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ABSTRACT

The Late Ordovician (Hirnantian) glaciation is examined through the North Gondwana record. This domain extended from southern high palaeo-latitudes (southeastern Mauritania, Niger) to northern lower palaeo-latitudes (Morocco, Turkey) and covered a more than 4000 km-wide section perpendicular to ice-flow lines. A major mid-Hirnantian deglaciation event subdividing the Hirnantian glaciation in two first-order cycles is recognised. As best illustrated by the glacial record in western Libya, each cycle comprises 2–3 glacial phases separated by ice-front retreats several hundreds kilometres to the south. From ice-proximal to ice-distal regions, the number of glacial surfaces differentiates (i) a continental interior with post-glacial reworking of the glacial surfaces), (ii) a glaciated continental shelf that is subdivided into inner (1–2 surfaces), middle (2–5 surfaces) and outer (a single surface related to the glacial maximum) glaciated shelves, and (iii) the non-glaciated shelf. Ice-stream-generated glacial troughs, 50–200 km in width, cross-cut these domains. These troughs are zones of preferential glacial erosion and subsequent sediment accumulation. A glacial depositional sequence, bounded by two glacial erosion surfaces, records one glacial phase. The position either within or outside a glacial trough controls the stratigraphic architecture of a glacial sequence. Glaciomarine outwash diamictites are developed at or near the maximum position of the ice-front. During ice-sheet recession, and in an ice-stream-generated trough, a relatively thin sediment cover blankets the foredeepened erosion surface. An initial rapid ice-sheet withdrawal is inferred. Marine-terminating ice fronts then evolve later into more slowly retreating, land-terminating ice fronts. In adjacent inter-stream areas where a more gradual ice-sheet recession occurred, fluvio-glacial deposits prevailed. The progradation of a delta-shelf system, coeval with fluvial aggradation, that may be locally interrupted by a period of isostatic rebound, characterises the late glacial retreat to interglacial conditions. This model should facilitate the sequence stratigraphic interpretation of Late Ordovician glacial deposits and other ancient glacial successions.

Keywords Glacial record, Hirnantian, North Africa, ice stream, sequence stratigraphy.

INTRODUCTION

The Late Ordovician glacial record comprises extensive exposures distributed over the former North Gondwana cratonic platform. The size of this domain is >1500 km from south to north (in present-day coordinates), and extended from Mauritania to Arabia. Southern regions were positioned near the ice centres while the northern part of the platform was located at lower palaeo-latitudes (Fig. 1). During the 1960s–1980s, studies in Morocco (Destombes, 1968a, Hamoumi, 1988), Algeria (Beuf *et al.*, 1971), Libya (Klitzsch, 1981; Massa, 1988), Mauritania (Deynoux, 1980; 1985; Deynoux & Trompette, 1981) and Arabia (McLure, 1978; Vaslet, 1990; McGillivray & Husseini, 1992)

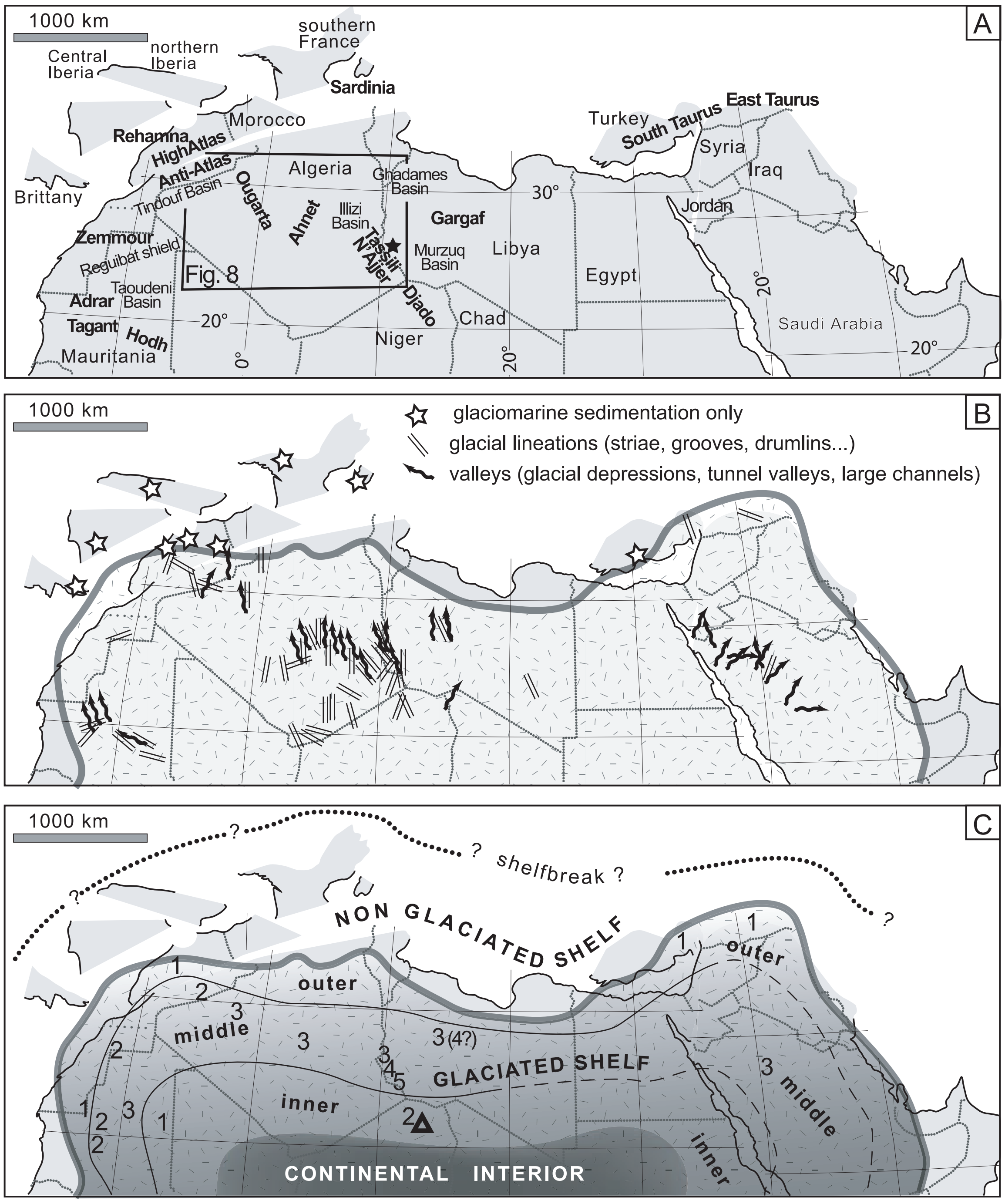

Fig. 1 The North Gondwana platform during the Hirnantian glacial event. (A) Main names cited in the text (see also Fig. 8). Names in bold indicates study areas comprising the data base. The black star locates the pre-glacial (Late Ordovician) trilobite-bearing lonestone found within the syn-glacial strata. (B) Location of areas that experienced grounded ice (glacial lineations and palaeovalleys) and those that have never been glaciated (glaciomarine sediments only). The outlined surface corresponds to the envelope of the ice fronts during the Hirnantian glacial maximum (modified from Deynoux & Ghienne, 2004). (C) Subdivisions of the glaciated platform in five domains (name in bold) based on the number of glacial surfaces preserved. The location of the shelfbreak (continental margin) is not known but was located to the north of the study area, beyond the maximum ice fronts. The Δ locates mid-Hirnantian graptolite-bearing marine facies in the Djado area, suggesting the marine limit of the associated deglaciation was located to the south of this point.

showed the extent, diversity and complexity of the syn-glacial strata. Renewed interest arose in the 1990s, when oil companies recognised the association of syn-glacial strata (reservoir rocks) with lower Silurian shales (source rocks) as one of the most significant plays in the North African Lower Palaeozoic succession (Lüning *et al*., 2000). Recent work has included detailed field and subsurface studies conducted in Mauritania (Ghienne, 1998; Ghienne & Deynoux, 1998; Ghienne, 2003), Morocco (Ouanaimi, 1998; Sutcliffe *et al*., 2000, 2001; Le Heron *et al*., in press, a), Algeria (Hirst *et al*., 2002; Eschard *et al*., 2005), Niger (Denis *et al*., submitted), Libya (McDougall & Martin, 2000; Smart, 2000; Ghienne *et al*., 2003; Le Heron *et al*., 2004; El-ghali, 2005; Moreau, 2005), Jordan (Abed *et al*., 1993; Powell *et al*., 1994; Turner *et al*., 2005), Saudi Arabia (Senalp & Al-Laboun, 2000) and the Horn of Africa (Ethiopia and Eritrea, Kumpulainen, 2005). In addition to these areas, studies have also been undertaken around the northern Gondwana periphery to better provide an overall understanding of the glacial record as a whole, e.g. in Sardinia (Leone *et al*., 1995; Ghienne *et al*., 2000) and in Turkey (Monod *et al*., 2003).

This paper proposes a large-scale reconstruction of the North Gondwana platform in present-day North and West Africa during the Late Ordovician glaciation. The number of glacial advance-retreat events recorded from the near-polar ice centre to lower palaeo-latitudes, and the presence or absence of ice-stream tracks, are used to subdivide the platform into a number of domains characterised by a specific palaeo-glaciological evolution, particularly subglacial processes, stratigraphic architecture and depositional environments. Finally, a conceptual glacial depositional sequence that could be expected within a typical glacial advance-retreat event is depicted. Such a sequence will form the basis for a more robust stratigraphic analysis of the Late Ordovician glacial record and more generally for ancient glacial successions.

PRE-GLACIAL SETTING

No evidence for Late Ordovician glacial sediments older than Hirnantian (Fig. 2) has thus far been found in North or West Africa. However, this does not preclude the possibility that glaciers grew

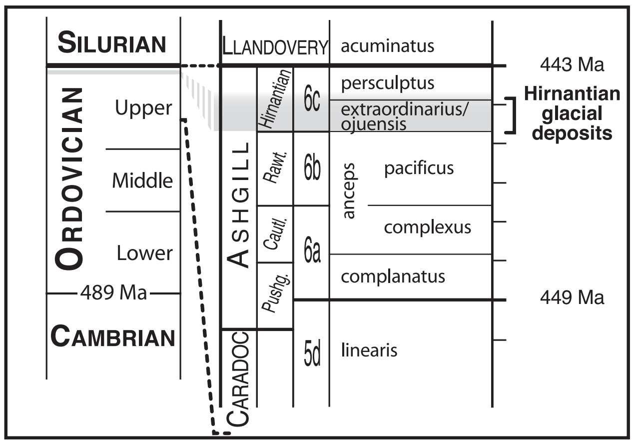

Fig. 2 Late Ordovician stratigraphic chart modified from Webby *et al.* (2004) showing the time range corresponding to Hirnantian glacial event.

elsewhere on Gondwana both before and after the Hirnantian. Saltzman & Young (2005) proposed a glacio-eustatic lowstand during the early Late Ordovician (Fig. 2) and, in South America, glacial deposits are recognized in the Silurian (Grahn & Caputo, 1992; Caputo, 1998). Ghienne (2003) suggested that the Hirnantian simply reflected a continent-wide ice maximum, during which ice sheets reached the North and West African sedimentary basins where their glacial sedimentary record could be preserved. In this paper, preglacial time is defined as the period preceding the Hirnantian, i.e. the Cambrian and Ordovician, including the main part of the Ashgill with the exception of the Hirnantian (Fig. 2). Le Heron *et al.* (2005) published a schematic lithostratigraphic summary of Hirnantian glaciogenic rocks across Africa and Arabia. A regional correlation scheme, including the names of the main preglacial and glacial formations in this huge region, is contained therein.

