The Hirnantian glacial landsystem of the Sahara: a meltwater-dominated system

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During the Hirnantian (443 Ma), ice sheets expanded towards the present-day north over North Africa and the Arabian Peninsula when the western part of the Gondwana supercontinent straddled the South Pole. A glacigenic succession is exposed around the flanks of several Saharan cratonic basins, including Murzuq and Al Kufrah basins in Libya. As a result of the present-day hyper-arid context of the outcrops, a suite of palaeo-glacial landforms has been identified and, in some cases, mapped. These landforms occur along glacial erosion surfaces, defined as unconformities derived through direct ice sculpting, meltwater erosion or a combination of these processes. Unconformities, mostly resulting from ice sculpting and including glacially striated pavements and mega-scale glacial lineations (MSGLs), are identified at a number of locations along these erosion surfaces, in association with drumlinized features. The majority of reported examples are of ‘soft sediment character’; that is, generated through the deformation of unconsolidated sediment. Features mainly associated with meltwater erosion include tunnel valleys which occur in swarm-like belts, defining palaeo-grounding-line positions as the ice fronts retreated. A ‘smeared’ series of palaeo-ice-stream footprints, resulting from multiple advance–retreat cycles, is characteristic of the landsystem. Deformation of sediments into a series of push moraines, expressed as kilometre-scale fold–thrust belts, allows the locations of the former ice front to be identified.

Background to the Hirnantian glaciation of North Africa

The Hirnantian glacial record of North Africa is a classic example of a continent-scale archive of an ancient palaeo-ice sheet. Expeditions to the Sahara during the late 1960s, focusing on the Algerian record, revealed a full suite of glacial indicators including striated pavements, pingos, roches moutonnées and a variety of meltwater channels (Beuf *et al.* 1971). Subsequently, largely as a result of their significance as hydrocarbon reservoirs, more recent studies re-evaluated these outcrops from a sedimentological perspective. Much effort focused on unravelling the glacial stratigraphy in neighbouring Libya (Ghienne *et al.* 2003, 2007; Le Heron *et al.* 2004, 2005, 2010; Moreau *et al.* 2005; Moreau 2011; Girard *et al.* 2012*a*, *b*), as well as in the comparatively easier-to-access Morocco (Destombes *et al.* 1985; Le Heron 2007; Le Heron *et al.* 2007; Ravier *et al.* 2014) and also Niger (Denis *et al.* 2010). Given that much of the previous emphasis has been on contributions to stratigraphy and sedimentology, there is justification in providing a very brief resumé of the Hirnantian in Libya from a glacial landsystem perspective (*sensu* Eyles 1983; Evans 2003; Benn & Evans 2010). Here, we focus mainly on glacial landforms cropping out at the flanks of two sedimentary basins, namely the Murzuq and Al Kufrah basins (Fig. 1a–c), with a few additional examples from temporally equivalent strata in Morocco and South Africa for comparison.

At the end of the Ordovician, North Africa occupied high southern latitudes with a palaeo-south pole located some distance to the west of the study area (Fig. 1d) (Stampfli & Borel 2002). Suites of subglacial bedforms enable the direction of palaeo-ice-sheet flow to be deduced, mostly implying a NW-directed palaeo-flow over the study area (Fig. 1e). Rocks of glacigenic origin typically rest unconformably upon a suite of older, pre-glacial strata across North Africa (Fig. 1f). We describe and evaluate the character of these unconformities in this paper.

Subglacial unconformities formed from direct ice erosion, deformation or sculpting

In North Africa, Ghienne *et al.* (2007) viewed the glacial sedimentary system as falling into two palaeo-geographic domains: areas dominated by ice streams occupying cross-shelf troughs, which are depressions tens to hundreds of kilometres wide eroded into the pre-glacial substrate; and inter-ice stream areas. This model viewed an ice-stream-dominated sedimentary system as distinct from an inter-ice-stream area, where the effects of subglacial erosion were less prominent and the impact of meltwater release was more pronounced. This model, which was expanded and developed by Le Heron & Craig (2008) into an overall reconstruction, relies on the application of the Stokes & Clark (1999, 2001) criteria to recognize the footprints of palaeo-ice streams, dovetailing outcrop observations with satellite image interpretation (Moreau *et al.* 2005).

