 | .295 | -.392 | .138 |
| S50 | 2.104 | -3.361 | -2.07 | -1.827 | -1.423 | -1.087 | .152 |
| S51 | 2.561 | -3.953 | -2.992 | -1.578 | -2.444 | -1.331 | -.281 |
| S24 | .502 | .189 | -1.991 | .021 | .798 | -.974 | .604 |
| S25 | -2.707 | 1.7 | -3.195 | -.93 | 1.759 | -1.461 | -.631 |
| S26 | .18 | -.658 | -1.161 | -.511 | 1.63 | .108 | .234 |
| S27 | -2.791 | .661 | -1.837 | .805 | .274 | -.459 | .035 |
| S28 | .404 | -.554 | -.803 | 1.49 | .886 | -.477 | .174 |
| S30 | -.591 | .074 | 2.968 | .896 | .64 | -2.317 | .393 |
| S33 | 1.312 | .772 | .957 | 1.05 | .23 | -1.612 | .508 |
| S34 | .574 | -.588 | -.392 | -.884 | -.445 | -.915 | .543 |
| S35 | -2.635 | 1.048 | -.066 | -.029 | -1.115 | .435 | -.366 |
| S37 | -2.092 | .752 | -1.418 | -.72 | .49 | -.167 | -.36 |
| S38 | -.561 | 2.449 | -.195 | 3.932 | -1.365 | -2.39 | -.147 |
| S39 | -2.724 | .603 | .932 | -2.448 | -.767 | .728 | 7.061 |
| S40 | .308 | -.068 | .169 | -.396 | .061 | .772 | .604 |
| S52 | -.774 | -.238 | -1.023 | -.732 | 1.253 | -.117 | .183 |
| S54 | 2.101 | -.858 | 1.261 | .012 | 1.244 | 1.604 | -.492 |
| S55 | -2.237 | -.646 | 1.495 | -.501 | -2.979 | -.552 | -1.984 |
| S56 | -.671 | -.849 | .323 | 1.484 | -2.834 | .044 | .287 |
| S57 | -.193 | -1.145 | -.135 | -.729 | -.391 | -.16 | -.393 |
| S58 | -3.071 | .942 | -.401 | .032 | -1.164 | .501 | .111 |
| S59 | -1.508 | .134 | .16 | -.255 | -.337 | .767 | -.113 |
| S60 | -1.823 | .471 | -1.111 | -.254 | 1.212 | -.18 | -.512 |
| S61 | -.831 | -.412 | 3.711 | .394 | .653 | -1.67 | .325 |
| S62 | -.497 | -.51 | -.598 | -.977 | .298 | -.236 | .186 |
| S64 | .966 | -2.057 | -.431 | -.385 | -.376 | .68 | -.4 |

Table 10.17 cont.

| Sample Number | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|
| S66 | .702 | -1.635 | 3.484 | -.53 | -.2 | -1.448 | -.705 |
| S67 | -.642 | -.435 | .325 | -.554 | -.3 | .401 | -.3 |
| S68 | .064 | -.615 | .543 | .03 | .565 | .656 | -.324 |
| S69 | -.074 | -.847 | .646 | -.056 | .23 | .445 | -.663 |
| S70 | -.12 | -.457 | 1.572 | .874 | 2.116 | 2.468 | -.059 |
| S71 | -2.84 | .907 | -.626 | -.213 | -.566 | -.634 | -.597 |
| S72 | -3.049 | .65 | -.79 | -.385 | -.429 | -.531 | -.167 |
| S73 | -1.848 | .089 | .21 | -.267 | -.07 | 1.577 | -.032 |
| S74 | .634 | -1.114 | .466 | .552 | -.036 | .069 | .459 |
| S75 | -.698 | -.393 | .7 | .176 | .261 | 1.686 | -.409 |
| S76 | -.3 | -1.297 | 3.443 | .047 | -.272 | -.77 | -1.104 |
| S77 | 1.651 | -1.475 | -1.072 | -.675 | .225 | .046 | -.004 |
| S80 | .323 | -.537 | -.949 | .674 | .077 | .792 | -1.215 |

Table 10.18 Groups and their interpretation.

a) Glacial

(Group 1)
Ippollitts (S58)
Ippollitts (S71)
Ippollitts (S72)
Weedon Bec (S59)
Upper Sundon (S17)
Upper Sundon (S73)
Ridgmont (S47)
Ridgmont (S48)
St. Neots (S35)
Wootton (S29)
Stoke Goldington (S27)
Broughton Grounds (S56)
Winslow (S75)

Reworked

(Group 7)
Bletchley (S46)
Broughton Ground (S67)
Marsworth (S40)

Clifton (S1)
Rushings (S21)
Aspley Guise (S38)

Lodge Farm (S55)

Marsworth (S39)

b) Fluvial

Ouse terrace:

(Group 2)
Buckingham (S44)
Great Barford (S13)
Great Barford (S14)
Great Linford (S24)
Stoke Goldington (S26)
Stoke Goldington (S52)
Little Paxton (S34)
Willington (S41)
Bromham (S62)
Radwell (S16)

Reworked

Nether Heyford (S60)
Buckingham (S25)
Bromham (S37)
(Group 4)
Blunham (S12)
Leighton Buzzard (S6)
Clifton (S2)
Buckingham (S43)
Toddington (S74)
(Group 8)
Lidlington (S77)
Lidlington (S80)

Ouzel terrace and tributary:

(Group 3)
Bow Brickhill (S57)
Bow Brickhill (S69)
Broughton (S23)
Broughton (S68)
Elstow (S64)

(Group 10)
Kempston (S50)
Elstow (S51)

(Group 6)
Stewartby (S66)
Millbrook (76)

Reworked

(Group 5)
Fox Corner (S20)
Fox Corner (S70)
Bletchley (S42)
Simpson (S54)

Aspley Guise (S22)

(Group 11)
Stewartby (S49)
Rowsham (S45)

Milton Malsor (S30)
Milton Malsor (S61)

Nene terraces:
Clifford Hill (S28)
Earls Barton (S32)
Rushden (S33)

c) Odd
Leighton Buzzard (S5)
Leighton Buzzard (S7)
Pitsford (S31)

Table 11.1 Stoke Goldington - Uranium Series Date (M. Ivanovich).

| (U) | Activity ratios | | | | Age | Error |
|---|---|---|---|---|---|---|
| (ppm) | ${}^{234}\text{U}/{}^{238}\text{U}$ | ${}^{230}\text{Th}/{}^{234}\text{Th}$ | ${}^{230}\text{Th}/{}^{232}\text{Th}$ | $({}^{234}\text{U}/{}^{238}\text{U})_o$+ | (1000 yr) | (1000 yr) |
| 0.55 | 1.73 | 0.940 | 1.5 | 2.31 | 208 | +44<br>-33 |
| +/-0.03* | +/-0.11 | +/-0.68 | | +/-0.20 | | |

* All errors quoted on 1 standard deviation error due to nuclear counting uncertainties only.

\+ Initial ${}^{234}\text{U}/{}^{238}\text{U}$ activity ratio at zero age.

Table 12.1 Proposed correlation of the Ouse deposits

| 1 ? | 2 | Glacial deposits | Fluvial deposits (inc. Milton Sand) |
|---|---|---|---|
| Flandrian | Flandrian | | Floodplain sediments (alluvium) |
| Devensian | Devensian | | Early Devensian terrace deposits |
| Ipswichian | Ipswichian | | Late Ipswichian terrace deposits |
| 120Ka | | | Ipswichian deposits |
| W3 | Wolstonian 2 | Stoke Goldington Fluvioglacial gravels (Glacial Event III) | |
| | | | Stoke Goldington lower gravel |
| W? 170Ka | intra-Wolstonian interglacial | | Stoke Goldington Interglacial deposits |
| W2 | Wolstonian 1 | | Biddenham terrace gravels |
| W? | Hoxnian | | Biddenham temperate deposits |
| W1 | Anglian | Deep channels and main part of chalky till (Glacial Event II) | Subglacial Drainage |
| Hoxnian | Pre-Anglain temperate | | Pre-Glacial II river deposits (found incorporated in glacial II till) |
| Anglian | | Pre-Glacial II glacial event(s) (Glacial Event I) | |
| | | | Milton Sand (? pre-glacial) |

Plate 1. Site 2. Broughton - showing horizontally bedded gravel (2.5-4m) extracted to the local bedrock (Oxford Clay).

Plate 2. Site 8. Great Linford - Horizontally bedded gravel (3-3.5m) overlain by dark grey flaky clay (50cm).

Plate 3. Site 13. Elstow - showing fine gravel in a shallow channel in the Oxford Clay.

Plate 4. Site 14. Millbrook - showing till fingering up into the gravel.

Plate 5. Site 19. Ridgmont - showing thin layer of fine gravel (0.5-1m) overlying chalky till.

Plate 6. Site 19. Ridgmont - showing pocket of gravel within upper 2m of chalky till.

Plate 7. Site 20. Upper Sundon - showing the main exposure of gravel (20m) with synclinal dip of c.30° from the east and west.

Plate 8. Site 21. Ippollitts - horizontally bedded outwash gravel (5-6m) overlain by chalky till (3-4m).

Plate 9. Site 23. St. Neots - fine clayey gravel within chalky till.

Plate 10. Site 26. Buckingham - poorly-sorted, poorly-bedded gravel (3-4m).

Plate 11. Site 30. Bromham - unbedded gravel overlies light-blue sticky clay which causes the ponding.

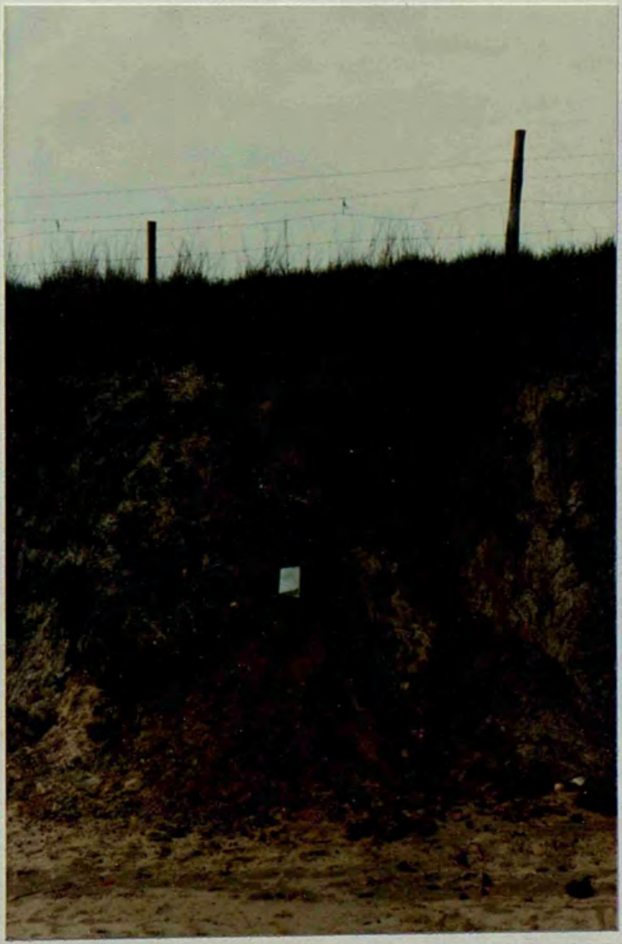

Plate 12. Site 37. Pitsford - 'Wedge' or 'gull' let down into the Northampton Sands. Till and gravel fill the gull.

