First order reconstructions of a Late Ordovician Saharan ice sheet

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Abstract: Synthesis of outcrop and subsurface sedimentological and geomorphological datasets across North Africa allows a tentative palaeo-glaciological model of the flow dynamics and recessional character of a 440 million year old (Hirnantian) ice sheet to be proposed. A system of 8 cross-shelf trough depocentres is identified from the Late Ordovician of the Sahara region. These are interpreted to have been carved and occupied by ice streams, providing evidence for widespread heterogeneous flow within the ice sheet. During retreat, two key geological features were produced: namely 1) laterally extensive, sinuous to linear piles of sediment dumped parallel to the ice margin and 2) large meltwater channels (tunnel valleys) cut near the grounding line.

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The goal of this paper is to present complete palaeo-glaciological reconstructions of the Late Ordovician Saharan ice sheet, whose ice margin extended 4000 km from the Atlantic coast of Morocco to Egypt. Whilst previous authors have discussed the maximum size and shape of Late Ordovician ice masses across Western Gondwana (e.g. Beuf *et al*. 1971; Vaslet 1990; Sutcliffe *et al*. 2000; Ghienne 2003; Le Heron *et al*. 2004), most have stopped short of discussing the regional distribution of flow heterogeneity within them, or their configuration during melting and recession.

The flux of modern ice sheets is controlled by networks of fast-flowing corridors of ice (or ice streams) that may account for up about 90 % of their mass loss (e.g. Bamber *et al*. 2000). There is widely cited evidence that large networks of former ice streams also drained both the European and Laurentide ice sheets during the Pleistocene (Punkari 1997; Jansson & Glasser 2005). The largest and hence most easily recognised examples of modern ice streams attain 20-100 km in width and are up to several hundred kilometres in length, exemplified by the modern day Lambert Glacier in East Antarctica (Bamber *et al*. 2000).

Although ice streams have been readily embraced by glaciologists as a valid drainage mechanism within modern (Bamber *et al*. 2000) and Pleistocene (Punkari 1997; Jansson & Glasser 2005) ice sheets, the ice stream paradigm has not penetrated into the majority of pre-Cenozoic ice sheet models, including most reconstructions of Late Ordovician ice masses (e.g. Vaslet 1990; Sutcliffe *et al*. 2000). Exceptions to this are Moreau *et al*. (2005) and Ghienne *et al*. (in press), both of whom clearly recognise the potential for ice streaming processes to be recorded in the sedimentary architecture of Late Ordovician glacially-related deposits. Important evidence for heterogeneous flow within Late Ordovician ice sheets at the small to medium scale (cm to several hundred metres) is supported by the record of glacier-induced soft-sediment deformation within glacially-related sediments (Le Heron *et al*. 2005). At the large scale, description of a >50 km wide, >300 km long palaeo-ice stream in western Libya (Moreau *et al*. 2005) within Late Ordovician sediments strongly supports the idea of heterogeneous flow operating at the largest scale.

Elsewhere, reapprasial of the glacial sedimentary record of the Neoproterozoic of Namibia has also begun to yield evidence for palaeo-ice streams in the form of large basin-shaped depressions thought to have been carved by fast-flowing ice (Hoffmann 2006). These recent findings suggest that widespread recognition of evidence for large-scale flow heterogeneities within former Late Ordovician ice sheets should now be possible.

Study area and Geological Setting

The sedimentary record of the Late Ordovician glaciation is represented by outcrops at the flanks of several large sedimentary basins from Egypt to the Atlantic coast of Morocco (**Fig. 1**). Information on Late Ordovician subcrop (oil industry proprietary data) has not yet been incorporated into regional reconstructions, but neglecting these data means that only a partial understanding of former ice sheet behaviour is possible. In this paper, we present new data and interpretations from both outcrop and the subsurface. The term “glacially related deposits” is used to refer to sediments deposited under the direct influence of grounded ice sheets.

North Africa was assembled during the Panafrican Orogeny in the Late Precambrian between 700-500 Ma (Unrug *et al.* 1996). The assembly process was complex: crystalline shield areas behaved rigidly whilst softer clastic successions were deformed around them in “mobile belts” of deformation (Hallett 2002). Gravitational collapse of the mountain chains then ensued (Unrug *et al.* 1996), forming a series of half-graben that were filled with “Infracambrian” flysch (Moussine-Pouchkine and Bertrand Sarfati 1997), possibly accompanied by strike slip deformation across the region (Neev *et al.* 1982). Any remaining post-orogenic rift topography was subject to extensive peneplanation leavingMid Cambrian sandstones resting unconformably upon underlying “Infrcambrian” flysch in both the Tassili N’Ajjers region (Eschard *et al.* 2005) and in the Dūr al Gussa region (Jacqué 1962).

Locally, rift tectonics affected Morocco episodically during the Cambrian and Silurian (Piqué 2001; Stampfli & Borel 2002). However, central North Africa was mostly characterised by gentle subsidence during the Cambrian and Ordovician, forming a series of intracratonic sag basins, although the far-field effects of rifting left some topography in the form of NNW-SSE and NW-SE striking horst and graben within the basin interiors (Klitszch 2000) (red ornament, **Fig. 1**). In a similar manner to younger ice sheets, it is reasonable to assume that the flow behaviour of Late Ordovician ice sheets was influenced by topography/ basement structure of the region. However, detailed mapping and stratigraphic investigations of "Infracambrian" to Silurian outcrops in SE Algeria (Beuf et al., 1971) and central Libya (Jacqué 1962) suggest that downcutting beneath Late Ordovician ice sheets produced the most significant unconformity following peneplanation of the PanAfrican mountain belt in the Lower Palaeozoic of North Africa.

The age of Late Ordovician glacially-related deposits is well constrained across North Africa. A Hirnantian (Late Ashgill age) is provided by shell beds bearing age-diagnostic *Hirnantia* fauna that are intercalated with glacially-related strata at outcrop in Libya and Morocco (Sutcliffe *et al*. 2001). In our database, a Hirnantian age is also supported by microfossil assemblages, where acritarchs *Veryhachium subglobosum*, *Villosacapsula irrorata*, *V. setosapellicula* and *Actinotodissus crassus* predominate in glacially-related strata of the Ghadames Basin, Libya (B. Thusu 2006, pers. comm.). Thirdly, glacially-related strata in the Anti-Atlas of Morocco (Destombes *et al*. 1985) are bounded below by shallow marine deposits yielding Early Ashgill (pre-Hirnantian) chitinozoa and above by Rhuddanian (earliest Silurian) chitinozoa-bearing shale (Bourahrouh *et al*. 2004). Rhuddanian (Early Silurian) age for post-glacial shale is also apparent from graptolites recovered from across the region, which extends continuously across the region from Morocco to eastern Libya (Lüning *et al*. 2000).

The biostratigraphic control outlined above enables Late Ordovician glacially-related rocks to be correlated as a regional sediment package with a high degree of confidence (**Fig. 2**). Their restricted stratigraphical extent, calibrated against interpretation of inflexions in stable oxygen and carbon isotope data from low palaeo-latitude carbonates on the Baltic margin (Brenchley *et al*.

2003, Kaljo *et al*. 2004), suggests that these rocks were deposited in a timeframe of about 0.5 Myr (Brenchley *et al*., 1994), possibly as little as 0.2 Myr if Late Ordovician ice sheets grew in response to changes in eccentricity of the Earth's orbit (Sutcliffe *et al*. 2000). Therefore, stratigraphic subdivision of glacially-related strata in North Africa, and the analysis of glacially-related features within them, can potentially provide high resolution understanding of the evolution of this ice sheet over ~0.2-0.5 Myr. The analysis of the products of the successive glacial cycles is potentially to within a comparable degree of temporal resolution to that achieved through studies of Pleistocene glaciation.

Elsewhere on Gondwana, separate ice sheets may have developed both earlier and later than the Hirnantian. In Nevada, USA, there is evidence for a positive δC_{13} excursion (4 ‰) in low palaeo-latitudinal carbonates that may record Caradocian ice sheet growth ~10 Myr prior to the Hirnantian (Saltzmann & Young 2005), although no sedimentological evidence for an older phase of ice sheet growth has yet been established. Likewise, there is well documented, well-dated evidence for Early Silurian (Wenlock) glaciation in Brazil (Diaz-Martinez *et al*. 2007). Therefore, the exact time interval over which global tendency toward "ice house" conditions, and hence regional ice centres, may have persisted at the Late Ordovician and Early Silurian is unclear, but the timing of ice sheet growth and decay across the Sahara is well established.