At a regional scale, and as mapped out in plan view, MSGLs plot a curvilinear course in *c.* 50 km wide, 200 km long belts. In the Ghat area of the Murzuq Basin for instance (Fig. 1b), two generations of cross-cutting MSGLs are identified, allowing for two generations of palaeo-ice-stream activity to be interpreted (Moreau *et al.* 2005) (Fig. 2a). The uppermost set of MSGLs is concealed by a drape of postglacial shale of early Silurian age (Fig. 2b). Successive generations of MSGLs are mostly sub-parallel, implying an inherited palaeo-topography that determined and/or controlled ice-stream pathways during glacial readvances, but some cross-cut at high angles (Fig. 2a). These characteristics contribute to an overall smeared aspect to the subglacial landform assemblage which can make the palaeo-ice-stream footprints (Stokes & Clark 2001) difficult to identify in other parts of the Sahara. Another example of a belt of MSGLs occurs at the northern flank of Al Kufrah Basin (Jabal az-Zalmah, Fig. 1c). On satellite imagery, regional tectonic overprint resulting from opening of the Sirte Basin to the north has resulted in a pervasive NW–SE-trending set of lineations that can be ground-truthed as faults and fractures unrelated to Hirnantian glaciation (Fig. 2c). The MSGLs are identified, like those in Ghat, as curvilinear belts of parallel lineations on the satellite imagery.

At outcrop at Jabal az-Zalmah (Fig. 1f), a 100 m amplitude unconformity cuts down into underlying strata. Across the basin, unconformities exhibit a series of parallel ridges and grooves with a consistent regional or local orientation (Fig. 2e). Close inspection illustrates that the ridges are at least 65 cm high (Fig. 1e). Elsewhere in Africa, similar belts of MSGLs are expressed in many regions glacierized by Hirnantian ice sheets (e.g. South Africa, Fig. 2d; central Algeria, Fig. 2e). The aspect ratio of the ridges is consistent with evidence of self-similar ridges and grooves on a centimetre-scale superimposed in the troughs between them (Fig. 2f). The centimetre-scale ridges and grooves are intimately associated with intrastratal deformation structures and dewatering structures, and are therefore interpreted as soft-sediment striations (Sutcliffe *et al.* 2000; Le Heron *et al.* 2005), with the ridges and grooves on individual sandstone lobes stacked in vertical succession over a few centimetres (Fig. 2g). Exceptions occur in the Djado region of Niger, where an assemblage of bedrock striations and subglacial hydrofractures has been described (Denis *et al.* 2010).

In other parts of North Africa, such as in the High Atlas of Morocco, examples of subglacially sculpted bedforms are clearly