Geological setting

Late Ordovician glacial deposits rest on a Cambrian to Ordovician, clastic-dominated succession that has an off-shelf gradient towards the NNW (Boote *et al*., 1998; Carr, 2002). These sediments progressively buried palaeorelief forms associated with both the late Neoproterozoic Panafrican Orogeny and Cambrian post-orogenic collapse/strike-slip basins. Early Ordovician tectonic activity uplifted large areas such as the Taoudeni Basin and Reguibat shield, Central Algeria, Ahnet, Eastern Tassili and southern Taurus (e.g. Beuf *et al.*, 1971; Crossley & McDougall, 1998) (for location names, see Fig. 1A), resulting in deep erosion of earlier strata or reduced sedimentation on the highs during the Middle to Late Ordovician. Continuous sedimentation occurred in subsiding areas, e.g. the Tindouf Basin and Ougarta in Algeria, Ghadames Basin in Libya, eastern Taurus in Turkey. Here, a complete Ordovician succession is preserved (e.g. Boote *et al.*, 1998). High eustatic sea level in the Late Ordovician (Ross & Ross, 1992) resulted in the flooding of previously uplifted areas (e.g. easternmost Turkey, Dean & Monod, 1990). In Algeria, shallow-marine Ashgill facies are known in the south of the Ougarta Range (Legrand, 1985) and Ashgill carbonates are identified in drill holes as far south as the Illizi Basin (e.g. *Oued Ahara* borehole, unpublished data). In SW Libya, some dropstones in glaciomarine facies include trilobites (located in Fig. 1A), yielding an age close to the Caradoc-Ashgill boundary (W.T. Dean, pers. comm., 2003). These fauna, which probably derived from higher southern polar palaeolatitudes, imply a southwards-directed Late Ordovician transgression, which penetrated far south onto the platform. Transgressive deposits have been difficult to recognise owing to glacially related erosion, but are herein considered as key evidence for the flooding of the main part of the North Gondwana platform prior to the Hirnantian glacial event.

Subglacial substrate

As a consequence of this pre-glacial flooding, it is clear that a large part of the glaciated areas should have been characterised by subglacial soft-sediment conditions. If Ashgill siliciclastics were not lithified in Hirnantian time, it is surprising that much older deposits were also very poorly lithified at that time, as suggested by three sets of observations: sand injections, cross-sections of palaeovalleys and a sand-dominated glacial record. Firstly, sand injections in the form of pipes or undulating dykes occur beneath glacial erosion surfaces cut in sediments as old as Early Ordovician (>30 Ma before the Hirnantian glacial event) in the western Murzuq Basin. Secondly, cross-sections of palaeovalleys, either subglacially or fluvially formed, show low-angle margins, with slopes typically in the 1–10° range. These gradients are more compatible with erosion in soft material than in consolidated sediments. In addition, in the Ahnet area (south Algeria, Fig. 1A), palaeovalleys have a flat bottom coinciding with the basal unconformity of the Cambrian-Ordovician succession above the slightly metamorphosed late Neoproterozoic shales and sandstones. This suggests a clear contrast between the underlying metamorphosed basement and the overlying non- to poorly lithified sandy succession. Thirdly, the Late Ordovician glacial record is sand-dominated, with subordinate finer-grained, silt-dominated units. Glacial conglomerates contain clasts from Precambrian basement lithologies (granites, metasediments e.g. quartzite), but not from the underlying Cambro-Ordovician sandstones (Oujeft sandstones in Mauritania, Hamra Formation in Algeria, Ash Shabiyat or Haouaz formations in Libya), which can be recognised by abundant *Scolithos* burrows. Notwithstanding small inliers of crystalline basement or rare carbonate-cemented Ordovician strata, the evidence presented above suggests that Late Ordovician ice sheets grew and decayed on largely unconsolidated substrates.

RECOGNITION OF GLACIAL EROSION SURFACES

In the sand-dominated setting of the Late Ordovician glacial record, depths of glacial erosion range from 10 to 500 m (maximum erosion depths in Saudi Arabia, e.g. McGillivray & Husseini, 1992), and widths of glacially-cut depressions range from 10 m to >100 km. Erosional features form lineations, ovoid to elongated spoon-shaped depressions, straight to slightly sinuous channels and palaeovalleys, or basin-scale incisions. Criteria used to distinguish glacial erosion surfaces from fluvial or transgressive wave-ravinement surfaces include: large-scale morphologies, glaciotectonic structures and specific depositional features such as esker structures.

Depths of erosion greater than 100 m normally point towards subglacial processes (Fig. 3). If the erosion feature is relatively narrow (<5 km), tunnel valleys are inferred (Ghienne & Deynoux, 1998; Hirst *et al.*, 2002; Le Heron *et al.*, 2004)

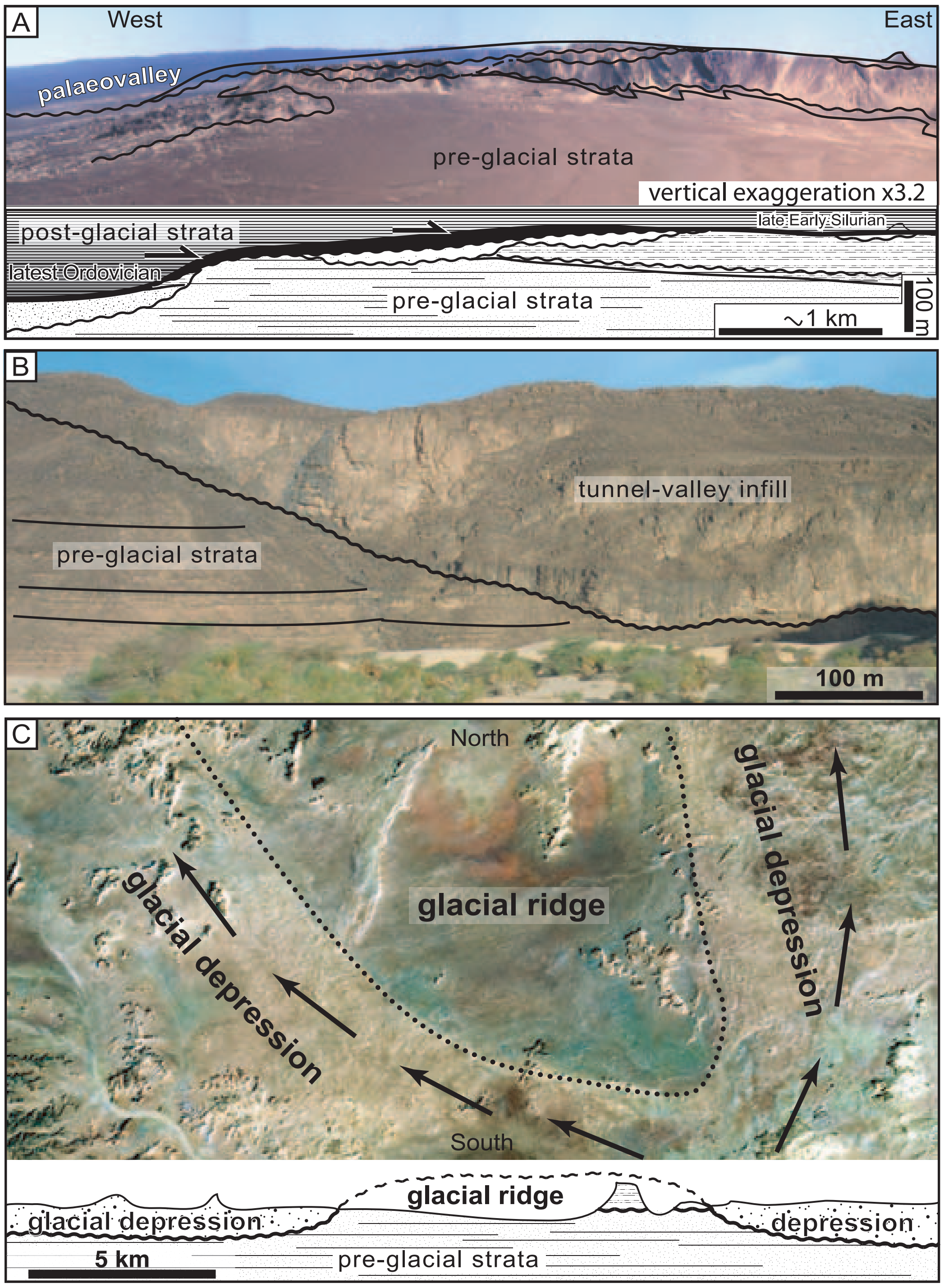

Fig. 3 Diversity in glacial erosion surfaces. (A) A wide palaeodepression within the Eastern Tassili n'Ajjer glacial trough (Ghat area, western Murzuq Basin, Libya) (view with vertical exaggeration, interpretation from field sections). Bounding surfaces of syn-glacial depositional units are gently dipping glacial erosion surfaces (wavy lines). The upper unit (in black) mainly represents a late to post glacial transgressive wedge, that reworked the latest glacial erosion surface (see also Fig. 5). The latest glacial palaeodepression was underfilled and post-glacial sediments progressively onlapped on the residual palaeotopography from the latest Ordovician to the Silurian (see also Fig. 9B). (B) An overfilled tunnel valley characterised by a narrow, steep-sided erosion surface (Adrar, Mauritania, modified from Ghienne & Deynoux, 1998). (C) Landsat image showing a glacial ridge (inverted topography, present-day lower area) with two adjacent palaeovalley-like depressions into a glacial trough (Tihemboka Arch, western Murzuq Basin).

(Fig. 3B). Conversely, basin-scale subglacial scours are inferred if the width is >50 km. In other circumstances, overdeepenings or the occurrence of erosional troughs that narrow in planform also suggest subglacial processes (Beuf *et al.*, 1971). However, the most reliable subglacial erosion surfaces are those associated with subglacial lineations. Subglacial lineations (mega-scale glacial lineations, flow-parallel and attenuated drumlins) are characterised by parallel bedforms, <100 m to >10 km in length, 1–30 m in height, with high elongation ratios (>10) (Moreau *et al.*, 2005) (Fig. 4 A, B & C). Most of them are erosional features cored by older sediments. Only the sediments directly beneath the sediment-ice interface are affected by intense glaciotectonic deformation (Deynoux & Ghienne, 2004, 2005).

The best outcrop-scale evidence for glacially cut erosion surfaces is preserved in the record of deformation structures formed beneath them as a combination of shear-induced and gravitational deformation structures within the sediment column. Glaciotectonic deformation includes all the deformation that can be linked with the subglacial shear zone. Structures or deposits resulting from processes at the ice-sediment interface (striae, grooves, lodgement till) are generally poorly preserved in the Late Ordovician glacial record (Deynoux & Ghienne, 2005; Le Heron *et al.*, 2005). Intraformational deformation structures are more readily preserved and are therefore most commonly observed. Soft-sediment intraformational striated surfaces (Fig. 4F) were formed at several metres in depth beneath the ice-sediment interface (Deynoux & Ghienne, 2004; Le Heron *et al.*, 2005). They are typically associated with intraformational grooves (Fig. 4D), drag and sheath folds (Fig. 4E), Riedel shears and water-escape structures. Intraformational striated surfaces are particularly well developed beneath mega-scale glacial lineations with which they are parallel. Deformation associated with glacial surfaces includes chaotic sandstone units ('grès bousculés' of Deynoux, 1980 and Deynoux & Ghienne, 2004), large-scale loading structures such as domes, cylindrical folds and sediment diapirs (Le Heron *et al.*, 2005), overturned fold and thrust-and-fold belts, 5–50 m high. However, the last may also occur in association with proglacial glaciotectonic processes, such as broadly arcuate belts, or with slide-generated structures.

