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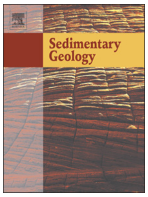

A world-class example of a Late Palaeozoic glaciated landscape in Chad

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ABSTRACT

Continental glacial deposits are rarely preserved in nature. Recent studies of the LPIA reveal the presence of periglacial deposits in Northern Chad covering an area of 20,000 km^2. Using satellite maps, this project managed to examine the entirety of the Ennedi Plateau. 3D reconstructions of this mountain range reveal complex glacial morphological features. This paper presents large-scale subglacial features interbedded with proglacial fluvial features and discussed the variables at play during the progressive, repetitive, and perhaps cyclical nature of the Carboniferous glaciation. Using remote sensing techniques, this paper shows that there are three major ice advance–retreat cycles that led to the deposition of mega-scale glacial lineations with a complex fluvial channel belt. Palaeo-geomorphological mapping of satellite images in northern Chad reveals that the Late Carboniferous Chadian ice sheet covered at least 20,000 km^2, a much greater extent than previously thought (ca. 6000 km^2). Glacial lineations (GLs) are dominant and extensive on the plateau. They are arranged in widespread ice stream networks and developed at multiple stratigraphic levels. This broadly indicates palaeo-ice flow to the north. We report a newly discovered pristine channel belt, covering at least 300 km^2 of a plateau in the Ennedi Plateau. A swarm of N–S trending channels, up to 250 m wide, is recognised. These are of both braided and meandering characters and are organised into channel belts of up to 500 m width. The mapped palaeo-morphology shows complex crosscutting relationships. The channel belt is intercalated with zones of GLs; hence, ice activity preceded and succeeded fluvial activity. Preserved planform sinuous channel geometries show distinctive point bar deposits and scroll bar geometries therein, which testify to a terrestrial, subaerial environment, rather than to their evolution in the subglacial realm, e.g. as eskers. Therefore, we find that cross-cutting, amalgamated channel systems record the complex phases of meltwater release during glacial retreat in the advance–retreat cycles of the Late Palaeozoic Ice Age in Chad.

1. Introduction

The Ennedi Plateau of northern Chad exhibits an extensive archive of Late Palaeozoic subglacial landforms on sandstone plateaux (Fig. 1A, B) (Le Heron, 2018). Until now this area has been subject to comparatively little investigation with only a first order geological framework and an overview geologic map available in the public domain (Wolff, 1964). Reconnaissance geological fieldwork has recently resumed at the far western extremity of the Ennedi region, where focus is on the record of the Late Ordovician glaciation and establishing a robust stratigraphy for the first time (Ghienne et al., 2023). Together with the Aïr region in Niger (Lang et al., 1991), the Ennedi Plateau is one of only two areas in northern Africa where evidence for Late Palaeozoic Ice Age (LPIA) deposits is known to be preserved. In Niger, ground trothing revealed evidence for soft-sediment striation surfaces and fluvioglacial deposits (Lang et al., 1991) which is an important anchor point for any discussion of LPIA glaciation in the Sahara because outcrops in Chad remain very difficult to access. This is in contrast to southern Africa where well preserved glacial deposits are widespread (e.g. Visser, 1997; Dietrich and Hofmann, 2019), but probably younger (Latest Carboniferous; Griffis et al., 2021). Well-exposed, shallow-dipping outcrops extend hundreds of kilometres along strike and are ideal for satellite image mapping. Whilst studies of ancient glacial and proglacial environments in the Palaeozoic have been built around traditional outcrop analysis (e.g. Frank et al., 2014) with few exceptions (e.g. Beuf et al., 1971), satellite imagery has been widely used to complement and enhance prior studies, e.g. in Uruguay (Assine et al., 2018) and Namibia (Andrews et al., 2019). Satellite imagery is available for analysis. These datasets play a powerful role in determining the