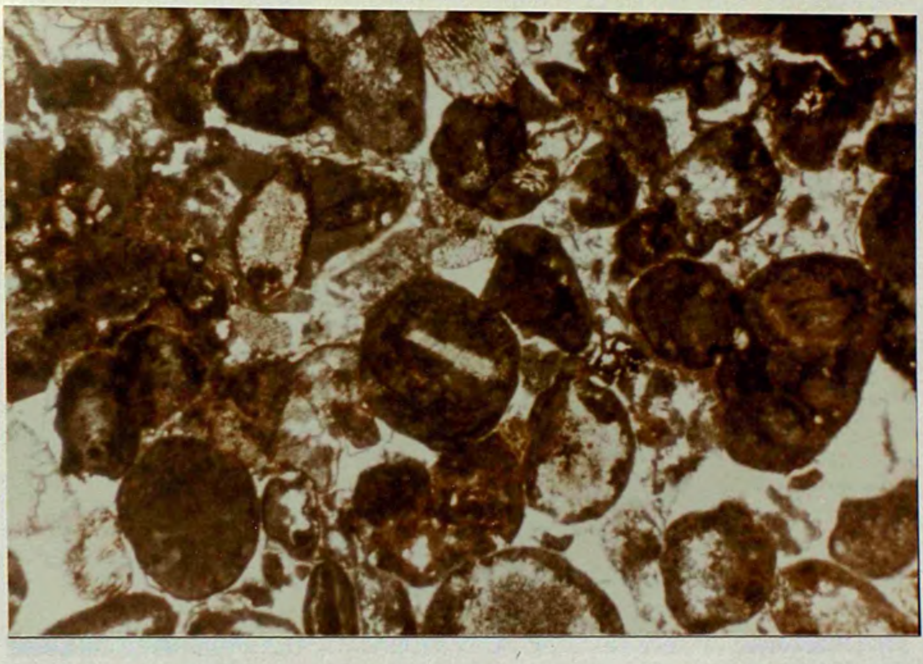

Plate 13. Limestone thin section - type 1 (x75) (see text for details; Chapter VIII).

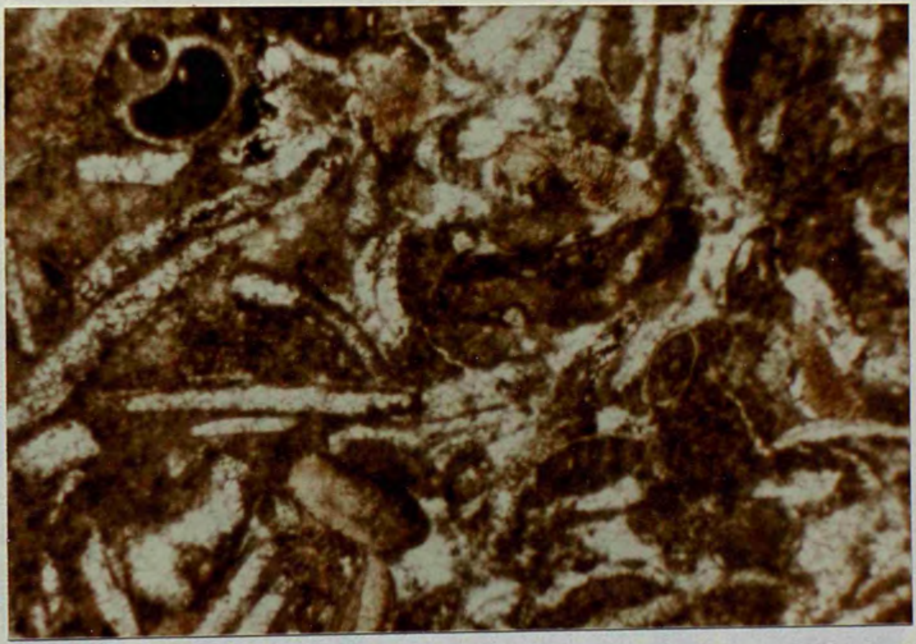

Plate 14. Limestone thin section - type 2 (x75) (see text for details; Chapter VIII).

Plate 15. Limestone thin section - type 3 (x75) (see text for details; Chapter VIII).

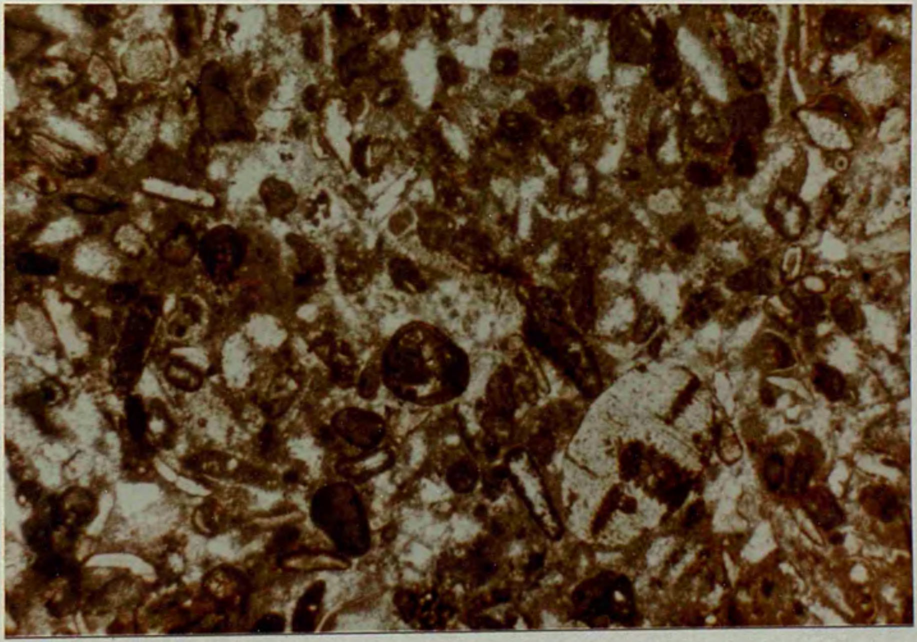

Plate 16. Limestone thin section - type 4 (x75) (see text for details; Chapter VIII).

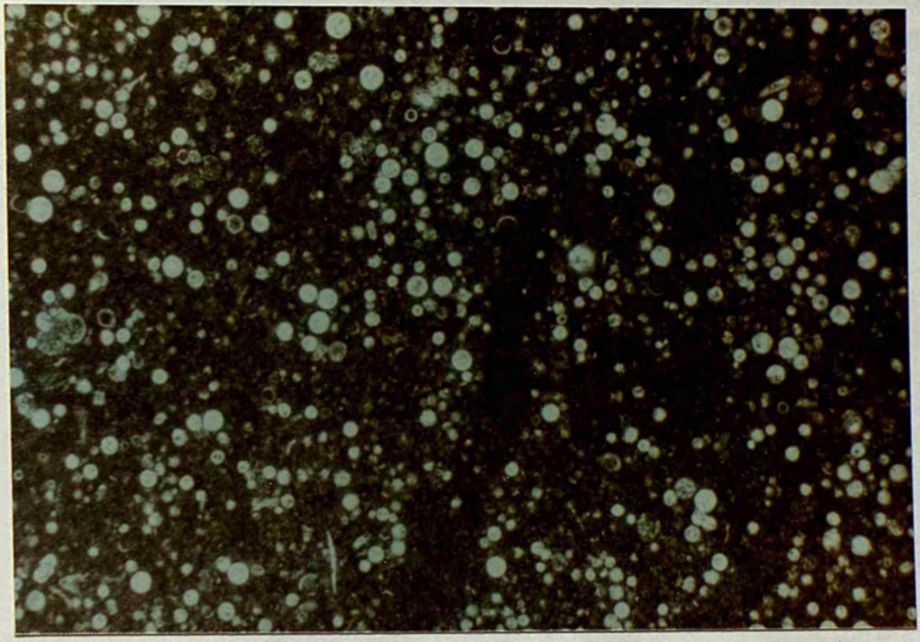

Plate 17. Chalk thin section (x75). N.B. globigerina foraminifera.

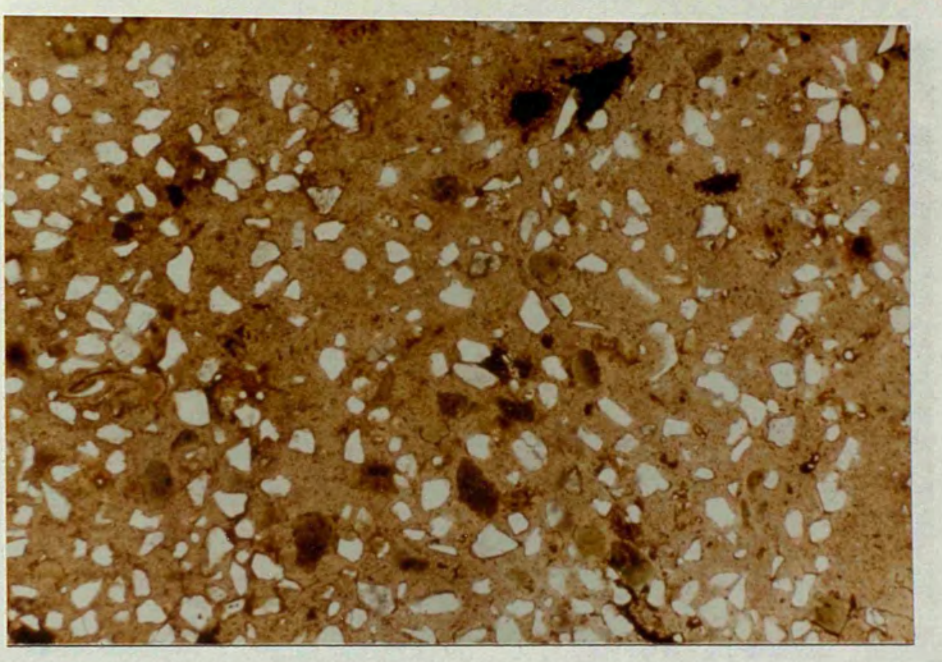

Plate 18a. Phosphatic nodule thin section (x75).
N.B. quartz grains in the phosphatic matrix.

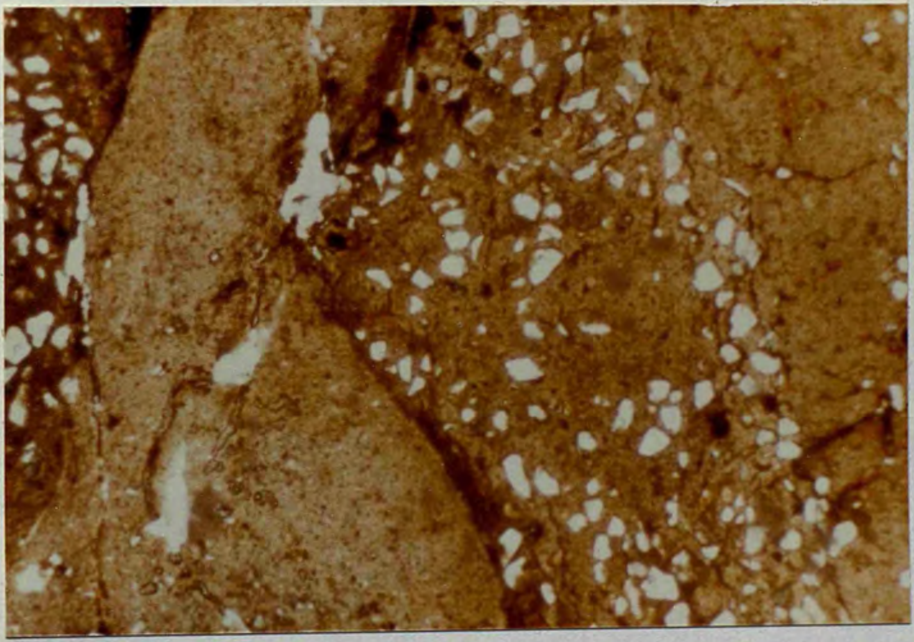

Plate 18b. Phosphatic nodule thin section (x75).
N.B. quartz grains in the phosphatic matrix.