HIRNANTIAN GLACIES CYCLES AND PHASES

It is established that the so-called Upper Ordovician syn-glacial strata in West and North Africa are, in fact, strictly Hirnantian in age (Destombes, 1968b; Destombes *et al.*, 1985; Paris *et al.*, 1995, 1998; Underwood *et al.*, 1998; Sutcliffe *et al.*, 2000). They are also time-equivalent with a significant isotopic excursion of global extent (Brenchley *et al.*, 2003). The Hirnantian is generally considered to have lasted less than 1 Ma, but the new Ordovician timescale suggests that it could have been as long as 2 Ma (Webby *et al.*, 2004) (Fig. 2). Within this time-slice, a number of glacial advances and subsequent retreats occurred (Ghienne, 2003). At present, the number, as well as the significance and extent, of each of these Hirnantian glacial events is not known, but is the subject of ongoing work. However, the comparison of the stratigraphic architecture of syn-glacial successions from distinct areas gives noteworthy temporal relationships.

Areas closest to the ice centre

Glacial erosion in the areas closest to the ice centre has resulted in reworking of pre-glacial sediments, and during later glacial phases, cannibalisation of the earlier glacial sequences. In these regions, geological mapping covering a minimum representative area of about 1000 km^2 has revealed several, laterally juxtaposed glacial erosion surfaces (Fig. 5) that generate a complex stratigraphic architecture (Ghienne, 2003; Ghienne *et al.*, 2003; Moreau, 2005).

Depositional sequences are bounded by subglacially-cut unconformities or correlative subaerial unconformities. These surfaces were formed regionally during major phases of glacial advance. Subaerial exposure commonly occurred beyond the ice front. Glacial depositional sequences, comprising a range of alluvial plain to shelf sediments (see below), were deposited on top of these surfaces during ice recession towards the south, and during ensuing interglacials. Four to five depositional sequences occur in Mauritania (Ghienne, 2003), Libya (Gargaf Uplift: Deynoux *et al.*, 2000; Le Heron, 2004; Ghienne *et al.*, 2003; western Murzuq Basin: Moreau, 2005; Moreau *et al.*, 2005; Le Heron *et al.*, in press, b) and Jordan (Turner *et al.*, 2005).

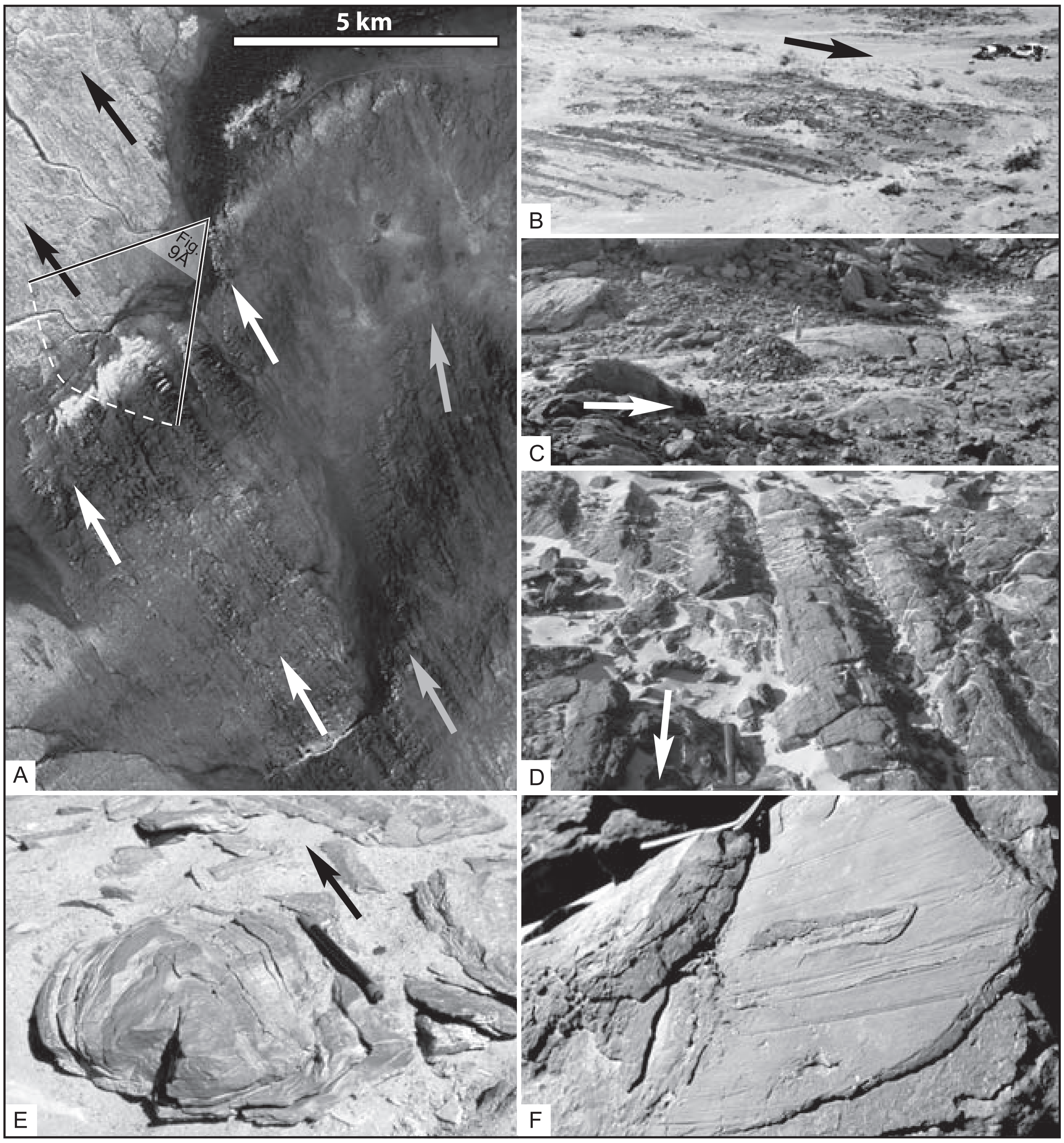

Fig. 4 Multi-scale glacial lineations associated with glacial erosion surfaces; all structures are in syn-glacial sands. Arrows show ice-flow orientation. (A) Landsat image showing three sets of ice-stream-generated mega-scale glacial lineations (Eastern Tassili n'Ajjer, Ghat area, western Murzuq Basin, Libya). (B) Glacial lineations (Tagant, Mauritania, cars for scale). (C) Asymmetrical glacial alignments shaped as a roche moutonnée (western Hodh, Mauritania, person for scale). (D) Grooves preserved within an intraformational subglacial shear zone (Ghat area, western Murzuq Basin, hammer for scale). (E) Sheath folds, the elongation of which is parallel to the shear orientation (Djado, Niger, pencil for scale). (F) Intraformational striae and ploughing structure in sandstones (Tihemboka Arch, western Murzuq Basin).

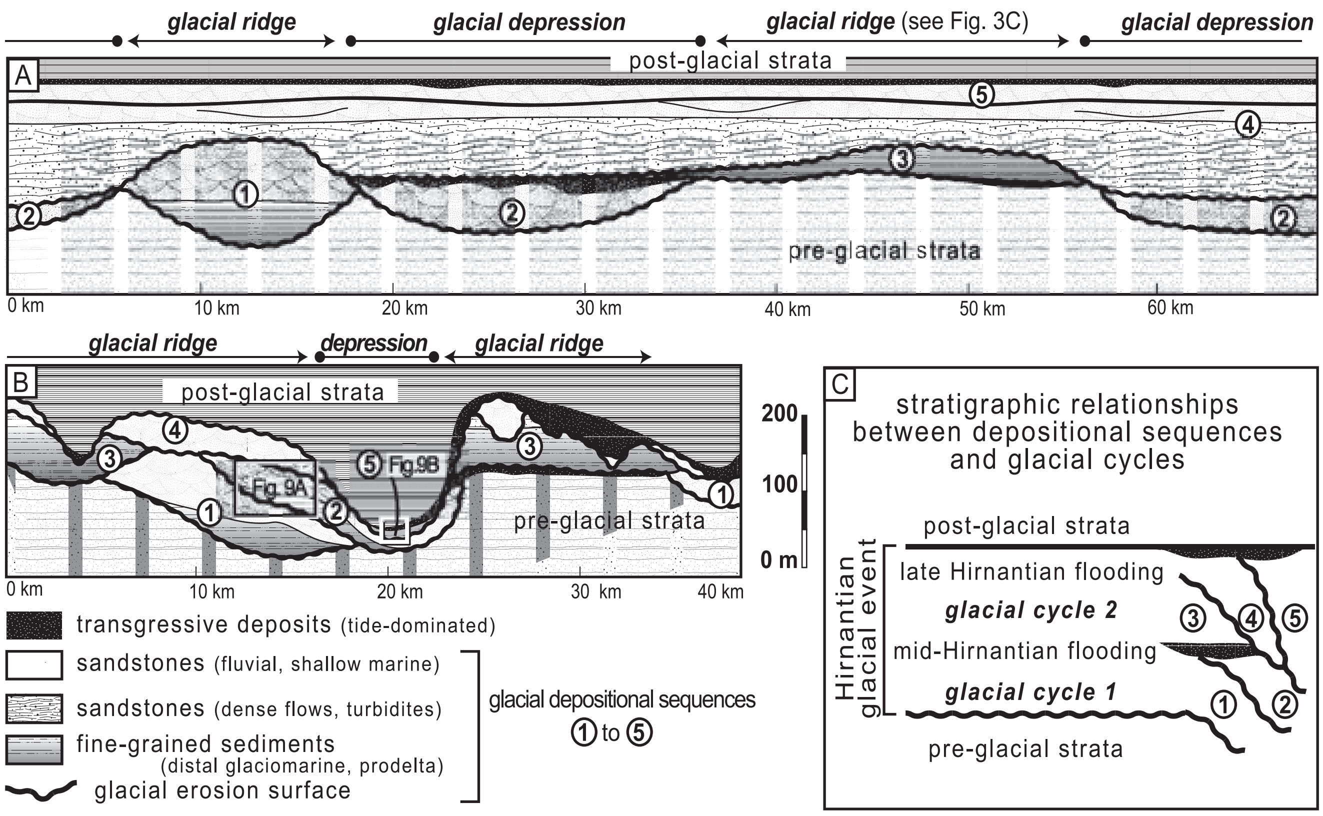

Fig. 5 Stratigraphic architecture of the syn-glacial strata in the western Murzuq Basin, Libya (profile location in Fig. 8A). Syn-glacial strata fill in palaeovalley-like depressions separated by glacial ridges. Indicated depressions and ridges were formed during the glacial maximum (fourth glacial phase). See text for more details about depositional facies. (A) Tihemboka Arch (26°10′N). (B) Eastern Tassili n'Ajjer, Ghat area (25°N). (C) Stratigraphic relationships and subdivision of the Hirnantian succession in two glacial cycles separated by the mid-Hirnantian deglaciation event, and five glacial phases of glacial advance and subsequent retreat.

In Mauritania and Libya, the most extensive ice sheet (e.g. phase 3 of Ghienne, 2003 in Mauritania; phase 4 of Moreau *et al.*, 2005 in western Libya) occurred after a major transgressive event characterised by the deposition of a tide-dominated succession (Fig. 5). This transgression is interpreted as a major phase of deglaciation within the Hirnantian.