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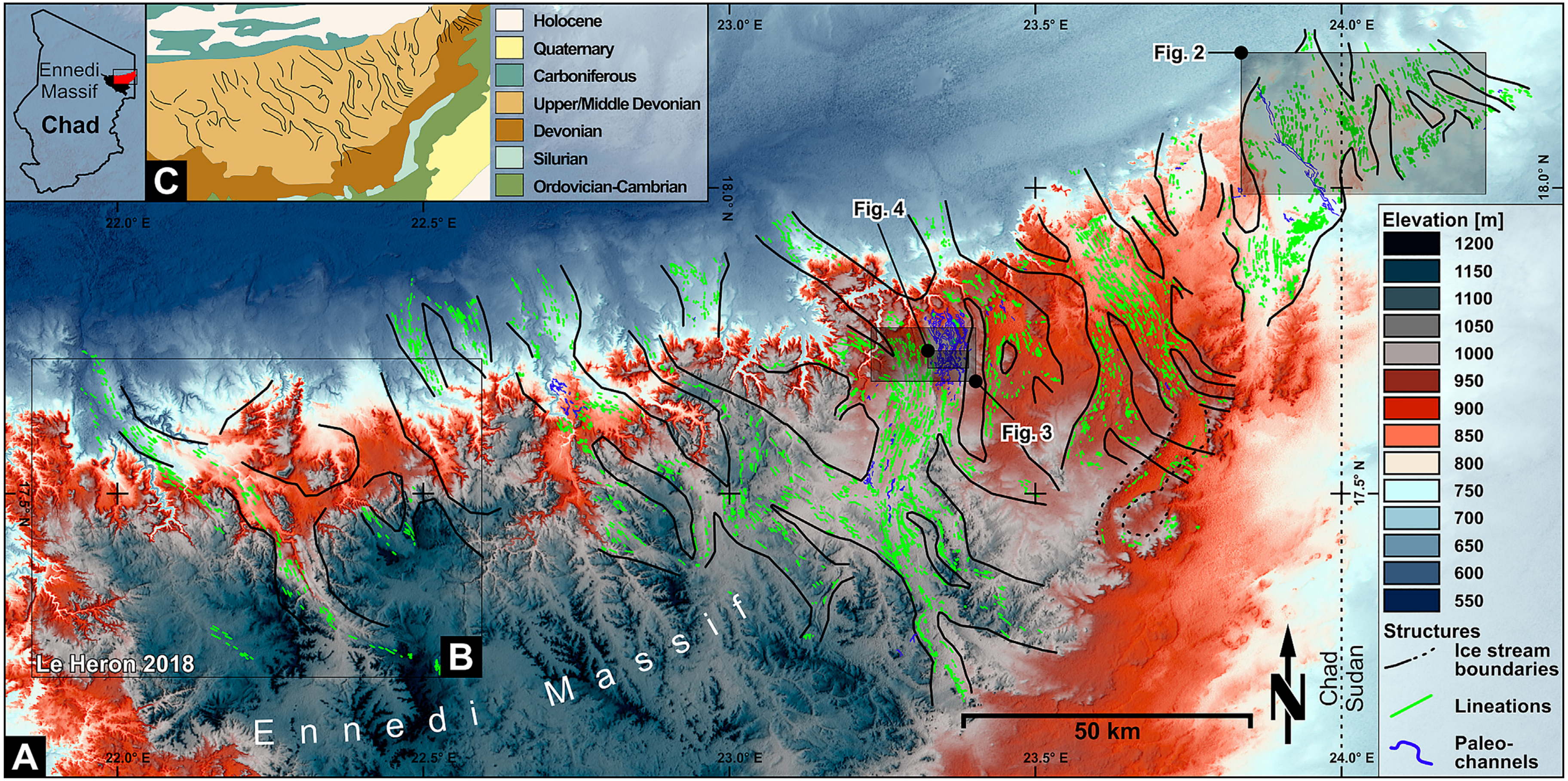

Fig. 1. False colour image based on Shuttle Radar Topography Mission (SRTM-1 Arcsec) of the Ennedi Plateau with mapped glacial lineations (GLs) and ice stream boundaries developed on Devonian deposits (A), inset images correspond to Figs. 2, 3 and 4. Area mapped in this paper shown next to the area mapped in Le Heron (2018) (B). (C) Geology after Persits et al. (1997).