In summary, the narrow time interval over which Saharan ice sheets grew and decayed in the Hirnantian provides an opportunity to attempt an ice sheet reconstruction of excellent temporal precision in the pre-Cenozoic record. The potential for high resolution palaeo-glaciological studies is much greater in the Late Ordovician than for either Late Precambrian or Permo-Carboniferous glaciations. To provide a comparison, despite intensive research, attempts to unravel the flow and recessional behaviour of Late Palaeozoic (Permo-Carboniferous) ice sheets in the Karoo Basin, South Africa must contend with a poor resolution dataset that defines glacial cycles of ~10 Myr duration (Visser 1997). The glacial record of this basin was deposited during a globally diachronous glaciation of perhaps one to two orders of magnitude longer than the Late Ordovician event (55-100 Myr: Eyles 1993). By comparison, much older glacial deposits of terminal Marinoan (Neoproterozoic) age are well dated worldwide but not well disposed to palaeo-glaciological studies due to extreme levels of uncertainty in palaeo-continental reconstructions (Shields 2005).

Rationale for ice sheet reconstruction

Establishing the maximum extent of grounded ice sheets (the ice maximum)

In northern Morocco, the maximum extent of Late Ordovician ice sheets was demonstrated by Le Heron *et al*. (2007). In this region, a dramatic increase in sediment thickness from c. 25 m in the Massif Central region to c. 400 m in the Tazzeka Massif led these authors to interpret a fossil shelf break, beyond which a grounded ice sheet could not advance (Le Heron *et al*. 2007; Fig. 2, p204). This view is strengthened by the complete lack of glacially-related facies in northern Morocco, a region where striated pavements, large channel systems and large-scale soft sediment deformation are conspicuously absent (Le Heron *et al*. 2007). In this slope region, the increase in sediment thickness is accompanied by a dramatic increase in mud content within the proglacial sedimentary succession. However, elsewhere across North Africa, Late Ordovician glacially-related sediments are mostly known from subcrop (**Fig. 1**). We therefore follow the ice maximum of Beuf *et al*. (1971) for our palaeo-glaciological reconstruction, who showed an ice margin at the glacial maximum that stopped short of northern Libya and Algeria. Mapping of subsurface well data in the northern Sahara by these authors revealed an abrupt increase in sediment thickness and a major sand: mud transition across the region, which was interpreted as an abrupt increase in shelf gradient at a shelf break. Similar bathymetric breaks have subsequently been identified in the Ghadames Basin of northern Libya by Echikh & Sola (2000).

We assume that the regionally developed shelf break was coincident with the Late Ordovician ice maximum for the grounded ice sheet, although by analogy to the modern West Antarctic ice sheet, floating ice shelves may have influenced high-latitude marine sedimentation in deeper water areas (Dowdeswell & Siegert 1999). During the Early Palaeozoic, terranes now forming large parts of western and central Europe (Portugal, Spain, France) were positioned immediately north of the present day African landmass (e.g. Sutcliffe *et al*. 2001). These terranes preserve ice distal glaciomarine deposits (ice rafted diamictites), but not evidence for ice grounding (striated pavements) (Robardet & Doré 1988). These observations suggest that an ice sheet grounded at its maximum extent on the present North African margin provides the most realistic scenario.

Locating palaeo-ice streams

Three key geomorphological and sedimentological criteria may be used to locate palaeo-ice streams on regional datasets, namely 1) attenuated and streamlined bedforms with length to width ratios of >10:1 (Stokes & Clark 1999), 2) elongate, ice flow parallel cross-shelf troughs and 3) stacked debrites and/ or turbidites on terminal fans at the mouths of these troughs. The first group of features, known as mega-scale glacial lineations (MSGLs), are highly attenuated, elongate ridges and grooves that are oriented parallel to ice sheet flow and produced by fast flowing ice streams (Stokes & Clark 2001). On modern high latitude shelves such as the Barents Sea, MGSLs occur within the second group of features, namely elongate and sinuous cross-shelf troughs. These features are also oriented parallel to palaeo-ice sheet flow, and fetch tens of km wide and hundreds of km long (Andreasson *et al*. 2004). On the Norwegian Shelf, of the 20 cross-shelf troughs organised parallel to the flow lines of the Fennoscandian ice sheet, all were occupied by palaeo-ice streams during Pleistocene glaciation (Ottesen *et al*. 2002). In the Bear Island trough, 3D seismic interpretation of Pleistocene glacially-related deposits identifies four glacial erosion surfaces, each bearing MSGLs produced by the Bear Island palaeo-ice stream during successive glaciations (Andreasson *et al*. 2004). The third group of features, namely thick sedimentary accumulations seaward of the cross shelf trough (i.e. trough mouth fans), is exemplified by Pleistocene accumulations on the Bear Island Fan (debrites: Taylor *et al*. 2002) or the Wilkes Land Continental margin (turbidites: Escutia et al. 200x). The large volumes of sediment within these fans suggest exceptionally high rates of sediment flux across a glaciated continental margin (~4 km^3 a^{-1}), best explained by palaeo-ice streams (Dowdeswell & Siegert 1999).

The above criteria, robustly demonstrated by rigorous application to Pleistocene ice sheet reconstructions, should be equally applicable to locating palaeo-ice streams within much older ice masses such as the Late Ordovician Saharan ice sheet. One problematic facet of palaeo-glaciological studies is the need to demonstrate the contemporaneity of ice streams. No accepted set of criteria currently exist, although mapping cross-cutting relationships of modern subglacial bedforms produced by recent ice sheets may help where they are exceptionally well exposed (Jansson *et al*. 2003). Furthermore, ice streams in West Antarctica may illustrate phases of shutdown and re-activation on the decadal timescale (e.g. Bamber *et al*. 2000), processes that are well beyond the resolution of the Late Ordovician glacial record.

Mapping ice sheet grounding lines

Ice sheets tend to deposit large volumes of relatively coarse-grained sediment at their grounding lines. Sediment may be concentrated into fan-shaped bodies (subaqueous ice contact fans) at meltwater conduits. In the Late Ordovician glacial record of Libya, these ice contact sediments crop out on the Gargaf Arch (**Fig. 1**) and reach up to 64 km^2 in area (Le Heron *et al*. 2006). The ice contact sediments may either represent disconnected fans ("beads" of sediment), or alternatively lie along more laterally continous sediment aprons whose geometry defines the position and morphology of a former ice margin, a characteristic exhibited by modern retreating glacier termini such as the snout of Sólheimajökull, southern Iceland (e.g. Mackintosh *et al*. 2002). Such ice contact deposits are conventionally termed terminal moraines amongst Quaternary workers (e.g. Matthews *et al*. 1995). Therefore, at an ice sheet scale, the identification of discontinuous ice contact fans, or "beads" of sediment, oriented orthogonal to its main flow direction may be used to pinpoint ancient grounding lines during the retreat phase.

Outcrop data: Regional ice flow indicators and the Glacial Maximum Unconformity

Reconstructions of former ice sheets must be underpinned by sound data that demonstrate its patterns of ice flow. Four examples of Late Ordovician striated pavements, spread out over the study area from Morocco to eastern Libya, are therefore shown on **Fig. 3**. The strike of the ridges and grooves was measured carefully in the field, accounting for magnetic declination in each case. The orientation of each of the four striated surfaces are indicated on **Fig. 1**. In each case, the striations are preserved on a sandstone surface. In many cases, multiple occurrences of striated surface occur, characterised by lobes separated by a few centimetres (**Fig. 3 B**) or separated by up to a metre of sandstone. Each of those figured is the youngest stratigraphic example of striations in each study area, i.e. the first striations to be encountered in sandstones beneath postglacial Lower Silurian shale.

Although some striated surfaces in the rock record might represent iceberg keel scour marks (Woodworth-Lynas & Dowdeswell 1994), detailed study at the western flank of the Murzuq Basin (**Fig. 1**) reveals that Late Ordovician examples are sub-parallel, do not crosscut, and hence a subglacial origin is more plausible (Le Heron *et al*. 2005). The stratigraphic separation of many striated surfaces on the scale of centimetres (**Fig. 3 B**) up to metres suggests that they are best interpreted as interstratal detachments resulting from slippage within a soft, deforming sediment column shearing beneath the ice sheet (Sutcliffe *et al*. 2000, 2005; Deynoux & Ghienne, 2004; Le Heron *et al*. 2005), rather than at the sediment-ice sheet interface where local topographic effects (e.g. pebbles or roches moutonées) can influence striation trajectories. In Hirnantian glacially-related deposits, it is argued that the striated surfaces also reflect larger-scale ice sheet flow behaviour because in the Ghat region (**Fig. 1**), ridges and grooves on striated surfaces strike exactly parallel to mega-scale glacial lineations mapped on satellite imagery (Moreau *et al*. 2005).

