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Late Ordovician glacial record of the Anti-Atlas, Morocco

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Abstract

Late Ordovician glaciogenic deposits are exposed intermittently along an 800 km long outcrop belt in the Anti-Atlas mountains of southern Morocco. These deposits are of economic significance as potential oil-bearing sandstones in the Tindouf and Boudenib basins and thus are here re-examined as analogues to subsurface hydrocarbon reservoirs. Glaciogenic deposits of the Upper Second Bani Formation rest unconformably upon underlying shallow marine clastic deposits. The unconformity is characterised by a series of palaeovalleys, some 0.5-1.0 km wide, and up to 100 m deep, which may have been cut under elevated hydrostatic pressures as tunnel valleys beneath a Late Ordovician ice sheet. The valleys and intervalley areas are filled with glaciogene sediments categorized into five facies associations, namely 1) a tabular sandstone association (shallow marine/ shoreface deposits), 2) a massive sandstone and conglomerate (ice contact debrites), 3) meandriform sandstone deposits (ice proximal sandur), 4) stratified diamictites (ice-rafted debris) and 5) sigmoidally bedded sandstones (intertidal sandstones). Deformation in these sediments is ubiquitous and includes soft-sediment striated pavements, metre-scale duplex systems, thrust and fold belts of deformation affecting some tens of metres of sediment, and pervasive lineations. These features are interpreted to record the complex nature of deformation processes operating beneath a Late Ordovician ice sheet including sliding at the ice-bed interface, folding and deformation within the sediment column, and a series of complex ramps, detachments and shear zones within an unconsolidated pile of sediment beneath the ice sheet.

Keywords: Morocco, Gondwana glaciation, Anti-Atlas, Ordovician, petroleum system.

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1. Introduction

This paper presents new sedimentological observations and interpretations of Late Ordovician glaciogenic deposits of the central Anti-Atlas, southern Morocco (**Fig. 1**). Across North Africa, investigation of correlative glaciogenic deposits is driven principally by their economic importance as oil and gas reservoirs in eastern Algeria and western Libya (e.g. Davidson et al., 2000; Le Heron and Thusu, 2006). In recent years, the sedimentology and stratigraphy of outcrop analogues to these "glaciogenic reservoirs" has been evaluated at the flanks of large Palaeozoic sag basins (Ghienne and Deynoux, 1998; Sutcliffe et al., 2001; Hirst et al., 2002; McDougall et al., 2003; Ghienne et al., 2003; Deynoux and Ghienne, 2004; Le Heron et al., 2004, 2005, 2006, 2007 Moreau et al., 2005; el Ghali, 2005). In these basins, Late Ordovician glaciogenic rocks comprise the reservoirs for huge oil fields containing up to 0.5 billion barrels of oil (Elephant Field, Murzuq Basin, Libya) (Davidson et al., 2000) and up to 1.3 trillion cubic feet of gas (Tiguentourine and Tin Fouye fields, Illizi Basin, Algeria (Hirst et al., 2002). However, they are notorious for significant and abrupt facies changes (Le Heron et al., 2006).

In the Anti-Atlas region of southern Morocco, evidence for Late Ordovician glaciation was first described by Destombes (1968, 1971), reviewed in Destombes et al. (1985), and briefly discussed by Sutcliffe et al. (2001). In this paper, re-examination of Late Ordovician glaciogenic deposits is timely because 1) significant conceptual advances in glaciology and glacial sedimentology have been made in recent years (e.g. Dowdeswell et al., 2002; Knight, 2006), and 2) these deposits are receiving increased economic interest because of success in extracting oil from correlative rocks elsewhere in North Africa. It is hoped that up-to-date descriptions and interpretations offered here may be useful to the oil and gas industry, as well as to the academic community, as Lower Palaeozoic rocks are important components of a Palaeozoic petroleum system in the Tindouf Basin (western Algeria/ southern Morocco: Askri et al., 1995), and are potential hydrocarbon reservoirs in the Boudenib Basin between the High Atlas and Anti-Atlas ranges (Emerging Markets, 2002; **Fig. 1**).

2. Geological Overview and Stratigraphy

In the central Anti-Atlas, the stratigraphy of the Lower Palaeozoic is robustly established (e.g Destombes et al., 1985; (**Table 1**) this region, in stark contrast to Lower Palaeozoic sedimentary rocks north of the southern Atlas thrust front, which crop out in disconnected inliers (e.g. Le Heron et al., 2007), those of the Anti-Atlas are readily correlated because they can be traced laterally for at least 800 km along strike along the Jbel Bani valley (**Fig. 1**). Geologically, the Anti-Atlas is on the fringe of the West African Craton, which was part of Gondwana during the Early Palaeozoic (Piqué, 2001).

Late Ordovician glaciogenic rocks in the Anti-Atlas are referred to the Upper Second Bani Formation (Destombes, 1968; Destombes et al., 1985; Sutcliffe et al., 2001) (**Table 1**). These rocks were deposited above an unconformity that cuts down into the Kataoua Formation (Caradoc to Early Ashgill; Bourahrouh et al., 2004) or overlying Lower Second Bani Formation (Late Ashgill; Destombes et al., 1985). The degree of erosion along this unconformity is variable, but incision generally penetrates deeper to truncate older stratigraphic levels in a westward direction (Destombes et al., 1985). In Zammour, at the western extremity of the Anti-Atlas range, incision at the base of the Upper Second Bani Formation penetrates Arenig strata (Destombes, 1971).

Careful measurement of the thickness of measured sections for Caradocian to Upper Ashgillian deposits enabled Destombes et al. (1985) to present isopach maps showing the shifting pattern of Ordovician depocentres over the Anti-Atlas. These maps showed that by Late Ashgill times, during deposition of the Lower Second Bani Formation, a pronounced NW-SE oriented depocentre centred on Tagounite developed (**Fig. 1**). This depocentre was later coined the Tagounite Trough (Sutcliffe et al., 2001). In the High Atlas of Marrakech, immediately to the northwest of this trough, Le Heron et al. (2007) described intense soft-sediment deformation, together with streamlined and polished glacial bedforms resembling roches moutonées, which led them to suggest that a fast-flowing ice stream within the ice sheet may have occupied the Tagounite Trough during the Late Ordovician glaciation.

3. Sedimentology of pre-glacial deposits

In this study, the contact between the Lower Second Bani Formation and the overlying Upper Second Bani Formation was examined between Foum Larjame and Foum Triyâ El Khira (**Fig. 1**). At Foum Larjame, a sedimentary log of a section at Foum Larjame illustrates the nature of the contact between these formations (**Fig. 3 A**). The Lower Second Bani Formation is characterised by stacked parasequences; each is 20-50 m thick and begins with stratified mudrocks, locally containing thin intervals of structureless diamictites, coarsening up into fine-grained sandstones. The sandstones are cross-bedded on a metre-scale, hummocky cross-bedded or parallel laminated. Concentrations of shell material, including *Hirnantia* brachiopods, occur within these sandstone beds in the upper part of the Lower Second Bani Formation, and were described by previous authors (Sutcliffe et al., 2001). Additionally, thin walled bivalves occur within the mudstones, which are locally incorporated as clasts within overlying conglomerates of the Upper Second Bani Formation. These shell beds increase in thickness from Foum Triyâ El Khira to Foum Larjame (from a few centimetres up to several metres) into the axis of the Tagounite Trough (see isopachs on **Fig. 1**). West of the axis of the Tagounite Trough, around Hassi El Abiod, these latter deposits are also affected by a progressive increase in abundance of large, crushed brachiopod shell fragments toward the west/ southwest. Here, a fragmented, mixed shelly fauna is preserved that includes crinoid stems, bivalves and mixed biogenic detritus. All taxa from this locality were documented extensively in Destombes et al. (1985). Upsection, the proportion of mudstone to sandstone increases, culminating with an aerially extensive, sharp surface that can be traced over several kilometres (**Fig. 3**).

Hamoumi (1999) interpreted parasequences of the Lower Second Bani Formation as shallow marine sediments deposited under a predominantly tidal regime. This interpretation was refuted by Sutcliffe et al. (2001) who interpreted these rocks as storm dominated shoreface deposits. The association of metre-scale cross-bedding, hummocky cross bedding and parallel laminae strongly supports the interpretation of Sutcliffe et al. (2001), and thus these facies are interpreted as migrating cross-shelf bars, oscillatory flow deposits, and upper flow regime shoreface deposits respectively. The mudstones at the base of the parasequences are interpreted as offshore sediments untouched by storm waves and hence colonised by communities of delicate thin-walled bivalves. The gradual westward thickening of shell beds in the central Anti-Atlas, coupled with the relative increase in abundance of large, crushed brachiopod fragments in the same direction, is interpreted as a distal to proximal trend from east to west over this part of the range. The increasing proportion of mudstone to sandstone upsection indicates that parasequences backstep, in turn suggesting that the sharp surface shown on **Fig. 3** is best interpreted as an important ravinement surface. A backstepping motif compares favourably with the description of similar backstepping parasequences immediately below Late Ordovician glaciogenic deposits in the Hodh and Adrar regions of Mauritania (Ghienne, 2003). Furthermore, in the wider North Africa area, transgressive deposits also characterise pre-glacial Ordovician deposits in western Libya (Ghienne et al., in press), suggesting that this can be regarded as a regionally widespread feature.