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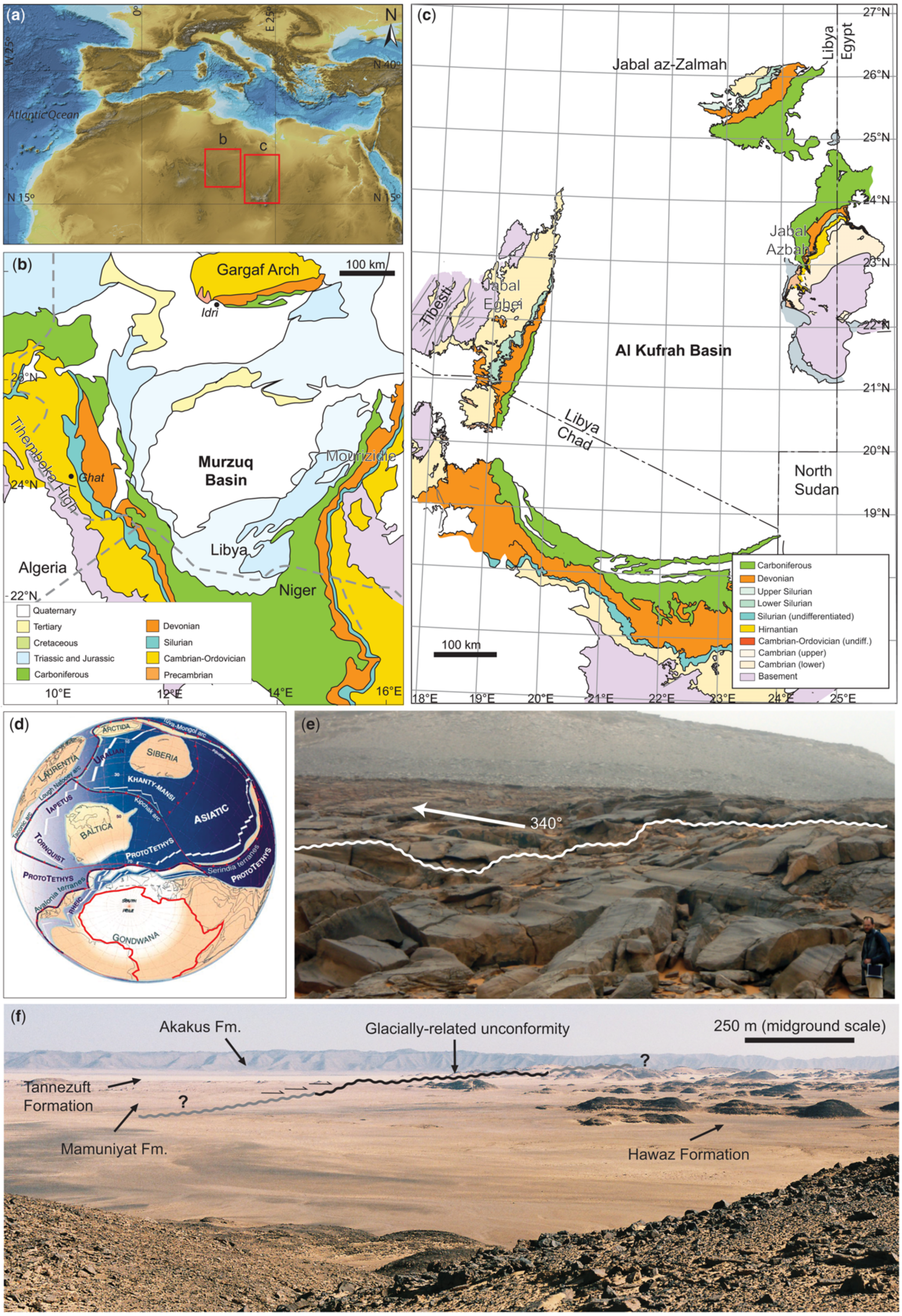

Fig. 1. (**a**) Overview map of North Africa showing the location of Murzuq and Al Kufrah basins (red boxes; map from GEBCO_08). (**b**) Geological map of Murzuq Basin showing Tihemboka Arch and Gargaf Arch. These two basin-flanking outcrop belts exhibit clear evidence for Hirnantian glacial landforms described in this paper. (**c**) Geological map of Al Kufrah Basin showing the Jabal Azbah, Jabal Eghei and Jabal az-Zalmah areas. Each of these outcrop belts expose Hirnantian glacial landforms. (**d**) Late Ordovician palaeogeographical reconstruction from Stampfli & Borel (2002), showing the palaeo-South Pole and North Africa (outlined in red) at high southern palaeo-latitudes. (**e**) Mega-scale glacial lineations (MSGLs) at outcrop from the Jabal Azbah region, Al Kufrah Basin. Wiggly lines in (e) and (f) denote unconformities. (**f**) Unconformity of about 100 m relief from the northern flank of Al Kufrah Basin, Libya (Jabal az-Zalmah).

identified (Ghienne *et al.* 2007; Le Heron *et al.* 2007), but their full palaeo-glaciological context cannot be properly determined. In this region, small, disconnected but high-quality outcrops occur at high elevations where, at Tizi N'Tichka, part of an interpreted palaeo-drumlin field crops out over a narrow (100 m^2) area (Le Heron *et al.* 2007). The small area over which these features are observed is a result of post-Hirnantian tectonic activity and erosion within the High Atlas (Piqué & Michard 1989; Michard *et al.* 2008). Smoothed and polished bedforms, coupled with hairpin structures and soft-sediment striae, testify to a subglacial origin. Criteria developed to recognize palaeo-ice streams suggest that drumlins may represent the slower-flowing fringes of an ice stream, either in a marginal or ice frontal location (Stokes & Clark 2001). This clearly demonstrates that, in spite of excellent overall outcrop quality, an understanding of the Hirnantian glacial landsystem is made difficult by patchy outcrop in key areas, which is the result of more recent tectonic processes.