Ice sheet margins

In ice-marginal areas, the effects of glacial erosion are less pronounced. Bounding surfaces of successive glacial depositional sequences are frequently preserved within a single vertical section (e.g. Monod *et al.*, 2003). A number of regressive-transgressive cycles are observed and interpreted in terms of glacioeustatically-driven rhythms (Leone *et al.*, 1995). These areas also preserve evidence of three to five glacial events, as best exemplified by the glacial record of Morocco (e.g. Le Heron *et al.*, in press, a) where the Hirnantian strata can be divided into two glacial successions separated by a major transgression (Fig. 6). This major transgression is interpreted to correlate with the deglaciation event associated with tidal deposits in areas closest to the ice centres. Furthermore, in Turkey, evidence for subglacial processes is found at only one stratigraphic interval (Monod *et al.*, 2003) above well-developed transgressive deposits. These regionally correlatable features indicate that a key interglacial transgression was followed by the most widespread and significant phase of ice sheet advance across North Gondwana.

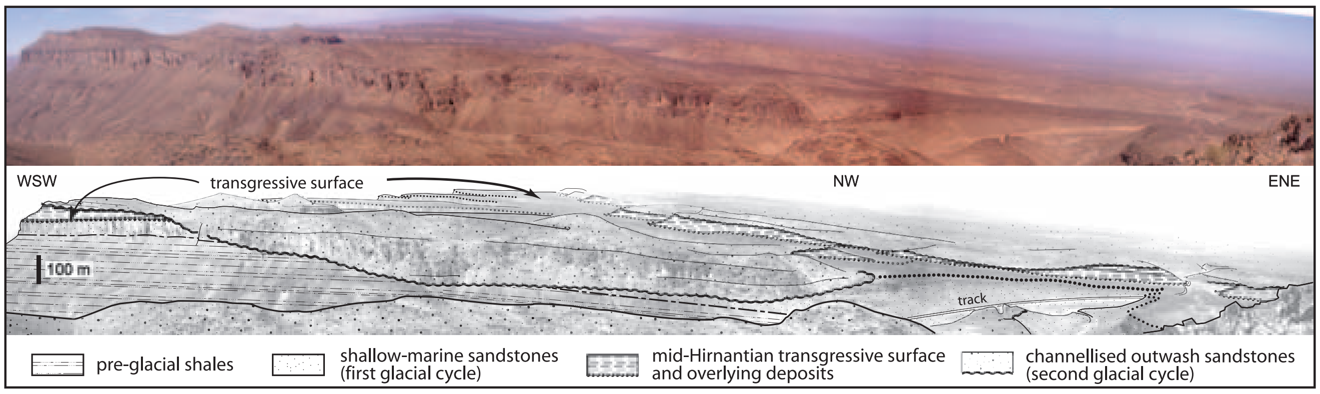

Fig. 6 The mid-Hirnantian deglaciation event in the Anti-Atlas (southern Morocco, northeast of Zagora). The glacially-related succession that mainly comprises shallow-marine and channellised outwash sandstones in contrast with pre-glacial shale-dominated sediments, is divided into two sedimentary wedges, separated by a major transgressive surface related to the mid-Hirnantian event. The panoramic view is c. 4 km in width in the foreground.

The Hirnantian glacial event: a multiphase glaciation

As glacial depositional sequences record major ice advances and retreats, they provide excellent potential for regional allostratigraphic correlation. The present understanding is that successive Hirnantian glacial events occurred within a single graptolite or chitinozoa biozone (*extraordinarius* and *elongata* Biozones respectively) (Paris *et al.*, 1995). Because no biostratigraphic subdivision is currently available, the best chronostratigraphic marker is probably the mid-Hirnantian transgression detailed above. This event of great amplitude is recorded as far south as the Djado area (northern Niger, location in Fig. 1C). Here, fauna-rich marine shales, originally considered as pre-Hirnantian strata (Legrand, 1993), and now attributed to the *extraordinarius* Biozone (P. Storch, pers. comm., 2004) were deposited between two major glacial erosion surfaces (Denis *et al.*, submitted). These data imply that the transgression advanced deep into North Africa at least within erosional troughs. This transgression is also recognised in non-glaciated area such as Sardinia (e.g. Storch & Leone, 2003).

This transgressive interval, coeval with a major deglaciation event, subdivides the Hirnantian into two first-order glacial cycles (Sutcliffe *et al.*, 2000) (Fig. 5C). Each cycle includes a limited number of glacial phases, the correlation of which throughout the North Gondwana is at present more controversial. At least two glacial phases are recognised within both the first (early Hirnantian) and the second (late Hirnantian) glacial cycles. Major ice recessions (~500 km) occurred between two successive phases, to compare with the mid-Hirnantian deglaciation associated with ice-front retreats >1000 km, possibly much more (Moreau, 2005).

Ice sheet size: the glacial maximum

Accurate reconstruction of pre-Pleistocene ice sheets, and the demonstration of synchronous, continent-wide ice fronts, is not straightforward. The size of both Permo-Carboniferous (Eyles *et al.*, 2003) and Neoproterozoic (Eyles & Januszack, 2004) ice sheets has recently been challenged, because their size may have been affected by enhanced polar wander or rates of rift propagation. Even assuming a maximum duration for the Hirnantian of 2 Ma (Webby *et al.*, 2004), and although the opening of the Palaeotethys (rifting of the Hun superterrane of Stampfli & Borel, 2002) occurred in Late Ordovician time, we argue here that these processes have not had a substantial impact on Hirnantian ice-sheet reconstructions. Synchronous growth of ice sheets, at least during the most protracted phase of glaciation, was likely from Mauritania to Turkey. This stands in contrast to Permo-Carboniferous centres of glaciation, which waxed and waned asynchronously over an interval of c. 55 Ma (Eyles *et al.*, 2003).

A reconstruction of the maximum size of the West Gondwana ice sheets, based on the occurrence of a regionally correlatable glacial erosion surface

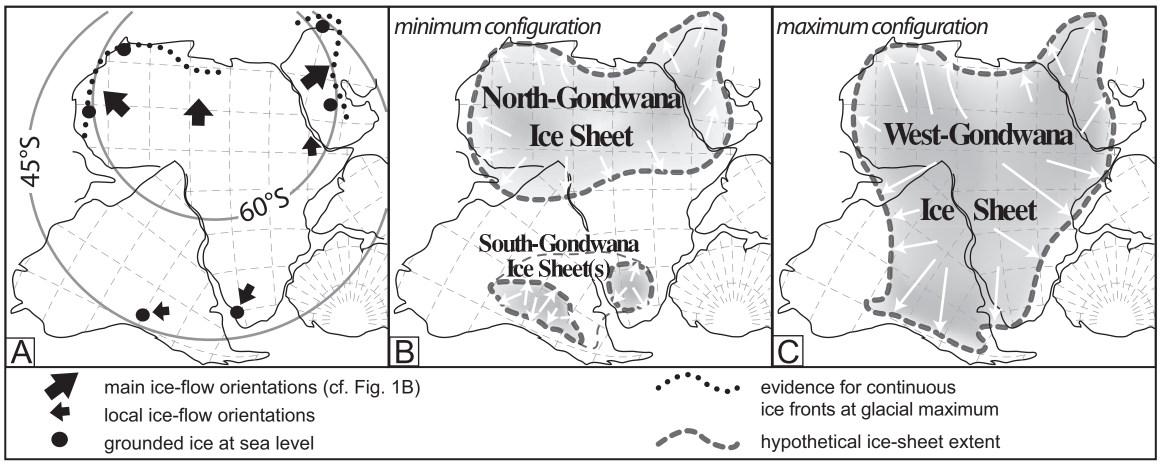

Fig. 7 The extent of the Late Ordovician glaciation. (A) Locations of identified subglacial deformation zones in the more distant areas from the ice centres. On the North Gondwana platform, these are from west to east: Tagant (western Mauritania), Rehamna (northern Morocco), Eastern Taurus (south-eastern Turkey) and Central Arabia. These four locations were glacierised at the Hirnantian glacial maximum, implying that grounded ice occurred at sea level close to the 60°S parallel. To include glacial successions from South America and South Africa (potentially of Hirnantian age) implies grounded ice occurring at sea level within the 45°S parallel. (B) The minimum-sized Hirnantian ice sheets, with a large North Gondwana Ice Sheet, and possibly penecontemporaneous subordinate ice centres in South America (linked with a pre-cordilleran setting) and South Africa, which may have coalesced together. (C) The maximum-sized Hirnantian West-Gondwana Ice Sheet, assuming fully coalescent synchronous glaciers.

following the major mid-Hirnantian interglacial, is presented in Fig. 7A. Ice-front migrations from place-to-place during the same glacial event (e.g. Boulton & Clark, 1990; Boulton *et al.*, 2001) means that ice fronts at the glacial maximum would have been best represented as an envelope rather than a continuous line. Late Ordovician ice fronts were continuous from Mauritania to western Libya. The existence of a continuous ice front between western Libya and Arabia is controversial, but likely at least during the most protracted phase of glaciation, which also affected southern Turkey (Monod *et al.*, 2003). Although Upper Ordovician glacial successions are also known in South Africa (e.g. Hiller, 1992) and South America (Caputo, 1998; Diaz-Martinez *et al.*, 2001), dating uncertainty still exists for the related glacial successions (e.g. Boucot *et al.*, 2003 for the South African example).

At the Hirnantian glacial maximum, the sedimentary record supports the concept of a continuous ice sheet across North Africa that possibly extended into Arabia, with WNW-to-NE oriented ice flow directions (Figs. 1B & 7A). A minimum-sized ice sheet at the glacial maximum had to incorporate a roughly symmetrical ice-front line, depicting a North Gondwana Ice Sheet (the Saharan Ice Sheet of Young *et al.*, 2004), characterised by southward-flowing ice in sub-Saharan Africa (Fig. 7B). As ice flowed from south to north in Eritrea and Ethiopia (Kumpulainen, 2005; Fig. 7A), this minimum-sized ice sheet must have reached Central Africa. A maximum-sized Hirnantian ice sheet may, in addition, have overridden South America and South Africa where subglacial deformation zones have been also identified (Blignault, 1981; Martinez, 1998; Le Heron *et al.*, 2004; Deynoux & Ghienne, 2005) (Fig. 7C). The maximum-sized ice-sheet scenario envisages a huge West Gondwana Ice Sheet (Vaslet, 1990; Sutcliffe *et al.*, 2000; Ghienne, 2003) centred above Central Africa where no Upper Ordovician sediments crop out.

THE NORTH GONDWANA PLATFORM DURING THE HIRNANTIAN

This section proposes the subdivision of the North Gondwana platform, from the ice centre to lower palaeolatitudes, into several palaeogeographic domains based on the number of glacial erosion surfaces preserved. A second palaeogeographical scheme is then presented, providing a subdivision of the ice sheet perpendicular to ice-flow lines based on the occurrence of ice-stream-generated glacial troughs.

Palaeogeographic domains of the glaciated shelf

The number of glacial erosion surfaces distributed regionally define five proximal-to-distal palaeogeographic domains in North Gondwana (Fig. 1C). The continental interior corresponds to a domain that was not deglaciated until the close of the Hirnantian. The dominance of subglacial and post-glacial erosion in these areas means that the glacial record in this domain is limited and restricted to small-scale, fault-bounded intracontinental basins (Konaté *et al.*, 2003). It is conceivable that the continental interior may have been glacierised both prior and after the Hirnantian glaciation.