4. Stratigraphy of Late Ordovician syn-glacial deposits

Measured sections of the Upper Second Bani Formation were constructed at Foum Larjame and Tizi N'Tazzounghart (**Fig. 2 A, B**). These sections show that the typical thickness of this formation is in the range 60-80 m. The base of the formation is identified by a major increase in sand content within the succession, usually above an abrupt unconformity (**Fig. 4**).

The facies associations described in the following sections show some limited evidence for lateral substitution. However, in the majority of cases, the most significant *gradual* sedimentological changes occur vertically, because three unconformities within the succession hinder our ability to recognise *gradual* lateral facies change (ES1, ES2, ES3: **Fig. 4**). For the most part, therefore, facies associations make only one stratigraphic appearance in any given section.

5. Sedimentology of Late Ordovician syn-glacial deposits

Five facies associations are recognised within Late Ordovician glaciogenic deposits of the central Anti-Atlas, each of which are represented on the measured sections constructed at Foum Larjame and Tizi N'Tazzounghart (**Fig. 2 A, B**). The lateral and vertical organisation of facies associations at and between these localities is shown to scale on Fig. 4, which can be regarded as representative for the central Anti Atlas.

Stacked sandstone facies association

This facies association is widespread but best exposed at Tizi N'Tazzounghart, where it is preserved above a pronounced erosion surface that has a relief of ~50 m (ES1, **Fig. 4**). Attaining ~70 m thickness, it comprises medium-bedded, quartz arenite sandstones, organised into thinning upward cycles, each 10-50 m thick. The beds are tabular, sharp based, cross-bedded (sets 50 cm thick), contain massive to parallel laminated facies, and locally are intensely bioturbated. Scour features are well developed, exhibiting downcutting of ~1 m (**Fig. 5 A**). These rocks also contain complex deformation structures (see section 5).

The pronounced erosion surface at the base of the facies association is interpreted to result from major downcutting by a mechanism such as the exposure of the shelf during sea level fall at the start of glaciation, or alternatively glacial incision. The sharp-based, tabular sandstones are interpreted as stacked shoreface sediments, deposited by high-energy tractional processes during swash and backwash (parallel laminated facies). The shoreface was scoured by rip currents to produce shallow channels (**Fig. 5 A**), and colonised by organisms in well-oxygenated, nutrient-rich waters (bioturbation). Cross-beds within this depositional system record the local occurrence of low relief dunes. The organisation of these sandstones into subtle thinning upward cycles is difficult to interpret in the absence of accompanying grain size changes. However, these cycles are most likely to record phases of high wave energy activity alternating with lower energy episodes of shoreface agitation.

Massive sandstone and conglomerate facies association

This facies association frequently occurs above an irregular surface that records development of a system of palaeovalleys south of Tagounite (**Fig. 5 B**). The width of the palaeovalleys, which are cut along a major unconformity (UC2, **Fig. 4**) varies in the range 0.5-1.2 km, and their depth 50-100 m. This facies association is characterised by various sand-dominated lithologies with grain-sizes ranging from matrix-supported boulder conglomerates to fine-grained sandstones. The sandstones support clay rip-up clasts, intraformational sandstone clasts, and fine-grained sandstone boulders bearing delicate thin-walled bivalve assemblages. Poorly developed cross-bedding is represented by inclined (45°)

trains of pebbles. Concentrations of boulders occur within poorly defined lenses up to several metres thick and several tens of metres in width. The facies association forms continuous bodies in excess of 45 m thick (**Fig. 2 A**, 10-60 m; **Fig. 4**). Diffuse horizontal laminae are also preserved. At its basal contact, flute casts may be developed within this facies association.

The palaeovalleys south of Tagounite are interpreted to have formed by erosion that created an uneven topography genetically related to the facies association above it. A similar channelised topography is well known from equivalent rocks in the Tassili N'Ajjers region, Algeria, and the Gargaf Arch, Libya, where extensive soft-sediment deformation includes fold and load structures immediately beneath palaeovalleys up to several kilometres wide (Le Heron et al., 2004), and striations within them (Le Heron et al., 2005). The styles of soft-sediment deformation in Libya and Algeria suggest that those examples were cut under a combination of ice sheet loading (to account for deformation of underlying sediments), and elevated subglacial hydrostatic pressures (possibly during a subglacial flood), to form tunnel valleys (Le Heron et al., 2004; Ghienne et al., in press). The presence of boulder conglomerates indicates *en masse* transport of sand and boulders with large dispersive pressures typical of non-cohesive debris flows. In this context, it is suggested that the parallel lamination within the sandstones is more likely to have originated by internal shearing within a debris flow rather than tractional processes. Nevertheless, organisation of some pebble-sized clasts to define poorly developed cross-beds testifies to at least local traction current development. The poorly defined lenses of boulder-sized material, occurring in diffuse patches rather than within well-defined channels, in conjunction with the large thicknesses (>80 m) of this facies association, support their interpretation as stacked debrites.

Comparable debris flow deposits in the Late Ordovician glacial record of Libya and northern Morocco are interpreted to record efflux adjacent to an ice front (Le Heron et al., 2004; Le Heron et al., 2006, 2007). These deposits record either the development of a positive-relief terminal moraine on a flat surface, or alternatively infill palaeovalley accommodation created by subglacial erosion. Therefore, in the central Anti-Atlas, where large-scale palaeovalleys are commonplace (**Fig. 5 B**), the massive sandstone and conglomerate facies association is interpreted as an ice contact deposit, the extent and thickness of which is ultimately controlled by the width and depth of incision at the base of the palaeovalleys (**Fig. 4**).

Meander channel sandstone facies association

This facies association is recognised on the basis of its cross-sectional and planform architecture. Lenticular bodies of coarse-grained sandstone to granular conglomerate attain 20-25 m across and 2-3 m thick, cropping out prominently relative to adjacent, poorly exposed, finer-grained and more thinly bedded sandstone and siltstone. The meandering bodies can be traced laterally for approximately 50 m whereupon they shift position to define a meandriform geometry in plan. Metre-scale cross-bedding is observed within the sandstone packages.

The meandriform character of these sandstones represents laterally shifting channel belts separated by similarly sandy interchannel areas, for which there are two possible interpretations. Plausible depositional settings include a turbidite channel complex on the topset to an underflow-dominated fan, or alternatively a system of laterally migrating fluvial channels. In the context of Late Ordovician high latitude glaciation, both alternatives are associated with moderate sediment delivery to a low gradient basin, compatible with the topsets of either a submerged (turbidite) or emergent (fluvial) ice contact delta. Research into Icelandic sandar (Knight, 2006) demonstrates that channels rapidly increase in width with distance from modern glaciers accompanied by a decrease in sediment calibre from boulder conglomerates to granular sands over as little as ~10 km. Therefore, the occurrence of coarse-grained sandstone to granular conglomerate within the channels tends to suggest that sediments of the meander channel facies association were deposited in relative proximity (less than several tens of kilometres) to the ice margin.

Sandy diamictite facies association

This facies association comprises olive green, buff yellow to orange coloured, sandy diamictite that attains a thickness of >10 m. It is best exposed at Jbel Hamsailikht, where astratified diamictite rests directly above a striated pavement (**Fig. 5 C**), but also crops out in poor exposure at Tizi N'Tazzounghart and Foum Larjame (**Fig. 4**). The matrix of the diamictite, which is stratified into laminae 0.5-3 cm thick, shows no vertical grain size changes upsection, and no mud-rich intercalations were observed. Clasts within the deposit are few, but rare sandstone boulders are observed (**Fig. 5 D**). The boulders deform underlying laminae and are well rounded.

Following interpretation of similar, coeval, clast-poor diamictites elsewhere in North Africa (Ghienne, 2003; Le Heron et al., 2004, 2005, 2006, 2007; Ghienne et al., in press), this facies association is interpreted as a glaciogenic deposit. These rocks were deposited above a subglacially cut, striated pavement during glacial retreat. In northern Morocco, up to 400 m of similar sandy diamictite, punctuated by sandstone channels, occurs in the Jbilet region (Le Heron et al., 2007). There, it is massive and hence a debris flow origin is preferred. However, in the Anti-Atlas, diamictites are stratified (**Fig. 5 D**). Stratified diamictites can form during subglacial shearing (Alley, 2000), but this process is discounted because the Anti-Atlas examples clearly lie above, rather than below, a striated pavement (see **Fig. 4**). The large boulders (**Fig. 5 D)** in the diamictite, unlike those in Quaternary deformation tills, do not show orbital (rotational) structures produced as the clast rotates within a shearing pile of sediment (Van der Wateren et al., 2000). Furthermore, the absence of attenuated sheath folds, and interweaving fault systems that are common in subglacially deformed sediments (Alley, 2000), discounts a basal till origin. The rarity of clasts within the diamictite, coupled with the two dimensional nature of its exposure, precludes any attempt to apply an eigenvector analysis to the clast orientations (e.g. Dowdeswell and Sharp, 1986). However, it is suggested that the stratification and outsized boulders within the diamictite are simply interpreted as ice-rafted debris with dropstones probably introduced by icebergs.