Subglacial unconformities produced by meltwater interaction with the substrate

A second, widespread type of unconformity in Late Ordovician sediments from North Africa results from meltwater erosion. Across the Sahara, tunnel valleys are interpreted from widely spaced locations such as Mauritania (Ghienne & Deynoux 1998), the Anti Atlas of Morocco (Le Heron 2007; Loi *et al.* 2010; Ravier *et al.* 2014), the Tassili N'Ajjers plateau of eastern Algeria (Deschamps *et al.* 2013), the Ghat area of westernmost Libya (Moreau 2011), the Gargaf Arch in central Libya (Ghienne *et al.* 2003; Le Heron *et al.* 2004) and possibly in Jabal Eghei on the western flank of Al Kufrah Basin (Le Heron *et al.* 2015). On the Gargaf Arch, central Libya, dense palaeovalley clusters are mapped from satellite imagery (Fig. 3a) (Le Heron & Craig 2008). At least three generations can be identified here by cross-cutting relationships (Fig. 3a), but the amount of time separating the generations, and whether the valleys were cut in a phased retreat or over multiple cycles, remains obscure. At outcrop, evidence for angular truncation of underlying units, such as pre-glacial deposits or those of a preceding glacial cycle, is commonplace. Both the Jabal Eghei (Fig. 3b) and Ghat examples (Fig. 3c) are low-relief incisions, characterized by an undulating contact between underlying, sandstone-dominated marine deposits of the Hawaz Formation and thickly bedded sandstones of the Mamuniyat Formation (the Hirnantian glacial succession) above. By contrast, some of the tunnel valley margins are steeper (e.g. on Gargaf Arch, Fig. 3d). Immediately beneath the incision deflection of underlying pre-glacial strata is commonplace, and a suite of gravitational load structures (Fig. 3e) and/or striated surfaces commonly occur just above the base of the incisions (Le Heron *et al.* 2004). The predominance of tunnel valleys across North Africa therefore allows the landsystem to be described as a glacial meltwater-dominated type.

The characteristics listed above led Le Heron *et al.* (2004) to interpret these structures as tunnel valleys, although the scale variability of channelized sandstone bodies suggests that caution should be exercised. The Hirnantian tunnel valleys are geometrically identical to those in younger glacial environments (e.g. van der Vegt *et al.* 2012) and measure hundreds of metres to kilometres in width, extend downflow for up to tens of kilometres and are several tens to hundreds of metres deep. Smaller, ribbon-like channels measuring a few tens of metres in width form dense networks over the Algerian–Libyan border (Beuf *et al.* 1971; Girard *et al.* 2012*a*, *b*). These are variably interpreted as turbidite channels (Hirst *et al.* 2002; Hirst 2012) and waning-flow deposits from a jökulhlaup (Ghienne *et al.* 2010; Girard *et al.* 2012*b*). Meanwhile, the true tunnel valley incisions can be distinguished by: (1) their size; (2) the presence of deformation immediately beneath them; and (3) the presence of striated surfaces. The latter two phenomena support a subglacial genesis, testifying to the presence of overlying ice. In planform, the Hirnantian tunnel valley networks may be partly isolated phenomena (as in Morocco; Clerc *et al.* 2013; Ravier *et al.* 2014) or form dense clusters or 'swarms' (as in SE Algeria; Deschamps *et al.* 2013).

As demonstrated through satellite image interpretation, the planform distribution of tunnel valleys is typically complex and testifies to multiple generations and cross-cutting relationships. A cross-section through a cross-cutting pair of tunnel valleys from Morocco is shown in Figure 3f. A highly irregular base to the tunnel valley is apparent, lateral facies changes occur abruptly within the palaeovalley fills and deformation towards the top of the palaeovalley is apparent on the northern side (Fig. 3f). This style of deformation, which in Morocco is attributable to a phase of glacial readvance (Le Heron 2007), is discussed further below.