The inner, middle and outer domains of the glaciated continental shelf were subject to multiple phases of ice-sheet growth and decay. On the inner glaciated shelf, typified by the Niger succession (Denis *et al.*, submitted), two glacial erosion surfaces and associated overlying sequences are recorded, and, are separated by the mid-Hirnantian graptolitic shales (see above). This domain was deglaciated during the mid-Hirnantian, but remained glacierised during phases of ice-front retreat within each of the two first-order glacial cycles. Glacio-isostacy should have played a significant role in developing thestratigraphic architecture. The middle glaciated shelf corresponds to the area subjected to from 2 to 5, possibly more, phases of subglacial erosion. In this zone, encompassing the well-known successions in Mauritania, Algeria and Libya, both glacio-eustatic and glacio-isostatic processes were operative, and the most complete record of multiple advance and retreat events of the Hirnantian ice sheets is preserved. The outer glaciated shelf, including northern Morocco and Turkey, was glacierised only during the most protracted advance phase of the Hirnantian glacial maximum (Figs. 1C & 7A). Glacio-eustacy was probably more important than glacio-isostacy in these regions (e.g. Boulton, 1990). The shelf areas beyond the outer ice-sheet limit comprise a sedimentary record controlled solely by glacio-eustacy. In these areas, distal glaciomarine sediments are locally preserved (Fig. 1B; e.g. Sardinia, Brittany, Bohemia: Robardet & Doré, 1988 and references therein; western Taurus, Turkey: Monod *et al.*, 2003; northernmost Morocco: Le Heron *et al.*, in press).

Ice sheet configuration: the case study of Algeria

Legrand (1974, 1985) published a map of Algeria showing well-defined, 50–200 km wide, so-called sediment 'thicks' of 'upper Caradoc-Ashgill-lower Silurian' strata, separated by 150 to 300 km wide sediment 'thins'. This map is reproduced in Fig. 8A including data collected by the authors from Morocco (Anti-Atlas, Tamlelt area), Ougarta (NW Algeria) and Tassili n'Ajjer (western Murzuq Basin, Libya). It excludes smaller-scale variations, such as steep contour gradients over <10 km that could be attributed to tunnel valley incisions or fluvial incised valleys. Recent biostratigraphic work confirms that the strata outlined by Legrand (1985) are well constrained to Hirnantian syn-glacial strata (Paris *et al.*, 1995; Oulebsir & Paris, 1995; Vecoli & Le Hérissé, 2004).

It seems likely that areas with thick Hirnantian successions outline depositional lows and areas typified by thin successions designate palaeo-highs. North of the Hoggar, the data reviewed above are interpreted as a series of Late Ordovician glacially formed erosional troughs separated by plateaux or 'interfluves'. Four glacial troughs are identified across the Algerian middle glaciated shelf, from Ahnet to Tassili n'Ajjer, where the glaciogenic sediments reach >300 m in thickness. It is stressed that the isopach maps may mask the amalgamation of multiple glacial cycles in the stratigraphic record. In the interfluves, with the exception of deep but narrow palaeovalleys, the contact between pre-glacial and syn-glacial strata is stratigraphically higher.

The glacial troughs are very difficult to identify in the field as they are comparable in scale to tectonic structures (e.g. zones of preferential subsidence or post-depositional lithospheric bending). However, the easternmost glacial trough on Fig. 7A is the northward extension of a glacial trough already described in western Libya (Moreau *et al.*, 2005). This well-defined trough is >200 km in length and >80 km in width, and the depth of glacial erosion is up to 300 m, despite residual relief forms occurring on the upper surface of pre-glacial strata (Fig. 5). This trough contains several glacial surfaces

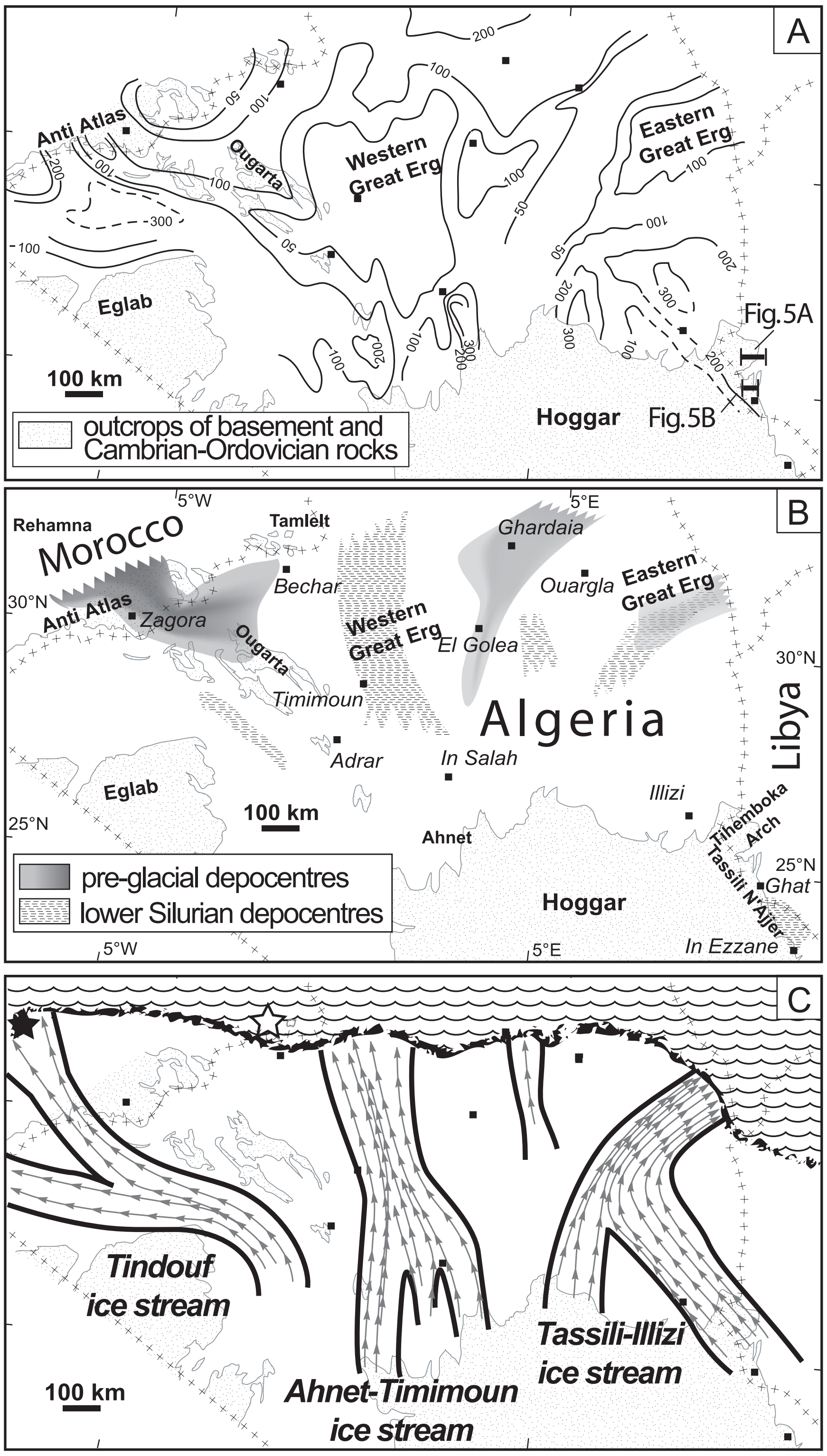

Fig. 8 Glacial troughs and ice streams in Algeria. (A) Isopach map corresponding to the syn-glacial Hirnantian strata (modified from Legrand, 1974). Erosional troughs are identified at the northern edge of the Hoggar Massif. (B) Pre-Hirnantian preferential depocentres (from Legrand, 1974 and Destombes *et al.*, 1985) and earliest to Early Silurian depocentres corresponding to depositional lows (from Klitsczh, 1981; Legrand, 1985; Lüning *et al.*, 2000). (C) Potential locations of major ice streams in Algeria as inferred from the locations of glacial erosional troughs and ice-flow orientations (cf. Fig. 1B). The black star is the northernmost glacierised area (Le Heron *et al.*, in press, a); the white star indicates an area that was not glaciated (Tamlelt area, southeastern Morocco, unpublished data). Ice-stream fronts correspond to the Hirnantian glacial maximum. They are tentatively figured as shallow-marine ice fronts with no ice shelves.

characterised by mega-scale glacial lineations (Fig. 4A) (Clark, 1993; Stokes & Clark, 2001). These lineations have elongation ratios ranging from 5 to >20 and are 1–30 m in height. The lineations make up a large-scale undulating morphology on the glacial erosion surface, which is superimposed on wide elongated ridges separated by straight valley-like depressions (Figs. 3C & 5). The morphology, comparable to the landforms produced by former Antarctic (e.g. Canals *et al.*, 2000; Anderson *et al.*, 2002; Evans *et al.*, 2004) or Scandinavian (Ottesen *et al.*, 2005) ice streams, defines a Late Ordovician ice-stream pathway (Moreau *et al.*, 2005). As a working hypothesis, the other glacial troughs of Algeria are interpreted as palaeo ice-stream pathways.

North of the glacial troughs, the general thinning of the sediment wedge is interpreted either as a decrease in the depth of erosion, or a decrease of sediment thickness in glacial troughs that are gradually underfilled. The latter scheme makes sense with the occurrence of elongate areas that Legrand (1985, 2003) and Lüning *et al.* (2000) have mapped, where lower Silurian organic-rich shales preferentially occur (Fig. 7B). These elongate areas are interpreted as depositional lows within which postglacial lower Silurian deposits may have accumulated, in contrast to highs that were not covered by sediments until middle Silurian time. Those depositional lows are interpreted as reflecting glacial troughs that remained underfilled after the ice-sheet retreat.

Connecting the overfilled glacial troughs of the Hoggar Massif (Fig. 8A) with underfilled depressions containing lower Silurian deposits to the north (Fig. 8B), a network of ice streams is reconstructed at regional scale (Fig. 8C). Hence, the Late Ordovician ice sheet over Algeria and western Libya was drained by a number of north-flowing ice streams separated by more stagnant ice in inter-stream areas. The shelfbreak extended a long distance from the ice fronts (Fig. 8C) and the existence of a shallow shelf (<200 m deep) may have restricted the formation of extensive frontal ice shelves.

More subtle depocentres are found northward in the Algerian outer glaciated shelf. However, they coincide spatially with pre-glacial depocentres (Fig. 8B) and are therefore not interpreted as erosional features. They cannot be considered as proxies for distal ice-stream pathways.

STRATIGRAPHIC ARCHITECTURES IN THE LATE ORDOVICIAN GLACIAL RECORD

Distinctive stratigraphic architectures faithfully reflect the position of each area on the shelf. For instance, low accommodation space and repeated ‘cannibalisation’ characterised the middle glaciated shelf, while restricted glacial erosion and greater accommodation space prevail on the outer glaciated shelf. This palaeogeographic subdivision of the glaciated shelf, parallel to ice flow, is coupled with a flow-transverse subdivision of the ice sheet into ice-stream troughs and inter-stream areas. That means a great deal of lateral variability should exist in the Late Ordovician glacial record. In the following section, the stratigraphic architectures of ice-stream pathways and inter-stream areas are compared for the middle and outer glaciated shelf.