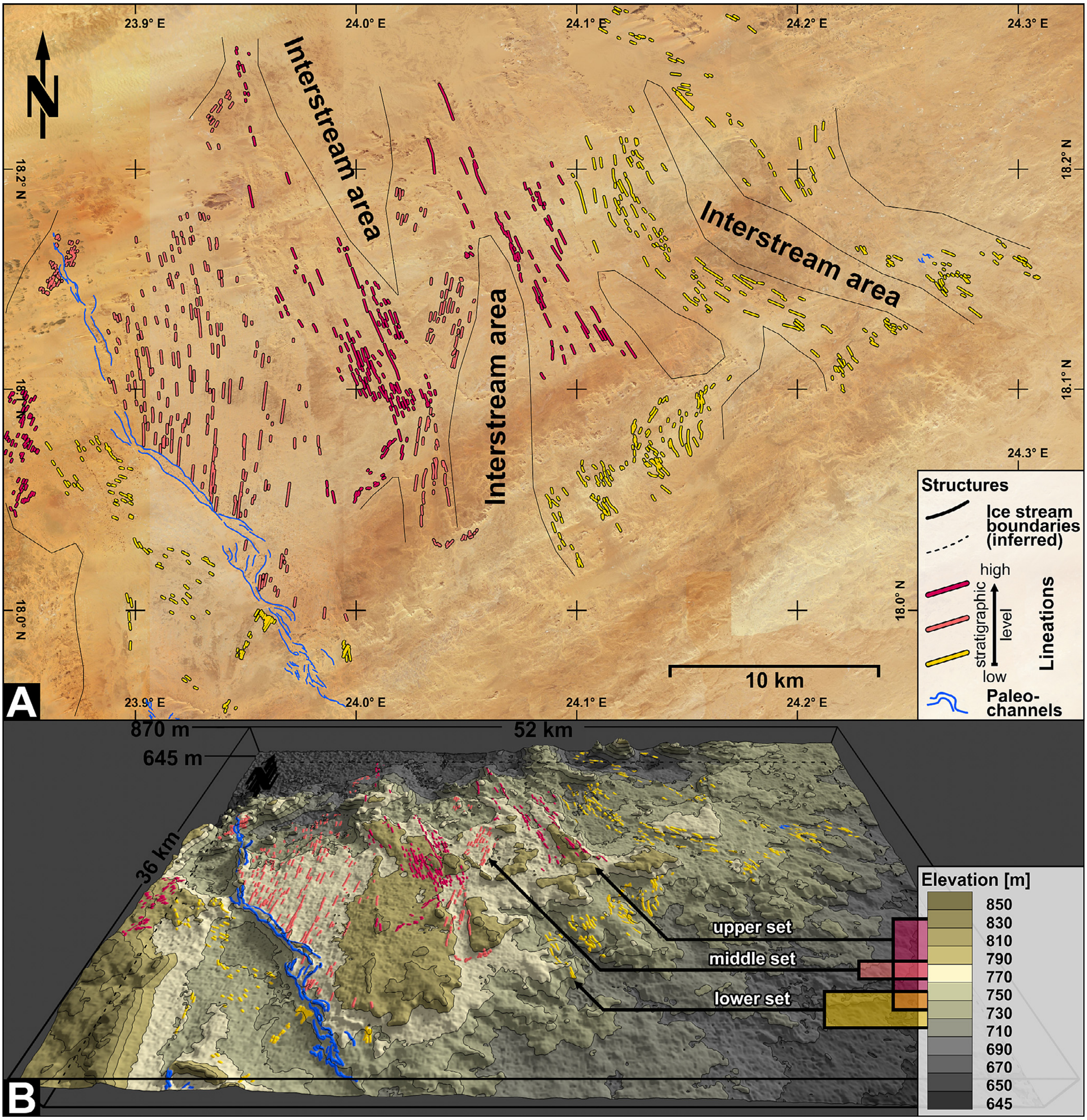

Fig. 2. (A) Satellite image (Microsoft BingMaps) with mapped GLs, grouped according to the stratigraphic level they occur on. (B) SRTM data converted to a 3D-Model of (A) highlighting the stratigraphic relationship between colour coded sets of GLs.

character of flow and meltwater release in ancient ice sheets. At outcrop, prior studies of LPIA glacial landscapes have tended to be relatively localised, concentrating for example on subglacial deformation in soft sediment (e.g. Vesely and Assine, 2014; Le Heron et al., 2019), together with detailed characterisation of glacial bedrock terrains (Isbell et al., 2023). To date, the role of meltwater in the formation of glacially related unconformities in the LPIA is often unclear. In this case, satellite images can play a powerful role in characterising the patterns of meltwater release and distribution in the LPIA record, that is simply not achievable at the local outcrop context. Large-scale glacial sediment landform assemblages are well documented from the Tibesti of the Libyan–Algerian border areas, including palaeo-ice streams (Moreau et al., 2005), tunnel valleys and channel-dominated proglacial systems (Girard et al., 2015; Bataller et al., 2021). These studies set an excellent precedent for LPIA investigations.