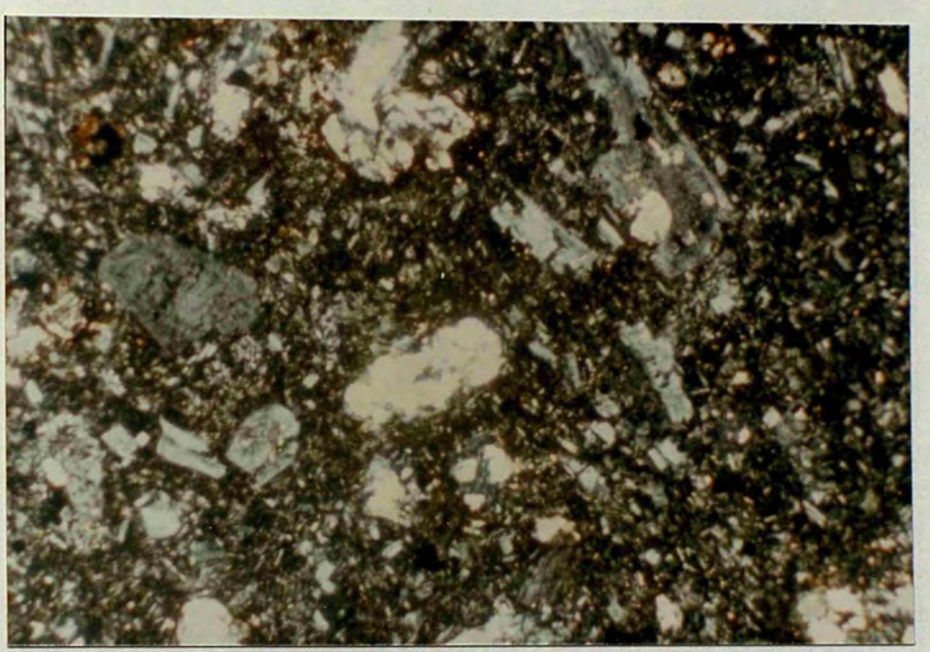

Plate 19a. Igneous thin section (x75). This, together with th next two plates, displays the dissimilarity in the types of igneous pebbles.

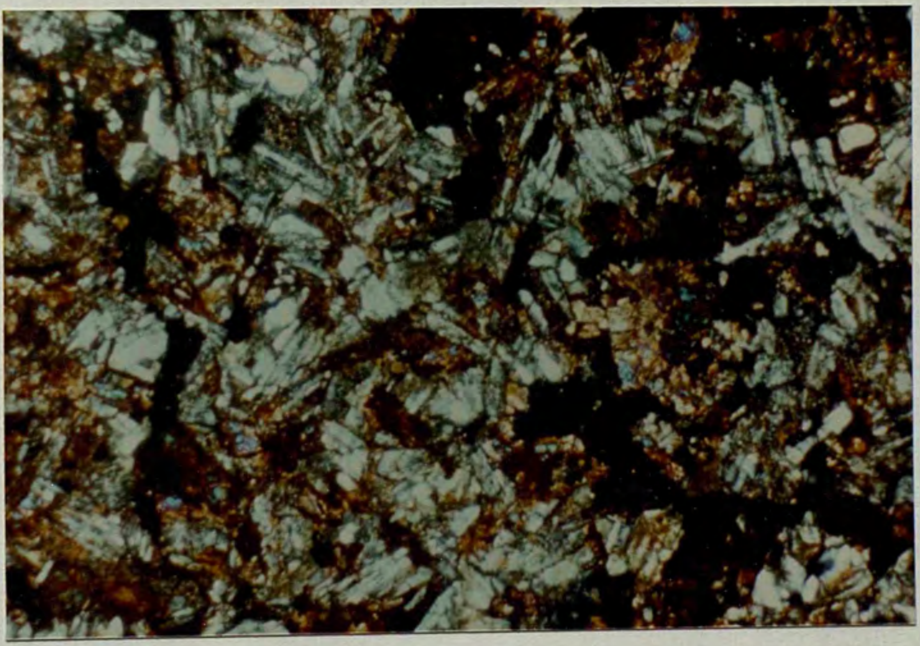

Plate 19b. Igneous thin section (x75).

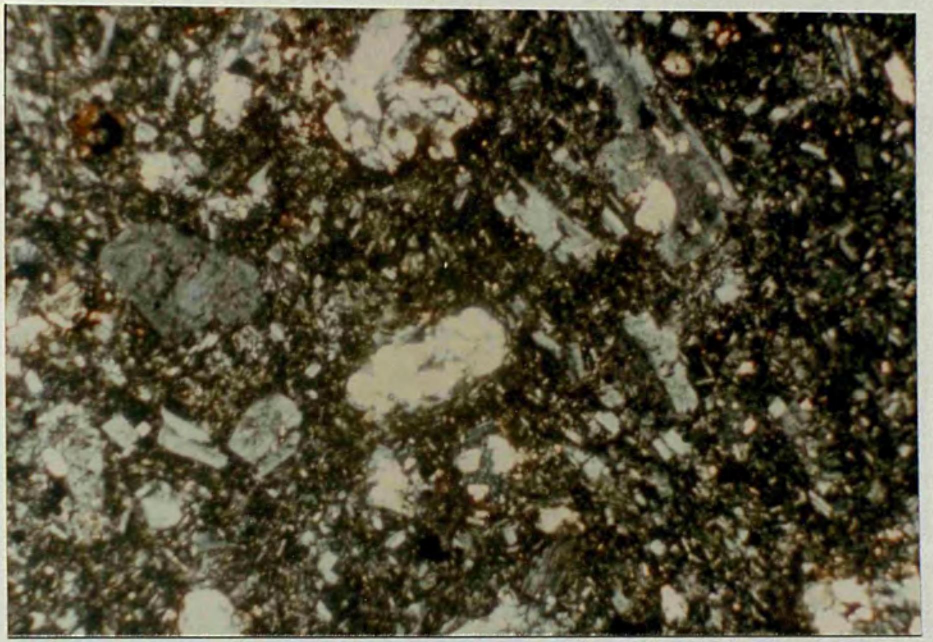

Plate 19a. Igneous thin section (x75). This, together with the next two plates, displays the dissimilarity in the types of igneous pebbles.

Plate 19b. Igneous thin section (x75).

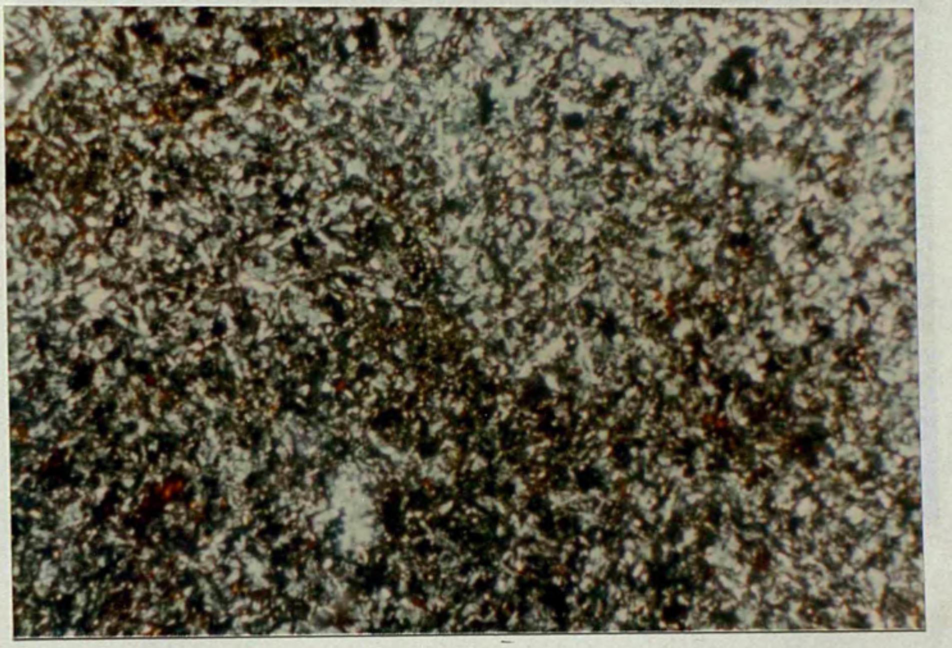

Plate 19c. Igneous thin section (x75).

Plate 20. Stoke Goldington - floodplain and terrace to the south of the pit.

Plate 21. Stoke Goldington - floodplain, pit and terrace.

Plate 22. Stoke Goldington - section at point A (October, 1981). Basal gravel (c) up through clay (d - i).

Plate 23. Stoke Goldington - section at point A (October, 1981). Close up of clay (d - i).

Plate 24. Stoke Goldington - section at point A (october, 1981). Close up of basal gravel (c) and clay (d - i).

Plate 25. Stoke Goldington - gravel face at point A' (October, 1981). Showing terrace gravel (j) overlain by cryoturbated fluvioglacial gravel (l).

Plate 26. Stoke Goldington - section at point C (November, 1981). Relationship of section at point C to the main gravel face.

Plate 27. Stoke Goldington - trench at point C. Pollen sampling (November, 1981).

Plate 28. Stoke Goldington - trench at point E (November, 1982). Cross-section of channel with present floodplain in the background.

Plate 29. Stoke Goldington - sampling clay (d - i) at point E (November, 1982). Max. thickness of clay 1.72m.

Plate 30. Stoke Goldington - section at point F (October, 1983). Showing terrace gravel (j) overlain by clay (k), and with fluvioglacial gravel (l) on top.

Plate 31. Stoke Goldington - section at point F (October, 1983). Showing extraction of the fluvioglacial gravel (l) to the surface of the terrace gravel (j).