Ice-marginal deformation structures

Given the evidence for the advance of Hirnantian ice sheets over unconsolidated substrates, a wide range of soft-sediment deformation structures, including the soft-sediment striated surfaces and MSGLs detailed above, are found in North Africa. Le Heron *et al.* (2005) synthesized the key groups of structures with interpretations for subglacial and proglacial (ice-marginal) modes of origin. In a subglacial environment, striated surfaces are widespread features; however, large-scale, dome-like fold structures interpreted as mud diapirs (30–100 m diameter) were also found to occur on the Gargaf Arch, central Libya. Similar features were also described by Beuf *et al.* (1971) from eastern Algeria. These structures superficially resemble pingos but: (1) lack the ice-cracked upper surface that characterizes these periglacial structures; and (2) are developed within, and onlapped by, strata of shallow marine origin (Le Heron *et al.* 2005). Fold–thrust belts at the ice margin, interpreted as push moraines (Aber & Ber 2007), are recognized structures (Fig. 4a–c). Footwall deformation beneath the thrust surfaces is complex and chaotic, although intrastratal deformation in hanging-wall anticlines can also be observed (Fig. 4a). The vergence of the fold structures in the hanging wall, coupled with the dip direction of the thrust surface, allows the direction of tectonic transport (in this case ice movement) to be determined. In some cases, tight antiforms are not breached by thrust faults, forming relic ridges separated by tight synforms (Fig. 4b). Multiple ridges running parallel to one another are mapped out over several hundred square metres (Fig. 4c). Collectively, mapping of the interpreted push moraines can be integrated with the known distribution of tunnel valleys, allowing the former location of ice fronts to be inferred.

Palaeo-glaciological reconstructions: advancing and retreating ice masses over a marine shelf

Noting the regional distribution of belts of MSGLs at outcrop, together with examples interpreted from 3D seismic datasets in the subsurface of sedimentary basins (e.g. Moreau & Ghienne 2016), a tentative network of palaeo-ice streams draining the Hirnantian palaeo-ice sheet is mapped (Fig. 4d). The limitation of this approach is that, while established criteria to locate palaeo-ice streams provide an essential constraint (Stokes & Clark 1999), the incomplete nature of the sedimentary record in some areas coupled with sparse data in others leaves large parts of the region poorly known. Phanerozoic tectonism and Cenozoic volcanism in the Tibesti Mountains, for example, renders a large part of the region devoid of Hirnantian strata that could be used to better constrain this regional model. The position of the ice margin during retreat phases is constrained largely by the distribution of 'swarms' of tunnel valleys (Fig. 4d). Well-constrained geometries at outcrop can be traced into the subsurface via 3D seismic data (Smart 2000;