Sigmoidally cross bedded sandstone facies association

This facies association comprises undeformed (i.e. horizontal) fine-grained, ferruginous sandstones, within which cross-bedding is well developed. Typically, sets are 10-50 cm in thickness, and sigmoidal cross-bed geometries, with well-defined topsets, are typical. The foresets appear to be bimodal, dipping both to the NW and SE. (**Figs. 2 A, 7 A, B**). Interference ripples are common with ripple crests in multiple orientations. Surfaces bearing current ripples are stacked closely in vertical section (**Fig. 7 C**). Measurement of available rippled surfaces indicates both NW and ESE-directed sediment transport (**Fig. 2 A**). Vertical trends include beds thickening upsection, accompanied by the appearance of thin (one clast thick) granule lags and 2 m deep channels.

The sigmoidal geometry of cross-beds suggests that the stoss slope of each bedform experienced a higher rate of sediment supply than erosion (i.e. rapid sediment accumulation), and was probably submerged during deposition. signifies high accommodation space. Palaeocurrent data are limited, but both the sigmoidal cross-beds and current ripples show evidence for sediment transport to both the NW and SE. On the basis of earlier investigations of Cambrian and pre-glacial Ordovician deposits south of Ouarzazate, NW transport is consistent with regional (seaward) palaeoslope whereas SE sediment transport implies a reversal of palaeoslope (Destombes et al., 1985). Discounting local topographic effects (as the rocks are horizontal), a high sediment supply feeding multidirectional dunes is more consistent with a tidal than fluvial depositional environment. The development of interference ripples in multiple orientations is interpreted as the result of standing waves reflected off neighbouring bedformsThe organisation of beds into thickening upward successions suggests that the cross-beds are organised into discrete tidal bars, whilst the appearance of granule lags above these thickening upward successions is indicative of high-energy transport and effective winnowing of the sand fraction. Evidence for channels implies that energy levels were sufficient to cut a significant topography on to the upper surface of some tidal bars.

6. Glaciotectonic deformation features

The major types of glacially-related soft-sediment deformation structures in Late Ordovician glaciogenic sediments of West Gondwana were reviewed recently by Le Heron et al. (2005). In the Anti-Atlas of Morocco, a variety of deformation structures occur within the Upper Second Bani Formation, and locally also affect the Lower Second Bani Formation, but deformation is strictly confined to these intervals and is sealed by the Early Silurian Aïn Deliouine Formation (**Fig. 3 A, B**). This stratigraphic confinement of large-scale deformation structures in the Anti-Atlas, which include large folds and associated thrusts, combined with their preservation within rocks deposited during the waxing and waning of large North African ice sheets (Ghienne, 2003; Le Heron et al., 2007), strongly suggests that such features are glacially related. It is the purpose of this section to describe the styles of deformation affecting the Lower and Upper Second Bani Formations before offering interpretations based on understanding of contemporary ice sheet behaviour.

Observations

At Foum Triyâ El Khina (**Fig. 1**), a large palaeovalley incision is preserved (**Fig. 5B**), beneath which a suite of deformation structures occurs (**Fig. 8A**). The palaeovalley is cut into the stacked sandstone facies association, and it is filled with the massive sandstone and conglomerate facies association. In this part of the Anti-Atlas, regional dips are generally subhorizontal, but beneath the incision, southward dipping beds are strongly attenuated at the contact with the incision surface. Additionally, within the lowermost part of the palaeovalley fill, sandstones contain a conspicuous, metre scale fabric that defines a small duplex system: these indicate a top to the NW transport direction (**Fig. 8 A**).

Large-scale deformation structures affect both the stacked sandstone facies association and an overlying occurrence of the massive sandstone and conglomerate facies association south of Tagounite at Tizi N' Tazzounghart (**Figs 2 B, 4**). The deformation is preserved toward the top of a 100 m high cliff which appears unperturbed from afar (**Fig. 8 B**). However, within the tabular sandstone facies association, cuspate fold structures comprising broad-bottomed synclines separated by steep culminations/ antiforms are preserved; these are truncated by thrusts dipping at a low angle (5º) toward the west (**Fig. 8 C, D**). The steep culminations/ antiforms show variable northeastward and southwestward vergence. Duplex geometries are noted within the tabular sandstone facies association that indicate transport along thrusts toward the NE. However, deformation within massive sandstones and conglomerates immediately above is more complex with a high amplitude (30 m), short wavelength (15 m) westward verging antiform observed within the glaciogenic sediments (**Fig. 8 E, F**). The deformation is sealed by a flat lying surface which can be traced laterally and contains striations oriented 350˚ (**Fig. 8 E, F**).

To the west of the Rich Mel' Alg massif, tight folds are observed within the stacked sandstone facies association, and pervasive lineations are observed on the overturned limb of N-verging sheath folds that plunge 5°/ 340°. These structures have a rod-like morphology and resemble stretching lineations within metamorphic shear zones (Hatcher, 1995). At this locality, polished and streamlined surfaces are also present. There is a close relationship between these deformation features and lithofacies variations: the deformation structures are either capped or laterally replaced by the massive sandstone and conglomerate facies association.

East of Foum Zguid (**Fig. 1**), a series of five tight synclines, with wavelengths of 1-1.5 m, occurs within the stacked sandstone facies association. The axial surfaces of these structures are oriented 060°/ vertical. At the same locality, faults are also noted, planes of which dip steeply southward. Footwall folds beneath the fault surfaces are southward verging. In the immediate vicinity, at Jbel Hamsailikht, the striated surface shown on **Fig. 5 C** occurs. The striations on this surface trend 340º.

Interpretation

The deformation structures observed at both Tizi N' Tazzounghart and at Foum Triya El Khina are interpreted to have been generated by an overriding ice sheet. The duplex geometry of these metre- to tens of metre-scale thrust systems indicates ramping of sediment between a floor thrust and a roof thrust. The preservation of a roof thrust at both localities suggests that deformation occurred well within the sediment column, rather than the base of an ice sheet forming the roof thrust. Broad bottomed synclines separated by steep antiformal culminations have also been described from the Gargaf Arch, Libya and in the Western Cape Province, South Africa where they are considered to reflect the shearing of subglacial sediment partially coupled to an ice sheet, with a component of gravitational instability (Le Heron et al., 2005). Given regional evidence for northward, rather than southward, advancing ice sheets over the Sahara (Beuf et al., 1971), southwestward verging folds at Tizi N'Tazzounghart appear to be anomalous, and can potentially be explained by the presence of ramps within subglacial fault systems.

The pervasive lineations in the Rich Mel' Alg massif are identical to those described in Le Heron et al. (2005) from the Gargaf Arch and Ghat in the Libyan Sahara. These features indicate that strain was not uniformly distributed, but rather was concentrated at intervals to produce structures reflecting a high accumulation of finite strain within the sediment column. Their strike (at 340°) is interpreted to record the primary vector of elongation and attenuation within the subglacial substrate. The pervasive lineations are therefore interpreted to record ice sheet movement toward the NNW.

A proglacial deformation mechanism is suggested for the tight synclines east of Foum Zguid. Their metre-scale amplitude is comparable with seasonal (annual) push moraines that have formed over recent decades in the forefield of Breidermurkurjökull, southern Iceland (Boulton, 1986). The upright/ vertical aspect of their axial surfaces is better explained by proglacial, rather than subglacial, deformation because under the latter mechanism, attenuation and rotation of the fold axial surfaces would be expected to have occurred closest to the base of the ice sheet. During ice sheet advance, "bulldozing" of proglacial sediments produces folds the axial surfaces of which are perpendicular to the direction of ice flow. Given the evidence for NW to NNW ice advance indicated by fold vergence, striae and pervasive lineations discussed above, the 060º striking fold axial surfaces also support ice advance in this direction, implying shortening of the sediment column and hence compression along a 330º-150º axis.

Previous work in the Anti-Atlas (Destombes, 1968; Destombes et al., 1985; Sutcliffe et al., 2001) established that ice sheets advanced broadly to the NW on the grounds that striations in glaciogenic Upper Ordovician rocks trend SE-NW. Data on the soft-sediment deformation structures in the present paper lend support to these earlier interpretations..

7. ”Event stratigraphy” and glacial depositional model for the Anti-Atlas

The following sequence of events is proposed to explain the stratigraphic and sedimentological organisation of Late Ordovician glaciogenic deposits in the central Anti-Atlas summarised on **Fig. 4**. These events are 1) deposition of shallow marine, storm-dominated preglacial deposits, 2) glacioeustatic sea level fall resulting in significant downcutting and erosion to form a pronounced discontinuity surface (Erosion Surface 1, ES1), 3) deposition of sharp-based sandstones (stacked sandstone facies association), 4) major glacially-related incision (ES2, tunnel valleys) followed by 5) deposition of subaerial, glaciogenic debris flow deposits (i.e. massive sandstone and conglomerate facies association), 6) the deposition of finer grained deposits (the meander channel sandstone facies association) on a sandur at a distance of up to tens of kilometres from the ice front, 7) ice sheet re-advance, intense proglacial and subglacial deformation culminating in the formation of a soft-sediment striated surface (ES3), 8) ice sheet retreat and deposition diamictites passing vertically into transgressive tidal deposits (sigmoidally cross bedded sandstone facies association), 9) offshore mud deposition during the earliest Silurian (Aïn Deliouine Formation).