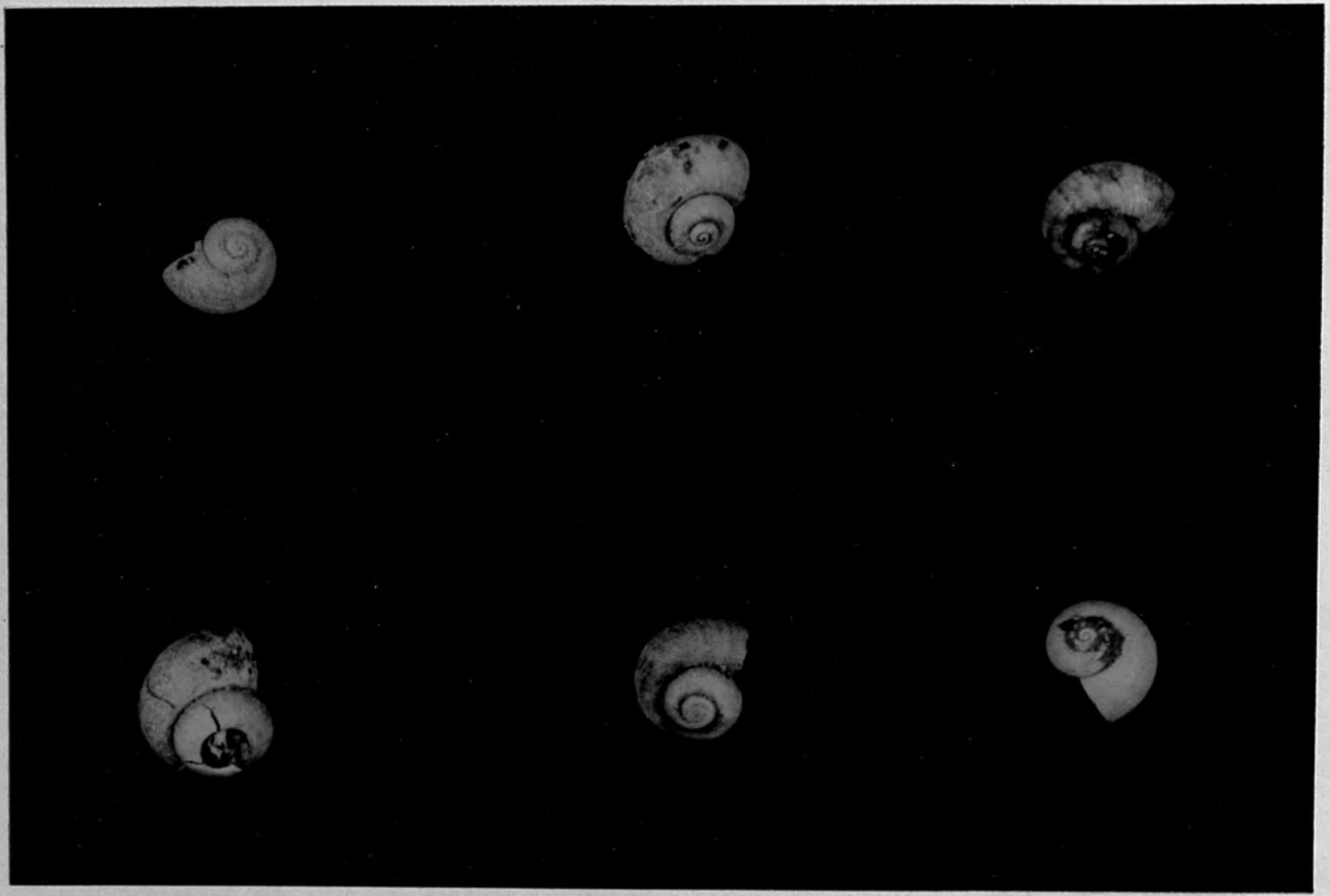

Plate 32a. *Valvata piscinalis* from Stoke Goldington.

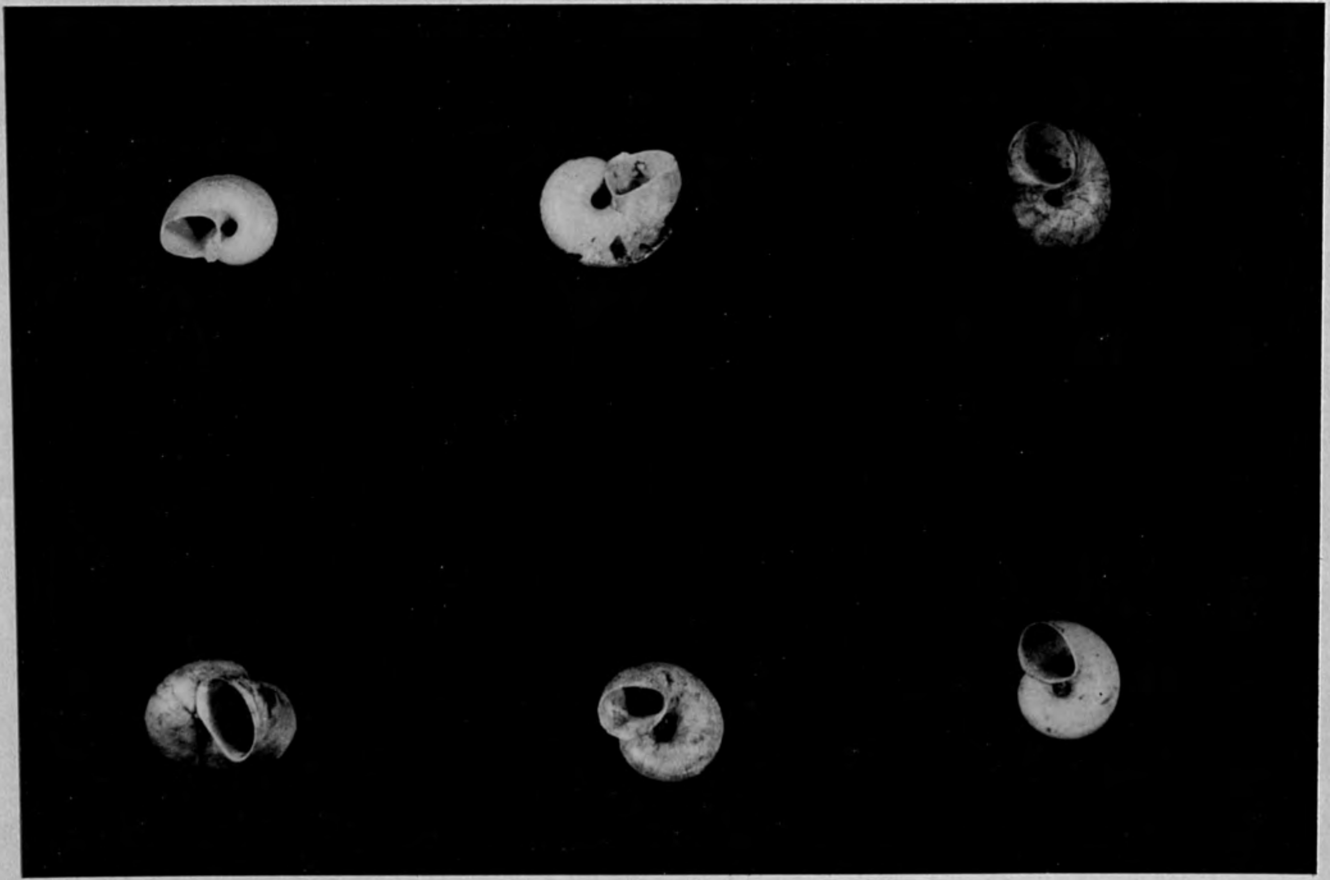

Plate 32b. Valvata piscinalis from Stoke Goldington.

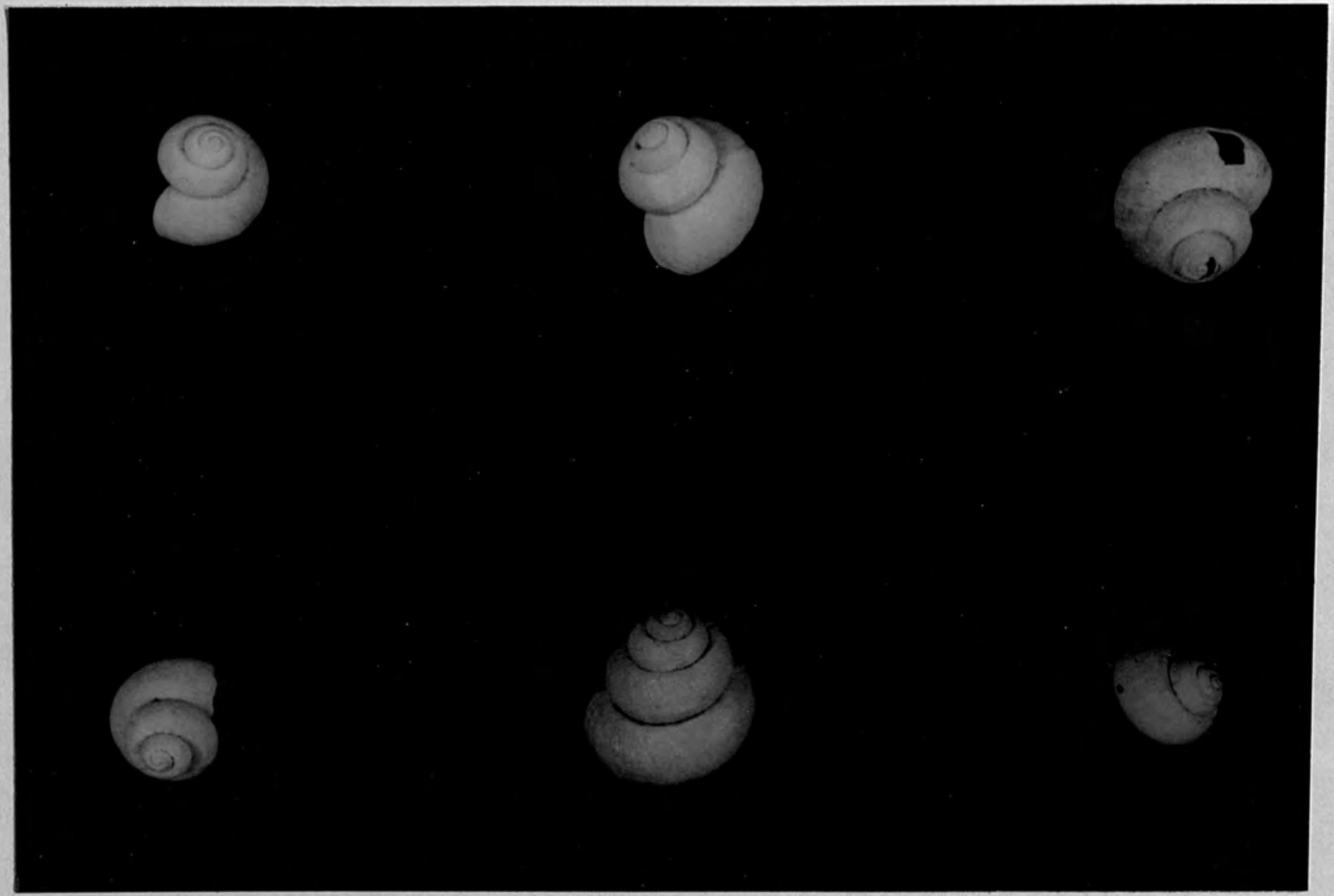

Plate 33a. Valvata piscinalis from Warwick Avon, Stratford.