The aims of this paper are:

(1) Provide the first high quality, regional map of a glacial landsystem preserved in the Ennedi Plateau from satellite data.
(2) Document a complex set of palaeo-channels exposed in inverted relief.
(3) Present a tentative evolutionary model for the landsystem in terms of glacial cycles.

In so doing, we present new findings on the lateral transition from subglacial to proglacial settings, a relationship that is commonly very

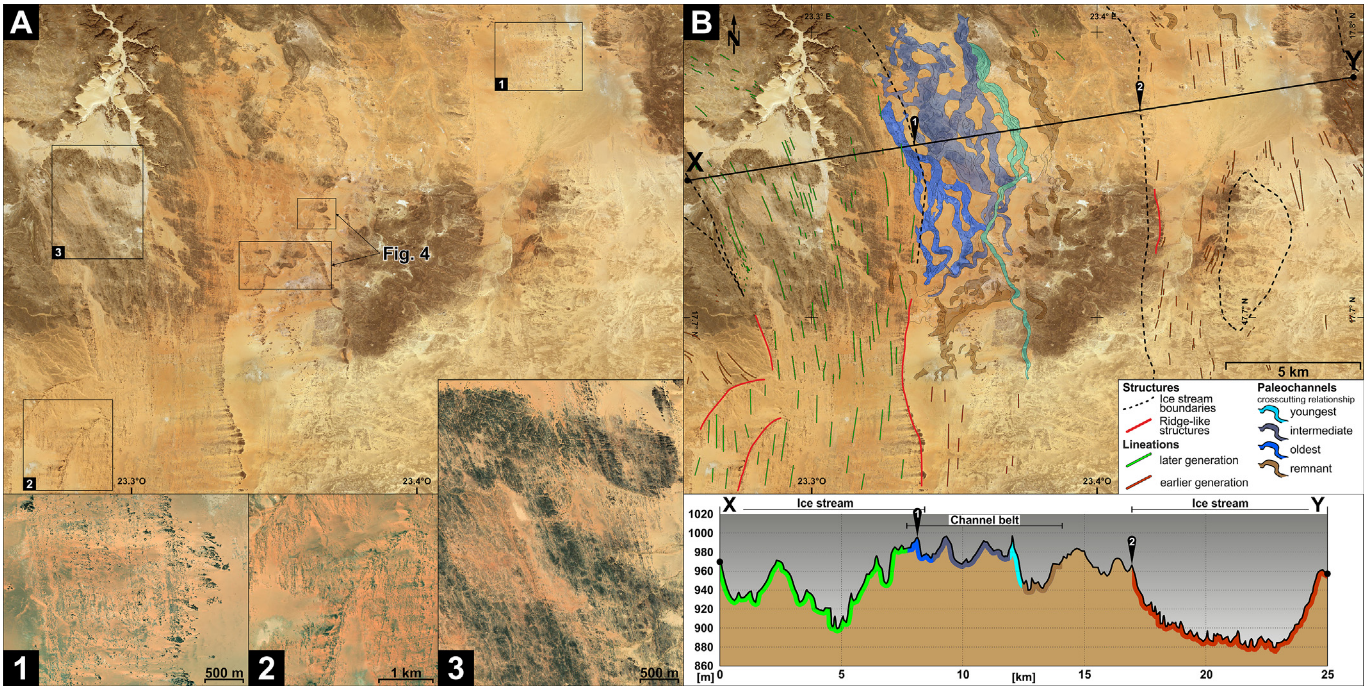

Fig. 3. Relationship between palaeo-ice stream tracks with their glacial lineations and associated inverted channel structures. Location of this area is shown in Fig. 1. A: Non-interpreted satellite image (Microsoft BingMaps) with specific features highlighted, and with zoomed-in areas as follows. Feature 1 shows N–S oriented, parallel glacial lineations; feature 2 shows a ridge-like structure representing a boundary between two sets of lineations, whereas feature 3 illustrates curvilinear structures. B: Interpreted satellite image, showing evidence for discrete channel generations crosscutting each other, together with the relationship between different generations of glacial lineations. The corresponding cross section (based on SRTM elevation data), drawn orthogonal to the main lineation orientation, illustrates the different present-day elevations at which each of the features occurs. A wide variety of channel forms can be observed, including sinuous and braided types, and multiple crosscutting relationships in the central area alongside isolated channel remnants. Note that in contrast to the palaeo-ice stream tracks, which occupy present day depressions, the channel belt sits on a regional high. The area shown in this map is used as template for the depositional model in Fig. 5.

obscure in the deep time record (Moreau et al., 2005) as the record is typically poorly preserved or obscured in satellite images. We explore the origins of the palaeo-channels and consider the role of meltwater production. We interpret the palaeo-channels to represent the development of proglacial sandar.

2. Methodology

Planform mapping and spatial analysis of 20,000 km^2 of the Ennedi Plateau were undertaken using satellite imagery acquired from BingMaps (Microsoft Corporation, 2023) and elevation data acquired from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second maps (U.S. Geological Survey, 2023) with a resolution of 30 m/pixel. These images are freely available in the public domain for examination. The SRTM images were processed in QGIS to generate digital elevation models (DEMs) at different scales. The study-area consists of sub-horizontal to gently northward dipping plateaux, exposing bedding surfaces over hundreds