Given that the striated surfaces result from subglacial shearing during ice sheet advance, they are interpreted to represent a subglacially cut unconformity. Recent work by Le Heron *et al*. (2006) demonstrated that in western Libyan outcrops, glacially-related deposits can be divided into four glacial allostratigraphic units, each of which is interpreted to record an individual cycle of glaciation. Each unit is separated by a set of closely spaced striated surfaces, and can be correlated for ~400 km between Ghat and the Gargaf Arch. These authors found evidence for large-scale downcutting in the stratigraphic unit beneath Lower Silurian shale which they attributed to the last phase of glaciation to affect the Murzuq Basin with a component of isostatic rebound superimposed. In northern Morocco, a similar four-fold glaciation was recognised by Le Heron *et al*. (2007) with large-scale channel incision and roches moutonées (**Fig. 3 A**) directly below the Lower Silurian shale. The uppermost occurrence of striated surfaces across the region are interpreted to have formed during the growth of ice sheets to their maximum position, as supported by major downcutting/ incision in both Libya and Morocco, and an associated suite of glacially-related soft-sediment deformation structures at this level (Ghienne *et al*. 2003). Based on this evidence, we term the uppermost striated pavement the Glacial Maximum Unconformity. Examination of subsurface well data in western Libya, southern Tunisia and Algeria identifies the Glacial Maximum Unconformity as the topmost discontinuity within the Late Ordovician glacially-related sediments, immediately underlying the Dalle M'Kratte mapping unit (**Fig. 2**).

Subsurface data

Subsurface mapping method

The physiography of the Late Ordovician glaciated shelf in Algeria, western Libya and southern Tunisia was assessed using a large well database covering parts of the Murzuq, Ghadames, Illizi, Oued Mya, Ahnet, Sbaa, Goubara and Tindouf basins (**Fig. 1**). Data from 460 subsurface wells across the Algerian Sahara were collated and correlated to generate a series of isopach maps for Late Ordovician glacially-related rocks (**Fig. 4**). This regional mapping enabled a stratigraphy to be developed for glacially-related sediments in the subsurface of Algeria (**Fig. 2**). Three allostratigraphic units were identified on the basis of wireline log response patterns (gamma ray log). The allostratigraphic units from base to top are 1) the El Golea mapping unit, 2) the Microconglomerate mapping unit and 3) the Dalle M´Kratte mapping unit. These three mapping units can be correlated across the region (**Fig. 5**). The example correlation panel presented in this paper extends across the Ahnet Basin (central Algeria), the Ghadames Basin (southern Tunisia, NW Libya) and the Murzuq Basin (SW Libya) (**Fig. 5**). Each unit takes its name from an "operational" stratigraphy used in the course of oil exploration within the Illizi Basin.

The El Golea mapping unit (**Figs 2, 5**) is characterised by an irregular to concordant contact upon underlying Cambro-Ordovician sandstones and mudrocks, and is exemplified by rapid excursions on the gamma and SP logs, with API values on gamma ray typically 20-50 API, interpreted to record alternations between muddy sandstone and silt. It is truncated by a more mud rich, typically massive unit (the Microconglomerate mapping unit; **Figs 2, 5**). This unit typically shows box shaped profile with moderate (~30-100 API) values on the gamma ray tool. In Algeria, the term "microconglomerate" was coined to refer to a diamictite with outsized grains typically of granule size (e.g. Legrand, 2003). Both the El Golea and Microconglomerate mapping units show relatively abrupt local thickness variations as a result of an extensive system of palaeovalleys at their bases, which probably represent separate phases of meltwater incision (e.g. Hirst *et al*. 2002; Eschard *et al*. 2005). These palaeovalleys are of the order of 100-150 m deep, 1-4 km wide, and up to 50 km long (Ghienne *et al*. in press). When scaled up, these local thickness changes are suppressed by larger scale variations at a basin scale that allow their regional thickness variations to be assessed. The topmost mapping unit (Dalle M'Kratte unit) truncates underlying glacially-related sediments and typically exhibits a bell-shaped profile on gamma ray logs. Of the three mapping units, the Dalle M'Kratte is the most readily correlated. This is attributed to it showing a large and significant increase in sandstone content compared to underlying glacially-related deposits, reflected in a dramatic decrease in gamma-ray values above the Glacial Maximum Unconformity (**Fig. 5**). Typical gamma ray values for the Dalle M'Kratte Formation are ~20 API, with intercalated mudstone intervals at ~100 API.

Description

Following the methods described above, two isopach maps are presented: 1), for the total thickness of Late Ordovician glacially-related deposits across Algeria, southern Tunisia and western Libya (**Fig. 4 A**); 2), for the total thickness of the Dalle M´Kratte unit across the same region (**Fig. 4 B**). The total thickness map shows that Late Ordovician glacially related deposits are unevenly distributed across North Africa. They are organised into regions where total sediment thicknesses attain >100 m (depocentres), in zones 50-100 km wide and 2-300 km long. These contrast with zones of much reduced total sediment thickness (<60 m). Across the region, depocentres are recognised in the southern Ahnet and Goubara basins, the western Telemazine Arch, the Oued Mya Basin, the western Illizi Basin and the Algerian part of the Ghadames Basin, the eastern Illizi Basin, and in the Awbari Trough (Murzuq Basin). In areas such as western Algeria and western Libya, individual depocentres are closely spaced (<50 km apart) (**Fig. 4 A**). Therefore, closely spaced depocentres are organised into single fairways (stippled line, **Fig. 4 A**). In contrast, the Dalle M´Kratte thickness map (**Fig. 4 B**) shows that depocentres for the topmost part of the glacially-related succession are strung together in a series of three E-W oriented belts, extending over a total distance of >1000 km.

Interpretation

The regional thickness distribution of Late Ordovician glacially-related deposits across central North Africa is considered to be the product of up to four phases of ice sheet advance and retreat across the region (Moreau *et al*. 2005; Le Heron *et al*. 2006, Ghienne *et al*. in press). Therefore, the thickness variations could be interpreted in terms of differential ice sheet erosion across the shelf, a predominantly depositional process, or a combination of the two. The closely spaced depocentres, which are organised into single fairways, are strike parallel to striated pavements along the Glacial Maximum Unconformity (**Fig. 3**). Their width and length is directly comparable to the largest-scale Pleistocene cross-shelf troughs, such as that occupied by the huge M'Clintock Channel palaeo-ice stream in Arctic Canada (Clark & Stokes 2001). It is therefore suggested that the thickest packages of sediment in the depocentres record greater overall accomodation space created by heightened erosion beneath ice streams. In contrast, the E-W oriented belts of depocentres for the Dalle M'Kratte Formation are interpreted as a predominantly depositional fabric because these features are orthogonal to the regional ice flow directions revealed by the striation data along the underlying Glacial Maximum Unconformity and cross-shelf trough orientations. Therefore, the three depocentre belts are interpreted as a series of linear end moraines deposited at the grounding line during a stepwise retreat of the ice margin from the Late Ordovician glacial maximum.

Remote sensing data

Mega-scale Glacial Lineations (Jbel Dalma)

LANDSAT$_{TM}$ data were interrogated for two outcrops in Libya, namely Jbel Dalma (**Figs. 1, 6**) and the Gargaf Arch (**Figs. 1, 7**). In Jbel Dalma, northeastern Libya, Cambro-Ordovician sandstones are undifferentiated (Bellini *et al*. 1991) but crop out as a 100 km long, ENE-WSW striking outcrop belt (**Figs. 1, 6**). In this region, Cambro-Ordovician sandstones are onlapped by Early Silurian shale (Lüning *et al*. 1999) and are crosscut by three sets of lineaments (**Fig. 6**). The dominant set strikes NW-SE (green ornament), crosscutting Cambro-Ordovician through Carboniferous strata. A second set strikes ENE-WSW (red ornament) and includes both short and very long (>50 km) lineaments. The third, a NE-SW to NNE-SSE striking set (blue ornament) is almost entirely restricted to the Cambro-Ordovician outcrop area, and comprises parallel, curved to straight, elongate lineaments with rare crosscutting relationships (**Fig. 6**). These lineaments are long (>10 km) and narrow (~100 m), and hence have an extremely high elongation ratio (100:1). NW-SE and ENE-WSW striking lineaments occur within all stratigraphic units, and are thus interpreted as tectonic structures. In contrast, the NE-SW oriented lineaments are interpreted as glaciogenic structures, reflecting both their restriction to the outcrop area of Cambro-Ordovician sediments, and the curved morphology of some of the lineaments. This interpretation is much strengthened by the occurrence of soft-sediment striae in the same region (**Fig. 3 D**) which are strike-parallel to the NE-SW lineaments. The scale and high elongation ratio of these lineaments easily classifies them as mega-scale glacial lineations (MSGLs) (Stokes & Clark 2001), comparable to those identified 1000 km west on the Algerian border (Moreau *et al*. 2005). They are hence interpreted as the footprint of a palaeo-ice stream.