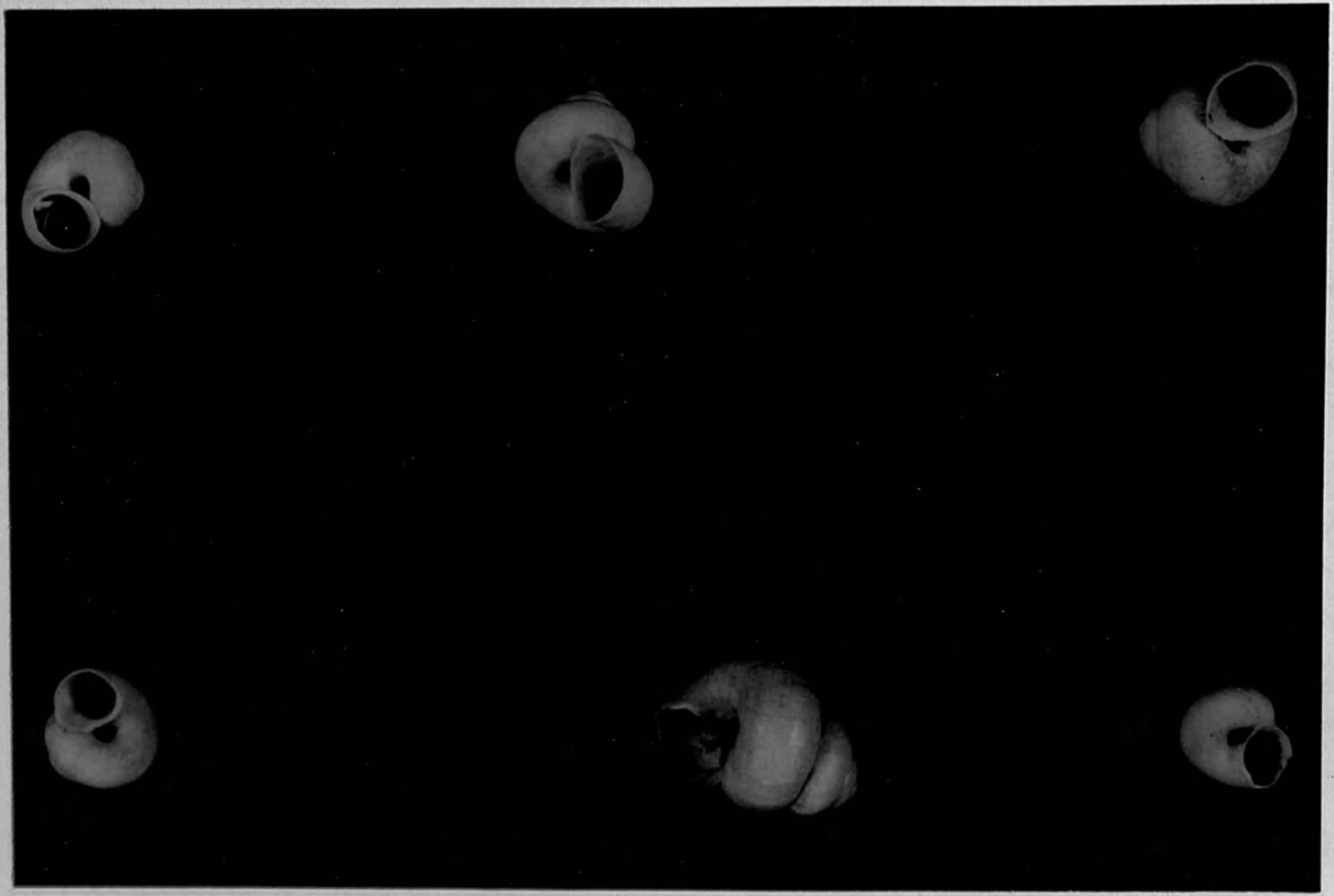

Plate 33b. Valvata piscinalis from Warwick Avon, Stratford.

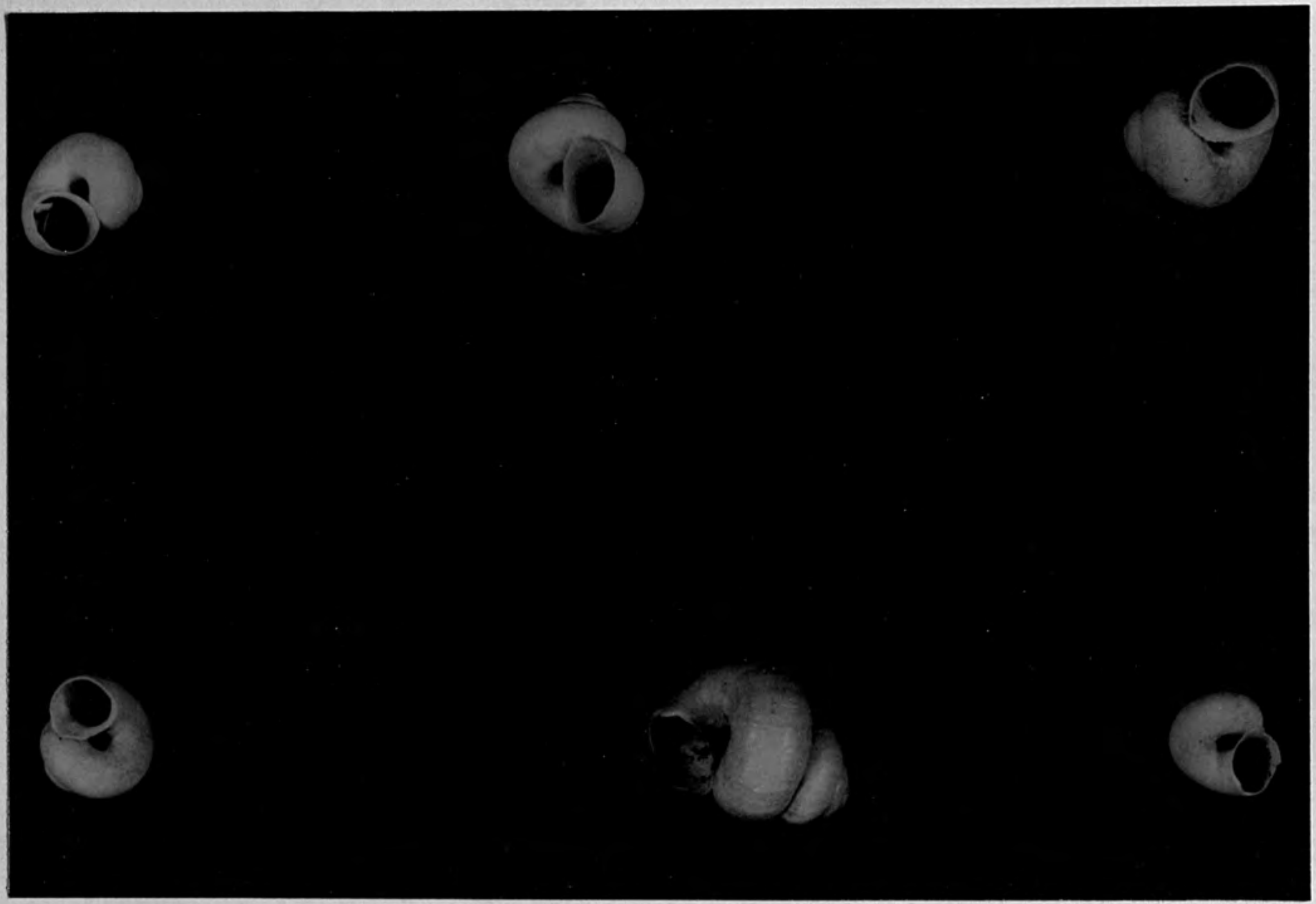

Plate 33b. *Valvata piscinalis* from Warwick Avon, Stratford.

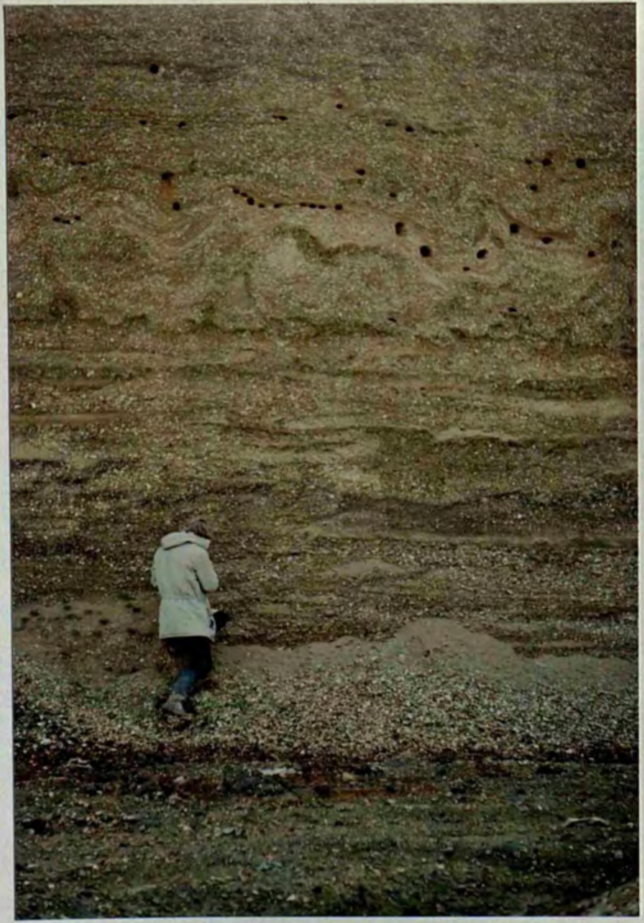

Plate 34. Stoke Goldington - showing terrace gravel overlain by involuted fluvioglacial gravel (October, 1981).

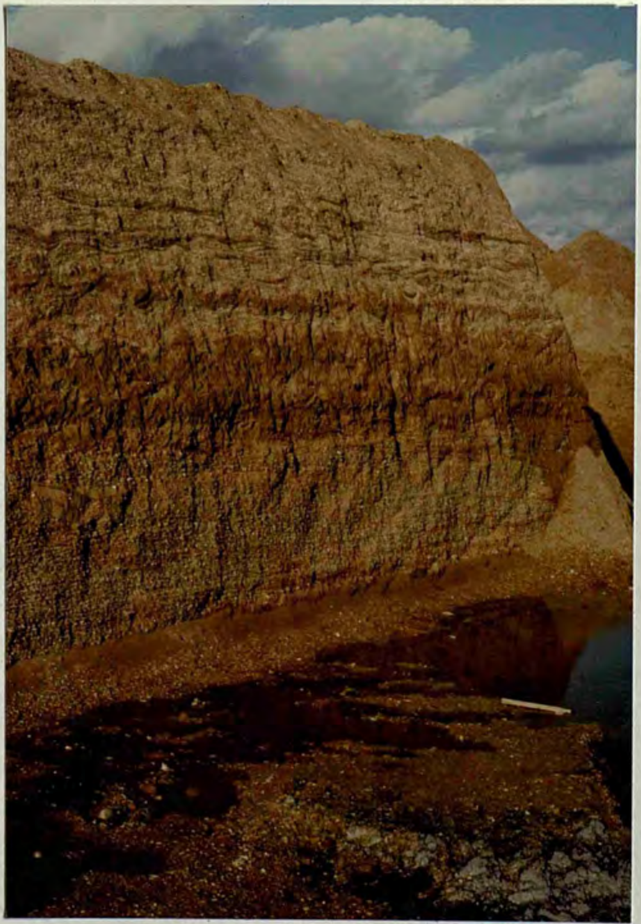

Plate 35. Stoke Goldington - horizontally bedded terrace gravel overlain by fluvioglacial gravel (October, 1981).

Plate 36. Stoke Goldington - gravel face, showing terrace and fluvioglacial gravels (October, 1981).

Plate 37. Stoke Goldington - maximum gravel face, looking north away from the present floodplain.

Plate 38. Stoke Goldington - gravel face, showing detail of cryoturbation in the fluvioglacial gravel (1) (November, 1981).

Plate 39. Stoke Goldington - horizontally bedded terrace gravel and fluvioglacial gravel (October, 1983). Looking west from point A.