of kilometres. The mapped area straddles strata mapped as middle to Upper Devonian (Wolff, 1964), but which are otherwise undifferentiated. Features mapped at the regional (small) scale include linear structures on different topographic levels on the plateaux. Crosscutting relationships were noted and differentiated, in particular faults and fractures crosscutting the linear structures were used to differentiate between these and tectonically produced features. Establishing the crosscutting relationships then allowed a tentative sequence of events to be elucidated.

3. Data

3.1. Description

Systematic mapping of the Ennedi Plateau shows an extensive set of structures. They are extending over more than 250 km along from E to W (Fig. 1). We recognise sets of glacial lineations of approximately 5–15 km in width and 20–100 km in length, organised within palaeo-ice stream pathways. On the large scale these have sharp boundaries (Fig. 1). The palaeo-ice stream tracks cover approximately 30 % of the Ennedi Plateau. A broad NW–SE trend for the palaeo-ice streams is recognised. However, tributaries feeding into large (10–15 km wide) trunk ice streams are also documented (e.g. centred on about 17.84°S, 23.62°E: Fig. 1). The glacial lineations themselves are elongated, ridge like structures, ca. 10–100 m in width and ca. 500–1000 m in length,. Crosscutting relationships can be demonstrated across the plateau, with multiple sets of glacial lineations recognised (Fig. 2A). An important observation is that these lineations occur at different stratigraphic levels (Fig. 2A). Some palaeo-ice stream margins are characterised by a sharp, ridge-like margin, whereas others are demarcated by palaeo-channels as described below.

In the inter-stream areas, and locally at the boundaries between sets of glacial lineations, palaeo-channel belts are preserved (Fig. 1). Individual palaeo-channels occur in positive (i.e. inverted) relief. At the regional scale (Fig. 1), the largest of the palaeo-channel belts consists of broadly N–S palaeo-channels, running broadly parallel to the GLs and the enclosing palaeo-ice streams. The northern part of this channel belt is shown in detail in Fig. 3. At this scale, based purely on the visual spectrum satellite image data (see Wohlschägl et al., this volume, for more detail), 4 generations of palaeo-channels can be elucidated, with clear crosscutting relationships. Surprisingly, the palaeo-channels occupy relatively elevated areas, with palaeo-ice streams and GLs ca. 30–70 m below them in adjacent, topographically low-lying areas (Fig. 3). The longest individual palaeo-channels attain 8 km in length and are a minimum of 5–8 m deep, as measured from the base to the crest of the inverted features.