Abrupt facies variations occur both laterally and vertically within sedimentary rocks deposited by ancient ice sheets. These variations record the complex interplay between ice sheet dynamics (whether an ice sheet was advancing or retreating), the location of sedimentary input points, glacioisostasy, the depth of water (if any) in which an ice sheet was grounded, and the composition and distribution of sediment within an ice mass (Brookfield and Martini, 1997). In the context of oil exploration in particular, it is important to consider how facies associations within glaciogenic sedimentary systems relate to one another, in order to predict the thickness, continuity, and geometry of oil-bearing sandstones. It is hoped that the event stratigraphy suggested in this paper and the associated depositional model described below will be of some use to the hydrocarbon exploration community operating in the Tindouf Basin, western Algeria, and the Boudenib Basin of southern Morocco .

Prior to the growth of Late Ordovician ice sheets across the Anti-Atlas, shallow marine conditions prevailed, during which storm-derived sands formed the upper part of coarsening upward successions (parasequences) that were deposited during the course of normal shelf progradation. The ubiquitous occurrence of shell beds suggests that these waters were well colonised by benthic organisms and hence oxygenated. At the beginning of glaciation, deep incision occurred, resulting in the creation of palaeovalleys 50-100 m deep and up to one km in width. These incisions probably originated as tunnel valleys cut beneath an ice sheet under enhanced hydrostatic pressure by analogy with comparable features in Algeria (Hirst et al., 2002), Mauritania (Ghienne and Deynoux, 1998) and Libya (Le Heron et al., 2004). Glaciotectonic deformation within some of the palaeovalley fills, such as those at Tizi N'Tazzounghart and Foum Triya El Khina, indicates the re-advance of ice sheets down the axes of the palaeovalleys which pushed, deformed, and then overrode their fill (**Fig. 8**).

Despite the relatively complex "event stratigraphy" give above, the lateral relationship between facies associations must also be carefully considered. As illustrated on **Fig. 4**, vertical facies transitions appear to predominate, as a consequence of crosscutting palaeovalleys and three unconformities dividing the succession. This would suggest that lateral facies transitions are more difficult to predict. The overall depositional environment for the Upper Second Bani Formation is illustrated on Fig. 9, which can also be used to predict the lateral distribution of facies in regions where truncation by unconformities is less evident. The model depicts an ice contact setting during a phase of ice sheet advance, characterised by deformation of sediment at and in front of the ice sheet. At the ice front, large subglacial meltwater conduits (tunnel valleys) drain the ice mass. Coarse-grained sandstones and conglomerates accumulate in this region, passing distally into more texturally mature meandering channel sandstones. Tidal deposits may be expected at the coastal fringe, passing offshore into diamictites.

Late Ordovician glaciogenic deposits can be readily correlated across the Anti-Atlas and High Atlas ranges, (**Fig. 2**) thereby allowing sedimentary and glacial processes to be compared for each region. Both Anti-Atlas (Foum Larjame; **Fig. 2** A) and High Atlas (Tizi N'Tichka; **Fig 2** C) sections show major downcutting/ channelling at the base of the glaciogenic succession, with abrupt upward fining of basal sandstones. Above these sediments, a high relief unconformity, which is draped with extensively deformed sandstones and boulder conglomerates, is recognised in both the Anti-Atlas and High Atlas regions (**Fig 2** A, 25 m; Log B, 33 m; Log C, 58 m), with NNW-SSE oriented striae (**Fig. 2 A**). In both regions, deformed sandstones are capped by a striated surface, and in turn sharply overlain by thinly stratified to massive sandstones and/ or clast-poor sandy diamictites in sharp discontinuity. These data strengthen earlier assertions that the two areas were connected palaeogeographically during the Late Ordovician glaciation (Le Heron et al., 2007), by providing the evidence of a linked glacial sedimentary system across this region.

The existence of a NW-SE oriented trough in the Anti-Atlas postulated for pre-glacial strata (the Katoua and Lower Second Bani formations) by Destombes et al. (1985) may be supported by thickening of both *Hirnantia*-bearing shell beds and beds bearing thin-walled bivalves westward into this depocentre. Given that Destombes et al. (1985) defined a depocentre on the basis of isopachs, these simple observations indicate that whilst palaeotopography would certainly have been cut by Late Ordovician ice sheets, it must have been in existence prior to their growth over northwest Africa.

8. Conclusions

This paper has provided interpretations for the sedimentary facies architecture and soft-sediment deformation structures within the Late Ordovician succession of the Anti Atlas of Morocco, and can be summarised as follows. The Lower Second Bani Formation, which largely formed the subglacial substrate for Late Ordovician ice sheets, was deposited in a wave-dominated shoreface to offshore environment in which shelly faunas were deposited in an overall transgressive setting. The thickness variations of shell beds within these preglacial deposits appears to mimic thickness variations recorded for the formation at a regional level (Destombes et al., 1985), suggesting that a topography may have existed prior to the advance of ice sheets in the Hirnantian. During the Late Ordovician glaciation, the Upper Second Bani Formation was deposited. This formation contains five facies associations Debris flows were discharged from the ice margin to produce debrites, whilst at a distance of up to tens of kilometres from it, meandriform channel complexes were deposited upon the sandur. Stacked sandstones were deposited upon a well oxygenated shallow marine/ shoreface, whilst diamictites with iceberg rafted dropstones were produced in a glaciomarine setting. The widespread deformation structures affecting the Upper Second Bani Formation occur specifically within debrites and the stacked tabular sandstone deposits. These deformation structures are sealed by shales of the overlying Aïn Deliouine Formation and include striated pavements, metre-scale duplex systems, larger (tens of metre scale) thrust and fold systems, and pervasive lineations. They are interpreted to record a spectrum of glaciotectonic processes, ranging from abrasion at the ice sheet-sediment interface to deformation deep within the subglacial substrate (locally within discrete shear zones).Stratigraphic comparison between the glaciogene Upper Second Bani Formation in the present paper with previously measured sections in the High Atlas of Marrakech (Le Heron et al., 2007) allows us to propose a contiguous glacial sedimentary system across NW Africa during the Late Ordovician.

Evidence for Late Ordovician glaciation in the Anti Atlas of Morocco has long been known (Destombes, 1971). However it is hoped that the new data and interpretations provided in this contribution allow a better understanding of the deposits of this ancient glaciation in this particular region, especially as they are now being actively explored for their hydrocarbon potential. The author hopes that this study may also be another step on the road to a regional ice sheet reconstruction.

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Figure captions

Figure 1. Location map of Morocco, highlighting Lower Palaeozoic outcrops (dark grey) in the Anti-Atlas region (shaded light grey). Numbers indicate outcrops examined during the course of this study. The NW-SE oriented contours are isopachs drawn for the Lower Second Formation, a deposit of pre-glacial Ashgill age directly underlying glaciogenic sandstones of the Upper Second Bani Formation (from Destombes et al., 1985). The contours are interpreted to indicate palaeotopography on the pre-glacial substrate, with a depositional trough centred on two key localities described in this paper, namely Foum Larjame and Tizi N'Tazzounghart (the Tagounite Trough). A (Zagora) and B (Erfoud) denote localities described in Sutcliffe et al. (2001), but not revisited in the present study.

Figure 2. Graphic logs for Late Ordovician glacially-related sediments of the Anti-Atlas (logs A and B), correlated with a measured section in the High Atlas of Marrakech (log C). For location of measured sections, refer to Fig. 1. Ubiquitous soft-sediment deformation occurs in both these areas and is represented on each log. Stratigraphic duplication of sandstones is particularly acute at Tizi N'Tazzounghart in the Anti-Atlas, and is considered strong evidence of extensive subglacial shearing within the sediment column. The NNW orientation of striae at Foum Larjame is interpreted as the true direction of ice advance across the shelf, whereas the eastward vergence of folds within a thrust duplex at Tizi N'Tazzounghart may reflect the development of lateral ramps within the subglacial substrate. Log C reproduced from Le Heron et al. (2007).

Figure 3. Spectacular ravinement surface (arrowed) representing abandonment of a parasequence in the upper levels of the Lower Second Bani Formation at Foum Larjame (20 m on Log A, Fig. 2-transition into thinly bedded sandstones). This ravinement surface is interpreted to record a regionally

significant transgressive event comparable to that described for pre-glacial Late Ordovician deposits in Mauritania (Ghienne, 2003) and Libya (Ghienne et al., in press).

Figure 4: Scale drawing of relationships between facies associations in the Upper Second Bani Formation. The sketch highlights the poor lateral continuity of the stacked sandstone facies association in the Tizi N'Tazzounghart area (c.f. Fig. 2 B), and the importance of major downcutting and incision, particularly at the base of the massive sandstone and conglomerate facies association. The meander channel formation, which is well developed in the Foum Larjame area, is not recognised at the equivalent stratigraphic horizon in Tizi N'Tazzounghart 30 km to the north. It is therefore interpreted to pinch out downdip.