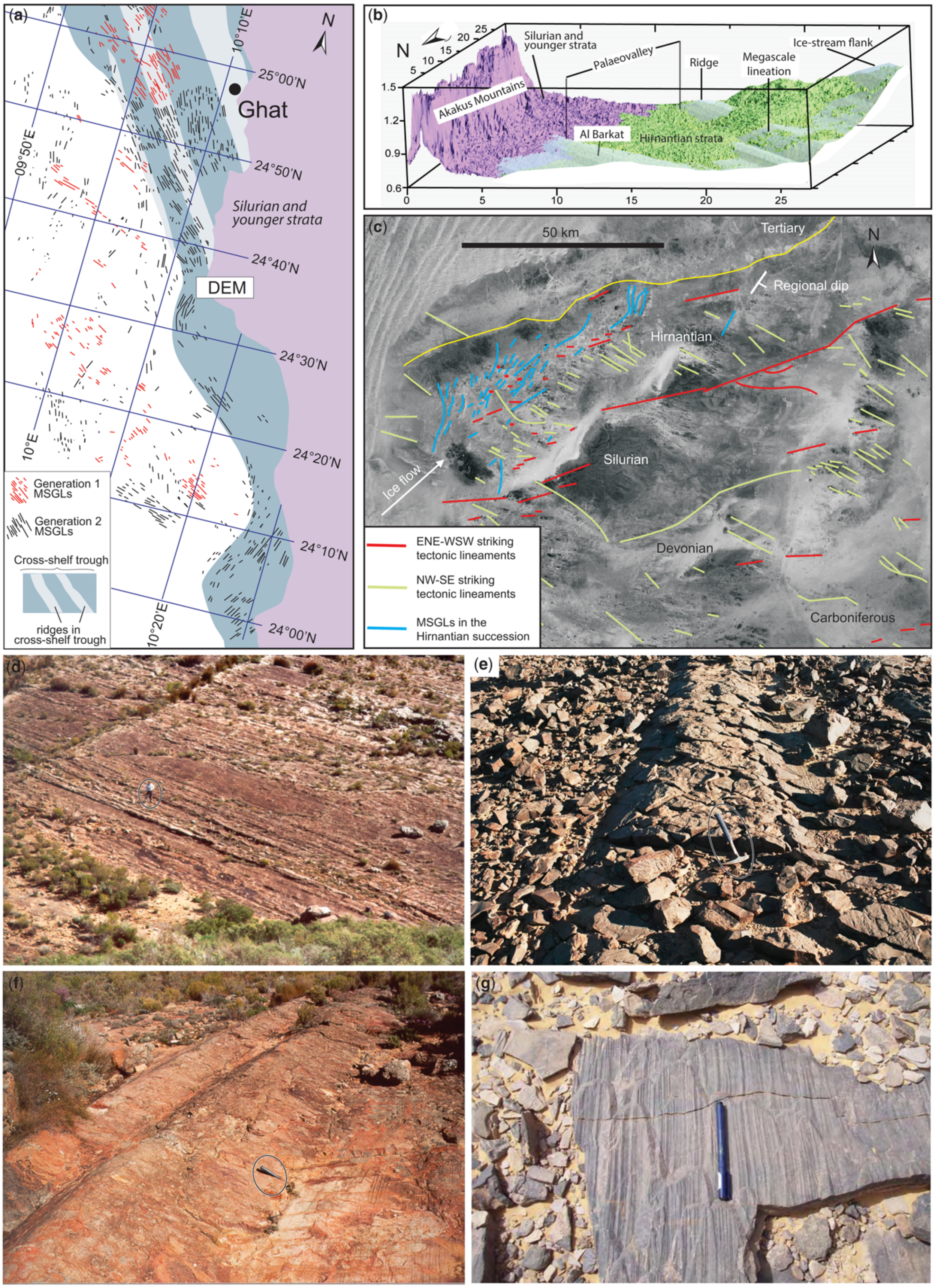

Fig. 2. Unconformities of subglacial origin in Hirnantian strata resulting from direct ice erosion, deformation or sculpting. (**a**) Palaeo-ice-stream footprint from the western flank of Murzuq Basin near Ghat (see Fig. 1b for regional context). Two generations of MSGLs with cross-cutting relationships, mapped from satellite imagery. Box ‘DEM’ refers to the location of (b). (**b**) Digital elevation model (DEM) of part of the ice-stream footprint showing glacial landforms and valley. Modified from Moreau *et al.* (2005). (**c**) MSGLs identified on satellite data at the northern flank of Al Kufrah Basin, eastern Libya (see Fig. 1c for regional context). From Le Heron & Craig (2008). (**d**) MSGL structures developed in the Pakhuis Formation, South Africa. (**e**) MSGL ridge from Dider, Tassili N’Ajjer (Algeria) showing superposed striations in the groove to the right of the ridge. (**f**) Close-up of a ridge (0.5 m amplitude) that forms part of the MSGL network shown in (d). (**g**) Striations developed on stacked lobes, illustrating their development in unconsolidated sediment (Le Heron *et al.* 2005). Photographs (d–g) from Le Heron (2004, unpublished).