Ice-stream-related depositional systems

The middle glaciated shelf: western Libya

In the Murzuq Basin (Libya), the depositional succession of the Hirnantian glacial record has been studied extensively (McDougall & Martin, 2000; Deynoux *et al.*, 2000; Sutcliffe *et al.*, 2000; Ghienne *et al.*, 2003; Le Heron, 2004; Le Heron *et al.*, 2004; El-ghali, 2005; Le Heron *et al.*, 2005). Most of the interpretations are based on field studies conducted in the Gargaf area, in the northern Murzuq Basin. In the following, we developed to some extent the glacial record of the western Murzuq Basin (Eastern Tassili n’Ajjer and Tihemboka Arch, see location in Fig. 8B). It characterises the stratigraphic architecture in ice-stream pathways on the middle glaciated shelf.

Despite partial reworking during later glacial cycles, 4–5 glacial depositional sequences are recognised, each separated by subglacial unconformities (Deynoux & Ghienne, 2004; Moreau *et al.*, 2005). The erosion depth of an individual unconformity is up to 200 m. The total thickness of the syn-glacial succession approaches 250–300 m. These sequences record the progressive infilling of glacially cut palaeovalley-like depressions. The long axis of younger depressions deviates from older examples (e.g. Smart, 2000), resulting in a complex depositional architecture (Figs 4A & 5) akin to Late Cenozoic alluvial terraces (e.g. Blum & Törnqvist, 2000).

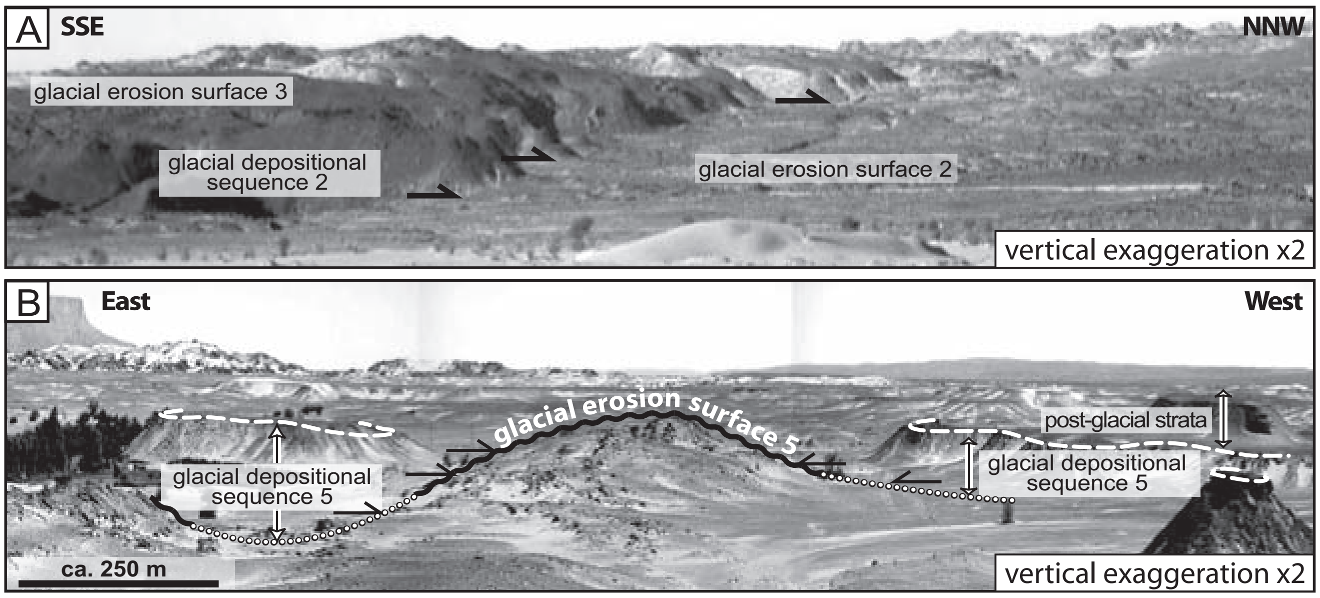

Fig. 9 Onlap relationships (black arrows) in the syn-glacial strata of the Eastern Tassili n'Ajjer (Ghat area, western Murzuq Basin). (A) A glacial depositional sequence onlaps on a glacial erosional surface with mega-scale glacial lineations (see location Fig. 4A). It is made up of fine-grained deposits at the base (distal glaciomarine, prodelta), truncated by fluvial sandstones at the top (depositional sequence 2 in Fig. 5B). (B) Glaciomarine and shelf deposits onlapping on a surface with mega-scale glacial lineations (depositional sequence 5 in Fig. 5B).

Depositional sequences 1–3. In the Eastern Tassili n'Ajjer (Ghat area), sequences 1–3 comprise coarsening upward successions, each 30–100 m thick, bounded above and below by a glacial erosion surface (Figs. 5B & 9A). Sequences 1 and 2 belong to the first glacial cycle, and sequence 3 to the second glacial cycle (Fig. 5C). The lowermost 20–75 m of each sequence comprises crudely laminated micaceous sandstones and shales with occasional lonestone-bearing diamictite horizons. These are interpreted as distal glaciomarine (plume) deposits or prodelta sediments. The middle section, 5–20 m thick, rests with a sharp or rapid transitional contact with the underlying section, and comprises well sorted medium-grained to poorly sorted coarse-grained sandstones. These deposits contain current and wave ripples, trough or tabular cross-laminae and plane beds with parting lineations. They are interpreted as shallow-marine to distal alluvial plain deposits. The upper part of each sequence includes sharp-based, coarse- to very coarse-grained sandstones bearing numerous internal erosional surfaces. Cross-laminated sandstones grade laterally into fine- to medium grained sandstones bearing horizontal to low-angle lamination with parting lineations and climbing ripple cross-lamination. These are interpreted as a series of amalgamated fluvial channels and associated overbank sediments, deposited on a flood-dominated aggrading braid-plain.

Each depositional sequence is considered to record (i) rapid retreat of a marine-terminating ice front, followed by (ii) flooding of the glacial erosion surface, then (iii) progradation of a fluvial-delta-shelf system. A braid-plain separated the retreating, land-terminating ice margin from the shoreline. An abrupt facies change occurs within the prograding succession, either pointed out by sharp-based shallow marine deposits or by erosionally based fluvial deposits. In each of these sequences, a sea-level fall or a fluvial incision may be attributable to the effect of glacio-isostacy. Fluvial aggradation is concomitant with renewed progradation.

Depositional sequence 4. This sequence is associated with the Hirnantian glacial maximum that occurred during the second glacial cycle (see above) (Fig. 5C). In the Tihemboka Arch, a thick sandstone wedge has been deposited on the glacial erosion surface (Fig. 5A). It is overlain by a sandstone sheet, which can be followed to the south into the Eastern Tassili n'Ajjer, resting here directly on the basal glacial erosion surface (Fig. 5A & B).

The sandstone wedge, 75–150 m thick, displays a coarsening and thickening-upward succession. The sandstones pass upwards from fine-grained massive sandy deposits, through a poorly stratified, medium-grained section characterised by sharp-based, horizontally laminated, graded, and de-watered sandstones, to low-angle or horizontally laminated deposits at the top. This succession is overlain by a channel-overbank system comprising cross-bedded medium- to coarse-grained sandstones. Channel fill structures, 10–40 m in thickness, 0.2–1 km in width, have transitional contact with overbank facies and any levée structures have been identified. These sandstones contain abundant subcritical climbing megaripples in 2–20 m thick beds (Fig. 10A & B), associated with deep-sided cut-and-fill structures and undulating bedforms that show a steep climbing (40°) to aggradational (90°) superposition (Fig. 10C). Large glaciotectonic structures in the form of thrusted fold belts (20–40 m in height) are also preserved within these strata.

The coarsening sandstone wedge described above is capped by a medium-grained sandstone sheet, extending from the Eastern Tassili n'Ajjer

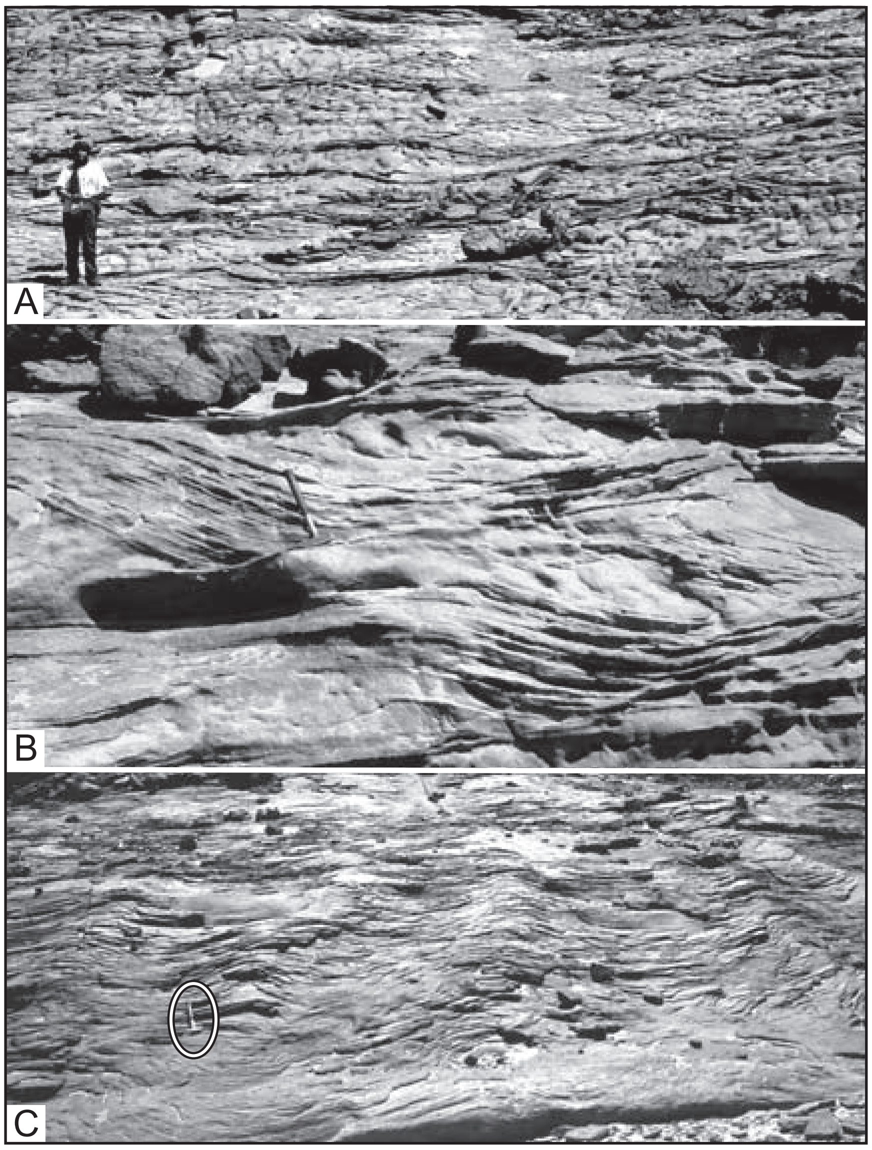

Fig. 10 Flood (possibly outburst)-dominated facies in an ice-stream-related outwash fan (glacial depositional sequence 4, Tihemboka Arch, western Murzuq Basin). (A) 2D climbing dunes composed of medium- to coarse-grained sandstones forming a 10 m-thick depositional package. (B) Close up view of facies illustrated in (A). (C) Nearly symmetrical, vertically climbing, large-scale bedforms interpreted as oversupplied climbing dunes or alternatively antidunes (encircled hammer for scale).

to the Tihemboka Arch. Its internal architecture is characterised by channel-fill structures and epsilon cross-stratification. The size of these structures increases towards the north. Horizontal lamination, climbing ripples and megaripples are ubiquitous.