Appendix I. Gross percentage data.

| | Qite | Qtz | Hs | Ss | Fes | Ls | Ch | Rc | C | Calc Stn | Cs | Ig | Sh | Misc H | PhN | Mstn | FeLs | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 3.7 | 5.55 | 7.4 | | 3.7 | 3.7 | 29.62 | | 1.85 | 3.7 | 1.85 | | 5.55 | | | | | | |
| S2 | 5.8 | 4.35 | 2.9 | 2.9 | 10.15 | | | | 1.45 | | | | | | 1.45 | | | | |
| S5 | 15.71 | 12.5 | 6.9 | 2.77 | 14.33 | | | .92 | 2.31 | | .92 | | | 1.38 | 1.85 | | | | |
| S6 | 8.26 | 7.43 | 13.21 | 2.47 | 12.39 | | | | 1.24 | | | | | | 2.89 | | | | |
| S7 | 12.12 | 7.95 | 9.47 | 3.03 | 13.63 | | | .37 | 2.27 | | .75 | | | 1.13 | 4.54 | | | | |
| S12 | 5.7 | 1.58 | 3.17 | 1.2 | 3.17 | 2.85 | 5.07 | | .32 | | .32 | .32 | .63 | | .63 | | | | |
| S13 | 17.89 | 2.87 | 9.9 | .95 | 1.59 | 17.25 | | .64 | 2.87 | .32 | | .64 | .95 | | .64 | | 1.28 | | |
| S14 | 8.93 | .28 | 5.18 | 1.15 | 1.73 | 18.15 | 2.01 | .86 | 3.74 | .28 | | .28 | .57 | .28 | .28 | | | | |
| S16 | 8.35 | 1.55 | 7.43 | .3 | 1.85 | 20.74 | 1.85 | 1.55 | 3.4 | | .3 | .3 | .3 | | | | 3.4 | | |
| S17 | 1.88 | .27 | 3.23 | 1.61 | 7.54 | 5.66 | 57.14 | .27 | | .81 | | .81 | 2.42 | | | | | | |
| S20 | 6.12 | | 12.23 | .51 | 36.22 | | | .51 | 1.53 | | .51 | 1.02 | | | | | | | |
| S21 | 5.76 | 3.05 | 6.1 | 2.36 | 3.73 | 8.81 | 29.83 | .34 | 2.71 | 1.35 | | .34 | 4.4 | | .67 | | | .34 | |
| S22 | 6.42 | 1.78 | 4.63 | 1.07 | 53.21 | 8.57 | 5.71 | 1.07 | .71 | 1.42 | | 1.42 | 2.85 | | .35 | | | | 1.42 |
| S23 | 8.7 | 1.97 | 5.36 | .84 | 13.33 | 5.36 | 9.6 | 1.13 | 3.1 | .56 | | .84 | 3.95 | | 1.69 | | .28 | | |
| S29 | 2.75 | | .91 | 3.67 | 3.67 | 11.0 | 39.45 | .91 | | 2.75 | | .91 | 4.58 | | | | 1.85 | | |
| S31 | 16.82 | 3.56 | 21.35 | 1.61 | 22.97 | | | 2.91 | 3.23 | | | .64 | | | | 1.29 | | .32 | |
| S32 | 9.66 | 1.0 | 6.66 | 1.66 | 25.32 | 14.33 | 2.33 | .66 | .33 | .66 | | .33 | .66 | | .33 | | 2.66 | | |
| S41 | 8.3 | 2.67 | 7.82 | | 1.48 | 17.21 | 1.48 | 2.07 | 2.07 | | | | .29 | | .59 | | | | |
| S42 | 10.71 | 1.09 | 13.46 | | 5.49 | | | .82 | 1.64 | | .82 | .82 | | .27 | .27 | | | | |
| S43 | 6.64 | 2.95 | 7.01 | | 9.95 | | | 1.47 | 2.21 | | | | | | | | | | |
| S44 | 5.45 | 1.21 | 6.97 | .3 | 2.72 | 41.81 | 12.42 | 1.21 | 2.11 | 1.81 | | .6 | .91 | | | | | | |
| S45 | 8.69 | 1.45 | 10.62 | | .96 | 2.41 | 3.38 | .48 | .48 | | | | .48 | | 15.45 | | | | |
| S46 | 6.97 | 1.16 | 13.37 | | 14.53 | 7.55 | 20.34 | | 4.65 | | | | 3.48 | | 1.74 | | | | |
| S47 | 3.01 | .27 | 3.56 | | 2.46 | 10.68 | 37.8 | .54 | .27 | 1.1 | | .27 | 7.39 | | .27 | .82 | | | |
| S48 | 2.25 | .32 | 5.14 | | .96 | 8.68 | 27.65 | | 1.28 | .32 | | .32 | 10.93 | | 1.28 | | | | |
| S49 | 4.16 | .27 | 7.77 | .55 | 40.0 | | | .55 | 1.11 | | | .27 | | | 5.0 | .27 | | | |

Appendix I cont.

| | Qite | Qtz | Hs | Ss | Fes | Ls | Ch | Rc | C | Calc Stn | Cs | Ig | Sh | Misc H | PhN | Mstn | FeLs | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S50 | 2.19 | 1.09 | 13.18 | | 2.19 | 1.09 | | 5.49 | 7.69 | | | | 1.09 | | 2.19 | | | | |
| S51 | 6.78 | 1.81 | 12.66 | | 8.14 | 2.26 | 2.71 | .9 | 6.33 | .45 | | | 5.43 | | 1.81 | | | | |
| S24 | 10.62 | 2.07 | 5.95 | 1.55 | 4.65 | 33.16 | 1.03 | 1.55 | 2.86 | 1.29 | | | .51 | | | .26 | | | .26 |
| S25 | 5.37 | 1.07 | 1.79 | .71 | .35 | 61.64 | 8.6 | | 2.17 | 5.37 | | | .71 | | .35 | | .35 | | |
| S26 | 7.36 | 1.05 | 8.94 | .26 | 2.36 | 34.99 | .52 | 1.31 | 2.1 | .26 | | .52 | | | | | | | |
| S27 | .86 | | .86 | .86 | 2.29 | 31.6 | 29.88 | .86 | 1.71 | 2.29 | | .28 | 2.58 | | .28 | .57 | 1.43 | | |
| S28 | 5.85 | 1.88 | 10.87 | .21 | 31.58 | 7.53 | 2.09 | 1.25 | 2.09 | 1.25 | | .21 | .41 | | | .62 | 1.67 | | |
| S30 | 1.94 | | .97 | 1.94 | 82.03 | .97 | .48 | .48 | .48 | | | | | | | | .48 | | |
| S33 | 5.96 | .27 | 8.13 | 4.87 | 29.80 | .81 | .54 | 1.35 | 1.89 | .27 | | .27 | | .27 | .54 | | | | |
| S34 | 3.70 | 2.15 | 5.1 | 1.07 | .27 | 5.37 | .8 | 2.15 | 2.95 | | | | .54 | | | | | | |
| S35 | .24 | .24 | | .98 | 12.47 | 12.49 | 38.72 | .49 | .98 | 2.45 | .24 | .24 | 5.14 | | .24 | .24 | | | |
| S37 | 4.36 | .27 | 1.63 | .27 | 1.9 | 19.89 | 24.52 | | 2.7 | 3.81 | | .27 | .81 | | | | .27 | | |
| S38 | 6.61 | 2.03 | 4.32 | 6.1 | 29.75 | 14.5 | 6.61 | .25 | .76 | 2.03 | | .25 | 9.16 | | .5 | | 1.27 | .25 | .25 |
| S39 | | .91 | .91 | | | 14.53 | 37.27 | | .91 | | | | | | | | | | 9.09 |
| S40 | 9.84 | 1.75 | 9.62 | | 4.58 | 2.84 | 33.04 | .21 | .87 | | | | | | | | | | |
| S52 | 5.44 | .21 | 8.71 | | 5.65 | 32.02 | 3.26 | | 1.96 | 1.74 | | .21 | .87 | | .21 | | | | .42 |
| S54 | 8.04 | 1.0 | 16.07 | | 23.11 | | | .5 | 1.75 | | .25 | 1.0 | | .25 | 4.27 | | | | |
| S55 | | | | | 14.76 | 6.81 | | | 1.13 | | | | 21.58 | | 2.27 | | | | |
| S56 | 4.49 | | 5.98 | | 10.46 | 5.09 | 35.62 | 2.09 | .89 | .29 | | | 5.09 | | 5.09 | | | .29 | |
| S57 | 4.2 | .56 | 7.28 | | 12.6 | 8.96 | 11.48 | 1.96 | 2.8 | 1.12 | | .28 | 3.36 | | 3.08 | | | | |
| S58 | .86 | | 1.72 | .57 | 2.86 | 8.59 | 56.44 | .57 | .28 | 2.86 | | | 2.57 | | .57 | .28 | .28 | | |
| S59 | 2.2 | 1.4 | 4.2 | .6 | 9.61 | 11.22 | 35.87 | 1.2 | 1.2 | 1.2 | | .6 | 3.4 | | .8 | | | | |
| S60 | 4.33 | .65 | 5.42 | | 7.58 | 27.76 | 17.78 | .43 | 1.3 | 2.6 | | .43 | 1.95 | | .43 | | 1.08 | | |
| S61 | .43 | .43 | .87 | | 95.62 | .43 | | | | | | | | | | | | | |

Appendix I cont.

| | Qite | Qtz | Hs | Ss | Fes | Ls | Ch | Rc | C | Calc Stn | Cs | Ig | Sh | Misc H | PhN | Mstn | FeLs | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S62 | 4.08 | .75 | 5.43 | | 1.36 | 17.97 | 9.36 | .6 | 2.72 | .75 | | .15 | .9 | | .45 | | | | |
| S64 | 5.88 | .65 | 11.76 | | 6.53 | .65 | 3.27 | 3.27 | 3.27 | | | .65 | 5.23 | | .65 | | | | |
| S66 | 4.51 | | 7.09 | | 46.45 | | | | 1.29 | | | | | | 15.48 | | | | |
| S67 | 5.44 | 1.0 | 4.63 | | 6.65 | 7.86 | 21.37 | .8 | 1.81 | .8 | | .4 | 3.63 | | 3.02 | | | | |
| S68 | 7.03 | 1.0 | 9.18 | | 15.35 | 4.59 | 10.81 | .71 | 1.15 | .71 | | .57 | 2.72 | | 1.72 | | .28 | | |
| S69 | 6.94 | .61 | 7.55 | | 18.77 | 5.71 | 10.2 | .81 | 1.83 | .81 | | .61 | 4.49 | | 3.47 | | .2 | | |
| S70 | 4.91 | 1.64 | 9.83 | | 26.23 | 6.55 | 14.75 | | | | | 1.64 | | | | | | | |
| S71 | .79 | .79 | 3.17 | | 3.97 | 3.97 | 43.65 | .79 | .79 | 2.38 | | | 4.76 | | | | 2.38 | | |
| S72 | .21 | | 3.37 | .42 | 1.47 | 22.36 | 49.15 | 1.26 | .42 | 1.26 | | | 4.43 | | | | 1.68 | | |
| S73 | 3.39 | .78 | 3.91 | | 4.7 | 12.27 | 47.78 | .52 | 1.04 | .78 | | .78 | 3.13 | | .52 | | | | |
| S74 | 3.7 | 1.23 | 12.34 | | 4.94 | | | 2.47 | | | | | | | | | | | |
| S75 | 4.33 | 1.44 | 7.22 | .36 | 4.69 | 9.74 | 22.74 | .72 | .72 | | | 1.08 | 5.41 | | 1.44 | | | | |
| S76 | 3.05 | | 4.36 | | 55.46 | 2.62 | .43 | | .87 | | | .43 | 5.67 | | 10.48 | | | | |
| S77 | 9.79 | 1.4 | 16.08 | | 9.09 | 13.28 | 6.29 | .7 | 4.19 | | | | 2.79 | | .7 | | | | |
| S80 | 10.88 | 1.16 | 13.66 | .46 | 13.66 | 16.44 | 5.32 | .23 | 2.31 | 2.31 | | .46 | 9.03 | | 2.31 | .23 | | | |

Qite=Quartzite; Qtz=Quartz; Hs=Hard sandstone; Ss=Soft sandstone; Fes=Ferrous sandstone; Ls=Limestone; Ch=Chalk; Rc=Rhaxella chert; C=Chert; Calc Stn=Calcareous sandstone; Cs=Cherty sandstone; Ig=Igneous; Sh=Shell; Misc H =Miscellaneous hard; PhN=Phosphatic nodules; Mstn=Mudstone; FeLs=Ferrous Limestone; Sch=Schist; Grt=Grit.