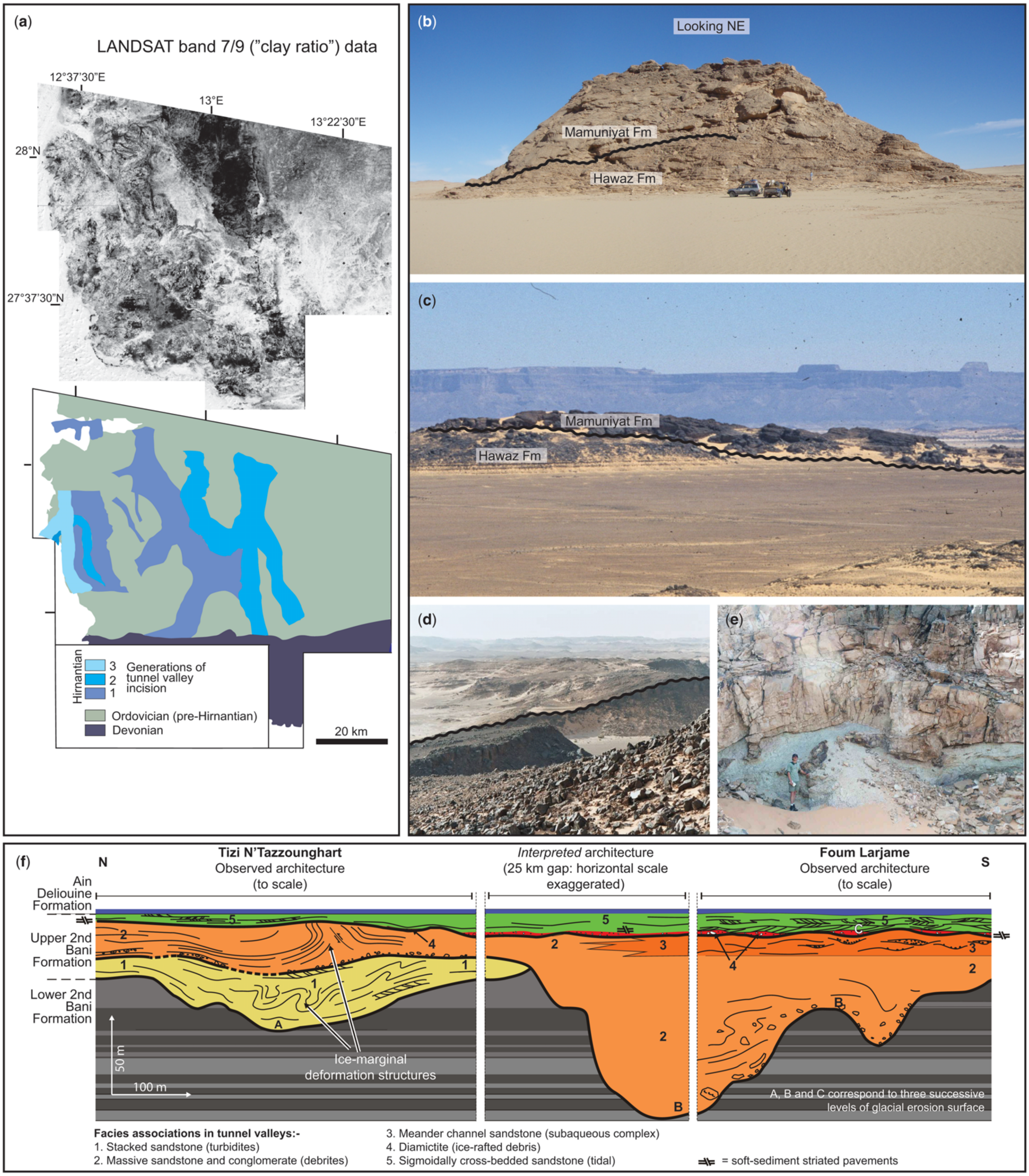

Fig. 3. Unconformities of subglacial origin primarily resulting from meltwater interaction with the substrate. (**a**) Satellite image and interpretation of the western part of Gargaf Arch (see Fig. 1b for regional context) and interpretation of a multigenerational series of tunnel valley incisions. From Le Heron & Craig (2008). (**b**) Undulating base of a tunnel valley in Jabal Eghei, eastern Al Kufrah Basin (Libya). Wiggly lines in (b–d) denote unconformities. (**c**) Down-cutting tunnel valley margin in Ghat, SW Murzuq Basin, Libya. (**d**) Palaeovalley flank on Gargaf Arch, Libya. (**e**) Detail of a substrate-palaeovalley fill contact on the Gargaf Arch, represented by the contact between green siltstone and sandstone. Note the highly irregular contact at the local scale, including metre-scale detached load balls. Photograph (b) from Le Heron *et al.* (2015); photographs (c) and (e) (previously unpublished) from Le Heron (2004); photograph (d) from Le Heron *et al.* (2004). (**f**) Sketch illustrating the contact between two superposed palaeovalley incisions in the Anti-Atlas, Morocco. Modified from Le Heron (2007).