Planform morphologies include sinuous single-thread channels and braided channels, which exhibit numerous crosscutting relationships (Fig. 4). At the metre-scale resolution, palaeo-channels display bank-attached bar architectures. Channel bars and sharp margins between

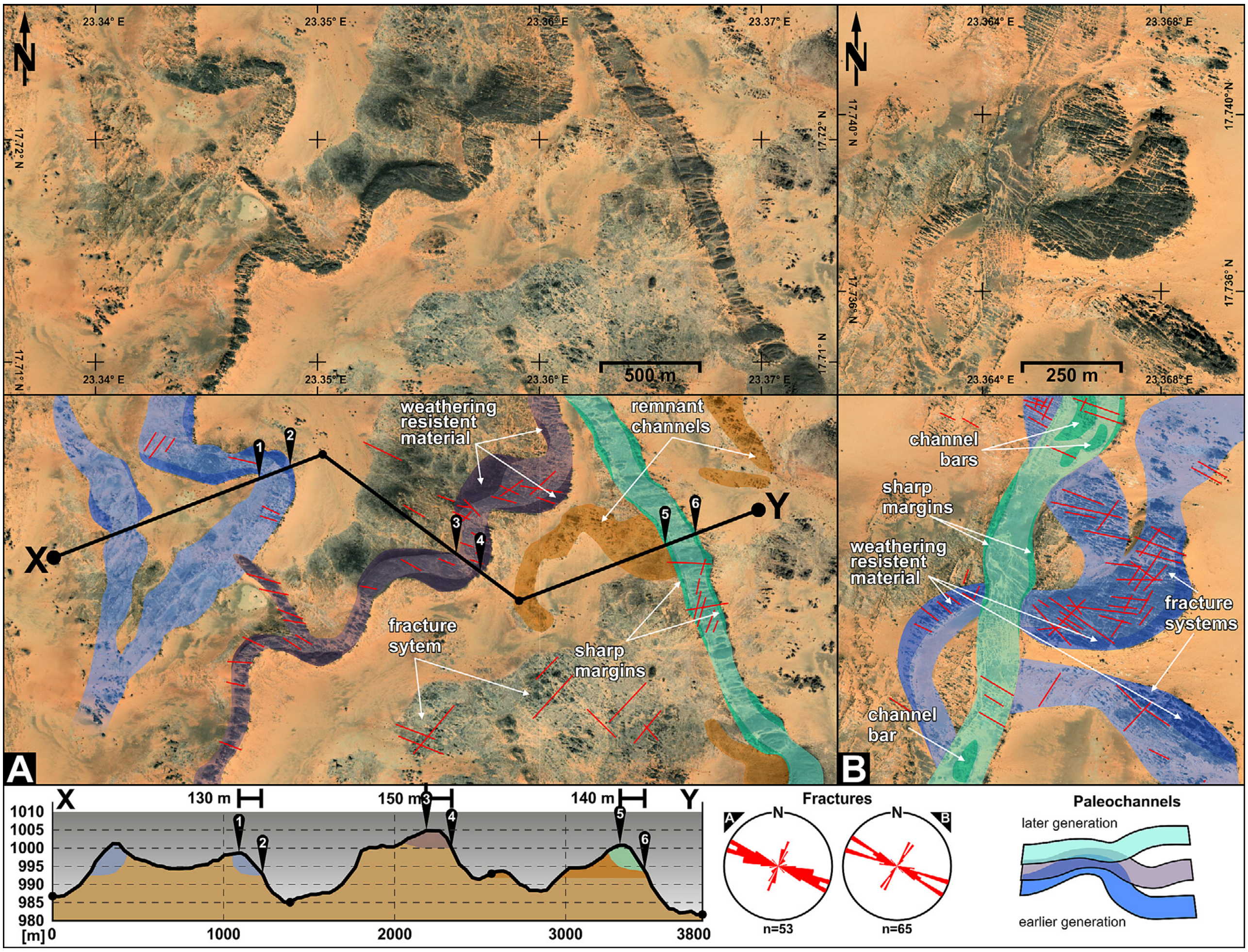

Fig. 4. Close up view of satellite image (Microsoft BingMaps) with associated interpretations shows three discrete channel generations crosscutting each other and corresponding cross section (based on SRTM elevation data) for (A) (based on SRTM). Darker shades of each colour for the associated channel generation show features of internal architecture, where the rock is more resistant to weathering and thus highlights lateral and channel-internal variations in the rock texture. All exposed rocks show a WNW–ESE and NNE–SSW-trending fracture pattern, highlighted in rose plots for (A) and (B). See Fig. 3 for precise location. Note that the cross-section demonstrates unequivocally that the channel forms are set in positive relief with respect to the surrounding desert plain.

channel bodies and the surrounding sediment are observed (Fig. 4). Cross-sectional profiles of bends in single-thread systems are markedly asymmetrical (Fig. 4). Abundant fracture sets cross-cut these palaeochannels, and show pronounced WNW–ESE and secondary ENE–SWS orientation (Fig. 4). These crosscut not only the stratigraphy in the study area, but also under- and overlying strata. The fractures do not appear to have an obvious relationship to palaeo-channel orientation.