Densely spaced tunnel valleys (Gargaf Arch)

On the Gargaf Arch (**Figs 1, 7**) the Late Ordovician glacial sequence is crosscut by wide (to c. 6 km), long (to > 30 km) and deep (to >100 m) glacial palaeovalleys. These have been noted previously (Ghienne *et al*. 2003; Le Heron *et al*. 2004), but their dense distribution and planform geometry is apparent for the first time on processed LANDSAT$_{TM}$ data (**Fig. 7**). Crosscutting relationships show that several generations of palaeovalleys are present in the same region (i.e. they are multigenerational), with at least three phases of incision and fill recognised (**Fig. 7**), and they are consistently oriented N-S. Previous, detailed studies interpreted these as tunnel valleys that were cut subglacially and filled during ice sheet retreat (Le Heron *et al*. 2004). Densely spaced, multigenerational tunnel valley systems were also mapped by Beuf *et al*. (1971) across the Tassili N'Ajjers region of south-eastern Algeria (**Fig. 1**). The densely spaced nature of tunnel valleys on the Gargaf Arch and in the Tassili N'Ajjers region suggests that meltwater processes may have been concentrated at these localities during ice sheet retreat. By contrast, no tunnel valleys are observed in Jbel Dalma. The multigenerational occurrence of these valleys is interpreted to record the release of large volumes of meltwater on the Gargaf Arch during successive glacial cycles. We discuss the reasons for the dense spacing of these valleys and their multigenerational nature in the context of ice sheet reconstruction below.

Palaeo-glaciological reconstructions

Ice maximum map

The positioning of an outcrop-defined palaeo-ice stream in western Libya (Moreau *et al*. 2005) in an Ordovician depocentre (Fello *et al*. 2006), immediately southeast of a cross-shelf trough in eastern Algeria (**Fig. 8 A**, locality 3) affirms the genetic link between ice streams and cross-shelf troughs in North Africa. Based on this relationship, and the interpretation of cross-shelf troughs given above, eight palaeo-ice streams are proposed to have drained the North African ice sheet at its glacial maximum (**Fig. 8 A**), flowing towards the northwest, north or northeast, with dimensions of 100- >600 km length, 50-100 km width, spaced 200-1000 km apart, and defining a drainage system flowing outward from the central/ southern part of the Sahara. From west to east, these occupied 1) the Anti-Atlas, 2) southern Ahnet and Goubara basins, 3) western Telemazine Arch, 4) Oued Mya Basin, 5) western Illizi Basin and the Algerian part of the Ghadames Basin, 6) Tihemboka Arch and the eastern Illizi Basin, 7) Awbari Trough, Murzuq Basin, and 8) the Jbel Dalma high and southern Cyrenaica (**Figs. 1, 8 A**). Ice Streams 2-5 are defined using the subsurface data (**Fig. 4 B**) and a critical outcrop control point (Moreau *et al*. 2005). Ice stream 1 is positioned on the basis of a ~100 m deep, 50 km wide NW-SE trough in Late Ordovician glacially related sediments described at outcrop in the Anti Atlas of Morocco (Destombes *et al*. 1985). Ice Stream 7 corresponds to a 60 km wide cross-shelf trough (the Awbari Trough) carved into pre-glacial sediments, defined by published well and seismic data (Aziz 2000), and bearing evidence of mega-scale glacial lineations within it (Moreau 2006). Ice Stream 8, defined on the basis of mega-scale glacial lineations (MGSLs) on satellite imagery (**Fig. 6**), can also be traced into the subsurface by identifying a cross-shelf trough in southern Cyrenaica (see **Fig. 1**), where a major kink/ inflexion in contours of Early Silurian shale (El Arnauti & Shelmani 1985) point to an underfilled, glacially-sculpted basin.

Inter-stream areas are interpreted in the Tassili N'Ajjers (Algeria), on the Gargaf Arch (central Libya), in Dur Al Gussa (central Libya), and at Jbel Arkenu (**Figs. 1, 8 A**). For the first two localities, this interpretation is supported by biostratigraphic data (Legrand 2003; Lüning *et al.* 2000), which show that both areas were topographically elevated relative to the surrounding shelf prior to the Early Silurian. In Dūr al Gussa, extremely thick ice may have existed (an inter-stream ice thick), since Silurian shale directly onlaps Neoproterozoic basement, implying protracted glacioisostatic rebound (Le Heron *et al.* 2006) and presumably a thick column of ice was therefore present. At Jbel Arkenu (**Fig. 1, Fig. 8 A**), Late Ordovician glacially-related sediments rest directly on Cambrian deposits (Bellini & Massa 1980) and thus a long-lived syn-glacial palaeo-high is inferred.

Elsewhere, palaeo-ice streams are tentatively positioned in southernmost Algeria on the border with Mali and Niger (Ice Stream 9; major deflection and distinctive NW-SE oriented isopachs for the Lower Silurian in Legrand 2003), and in the Hodh-Adrar regions of Mauritania (Ice Stream 10; regionally convergent ice-flow indicators (striae, roches moutonnées) according to Ghienne 2003). In both cases, the convergent ice-flow indicators, which are usually symptomatic of accelerating ice (Stokes and Clark, 2001), are suggested to record the channelling of ice into glacially sculpted depressions.

Ice sheet decay map

Data shown on **Fig. 4 C** correspond to isopachs of the youngest (topmost) glacially related strata in subsurface Algeria and western Libya. Detailed outcrop work in Libya (Le Heron *et al*. 2006) and Morocco (Le Heron *et al*. 2007) interprets these youngest sediments as having been deposited following retreat from the ice maximum. The data show that sediments are organised into three W-E striking linear aprons 500-1000 km in length. The southernmost of these linear aprons, which can be traced between the southern Ahnet Basin and the northern Illizi Basin (**Fig. 1**), coincides exactly with large meltwater channels/ tunnel valleys mapped in the Illizi Basin and on the Gargaf Arch (**Fig. 8 B**). Furthermore, a system of similar large-scale meltwater channels/ tunnel valleys mapped at outcrop in the Tassilis N'Ajjers (**Fig. 8 B**) is also exactly strike parallel and to the south of these linear aprons of sediment. Together, we interpret the association of very-large scale linear sediment aprons and strike-parallel large meltwater channels/ tunnel valleys as successive grounding lines during ice sheet recession, with the older (basinward) grounding line in the north, and the last/ youngest (landward) grounding line in the south (**Fig. 8 B**). These interpretations indicate that pinning points were available to the ice sheet as it decayed, in turn implying a relatively stable, normal or seaward dipping shelf.

Conclusions

This paper has provided, for the first time, reconstructions of the Late Ordovician Saharan ice sheet in terms of its probable flow and decay mechanisms. It is the most detailed reconstruction possible based on the current dataset. An understanding of these mechanisms is especially important in exploration of glacially-related Late Ordovician hydrocarbon reservoirs in North Africa: constraining the position of palaeo-ice streams is important to understand the spacing of large, glacially sculpted cross-shelf troughs as sediment depocentres. Furthermore, understanding the position of grounding lines during ice sheet recession is critical because oil-bearing sands were deposited next to the ice front. The release of further data acquired during oil exploration will be used to refine this first-order model.

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Figure captions

Figure 1. Sketch map showing the principal Saharan Palaeozoic cratonic basins, key basin-flanking uplifts, and other geographic features in North Africa. The main geological structures are shown in red; these are thought to have formed topographic highs and lows, influencing sedimentation patterns, and hence ice sheet dynamics during the Late Ordovician. Map based on data from Boote *et al*. (1998) and Klitzsch (2000).

Figure 2. Stratigraphy of Late Ordovician glacially-related deposits and their correlation across northern Morocco, southern Morocco, Algeria (subsurface), Algeria (Tassili N'Ajjers outcrop) and western Libya (Murzuq Basin) and eastern Libya (Al Kufrah Basin). The correlation emphasises the Glacial Maximum Unconformity. At outcrop, this unconformity is represented by the uppermost (youngest) striated pavement found in each region, and regionally corresponds to the surface along which Late Ordovician ice sheets grew to their maximum extent (the Late Ordovician ice maximum). The package immediately above this unconformity was thus deposited during retreat from the ice maximum position, prior to Early Silurian postglacial transgression. In the subsurface of Algeria, this uppermost package is known as the Dalle M'Kratte Formation. Stratigraphic chart compiled from information in Destombes *et al*. (1985), Bellini *et al*. (1991), Eschard *et al*. (2005) and Le Heron *et al*. (2006, 2007).

Figure 3. Soft-sediment striated pavements along the Glacial Maximum Unconformity in the Late Ordovician record of North Africa. A: Streamlined bedform (a roches moutonnée) at Tizi N'Tichka (in the High Atlas of Marrakech, Morocco (31°18.299'N 07°20.729'W). B: Soft-sediment striated pavement south of Ghat town, Tihemboka Arch, western Murzuq Basin (24°52.512'N 10°10.675'E). C: Cross-cutting striae along the base of a tunnel valley on the Gargaf Arch, northern

Murzuq Basin, Libya (27°49.860’N 12°36.958’E). D: Streamlined, polished and striated sandstone surface in Jbel Dalma, northern Al Kufrah Basin, Libya (25°48.555’N 23°32.087’E).