Within the sandstone wedge, the climbing megaripples suggest deposition from highly concentrated sediment-laden streamflows with high rates of sediment fall-out. Such highly concentrated flows are most probably achievable by long-lived, turbulent glacial outburst floods (Russell & Arnott, 2003; Russell *et al.*, 2003). The origin of undulating climbing to aggradational bedforms (Fig. 10C) is enigmatic, and could reflect over-supplied climbing megaripples or alternatively antidunes. This last interpretation has been proposed for correlative deposits near Djanet, Algeria (Hirst *et al.*, 2002). Distal counterparts of this flood-dominated environment comprise poorly stratified to massive, largely dewatered sandstones deposited in environments dominated by high-density sandy turbidites. The overall sandstone wedge is interpreted as an ice-contact, flood-dominated outwash fan. The channel structures form the distributary system, which was directly linked with the subglacial drainage system. It is uncertain whether the sandstone wedge was deposited on a large submarine outwash related to a marine ice front or as part of a fan delta system related to an ice front terminating on land. In either case, its scale exceeds comparable depositional systems in the literature (Powell, 1990; Lønne, 1995; Lønne *et al.*, 2001) by one to two orders of magnitude. The size and thickness of the sand wedge suggests that the ice-sheet retreat occurred in the study area much more slowly than for sequences 1–3. This suggests that deposition occurred during a phase of stabilisation of the ice sheet. The overlying sandstone sheet was deposited by a regional-wide sinuous to meandering, sand-dominated fluvial system when ice-front position retreated further to the south and a delta most probably developed to the north.

Depositional sequence 5. This sequence is restricted to the Ghat area (Eastern Tassili n'Ajjer) and is considered as compelling evidence for a locally developed, fifth phase of ice-sheet advance. To the north of a boundary zone corresponding to the maximum ice advance, a sandstone wedge that is similar to but thinner than that of sequence 4, contains a channel-fill network and associated overbank deposits. To the south of the boundary zone, a glacial erosion surface bears fan-shaped drumlins with associated subglacial channel fills, both of which cross-cut older glacial lineations (Moreau *et al.*, 2005). A thin veneer (5–20 m) of distal glaciomarine deposits caps this surface in the axis of glacially cut depressions that remained essentially underfilled after the ice sheet retreated (Figs. 3A, 5B & 9B).

This depositional sequence had preserved the spatial relationship between a subglacial drainage network to the north and the proglacial outwash system to the south. The thin glaciomarine deposits that blanket the glacial surface suggest a rapid ice-sheet withdrawal. Post glacial evolution in a very last phase of Ordovician sedimentation was characterised by tide-dominated reworking processes and the deposition of a transgressive wedge on the flanks of underfilled palaeovalleys (Figs 3A and 5B).

The outer glaciated shelf: High Atlas and Meseta (Morocco)

Glacial troughs have not been found at outcrop on the outer glaciated shelf. However, a large depocentre of marine sediments has been identified in northeastern Morocco (Tazzeka Massif, Khoukhi & Hamoumi, 2001) beyond the maximum ice-front position on the non-glaciated shelf. Here, a relatively deep (200−400 m) marine fan was deposited at the continental margin (Le Heron *et al.*, in press, a). This fan system is not an analogue to the trough-mouth fans identified in front of Quaternary ice streams beyond the shelfbreak (Vorren & Laberg, 1997), within which sedimentation is dominated by very thick, poorly evolved diamictite facies. However, focused and massive sand-dominated deposition is interpreted as the signature of a sediment delivery system fed by an ice stream.

To the south, on the outer glaciated shelf, the two major Hirnantian glacial cycles are recorded, with sediments related to the first (lower) glacial cycle being somewhat more ice-distal than those of the second (upper) glacial cycle. Only the latter is discussed below. Further details are given in Le Heron *et al.* (in press, a).

In the Rehamna inlier, a thin sandy diamictite interpreted as a till is observed in close association with subglacial features such as glaciofluvial

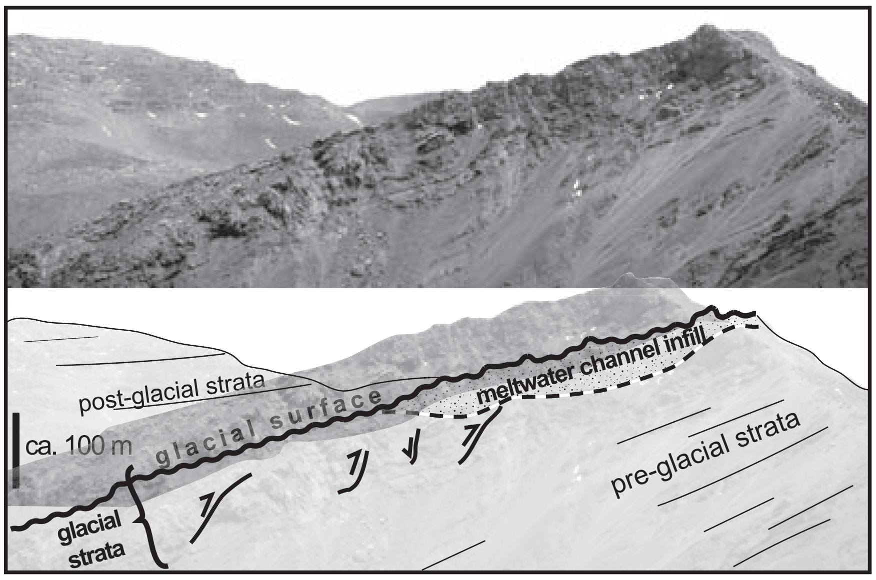

Fig. 11 The glacial succession in the High Atlas (Morocco). The following events are illustrated: (i) glaciotectonic deformation involving glaciomarine outwash fan facies, deposits of the first glacial cycle and subordinate pre-glacial strata, (ii) incision of a subglacial channel and sandy diamictite infill, (iii) truncation by a glacial erosion surface comprising streamlined bedforms (not illustrated, see Le Heron *et al.*, in press, a).

sandstones, sand intrusions and a striated surface. This till horizon rest above thin outwash facies and is overlain by well developed glaciomarine diamictite facies, up to 20 m thick. In the High Atlas, c. 100 km further to the south, the sedimentary succession of the second glacial cycle begins with thick outwash facies comprising sandstones interstratified with massive to poorly stratified, sandy, clast-poor diamictites (Ouanaimi, 1998). These sediments are deformed by glaciotectonic thrusts and gravitational loads, and are truncated by 20–40 m thick, 100–300 m wide channel structures (Fig. 10). The latter are filled with stratified coarse-grained sandstones, sandy diamictites and subordinate conglomerate lenses, including boulder-sized clasts of local origin. These deposits are capped by a glacial erosion surface with subglacial streamlined bedforms overlain by a thin (<2 m) diamictite.

The Rehamna succession, probably in close proximity to the maximum ice-front position, reflects more ice-marginal conditions than the High Atlas succession (Le Heron *et al.*, in press, a). Glaciomarine diamictites overlying the glacial surface in the Rehamna were probably deposited during an earlier phase of ice-front recession. This stage has immediately preceded an ice-sheet collapse that prevented further glacial sedimentation over the area, as suggested by the thin 'post-glacial' glaciomarine sediment blanket above the underlying glacial erosion surface in the High Atlas.

Combining observations from the three study areas (Tazzeka, Rehamna and High Atlas), the Moroccan succession related to the Hirnantian glacial maximum records: (i) deposition in a submarine, ice-contact outwash fan dominated by mass-flow diamictites and sandy turbidites, (ii) glaciotectonic deformation and incision by channels suggesting subglacial, focused, sediment input points, (iii) subglacial conditions characterised by fast-flowing ice indicated by streamlined bedforms on the outer glaciated shelf, whereas an ice-stream-related 'deep' marine fan developed on the non-glaciated shelf, and (iv) a rapid ice-sheet withdrawal. A depositional succession related to a glacial advance on a shallow-marine shelf, followed by the development of an ice stream and a subsequent ice-stream collapse is then apparent.

Depositional systems in inter-stream areas

The middle glaciated platform: Mauritania

Syn-glacial strata in eastern and western Mauritania (Hodh and Adrar, Fig. 1) are organised into four laterally juxtaposed and vertically superimposed depositional units (Ghienne, 2003). As in Libya, each depositional sequence rests on a glacial erosion surface and records essentially an ice-sheet recession with the influence of glacial processes rapidly disappearing up-section. Key differences with the record in western Libya include (i) a markedly thinner succession (c. 40–100 m), thickening only within palaeovalleys or subglacial depressions, (ii) widespread palaeorelief forms on the upper surface of pre-glacial strata, (iii) better developed fluvio-glacial, fluvial and delta facies, and (iv) poorly developed offshore marine facies.

In the Hodh area, syn-glacial strata of the first Hirnantian glacial cycle record the recession of a land-terminating ice margin characterised by episodic, high-frequency retreats and re-advances of the ice front, resulting in a complex depositional architecture (Deynoux, 1985; Ghienne, 2003). This architecture includes aggrading outwash sediments deposited near a stagnating ice front that is partly glaciotectonised by minor re-advances. Both tills and some glaciofluvial material were reworked by gravity processes and re-deposited in subglacially overdeepened zones (Ghienne, 1998). The final phase of ice retreat was accompanied by the incision and subsequent infilling of large subglacial or proglacial meltwater channels (Ghienne, 2003).

During the second glacial cycle, a rather thin (<50 m) succession was deposited, with the exception of tunnel-valley infills (Ghienne & Deynoux, 1998; Fig. 3B). The last depositional sequence lacks any glacial features in western Mauritania where erosion prevailed in shallow-marine environments. In the east, in the Hodh area, the sequence comprises a fining-up glaciomarine succession, characterised by thin (<10 m) submarine outwash-fan deposits at its base, truncated by nearshore sediments. This sequence indicates a significant relative sea-level fall ascribed to a late post-glacial isostatic rebound (Ghienne, 1998, 2003). It occurred, nevertheless, before the end of the Hirnantian (Paris *et al.*, 1998; Underwood *et al.*, 1998).

The outer glaciated shelf: Turkey (Taurus Mountains)

This area is characterised by laterally extensive (up to 100 km), superimposed depositional units (Monod *et al.*, 2003). Relatively clast-rich sandy diamictites, representing mass-flow or low- to high-density sandy turbidites, characterise glaciomarine outwash environments in front of a marine-terminating ice margin. The absence of large-scale channel structures suggest a limited availability of meltwater and line, rather than point, sources (e.g. grounding-line fans). Non-glacial shelf processes, e.g. storm deposits, are also present. A rather condensed shelf sedimentation regime not influenced by glacial processes, occurred during interglacial periods.

The glacial maximum is characterised by the deposition of a thin (<0.2 m) till horizon overlying a striated pavement. Upwards, a progressively fining-up, lonestone bearing glaciomarine succession records a gradual ice-front retreat. Therefore, in contrast to Moroccan successions, no evidence for a rapid ice-sheet withdrawal is identified in Turkey.

PLATFORM-SCALE FACIES MODEL

Only rarely have sequence stratigraphic methodologies have been applied successfully in glacial settings (e.g. Proust & Deynoux, 1993; Brookfield & Martini, 1999; El-ghali, 2005). Large-scale facies models for glacial sedimentary systems are thus still needed. When developed, they will form the basis of a more robust sequence stratigraphic approach to ancient glacial successions.