3.2. Interpretation

Mapping of the Ennedi Plateau greatly extends the known area of the LPIA ice sheet record in northern Africa. For the first time, the recognition of multiple sets of GLs at different stratigraphic levels is demonstrated, implying multiple phases of subglacial erosion and deposition. This stands in contrast to earlier interpretations where sinuous, parallel structures were recognised, but assignment to multiple events or timing could not be established (e.g. Le Heron, 2018). The recognition of crosscutting domains, expressed by differently oriented flow sets at each stratigraphic level, probably implies the development of multiple bedform populations suggestive of time-transgressive ice stream evolution (Stokes and Clark, 2001, their Fig. 8). Crosscutting domains on individual stratigraphic levels could be interpreted via two alternative models. In the first, multiple (re) advances in separate glacial cycles adequately explain crosscutting relationships. In the second model, oscillation of the ice margin in a single glacial cycle is invoked. We tentatively favour the first model, because individual domains are separated by an estimated 10 to 20 m of sediment (Fig. 2B), which can better be explained by accumulation during separate glacial cycles (stadial following interstadial), rather than short-lived oscillations. On the basis of our mapping, we recognise three separate stratigraphic levels of GLs, inferred to correspond to individual phases of ice stream development in the Ennedi Plateau, possibly related to three major glacial advances (Isbell et al., 2023). The crosscutting relationship between GLs in the different sets testifies to significant changes in the direction of ice movement in successive glacial cycles.

The palaeo-channel belts contain several features, resembling bar-like structures, meandriform appearance and cross-cutting relationships that permit detailed evaluation. The bank-attached bar architectures are interpreted as point bar deposits. This suggests that the channels likely meandered. Scroll-bar structures prove a meandering history. Individual bends in the preserved channel deposits are found to have been laterally accreting and translating downstream (Fig. 4). In cross-section, some of the single thread channels exhibit differential erosion, which may be interpreted as a signal of heterogeneous deposits within the channel, whereby subtle lithological differences have affected the durability of the resulting outcrop. The interpreter must, however, be aware of the inverted relief scenario which we interpret as follows. In an initial phase, channels were cut into a soft substrate that was then filled with fluvial material. These deposits were then buried and lithified. Finally, subsequent uplift and exhumation of the unit has exposed the outcrop, hence enabling its weathering and erosion, particularly of the sediment in between channels. In the Palaeozoic of the Sahara, this process of inverted channel development has many precedents, for example by direct comparison to Ordovician channels exposed in Mauritania, Algeria or Libya (Ghienne and Deynoux, 1998; Girard et al., 2012; Deschamps et al., 2013). The sharp palaeo-channel margins should be interpreted with caution, but it is proposed that these record the effects of preferential cementation. Such phenomena are associated with high permeability deposits and have been described from other ancient inverted channels in Utah (Pain and Oiler, 1995; Clarke and Stoker, 2011). The timing of the pervasive fractures that crosscut the palaeo-channels cannot be determined, other than to conclude that they are later features. Nevertheless, a structural influence on the channel pathways can likely be dismissed. Had the fractures already existed prior to channel incision and subsequently been reactivated, an influence on the orientation of meanders (for example) would be expected, and this is not the case.