Figure 5. A: Scour-and-fill sandstones within the stacked sandstone facies association, showing evidence for scour at the base of the more thinly laminated sandstones above the geological hammer (arrowed); these sandstones are interpreted to have been deposited within a high energy shoreface setting. B: Large palaeovalley incision, approximately 50 m deep, defining the base of the Upper Second Bani Formation and cutting down into poorly exposed, well bedded sandstones of the Lower Second Bani Formation. Incision is up to 500 m wide and is filled by the massive sandstone and conglomerate facies association. The incision may have formed by exposure of the shelf, which would then have been cut by fluvial incised valleys, or alternatively under enhanced hydrostatic pressure as a "tunnel valley" beneath a Late Ordovician ice sheet. View is to the northeast. C: Soft-sediment striated surface, produced by ice advancing toward the NNW (Jbel Hamsailikht, SW of Foum Zguid: 29°49.053'N 07°04.667'W). D: Large sandstone clast in a sandy, clast-poor diamictite lying directly above the striated surface shown in A. The lamination beneath the clast is deformed suggesting it was emplaced as a dropstone rather than entrained within a debris flow.

Figure 6: Field sketch showing the relationship between the meander channel sandstone, diamictite and the sigmoidally cross-bedded sandstone faciesd associations at Foum Larjame (see Fig. 3 for stratigraphic context). The three lenses of coarse-grained sandstone and granular conglomerate (A-C) can be mapped out to reveal their organisation in a meandering channel geometry.

Figure 7: A: Stacked tabular cross-bedded sandstones immediately above the ripples figured in B, at the top of the Upper Second Bani Formation. A bi-directional palaeocurrent pattern appears to be represented, indicating the migration of straight-crested bars to the NE and SW. These rocks are

interpreted as transgressive tidal deposits at the onset of post-glacial transgression. B: Line drawing showing features in photograph A. Thinly bedded sandstones with current ripples of different orientations on two closely spaced bedding planes. The trend of ripple crests is variable, although they are generally asymmetric indicating westward palaeoflow. See Fig. 3, log A for stratigraphic position of both photos.

Figure 8: A: Metre-scale S-C fabric in deformed sandstones immediately below a palaeovalley incision at Foum Triya El Khina (incision is figured in Fig. 5 B). An S-C fabric is a term in structural geology that describes compartmentalisation of rigid blocks of rock (e.g. sandstone), on a scale of millimetres to metres, by interconnected fault networks that geometrically define an arrangement of S and C shapes in cross section. Arrows indicate transport direction along faults in the duplex system. B: General view of the pronounced cliff (or “bani”) at Tizi N’ Tazzounghart, which does not reveal evidence of intense deformation from a distance. The talus covered, more gently sloping lower portion of the cliff is very poorly exposed but comprises mudrocks (Fig. 3, log B, 0-10 m). The overlying sandstones, in contrast, are intensely deformed. C: Deformation in the lower sandstones of the cliff top (see arrow in photo B; Fig. 3, log B, 10-33 m). D: Spectacular, large-scale soft-sediment deformation structures (Fig. 3, log B, 34-62 m), directly below the level of a striated surface. Apparent vergence of these structures implies a top-to-the-W transport direction.

Figure 9: Summary of depositional environments interpreted from the Upper Second Bani Formation. 6.

Table 1. Stratigraphic correlation of pre-glacial (mid to late Ordovician), syn-glacial (latest Ordovician, Hirnantian), and post-glacial (early Silurian) deposits across Morocco. This present paper specifically deals with descriptions and interpretations of sedimentary facies associations in the syn-glacial Upper Second Bani Formation of the central Anti-Atlas of southern Morocco and deformation structures contained within them. For a detailed analysis of Late Ordovician glaciogenic deposits in northern Morocco, see Le Heron et al. (2007).

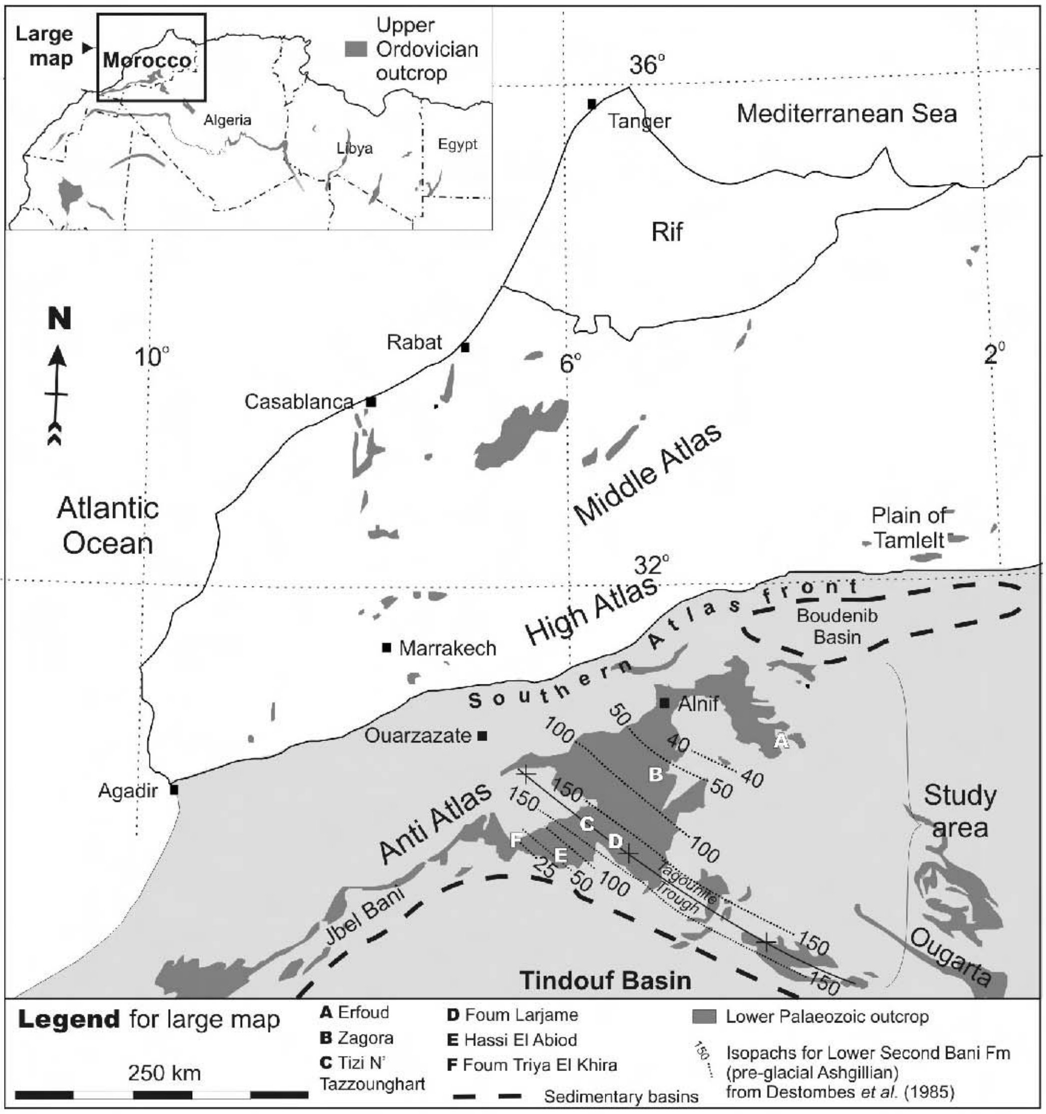
Large map
Morocco
Upper Ordovician outcrop
Algeria
Libya
Egypt
36°
Tanger
Mediterranean Sea
Rif
N
10°
Rabat
6°
2°
Casablanca
Atlantic Ocean
Middle Atlas
Plain of Tamlelt
32°
High Atlas
Southern Atlas front
Boudenib Basin
Marrakech
Alnif
Ouarzazate
Agadir
Anti Atlas
Jbel Bani
Tagounite trough
Study area
Ougarta
Tindouf Basin
A
B
C
D
E
F
25
40
50
100
150
Legend for large map
250 km
A Erfoud
B Zagora
C Tizi N' Tazzounghart
D Foum Larjame
E Hassi El Abiod
F Foum Triya El Khira
Sedimentary basins
Lower Palaeozoic outcrop
Isopachs for Lower Second Bani Fm (pre-glacial Ashgillian) from Destombes et al. (1985)