Appendix II. Ratio data.

| | nd | Ch | Ls | Fes | Fl | Fl-d | Fl% Fl+Ch | Rc-d | Qite+ Hs | Qite+ Hs%d-Fl | Qtz% d-Fl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 46.27 | 64.02 | 8.0 | 8.0 | 33.33 | 62.03 | 52.95 | | 11.1 | 54.41 | 27.21 |
| S2 | 14.5 | | | 70.0 | 71.0 | 83.04 | 100.0 | | 8.7 | 60.0 | 30.0 |
| S5 | 18.95 | | | 75.62 | 40.27 | 49.69 | 100.0 | 1.14 | 22.61 | 55.44 | 30.65 |
| S6 | 17.75 | | | 69.8 | 52.03 | 63.26 | 100.0 | | 21.47 | 71.05 | 24.59 |
| S7 | 21.2 | | | 64.29 | 44.69 | 56.71 | 100.0 | .48 | 21.59 | 63.3 | 23.31 |
| S12 | 13.55 | 37.42 | 21.03 | 23.39 | 74.9 | 86.64 | 93.66 | | 8.87 | 76.8 | 13.68 |
| S13 | 22.98 | | 80.64 | 6.92 | 42.17 | 54.75 | 100.0 | .83 | 27.79 | 79.74 | 8.24 |
| S14 | 24.17 | 8.32 | 75.09 | 7.16 | 56.19 | 74.1 | 96.55 | 1.13 | 14.11 | 71.84 | 1.43 |
| S16 | 28.44 | 6.5 | 72.93 | 6.5 | 48.60 | 67.92 | 96.33 | 2.17 | 15.78 | 68.73 | 6.75 |
| S17 | 75.18 | 76.0 | 7.53 | 10.03 | 18.32 | 73.81 | 24.28 | 1.09 | 5.11 | 78.62 | 4.15 |
| S73 | 69.18 | 69.07 | 17.74 | 6.79 | 20.36 | 66.06 | 29.88 | 1.69 | 7.3 | 69.79 | 7.46 |
| S20 | 36.73 | | | 98.61 | 41.30 | 65.28 | 100.0 | .81 | 18.35 | 83.52 | |
| S70 | 47.53 | 31.03 | 13.78 | 55.19 | 34.42 | 65.60 | 70.0 | | 14.74 | 81.66 | 9.09 |
| S21 | 51.15 | 58.32 | 17.22 | 7.29 | 30.17 | 61.76 | 50.28 | .7 | 11.77 | 63.01 | 16.33 |
| S22 | 73.99 | 7.8 | 11.7 | 72.7 | 9.38 | 36.06 | 61.91 | 4.15 | 11.19 | 67.29 | 10.7 |
| S38 | 69.92 | 9.45 | 20.74 | 42.55 | 15.26 | 50.73 | 69.78 | .83 | 10.93 | 73.75 | 13.7 |
| S23 | 35.61 | 25.44 | 15.05 | 37.43 | 43.5 | 67.56 | 81.92 | 1.75 | 14.06 | 67.3 | 9.43 |
| S68 | 35.98 | 29.49 | 12.76 | 42.66 | 44.33 | 69.24 | 80.69 | 1.11 | 16.21 | 82.33 | 5.08 |
| S24 | 42.45 | 2.43 | 78.12 | 10.95 | 34.18 | 59.39 | 97.07 | 2.69 | 16.57 | 70.9 | 8.86 |
| S25 | 78.08 | 11.01 | 78.94 | .45 | 11.47 | 52.33 | 57.15 | | 7.16 | 68.52 | 10.24 |
| S43 | 9.95 | | | 100.0 | 69.74 | 77.45 | 100.0 | 1.63 | 13.65 | 67.21 | 14.52 |
| S44 | 59.97 | 20.71 | 69.72 | 4.54 | 22.42 | 56.01 | 64.35 | 3.02 | 12.42 | 70.53 | 6.87 |

Appendix II cont.

| | nd | Ch | Ls | Fes | Fl | Fl-d | Fl% Fl+Ch | Rc-d | Qite+ Hs | Qite+ Hs%d-Fl | Qtz% d-Fl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S52 | 43.86 | 7.46 | 73.16 | 12.93 | 39.3 | 70.0 | 92.32 | | 14.19 | 84.26 | 1.31 |
| S26 | 38.39 | 1.35 | 91.14 | 6.15 | 40.26 | 65.35 | 98.72 | 2.13 | 16.3 | 76.35 | 4.92 |
| S27 | 71.78 | 41.63 | 44.02 | 3.19 | 23.56 | 83.49 | 44.09 | 3.05 | 1.72 | 36.91 | |
| S28 | 45.36 | 4.61 | 16.6 | 69.62 | 32.42 | 59.33 | 93.94 | 2.29 | 16.72 | 75.25 | 8.46 |
| S29 | 66.97 | 58.91 | 16.43 | 5.48 | 27.52 | 83.32 | 41.09 | 2.76 | 3.66 | 66.42 | |
| S30 | 85.9 | .56 | 1.13 | 95.49 | 10.19 | 72.27 | 95.5 | 3.4 | 2.91 | 74.42 | |
| S61 | 96.05 | | .45 | 99.55 | 2.18 | 55.19 | 100.0 | | 1.3 | 73.45 | 24.29 |
| S31 | 25.87 | | | 88.79 | 25.24 | 34.05 | 100.0 | 3.93 | 38.17 | 78.07 | 7.28 |
| S32 | 47.95 | 4.86 | 29.89 | 52.81 | 33.33 | 64.03 | 93.47 | 1.27 | 16.32 | 87.18 | 5.34 |
| S33 | 36.83 | 1.47 | 2.2 | 80.91 | 44.98 | 71.2 | 98.81 | 2.14 | 14.09 | 77.46 | 1.48 |
| S34 | 8.05 | 9.94 | 66.71 | 3.35 | 75.8 | 82.44 | 98.96 | 2.34 | 8.8 | 54.49 | 13.31 |
| S35 | 72.73 | 53.24 | 17.17 | 17.15 | 24.75 | 90.76 | 38.99 | 1.8 | .24 | 9.52 | 9.52 |
| S37 | 51.47 | 47.64 | 38.64 | 3.69 | 39.23 | 80.84 | 61.54 | | 5.99 | 64.41 | 11.02 |
| S62 | 30.79 | 30.4 | 58.36 | 4.42 | 55.43 | 80.09 | 85.55 | .87 | 9.51 | 69.01 | 5.44 |
| S39 | 51.8 | 71.95 | 28.05 | | 36.36 | 75.44 | 49.38 | | .91 | 7.69 | 7.69 |
| S40 | 40.46 | 81.66 | 7.02 | 11.32 | 37.19 | 62.46 | 52.95 | .35 | 19.46 | 87.07 | 7.83 |
| S41 | 21.05 | 7.03 | 81.76 | 7.03 | 55.19 | 69.91 | 97.39 | 2.62 | 16.12 | 67.85 | 11.24 |
| S42 | 5.76 | | | 95.31 | 64.56 | 68.51 | 100.0 | .87 | 24.17 | 81.44 | 3.67 |
| S46 | 47.64 | 42.7 | 15.85 | 30.5 | 26.16 | 49.96 | 56.26 | | 20.34 | 77.63 | 4.46 |
| S45 | 22.68 | 14.9 | 10.63 | 4.23 | 55.55 | 71.84 | 94.26 | .62 | 19.31 | 88.7 | 6.66 |
| S47 | 60.52 | 62.46 | 17.65 | 4.06 | 31.5 | 79.79 | 45.45 | 1.37 | 6.57 | 82.33 | 3.38 |
| S48 | 49.82 | 55.5 | 17.42 | 1.93 | 40.83 | 81.37 | 59.62 | | 7.39 | 79.04 | 3.42 |
| S49 | 45.82 | | | 87.3 | 40.0 | 73.83 | 100.0 | 1.02 | 11.93 | 84.13 | 1.90 |

Appendix II cont.

| | nd | Ch | Ls | Fes | Fl | Fl-d | Fl% Fl+Ch | Rc-d | Qite+ Hs | Qite+ Hs%d-Fl | Qtz% d-Fl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S66 | 61.93 | | | 75.0 | 25.16 | 66.09 | 100.0 | | 11.6 | 89.85 | |
| S50 | 6.56 | | 16.62 | 33.38 | 63.73 | 68.2 | 100.0 | 5.88 | 15.37 | 51.73 | 3.67 |
| S51 | 20.8 | 13.03 | 10.87 | 39.13 | 50.67 | 63.98 | 94.92 | 1.14 | 19.44 | 68.14 | 6.34 |
| S64 | 16.33 | 20.02 | 3.98 | 39.99 | 58.17 | 69.52 | 94.68 | 3.91 | 17.64 | 69.18 | 2.55 |
| S54 | 27.38 | | | 84.4 | 43.71 | 60.19 | 100.0 | .69 | 24.11 | 83.4 | 3.46 |
| S55 | 45.42 | | 14.99 | 32.5 | 53.4 | 97.84 | 100.0 | | | | |
| S56 | 61.64 | 57.79 | 8.26 | 16.97 | 24.55 | 64.0 | 40.8 | 5.45 | 10.47 | 75.81 | |
| S67 | 43.33 | 49.32 | 18.14 | 15.35 | 42.54 | 75.07 | 66.56 | 1.41 | 10.07 | 71.27 | 7.08 |
| S57 | 40.6 | 28.28 | 22.07 | 31.03 | 42.29 | 71.2 | 78.65 | 3.3 | 11.48 | 67.1 | 3.27 |
| S69 | 43.65 | 23.37 | 13.08 | 43.0 | 37.96 | 67.36 | 78.82 | 1.44 | 14.49 | 78.79 | 3.32 |
| S58 | 75.02 | 75.23 | 11.45 | 3.81 | 21.49 | 86.03 | 27.58 | 2.28 | 2.58 | 73.93 | |
| S71 | 61.11 | 71.43 | 6.5 | 6.5 | 32.54 | 83.67 | 42.71 | 2.03 | 3.96 | 62.36 | 12.44 |
| S72 | 80.77 | 60.85 | 27.68 | 1.82 | 13.92 | 72.39 | 22.07 | 6.55 | 3.58 | 67.42 | |
| S59 | 62.70 | 57.21 | 17.89 | 15.33 | 26.45 | 70.91 | 42.44 | 3.22 | 6.4 | 58.99 | 12.90 |
| S60 | 59.18 | 30.04 | 46.91 | 12.81 | 28.19 | 69.06 | 61.32 | 1.05 | 9.75 | 77.2 | 5.15 |
| S74 | 4.94 | | | 100.0 | 75.3 | 78.21 | 100.0 | | 16.04 | 81.17 | 6.22 |
| S75 | 44.38 | 51.24 | 21.95 | 10.57 | 40.07 | 72.04 | 63.8 | 1.29 | 11.55 | 74.28 | 9.26 |
| S76 | 74.66 | .58 | 3.51 | 74.28 | 16.59 | 65.47 | 97.47 | | 7.41 | 84.69 | |
| S77 | 32.15 | 19.56 | 41.31 | 28.27 | 35.66 | 52.56 | 85.01 | 1.03 | 25.87 | 80.37 | 4.35 |
| S80 | 49.76 | 10.69 | 33.04 | 27.45 | 21.53 | 42.85 | 80.19 | .46 | 24.54 | 85.48 | 4.04 |

nd=Non-durable; d=durable; Ch=Chalk; Ls=Limestone; Fes=Ferrous sandstone; Fl=Flint; Rc=Rhaxella chert; Qite=Quartzite; Hs=Hard sandstone; Qtz=Quartz.