Figure 4. Isopach maps of the Late Ordovician glacial deposits in subsurface Algeria, southern Tunisia and western Libya, based on simplified ENI data from approximately 460 wells. A: Total thickness isopach for Late Ordovician glacially related deposits, used to position cross-shelf trough fills and hence palaeo-ice streams on our ice-maximum reconstruction (Fig. 8 A). B: Total thickness of the Dalle M-Kratta unit, deposited following retreat from the Late Ordovician glacial maximum, used to position ancient ice grounding lines on our second map showing retreat from the ice maximum position (Fig. 8 B).

Figure 5. Example correlation panel of Late Ordovician glacially-related deposits across the subsurface of the Saharan platform, from the Ahnet Basin (central Algeria) (A), the southern Tunisian (B) and north-west Libyan (C) sectors of the Ghadames Basin, and from the Murzuq Basin, south-west Libya. For details about the stratigraphic subdivisions used in creating this correlation panel see the Subsurface Data section.

Figure 6. Interpreted LANDSAT$_{\mathrm{TM}}$ data over Jebel Dalma in eastern Libya (for location see Fig. 1). Two sets of lineaments are seen to crosscut strata deposited both prior to and following the Late Ordovician glaciation, and are interpreted as tectonic lineaments; these strike NW-SE (green) and ENE-WSW (red). A third set of lineaments is restricted to the Ordovician outcrop striking NE-SW (white). These are 3-20 km long, sinuous, divergent, and attenuated. They are interpreted as mega-scale lineations produced by an ice stream.

Figure 7. A: Greyscale LANDSAT$_{TM}$ data image of the western Gargaf Arch, central Libya, covering the outcrop area of Late Ordovician glacially-related deposits. The image was band-ratioed (band 7/9) and subjected to histogram stretching so that the image shading provides a guide to the clay content of sediments exposed at the surface. White and light grey shades indicate a high sand content; dark grey to black shades are characteristic of mud-rich lithologies. B: Interpreted planform distribution of tunnel valleys at outcrop from the LANDSAT$_{TM}$ data in A. At least three generations of palaeovalleys can be identified, interpreted to have been produced during multiple phases of ice sheet retreat. The “multigenerational” nature of these valleys suggests that the Gargaf Arch was an important ice sheet grounding line/ pinning point during the retreat of the Saharan ice sheet (Fig. 8 B).

Figure 8. Palaeo-glaciological reconstructions of the Late Ordovician Saharan ice sheet. A: Ice sheet configuration at glacial maximum position, showing widespread occurrence of ice streams separated by wide inter-stream areas. B: Ice sheet during its stepwise recession from the ice maximum, showing several grounding line positions, and hence implying gradual rather than catastrophic recession over at least this part of the ice sheet.

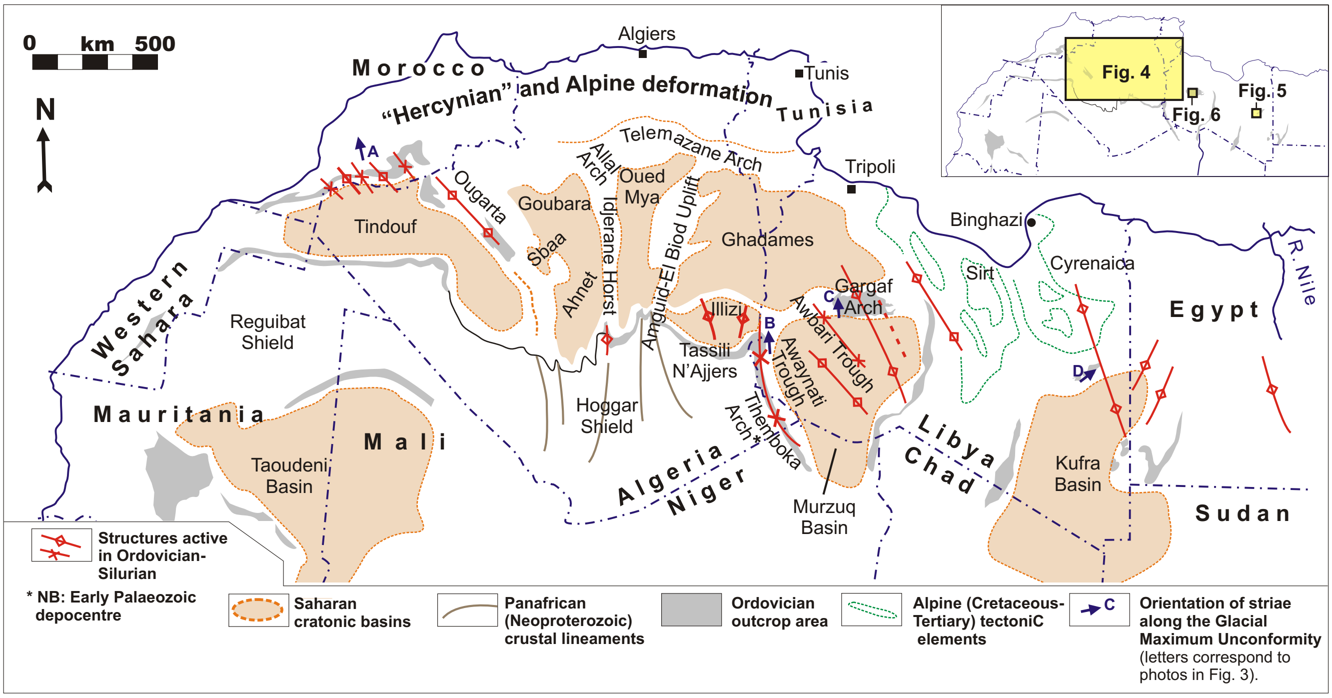

0 km 500
N
Algiers
Tunis
Morocco
"Hercynian" and Alpine deformation
Tunisia
Telemazane Arch
Allal Arch
Oued Mya
Tripoli
Goubara
Idjerane Horst
Amguid-El Biod Uplift
Ghadames
Binghazi
Cyrenaica
Sirt
R. Nile
Egypt
A
Tindouf
Ougarta
Sbaa
Ahnet
Western Sahara
Reguibat Shield
Illizi
B
C
Gargaf Arch
Awbari Trough
Awaynati Trough
Tassili N'Ajjers
Tihemboka Arch*
Hoggar Shield
Mauritania
Mali
Taoudeni Basin
Algeria
Niger
Libya
Chad
Murzuq Basin
D
Kufra Basin
Sudan
Fig. 4
Fig. 5
Fig. 6
Structures active in Ordovician-Silurian
* NB: Early Palaeozoic depocentre
Saharan cratonic basins
Panafrican (Neoproterozoic) crustal lineaments
Ordovician outcrop area
Alpine (Cretaceous-Tertiary) tectoniC elements
C
Orientation of striae along the Glacial Maximum Unconformity (letters correspond to photos in Fig. 3).