Figure 1

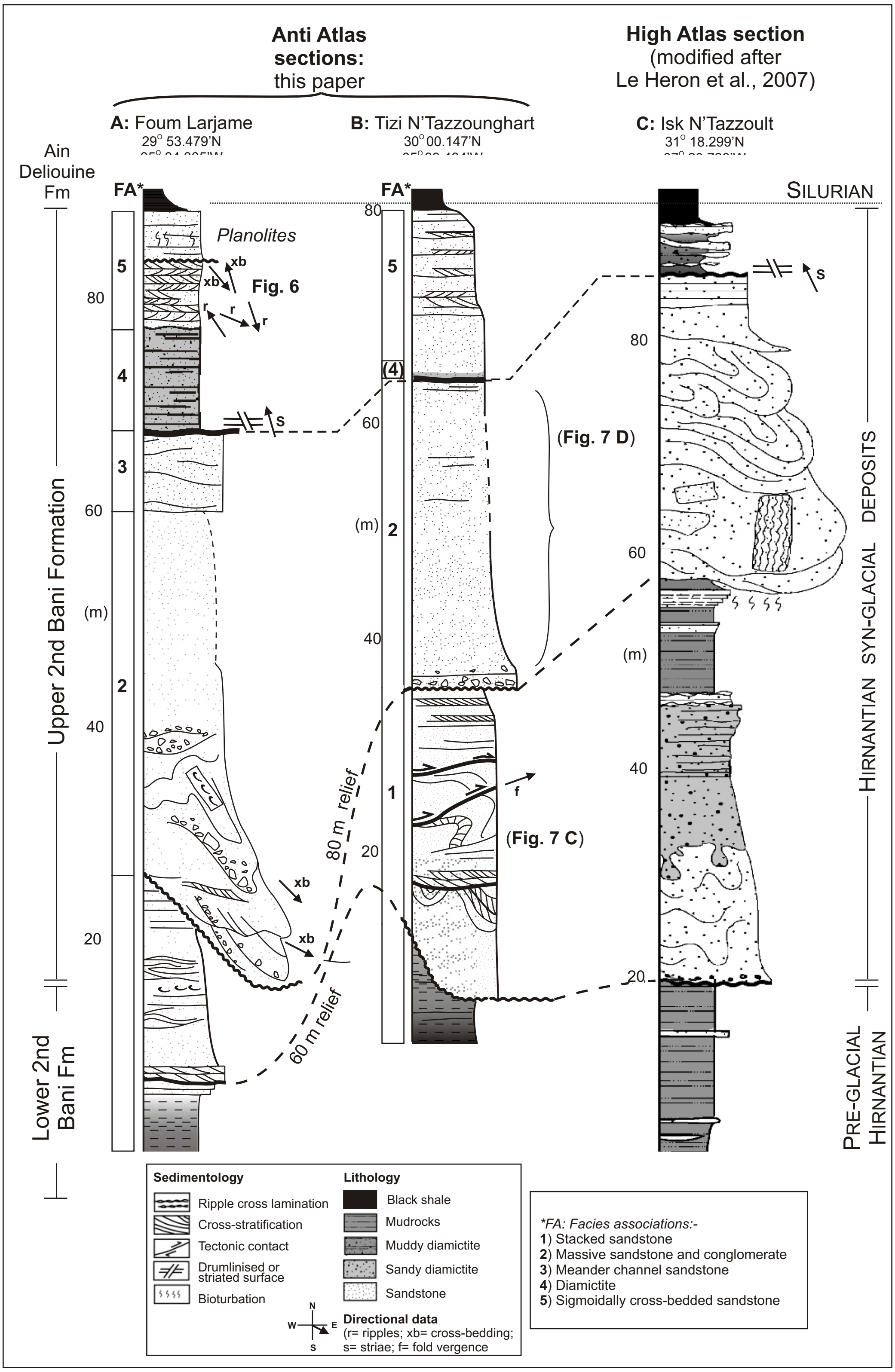
Anti Atlas sections: this paper
High Atlas section (modified after Le Heron et al., 2007)
A: Foum Larjame
29° 53.479'N
B: Tizi N'Tazzounghart
30° 00.147'N
C: Isk N'Tazzoult
31° 18.299'N
Ain Delioune Fm
Upper 2nd Bani Formation
Lower 2nd Bani Fm
FA*
Silurian
Hirnantian syn-glacial deposits
Pre-glacial Hirnantian
Planolites
Fig. 6
xb
r
s
f
(m)
80
60
40
20
1
2
3
4
(4)
5
(Fig. 7 D)
(Fig. 7 C)
80 m relief
60 m relief
Sedimentology
Ripple cross lamination
Cross-stratification
Tectonic contact
Drumlinised or striated surface
Bioturbation
Lithology
Black shale
Mudrocks
Muddy diamictite
Sandy diamictite
Sandstone
N
W
E
S
Directional data
(r= ripples; xb= cross-bedding; s= striae; f= fold vergence)
*FA: Facies associations:-
1) Stacked sandstone
2) Massive sandstone and conglomerate
3) Meander channel sandstone
4) Diamictite
5) Sigmoidally cross-bedded sandstone

Figure 2

Figure 3

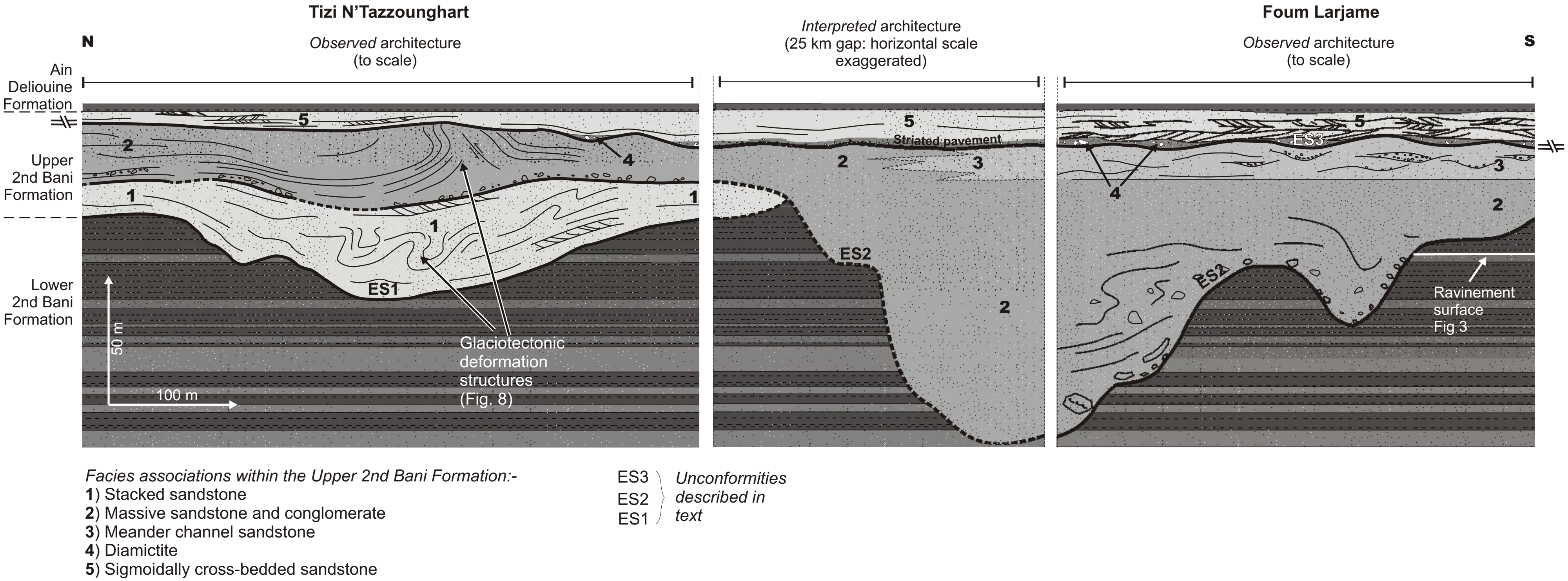
Tizi N'Tazzounghart
N
Observed architecture
(to scale)
Interpreted architecture
(25 km gap: horizontal scale
exaggerated)
Foum Larjame
S
Observed architecture
(to scale)
Ain
Delouine
Formation
Upper
2nd Bani
Formation
Lower
2nd Bani
Formation
5
2
4
1
1
1
ES1
50 m
100 m
Glaciotectonic
deformation
structures
(Fig. 8)
5
Striated pavement
2
3
ES2
2
5
ES3
4
3
2
ES2
Ravinement
surface
Fig 3
Facies associations within the Upper 2nd Bani Formation:-
1) Stacked sandstone
2) Massive sandstone and conglomerate
3) Meander channel sandstone
4) Diamictite
5) Sigmoidally cross-bedded sandstone
ES3
ES2
ES1
Unconformities
described in
text