Appendix III. Decalcified sample data.

| | Qite | Qtz | Hs | Ss | Fes | Rc | C | Cs | Ig | Sh | Misc H | PhN | Mstn | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 5.88 | 8.82 | 11.76 | | 5.88 | | 2.94 | 2.94 | | 8.82 | | | | | |
| S2 | 5.8 | 4.35 | 2.9 | 2.9 | 10.15 | | 1.45 | | | | | 1.45 | | | |
| S5 | 15.71 | 12.5 | 6.9 | 2.77 | 14.33 | .92 | 2.31 | .92 | | | 1.38 | 1.85 | | | |
| S6 | 8.26 | 7.43 | 13.21 | 2.47 | 12.39 | | 1.24 | | | | | 2.89 | | | |
| S7 | 12.12 | 7.95 | 9.47 | 3.03 | 13.63 | .38 | 2.27 | .75 | | | 1.13 | 4.54 | | | |
| S12 | 6.2 | 1.72 | 3.45 | 1.38 | 3.45 | | .34 | .34 | .34 | .69 | | .69 | | | |
| S13 | 22.04 | 3.54 | 12.2 | 1.18 | 1.97 | .78 | 3.54 | | .78 | 1.18 | | .78 | | | |
| S14 | 11.23 | .37 | 6.52 | 1.45 | 2.17 | 1.08 | 4.71 | | .36 | .72 | .36 | .36 | | | |
| S16 | 11.29 | 2.09 | 10.04 | .42 | 2.51 | 2.09 | 4.6 | .42 | .42 | .42 | | | | | |
| S17 | 5.18 | .74 | 8.89 | 4.44 | 20.74 | .74 | | | 2.22 | 6.66 | | | | | |
| S73 | 8.66 | 2.0 | 10.0 | | 12.0 | 1.33 | 2.66 | | 2.0 | 8.0 | | 1.33 | | | |
| S20 | 6.12 | | 12.23 | .51 | 36.22 | .51 | 1.53 | .51 | 1.02 | | | | | | |
| S70 | 6.25 | 2.08 | 12.5 | | 33.33 | | | | 2.08 | | | | | | |
| S21 | 9.6 | 5.08 | 10.17 | 3.95 | 6.21 | .56 | 4.52 | | .56 | 7.34 | | 1.13 | | .56 | |
| S22 | 7.72 | 2.14 | 5.58 | 1.28 | 63.94 | 1.28 | .86 | | 1.71 | 3.43 | | .43 | | | .43 |
| S38 | 8.75 | 2.69 | 5.72 | 8.08 | 39.39 | .33 | 1.01 | | .33 | 12.12 | | .67 | | .33 | .33 |
| S23 | 10.4 | 2.35 | 6.37 | 1.0 | 15.43 | 1.34 | 3.69 | | 1.0 | 4.69 | | 2.01 | | | |
| S68 | 8.39 | 1.2 | 10.95 | | 18.32 | .85 | 1.37 | | .68 | 3.25 | | 2.05 | | | |
| S24 | 16.46 | 3.21 | 9.23 | 2.41 | 7.23 | 2.4 | 4.41 | | | .8 | | | .4 | | .4 |
| S25 | 22.38 | 4.47 | 7.46 | 2.98 | 1.49 | | 8.95 | | | 2.98 | | 1.49 | | | |
| S43 | 6.64 | 2.95 | 7.01 | | 9.95 | 1.47 | 2.21 | | | | | | | | |
| S44 | 12.41 | 2.75 | 15.86 | .69 | 6.2 | 2.75 | 4.82 | | 1.38 | 2.07 | | | | | |

Appendix III. cont.

| | Qite | Qtz | Hs | Ss | Fes | Rc | C | Cs | Ig | Sh | Misc H | PhN | Mstn | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S52 | 8.68 | .34 | 13.89 | | 9.02 | | 3.12 | | .34 | 1.39 | | .34 | | | .34 |
| S26 | 11.47 | 1.64 | 13.93 | .41 | 3.69 | 2.05 | 3.27 | | .82 | | | | | | |
| S27 | 2.48 | | 2.48 | 2.48 | 6.61 | 2.48 | 4.95 | | .82 | 7.43 | | .82 | 1.65 | | |
| S28 | 6.7 | 2.15 | 12.44 | .24 | 36.12 | 1.43 | 2.39 | | .24 | .48 | | | .71 | | |
| S29 | 6.12 | | 2.04 | 8.16 | 8.16 | 2.04 | | | 2.04 | 10.2 | | | | | |
| S31 | 16.82 | 3.56 | 21.35 | 1.61 | 22.97 | 2.91 | 3.23 | | .64 | | | | 1.29 | .32 | |
| S32 | 12.08 | 1.25 | 8.33 | 2.08 | 31.66 | .83 | .41 | | .41 | .83 | | .41 | | | |
| S33 | 6.06 | .27 | 8.26 | 4.95 | 30.3 | 1.37 | 1.92 | | .27 | | .27 | .55 | | | |
| S34 | 4.01 | 2.29 | 5.44 | 1.14 | .28 | 2.29 | 3.15 | | .57 | | | | | | |
| S35 | .53 | .53 | | 2.11 | 26.98 | 1.05 | 2.11 | .53 | .53 | 11.11 | | .53 | .53 | | |
| S37 | 8.46 | .53 | 3.17 | .53 | 3.7 | | 5.29 | | .53 | 1.58 | | | | | |
| S62 | 5.67 | 1.05 | 7.56 | | 1.89 | .84 | 3.78 | | .21 | 1.26 | | .63 | | | |
| S39 | | 1.88 | 1.88 | | | | 1.88 | | | | | | | | 18.86 |
| S40 | 15.35 | 2.73 | 15.01 | | 7.16 | .34 | 1.36 | | | | | | | | |
| S41 | 10.21 | 3.28 | 10.58 | | 1.82 | 2.55 | 2.55 | | | .36 | | .73 | | | |
| S42 | 10.71 | 1.09 | 13.46 | | 5.49 | .82 | 1.64 | .82 | .82 | | .27 | .27 | | | |
| S46 | 9.67 | 1.61 | 18.54 | | 20.16 | | 6.45 | | | 4.83 | | 2.42 | | | |
| S47 | 5.97 | .54 | 7.06 | | 4.89 | 1.08 | .54 | | .54 | 14.67 | | .54 | 1.63 | | |
| S48 | 3.55 | .5 | 8.11 | | 1.52 | | 2.03 | | .5 | 17.25 | | 2.03 | | | |
| S49 | 4.16 | .27 | 7.77 | .55 | 40.0 | .55 | 1.11 | | .27 | | | 5.0 | .27 | | |
| S66 | 4.51 | | 7.09 | | 46.45 | | 1.29 | | | | | 15.48 | | | |
| S50 | 2.22 | 1.11 | 13.33 | | 2.22 | 5.55 | 7.77 | | | 1.11 | | 2.22 | | | |

Appendix III. cont.

| | Qite | Qtz | Hs | Ss | Fes | Rc | C | Cs | Ig | Sh | Misc H | PhN | Mstn | Sch | Grt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S51 | 7.17 | 1.91 | 13.39 | | 8.61 | .95 | 6.7 | | | 5.74 | | 1.91 | | | |
| S64 | 6.12 | .68 | 12.24 | | 6.8 | 3.4 | 3.4 | | .68 | 5.44 | | .68 | | | |
| S54 | 8.04 | 1.0 | 16.07 | | 23.11 | .5 | 1.75 | .25 | 1.0 | | .25 | 4.27 | | | |
| S55 | | | | | 15.85 | | 1.22 | | | 23.17 | | 2.44 | | | |
| S56 | 7.61 | | 10.15 | | 17.76 | 3.55 | 1.52 | | | 8.63 | | 8.63 | | .5 | |
| S67 | 7.78 | 1.44 | 6.63 | | 9.51 | 1.15 | 2.59 | | .57 | 5.18 | | 4.32 | | | |
| S57 | 5.35 | .71 | 9.28 | | 16.07 | 2.5 | 3.57 | | .35 | 4.28 | | 3.93 | | | |
| S69 | 8.35 | .73 | 9.09 | | 22.6 | .98 | 2.21 | | .73 | 5.4 | | 4.17 | | | |
| S58 | 2.7 | | 5.4 | 1.8 | 9.0 | 1.8 | .9 | | | 8.11 | | 1.8 | .9 | | |
| S71 | 1.66 | 1.66 | 6.66 | | 8.33 | 1.66 | 1.66 | | | 10.0 | | | | | |
| S72 | .82 | | 13.22 | 1.65 | 5.78 | 4.96 | 1.65 | | | 17.25 | | | | | |
| S59 | 4.26 | 2.7 | 8.14 | 1.16 | 18.6 | 2.32 | 2.32 | | 1.16 | 6.59 | | 1.55 | | | |
| S60 | 8.54 | 1.28 | 10.68 | | 14.95 | .85 | 2.56 | | .85 | 3.84 | | .85 | | | |
| S74 | 3.7 | 1.23 | 12.34 | | 4.94 | 2.47 | | | | | | | | | |
| S75 | 6.41 | 2.14 | 10.69 | .53 | 6.95 | 1.07 | 1.07 | | 1.6 | 8.02 | | 2.14 | | | |
| S76 | 3.15 | | 4.5 | | 57.2 | | .9 | | .45 | 5.85 | | 10.81 | | | |
| S77 | 12.17 | 1.74 | 20.0 | | 11.3 | .87 | 5.21 | | | 3.48 | | .87 | | | |
| S80 | 14.33 | 1.52 | 17.99 | .61 | 17.99 | .3 | 3.05 | | .61 | 11.89 | | 3.05 | .3 | | |

Qite=Quartzite; Qtz=Quartz; Hs=Hard sandstone; Ss=Soft sandstone; Fes=Ferrous sandstone; Rc=Rhaxella chert; C=Chert; Cs=Cherty sandstone; Ig=Igneous; Sh=Shell; Misc H=Miscellaneous hard; PhN=Phosphatic nodules; Mstn=Mudstone; Sch=Schist; Grt=Grit.