The database presented herein is regionally comprehensive (Fig. 1A) and should facilitate correlation of Late Ordovician depositional sequences across the North Gondwana platform. This correlation is complicated both by the number of palaeogeographic domains (e.g. inner, middle, outer glaciated shelves) and whether each study area lies within an ice-stream pathway or an inter-stream area. Based on the glacier dynamics inferred for each study area, a facies model illustrating the stratigraphic architecture of a glacial sequence is now proposed for two parallel S-N profiles (Fig. 12). The first set of diagrams on the left illustrates the stratigraphy within an ice-stream pathway, whereas the set on the right depicts an adjacent co-evally evolving inter-stream area. The model captures four phases in the temporal evolution of a glacial sequence, namely the glacial advance, the glacial maximum, the ice-margin recession and the interglacial minimum. The two points of maximum ice advance and ice retreat, as well as the marine limit, are not fixed palaeogeographically. They are located at different positions across the platform according to the amplitude of both the maximum and minimum ice extent associated with each glacial phase.

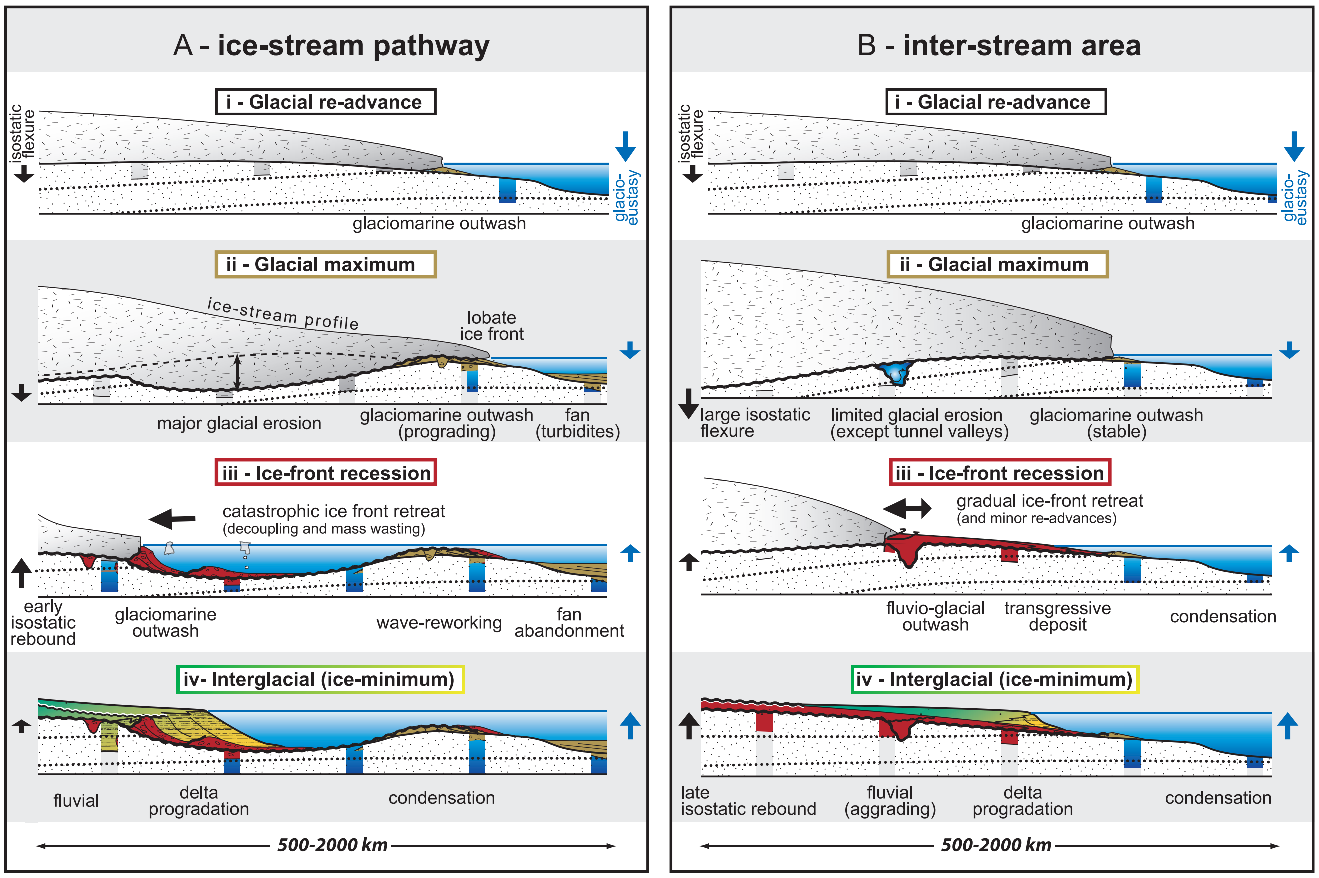

Fig. 12 An idealised glacial depositional sequence corresponding to a single glacial phase (glacial advance and subsequent retreat) in (A) ice-stream-related depositional environments (left, mainly based on the Libyan case study), and (B) inter-stream areas (right, mainly based on the Mauritanian case study, Ghienne *et al.*, 2003). (i) Glacial re-advance. (ii) Glacial maximum and initial retreat. (iii) Ice-front recession. (iv) interglacial (ice-minimum). The stratigraphic superposition of several glacial sequences (2–5), and the potential lateral migration of ice streams result in an intricate glacial record (e.g. Fig. 5). Post-glacial transgressive deposits are not figured. Vertical exaggeration: ~1000.

Glacial advance

This stage is generally poorly recorded on the glaciated platform where regressive successions are poorly developed possibly due to a rapid sea-level fall. Immediately prior to the ice maximum, glaciomarine outwash sediments are deposited in some areas such as northern Morocco. This infilling of accommodation space probably supported the ice sheet as it advanced northward on the shallow-marine platform, and was affected by concomitant fall in sea-level (e.g. Dahlgren *et al.*, 2002). It is not possible to ascertain whether ice streams had developed at this stage.

Glacial maximum and initial glacial retreat

While glaciomarine deposition occurred at the ice margin, subglacial erosion surfaces developed to the south. They are characterised by foredeepened depressions, glaciotectonic thrusts and folds, mega-scale glacial lineations and meltwater channels.

Focused sediment input-points located in front of ice-stream systems, may have been locally connected to some deeper turbiditic fans beyond a shelf edge inherited from the pre-glacial shelf architecture (e.g. in northern Morocco). This shelf edge may have controlled the maximum ice-stream advance (Le Heron *et al.*, in press, a), which does not appear to have reached the shelf-break, unlike ice sheets in Antarctica or Scandinavia during the Pleistocene Late Glacial Maximum (e.g. Ottesen *et al.*, 2005).

In contrast, linear and distributed sediment-input points built small-scale, diamictite-dominated outwash systems in front of inter-stream areas (e.g. in Turkey). Initial glacial retreat was generally associated with the deposition of relatively thick glaciomarine succession above a thin till. It is at this stage that large tunnel valleys began forming up-glacier in the inter-stream areas (e.g. Le Heron *et al.*, 2004).

Ice-front recession

As ice stream retreat, only a thin sediment cover remains, comprising fine-grained distal glaciomarine deposits that rest directly on top of each glacial erosion surface as in the eastern Tassili n'Ajjer. The preservation of fine-grained sediment above glacial erosion surfaces implies the sudden withdrawal of the ice sheet from the outer glaciated shelf. These processes strongly suggest decoupling at the ice/bed interface, mass-wasting, rapid retreat of marine-terminating ice fronts to a new set of pinning-points, and flooding of the deglaciated area (Eyles & McCabe, 1989; Anderson & Thomas, 1991). This suite of processes is in agreement with the interpretation of a glacial trough as a former ice-stream pathway, characterised by foredeepened topography where intense calving may have occurred. After initial rapid retreat, a more stable and slow retreat of ice fronts produced a renewed and voluminous ice-contact, flood-dominated, outwash system such as a submarine fan or fan delta (sequence 4, Tihemboka Arch). The latter system then evolves into a delta system once a flood-dominated fluvial plain becomes established in front of the land-terminating ice margin.

In inter-stream areas, the sediments from the ice-sheet recession stage comprise the tunnel-valley basal infill (Ghienne & Deynoux, 1998; Le Heron *et al.*, 2004). Glacial recession was more gradual as no sudden glacial withdrawal is observed (Turkey). With slow continuous retreat, a land-terminating ice margin deposited braided outwash sediments grading seaward into transgressive, shallow-marine deposits such as in Mauritania. During this time, a land-terminating ice margin may have persisted locally in inter-stream areas in a position to the north of some marine ice fronts that were established to the south in the axis of adjacent glacial troughs. Such a complex configuration may explain some peculiar fluvio-glacial drainage patterns. A source in a higher inter-stream area and a depocentre located within an adjacent glacial trough may be inferred when delta systems show evidence of progradation perpendicular to the regional palaeoslope

Interglacial (ice-minimum)

In both ice-stream and inter-stream areas, interglacial conditions resulted in high sea levels and the progradation of fluvial-delta-shelf systems as in western Libya and Mauritania. Fluvial aggradation occurs, locally temporarily interrupted by glacio-isostatic rebound. This aggradational-progradational pattern infilled any remaining accommodation space in glacially cut glacial troughs and tunnel valleys. In the proximal (southern) parts of the shelf, these sediments may actually form the bulk of syn-glacial strata preserved within each glacial depositional sequence. In northern parts of the platform, more restricted or condensed sedimentation occurs, although this may also have been fed by local highlands providing an additional sediment source (Le Heron *et al.*, in press, a).

CONCLUSIONS

The model given above should be regarded as a first attempt to merge numerous observations and interpretations in various parts of Northern Gondwana. The architecture of Late Ordovician glacial depositional sequences is mainly controlled by their location within or outside an ice-stream-generated trough. Ice-stream-dominated systems are characterised by up to 300 m deep incisions, a greater sediment supply typified by flood-dominated outwash-fan sedimentation, and a sedimentary record indicating rapid ice-sheet collapse. In inter-stream areas, shallower erosion surfaces are observed and sediment as well as meltwater supply are less vigorous. The general depositional features that can be portrayed for a complete cycle of glacial advance and subsequent retreat include:

1 Ice-proximal, coarse-grained glaciomarine successions are best developed at or near the maximum ice-front position and characterise the outer glaciated shelf in both ice-stream and inter-stream-dominated areas. Relatively deep marine fans occurred beyond the shelf edge in the axis of ice streams;
2 During ice-sheet recession, ice-sheet collapse in ice-stream-generated troughs resulted in a relatively thin ice-distal glaciomarine sediment cover blanketing the glacial erosion surface. Gradual ice-front recession in adjacent inter-stream areas resulted in well developed fluvio-glacial to fluvial facies;
3 Outwash systems preserved in ice-proximal segments of ice-stream troughs mark transitional conditions showing an evolution from marine-terminating to land-terminating ice fronts in association with a slowing down in the rate of ice-sheet recession;
4 Much of the Hirnantian strata in the middle glaciated shelf essentially record late glacial retreat to interglacial phases. In general, they are finer-grained than strata deposited several hundreds kilometres to the north when the ice-front position was at its maximum.

Several factors have resulted in a complicated glacial record: the stratigraphic superimposition of several, erosionally based, glacial sequences (e.g. Fig. 5B); the possibility that ice streams of successive glacial phases do not necessarily coincide spatially; and Hirnantian glacially induced reactivation of pre-existing basement faults (Ghienne *et al.*, 2003; Turner *et al.*, 2005; Denis *et al.*, submitted). The model presented herein should facilitate a better integration of outcrop and subsurface data, guiding the sequence stratigraphic interpretation of Late Ordovician glacial deposits and other ancient glacial successions. Future research looks forward to the development of a detailed chronostratigraphic framework, which will be the subject of a forthcoming paper.

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