Figure 4

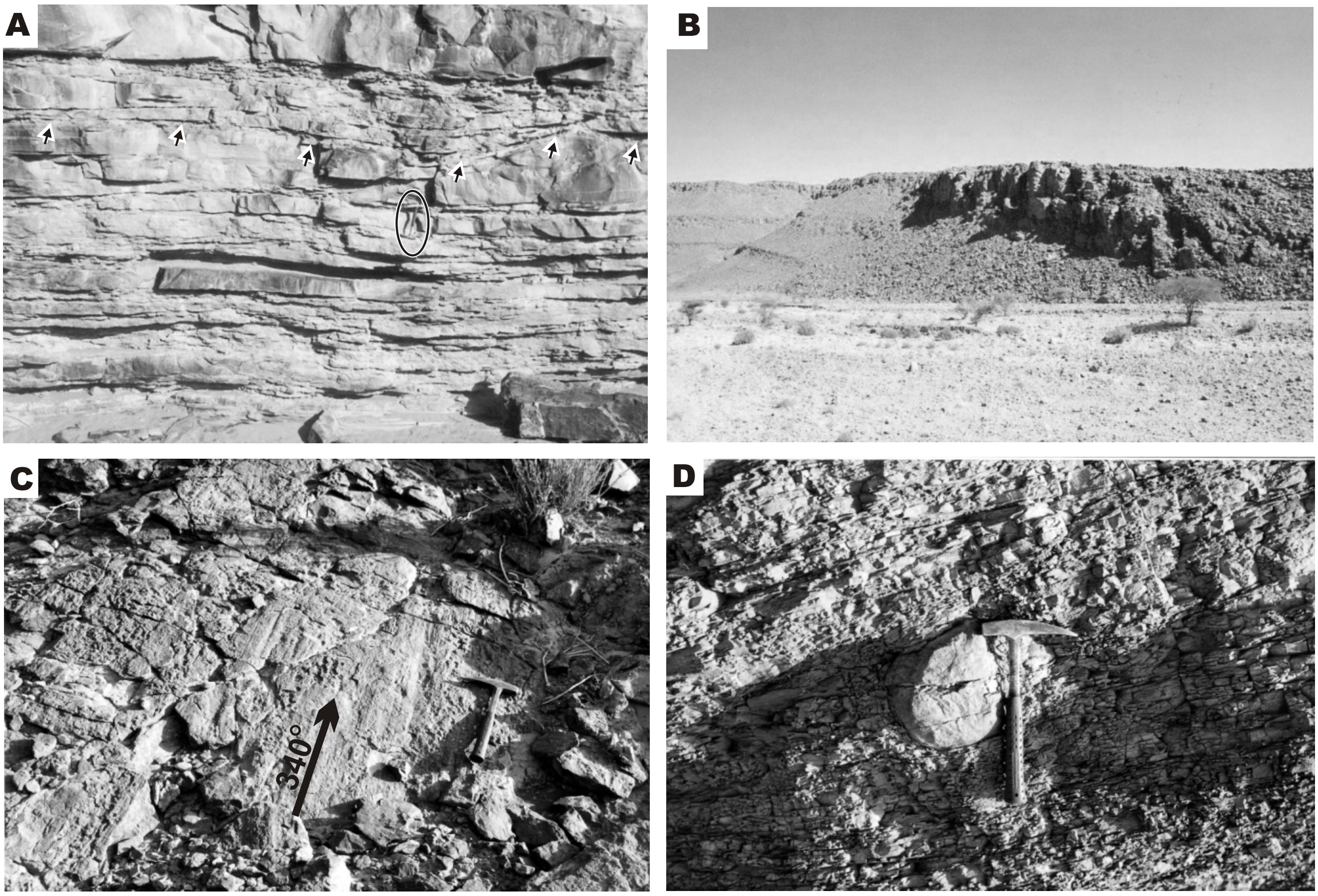

Figure 5

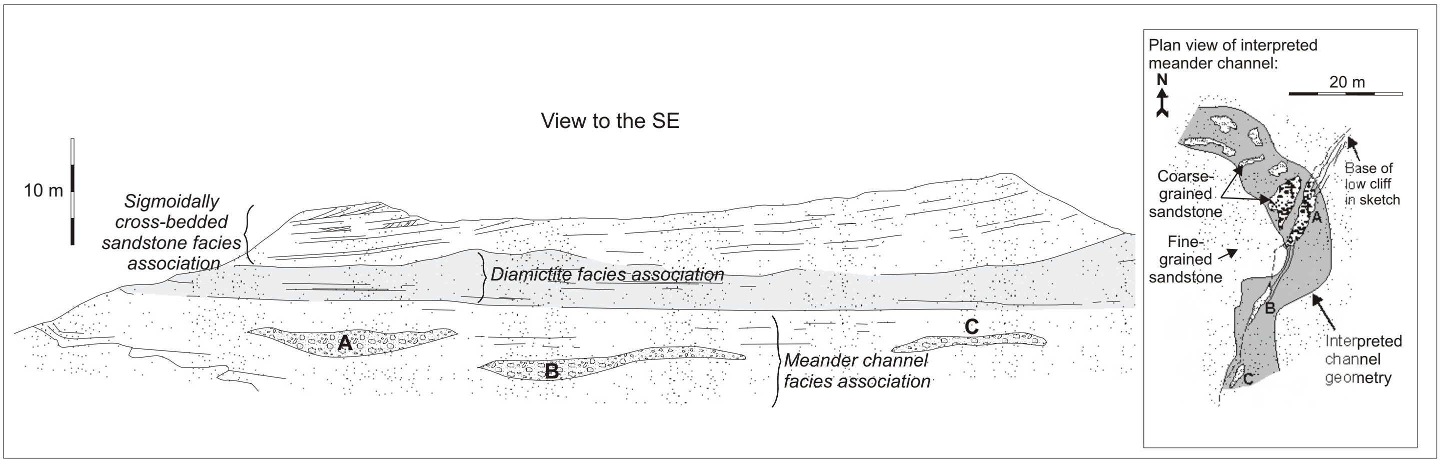
View to the SE
10 m
Sigmoidally cross-bedded sandstone facies association
Diamictite facies association
A
B
C
Meander channel facies association
Plan view of interpreted meander channel:
N
20 m
Coarse-grained sandstone
Fine-grained sandstone
Base of low cliff in sketch
A
B
C
Interpreted channel geometry

Figure 6

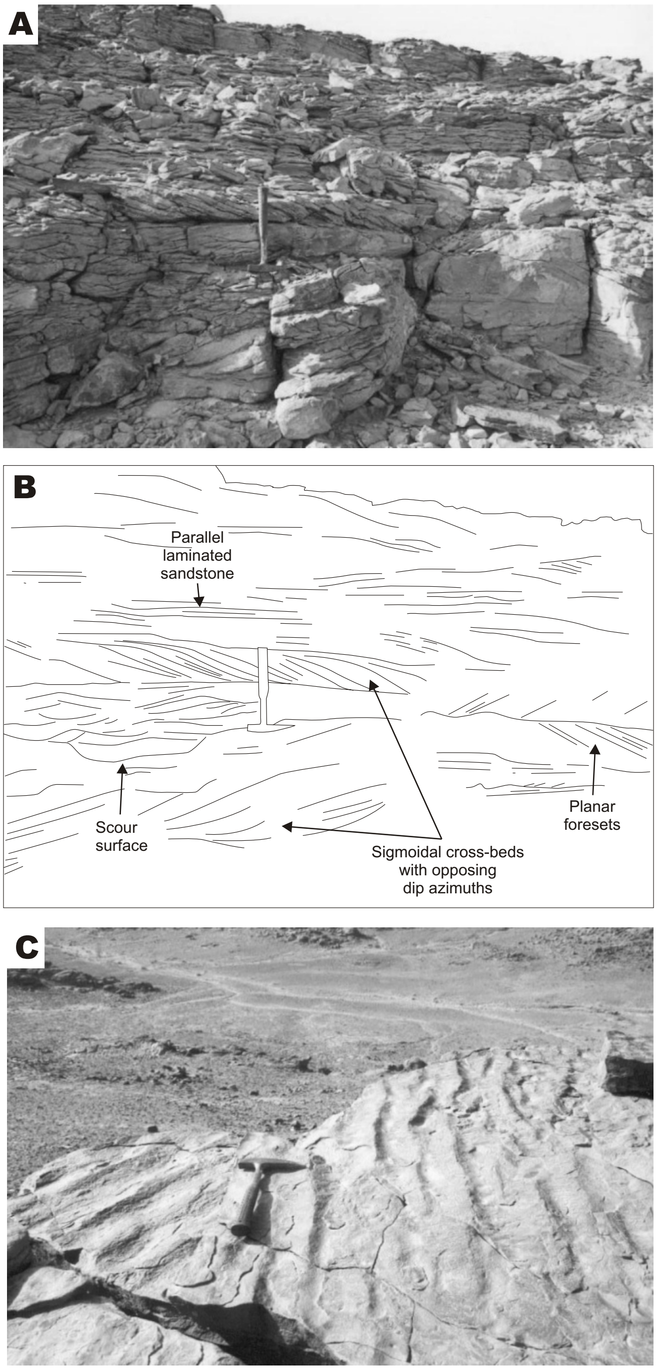
A
B
Parallel laminated sandstone
Scour surface
Sigmoidal cross-beds with opposing dip azimuths
Planar foresets
C