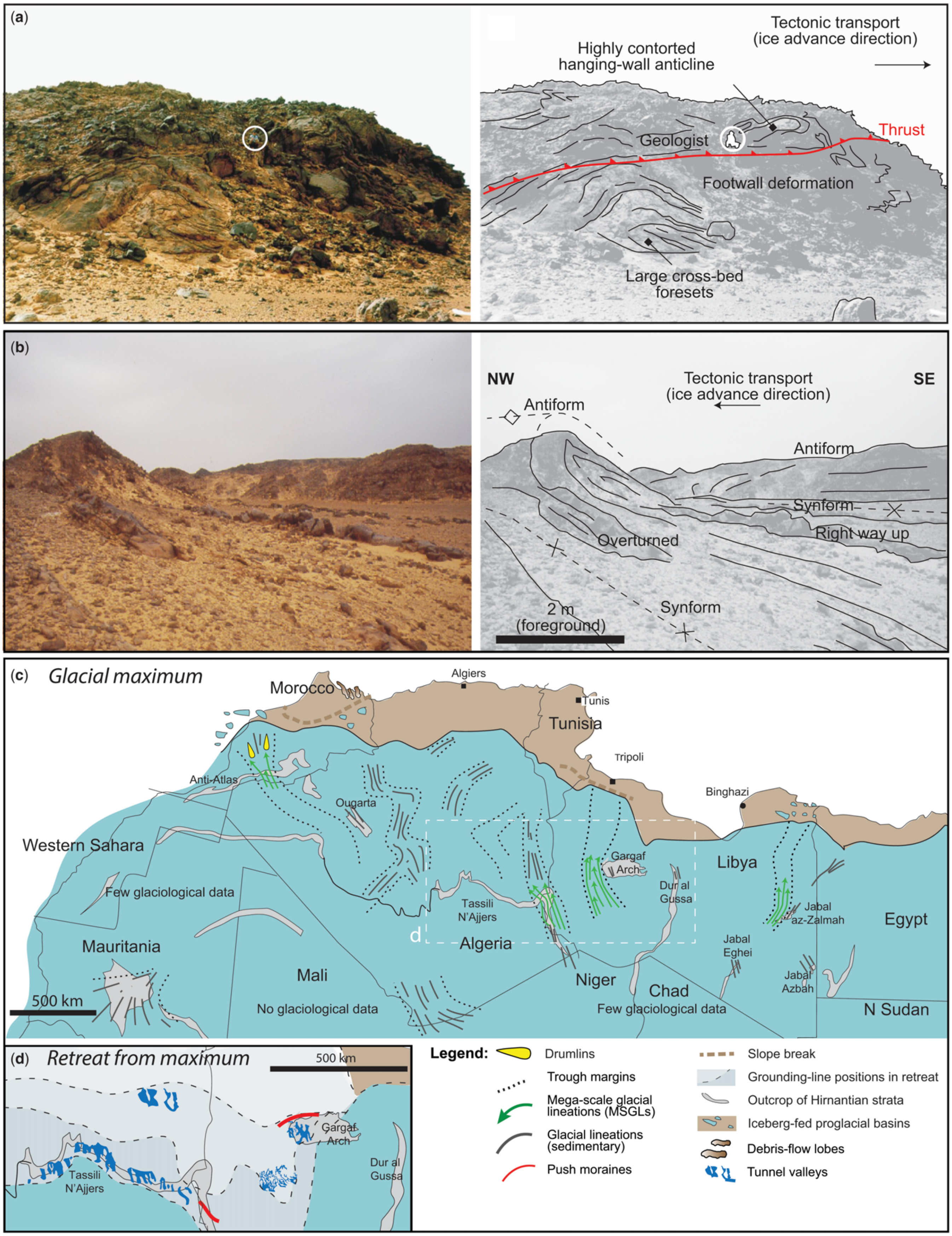

Fig. 4. Push moraine complex on Gargaf Arch, Libya and regional landsystem model for the Hirnantian ice sheet. (**a**) Low-angle thrust surface developed in cross-bedded sandstone. Note complex nature of folding in the footwall beneath the thrust. (**b**) Detail of tight to isoclinally folded antiform pair, separated by recessive synforms. Amplitude of the largest antiform reaches 30 m. Photographs (a) and (b) are from Le Heron (2004). (**c**) Landsystem sketch maps for Hirnantian ice sheets at the glacial maximum when a series of palaeo-ice streams were probably active, and (**d**) during retreat from this position when a regional network of tunnel valleys was incised. One of the key problems that persists with these models is the complete absence of Hirnantian strata over large areas (e.g. between Mourizidie and Jabal Eghei: see Fig. 1a–c). This will always make some parts of the palaeo-glaciological reconstruction speculative. Modified after Le Heron & Craig (2008).

Le Heron 2010), and the presence of kilometre-scale incisions can be deduced by sufficiently closely spaced well data (Lang *et al.* 2012). The proximity of an ice margin is also constrained by the presence of push moraines, which are well documented in the forefields of modern glaciers (Bennett 2001).

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