Figure 1

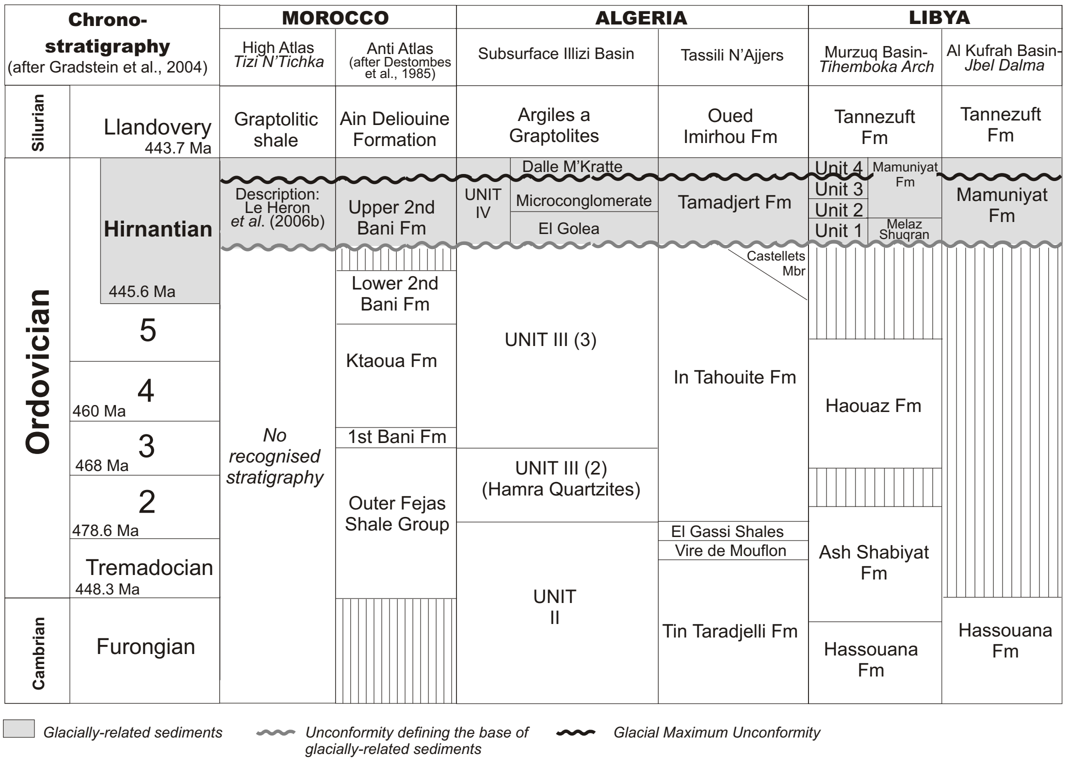

Chrono-stratigraphy
(after Gradstein et al., 2004)
MOROCCO
ALGERIA
LIBYA
High Atlas
Tizi N'Tichka
Anti Atlas
(after Destombes et al., 1985)
Subsurface Illizi Basin
Tassili N'Ajjers
Murzuq Basin-
Tihemboka Arch
Al Kufrah Basin-
Jbel Dalma
Silurian
Llandovery
443.7 Ma
Graptolitic shale
Ain Deliouine Formation
Argiles a Graptolites
Oued Imirhou Fm
Tannezuft Fm
Tannezuft Fm
Ordovician
Hirnantian
445.6 Ma
Description: Le Heron *et al.* (2006b)
Upper 2nd Bani Fm
UNIT IV
Dalle M'Kratte
Microconglomerate
El Golea
Tamadjert Fm
Unit 4
Unit 3
Unit 2
Unit 1
Mamuniyat Fm
Melaz Shuqran
Mamuniyat Fm
Castellets Mbr
5
4
460 Ma
3
468 Ma
2
478.6 Ma
Tremadocian
448.3 Ma
Lower 2nd Bani Fm
Ktaoua Fm
1st Bani Fm
Outer Fejas Shale Group
No recognised stratigraphy
UNIT III (3)
UNIT III (2)
(Hamra Quartzites)
UNIT II
In Tahouite Fm
El Gassi Shales
Vire de Mouflon
Tin Taradjelli Fm
Haouaz Fm
Ash Shabiyat Fm
Hassouana Fm
Hassouana Fm
Cambrian
Furongian
Glacially-related sediments
Unconformity defining the base of glacially-related sediments
Glacial Maximum Unconformity