Figure 7

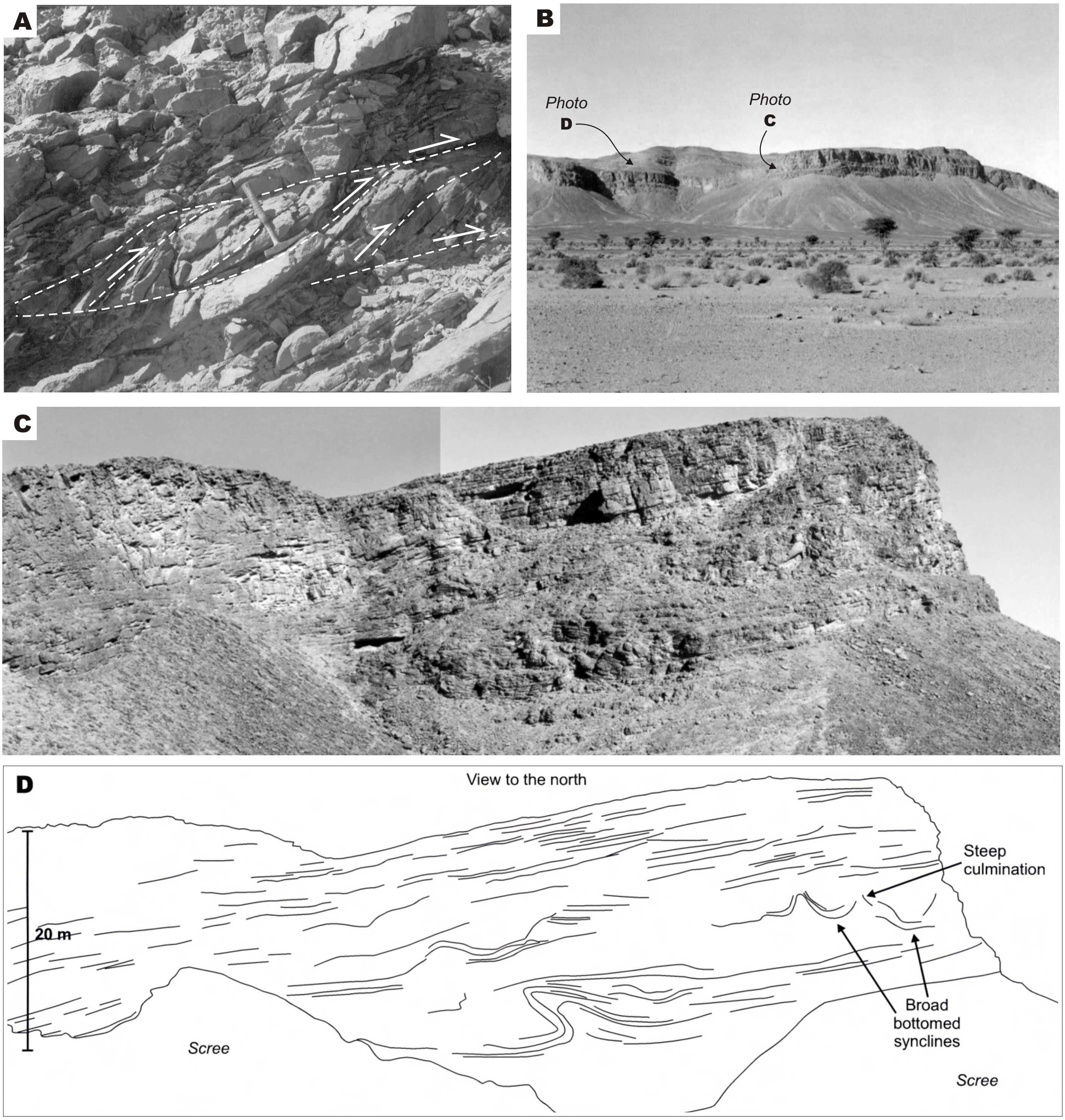
A
B
Photo
D
Photo
C
C
D
View to the north
20 m
Steep culmination
Broad bottomed synclines
Scree
Scree

Figure 8

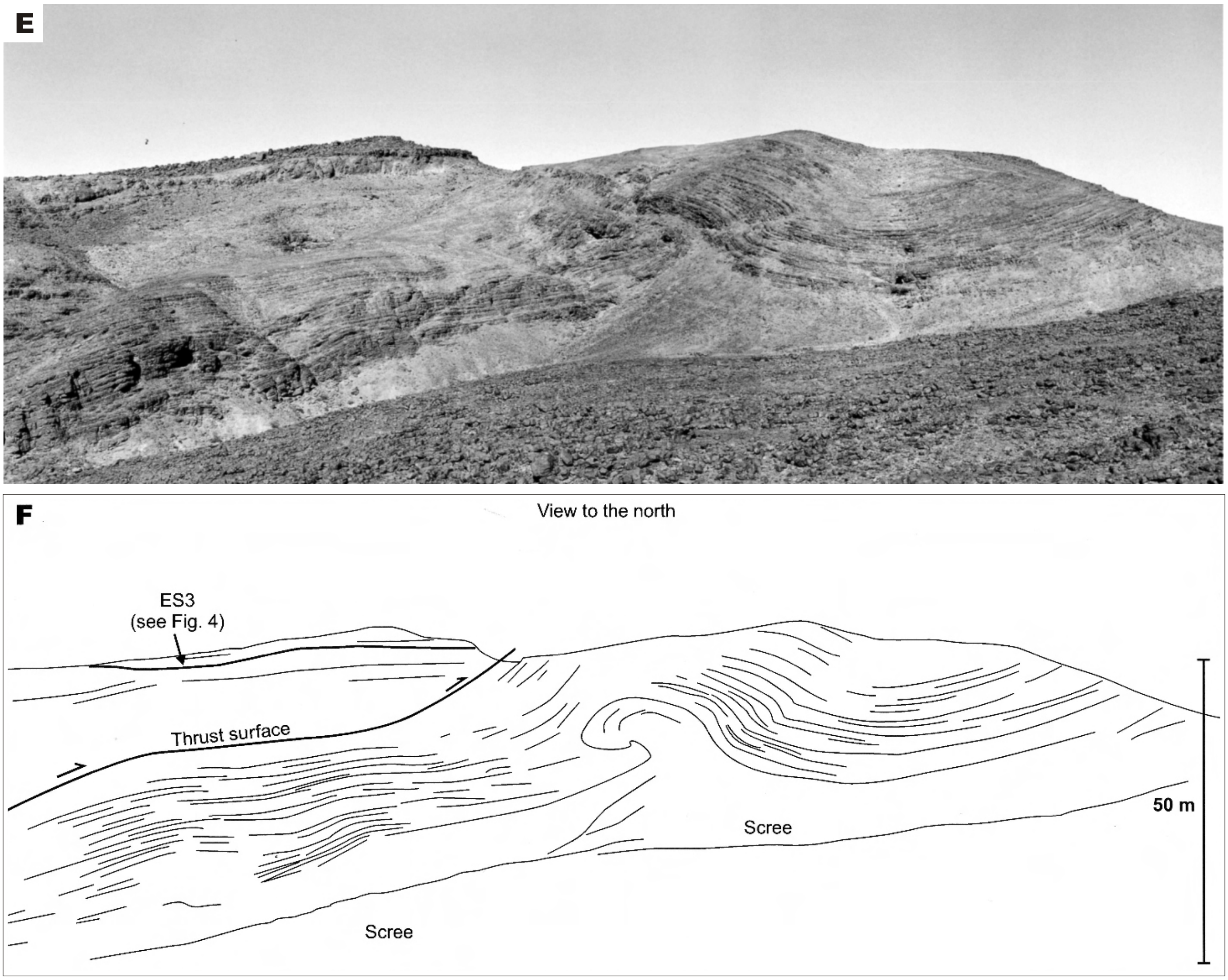

Figure 8 (Cont)

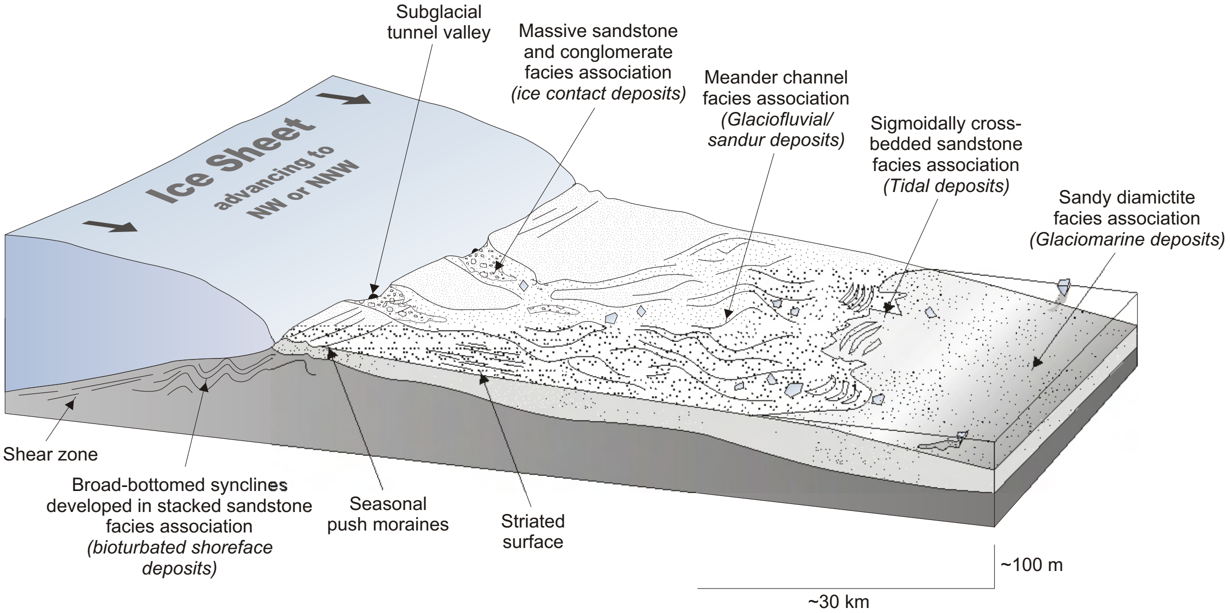
Subglacial tunnel valley
Massive sandstone and conglomerate facies association (ice contact deposits)
Meander channel facies association (Glaciofluvial/ sandur deposits)
Sigmoidally cross-bedded sandstone facies association (Tidal deposits)
Sandy diamictite facies association (Glaciomarine deposits)
Ice Sheet advancing to NW or NNW
Shear zone
Broad-bottomed synclines developed in stacked sandstone facies association (bioturbated shoreface deposits)
Seasonal push moraines
Striated surface
~100 m
~30 km

Figure 9