Figure 2

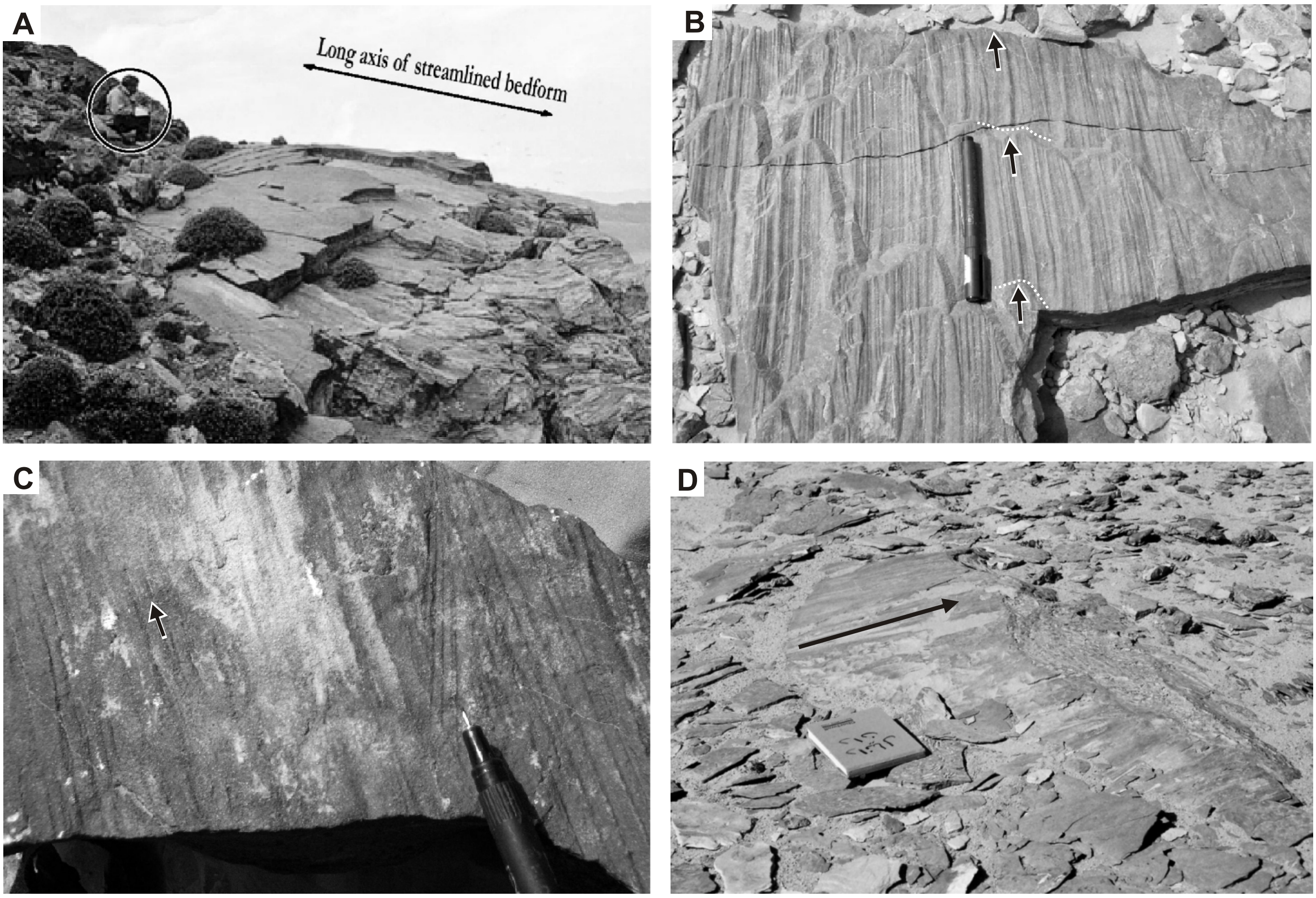


Figure 3

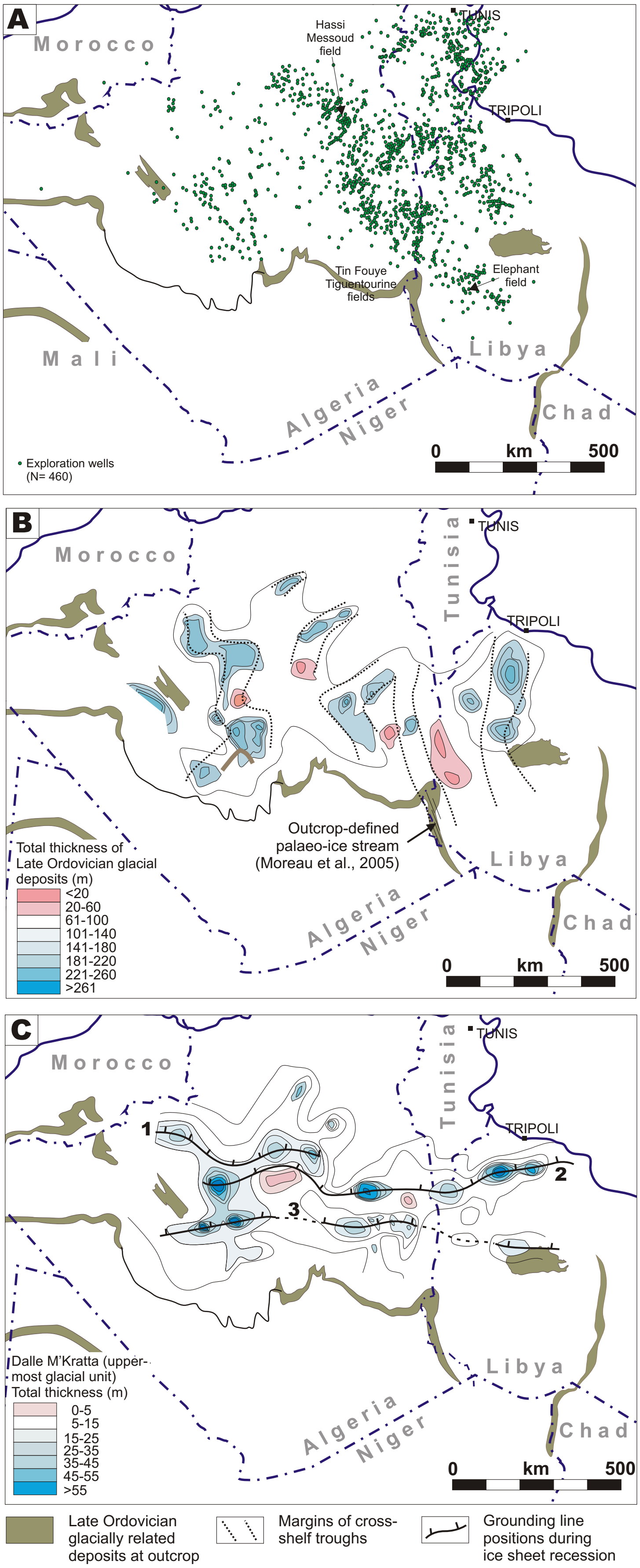

A
Morocco
Hassi Messoud field
TUNIS
TRIPOLI
Tin Fouye Tiguentourine fields
Elephant field
Mali
Libya
Algeria
Niger
Chad
0 km 500
Exploration wells (N= 460)
B
Morocco
Tunisia
TUNIS
TRIPOLI
Outcrop-defined palaeo-ice stream (Moreau et al., 2005)
Libya
Algeria
Niger
Chad
0 km 500
Total thickness of Late Ordovician glacial deposits (m)
<20
20-60
61-100
101-140
141-180
181-220
221-260
>261
C
Morocco
Tunisia
TUNIS
TRIPOLI
1
2
3
Libya
Algeria
Niger
Chad
0 km 500
Dalle M'Kratta (upper-most glacial unit) Total thickness (m)
0-5
5-15
15-25
25-35
35-45
45-55
>55
Late Ordovician glacially related deposits at outcrop
Margins of cross-shelf troughs
Grounding line positions during ice sheet recession

Figure 4

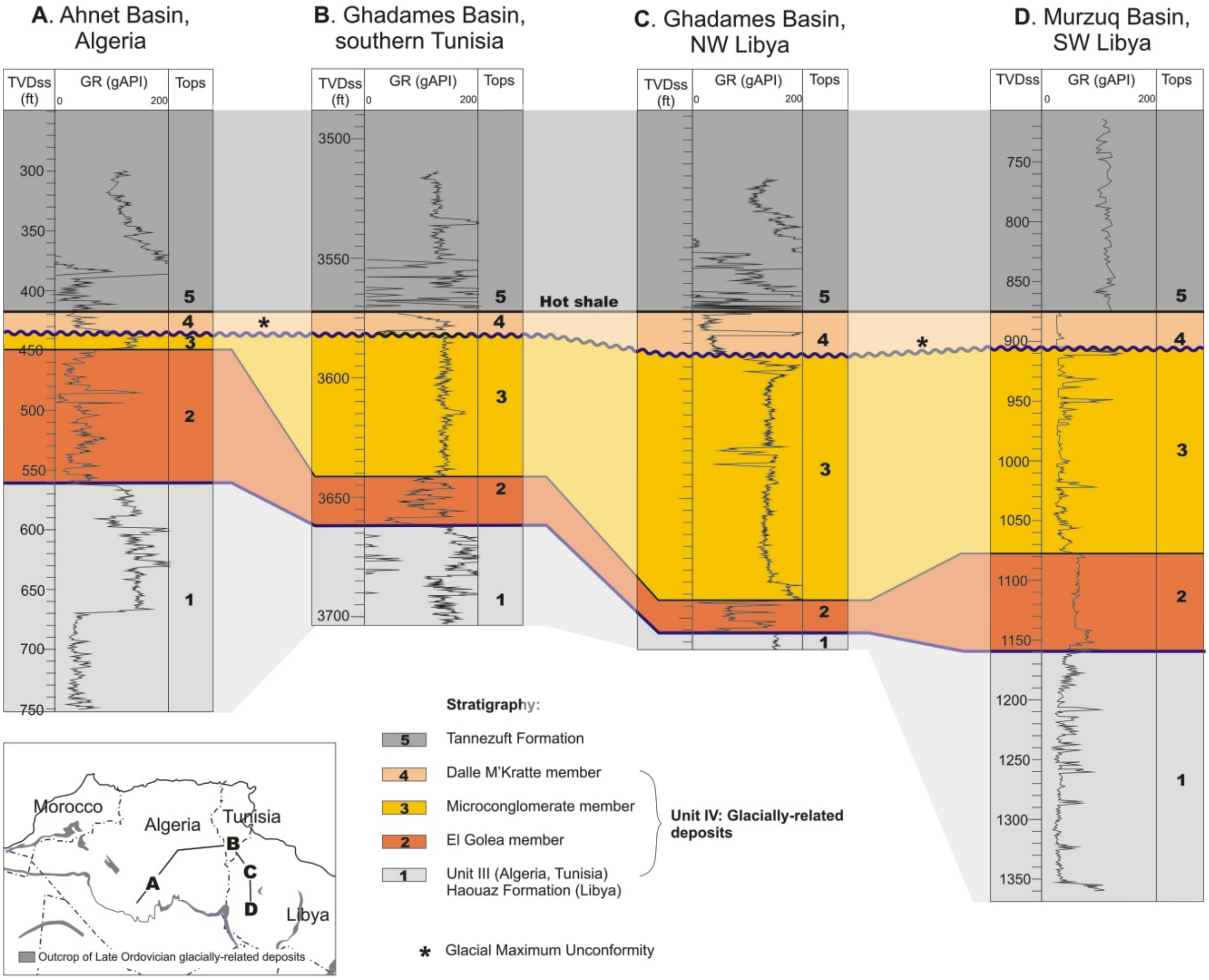

A. Ahnet Basin, Algeria
B. Ghadames Basin, southern Tunisia
C. Ghadames Basin, NW Libya
D. Murzuq Basin, SW Libya
TVDss (ft)
GR (gAPI)
0
200
Tops
300
350
400
450
500
550
600
650
700
750
3500
3550
3600
3650
3700
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
5
4
3
2
1
Hot shale
*
Stratigraphy:
5 Tannezuft Formation
4 Dalle M'Kratte member
3 Microconglomerate member
2 El Golea member
1 Unit III (Algeria, Tunisia) Haouaz Formation (Libya)
Unit IV: Glacially-related deposits
* Glacial Maximum Unconformity
Morocco
Algeria
Tunisia
Libya
A
B
C
D
Outcrop of Late Ordovician glacially-related deposits

Figure 5

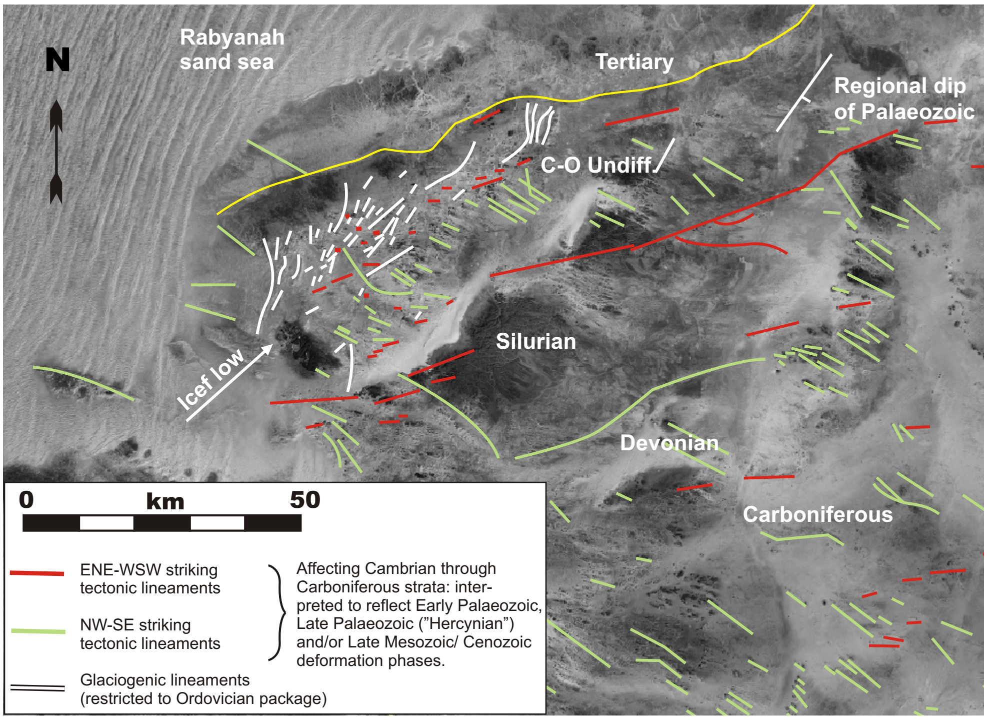

Rabyanah sand sea
N
Tertiary
Regional dip of Palaeozoic
C-O Undiff.
Silurian
Icef low
Devonian
Carboniferous
0 km 50
ENE-WSW striking tectonic lineaments
NW-SE striking tectonic lineaments
Affecting Cambrian through Carboniferous strata: interpreted to reflect Early Palaeozoic, Late Palaeozoic ("Hercynian") and/or Late Mesozoic/ Cenozoic deformation phases.
Glaciogenic lineaments (restricted to Ordovician package)

Figure 6

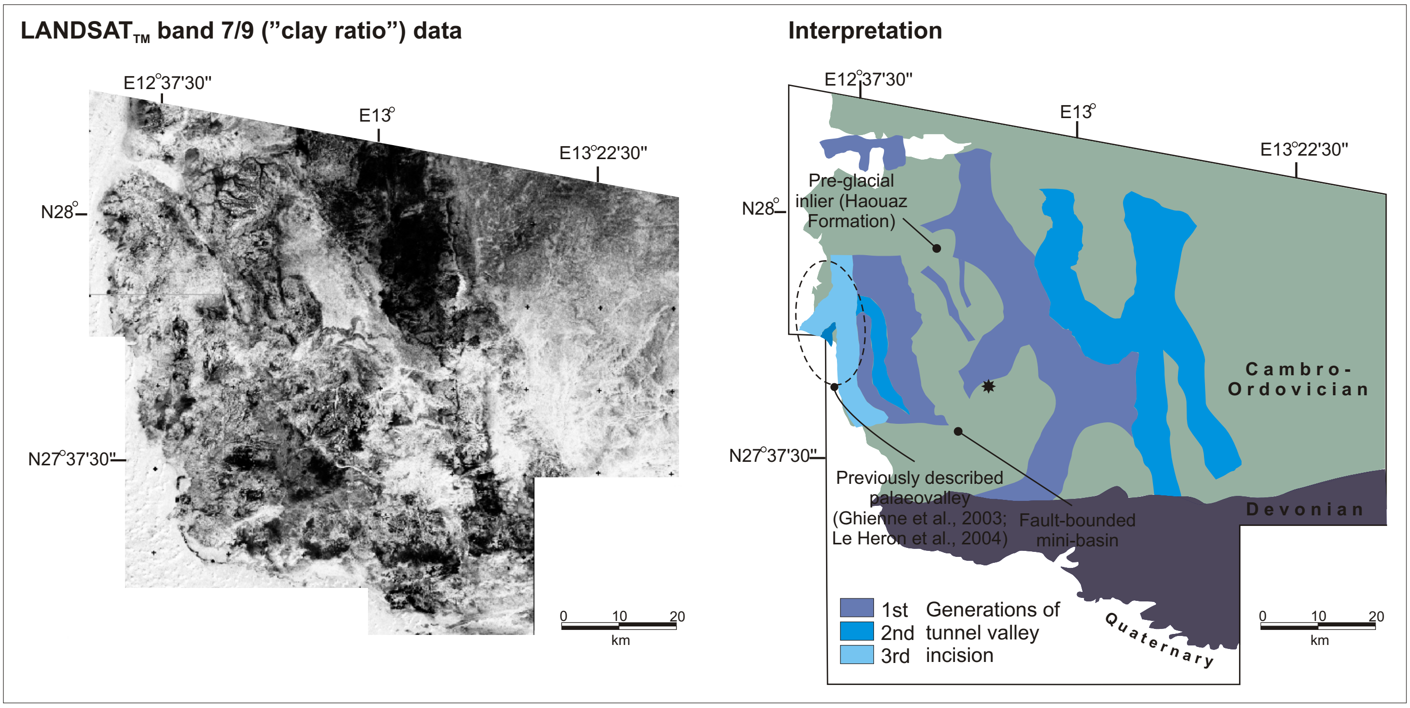
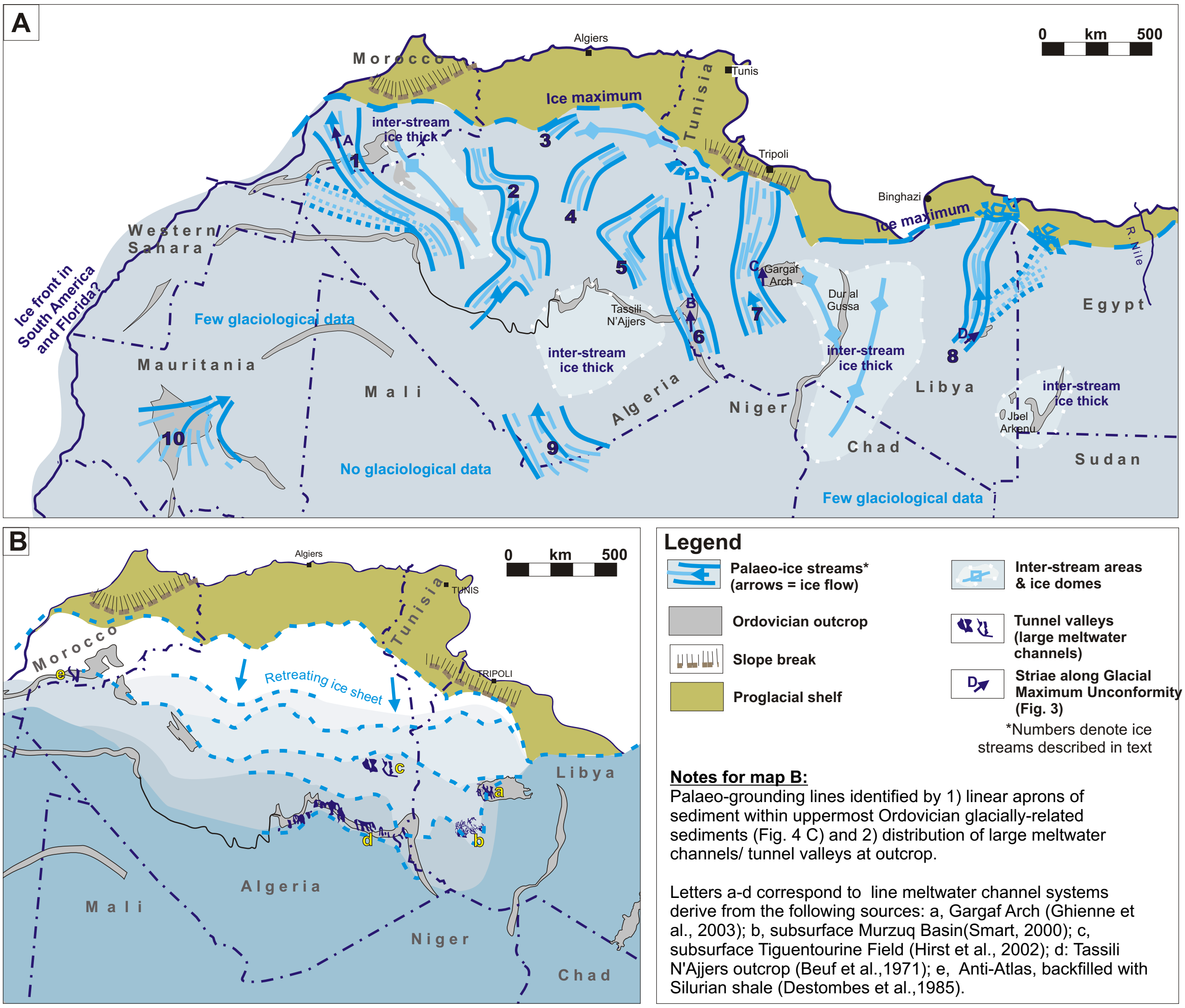

LANDSAT$_{TM}$ band 7/9 ("clay ratio") data
E12°37'30"
E13°
E13°22'30"
N28°
N27°37'30"
0 10 20
km
Interpretation
E12°37'30"
E13°
E13°22'30"
N28°
N27°37'30"
Pre-glacial inlier (Haouaz Formation)
Cambro-Ordovician
Devonian
Quaternary
Previously described palaeovalley (Ghienne et al., 2003; Le Heron et al., 2004)
Fault-bounded mini-basin
1st Generations of
2nd tunnel valley
3rd incision
0 10 20
km

Figure 7



Notes for map B:
Palaeo-grounding lines identified by 1) linear aprons of sediment within uppermost Ordovician glacially-related sediments (Fig. 4 C) and 2) distribution of large meltwater channels/ tunnel valleys at outcrop.

Letters a-d correspond to line meltwater channel systems derive from the following sources: a, Gargaf Arch (Ghienne et al., 2003); b, subsurface Murzuq Basin(Smart, 2000); c, subsurface Tiguentourine Field (Hirst et al., 2002); d: Tassili N'Ajjers outcrop (Beuf et al.,1971); e, Anti-Atlas, backfilled with Silurian shale (Destombes et al.,1985).

Figure 8