The explanation of inverted relief for the palaeo-channel bodies removes the need for interpretation of eskers beneath an ice mass (e.g. Beaud et al., 2018). Further, the highly meandriform palaeo-channels in the Ennedi contrast more generally with eskers which are typically low sinuosity ridges (e.g. Stoker et al., 2021). Instead, the presence of both braided and sinuous channel planform morphologies testifies to a highly dynamic system with variable discharge and sediment load, and characterised by cannibalisation via avulsion and repeated lateral migrations of meander bends over the floodplain. The elevated position of the largest palaeo-channel belt on a plateau flanked by GL-bearing palaeovalleys (Fig. 3), poses no paradox if these features were cut at different intervals. Two hypotheses for this exist, which can only be fully resolved through fieldwork. These are (i) that the palaeo-channel complex formed first and was then dissected by an ice stream by progressive incision and regional terrace development, or (ii) following an earlier phase of ice stream incision (forming the GLs) a package of strata was deposited into which the palaeo-channel complexes were cut. This latter model would imply that the flow was on the palaeo-highs.

Exploring the origin on the palaeo-channels further, we contend that the collective geometry of these structures provides affirmative evidence for genesis in a subaerial, as opposed to a subglacial setting. Thus, we suggest that they represent the evolution of a large proglacial sandur system (Magilligan et al., 2002; Marren et al., 2009). Note, however, that there are other contexts in which channels could develop in a glacial setting that need to be considered; e.g. in a subglacial environment. Beneath modern ice masses, sinuous meandering “channels” appear on numerical models of the northern part of the Greenland ice sheet, although it is acknowledged that this is a non-unique solution (Chambers et al., 2019, their Fig. 4).

Meandering channels also occur on the surface of many glaciers (Karlstrom et al., 2013). Note that the preservation potential of these in the rock record is nil. Furthermore, it would be hard to reconcile the crosscutting relationships in Fig. 3 or 4 with such an origin. Subglacial drainage is complex to model (Rada and Schoof, 2018; Chambers et al., 2019), and well developed zones of multigenerational, meandriform channels are unexpected. This is because the confining pressure of overlying ice would suppress the development of meandering channel bodies. Thus we firmly reject a subglacial origin of these channels in the Ennedi.

We propose that the channels represent a vast proglacial drainage plain or sandur. Modern sandar, such as those in northern Iceland, archive not only the products of steady state processes such as channel belt development, but also sheet flood deposits, hyperconcentrated flow deposits and debrites produced during jökulhlaup release (Marren et al., 2009). These processes conspire to produce highly complex, braided, anastomosing, and meandering planform geometries. In addition to recording wide incisions resulting from the 1999 jökulhlaup in Iceland (Russell et al., 2010), the current forefield of Solheimajökull, for example reveals complex fluvial meandering geometries with scroll bar deposits that developed in sand and gravel. These structures result from the lateral migration of channel systems, and rule out their development beneath an ice mass. Furthermore, the full spectrum of geometries is also known from the Late Ordovician record in the Sahara (Girard et al., 2012; Deschamps et al., 2013) and is well studied in quaternary glacial environments (e.g. Maizels, 1993).

4. Discussion

4.1. Timing of events

Based on our mapping, we suggest that the glacial record of the Ennedi contains sediments made up of different stratigraphic levels. This was produced by multiple glacial advances and subsequent development of proglacial drainage systems. In order to explain and visualise the stratigraphic development of the region, we present a sequential model of block diagrams (Fig. 5). Glacial lineations are abundant and these are organised into multiple flow sets. Bounding palaeo-ice streams can be mapped, and spectacular palaeo-channel complexes are described. Interpretations of crosscutting relationships together with the elevation data allow a tentative chronological model for the evolution of the Ennedi Plateau to be proposed (Fig. 5A–F). Glacial re-advances cut across earlier-formed channels, now preserved as remnants within ice stream pathways. This phenomenon occurs at multiple stratigraphic levels (see Figs. 1 & 3). An earlier advance (Advance 1 in Fig. 5) resulted in a northward-directed widespread glaciation of the Ennedi Plateau. Corresponding terminal moraines (see Fig. 3) record the ice front recession during this stage (Fig. 5B). Diachronous development of the prominent channel network followed this recession. This (glacio)fluvial package partially overlies the subglacial lineations illustrating a northward directed glacier drainage and southward directed recession. The variety of channel forms, their spatial dimensions and crosscutting relationships to each other indicate a relatively persistent period of ice-free conditions allowing the transformation of a sandur-like system into a meandering river system. Following this phase, a re-advance (Advance 2 in Fig. 5) overprinted both fluvial and pre-existing subglacial facies. This advance–retreat cycle (Fig. 5C & D) cuts into soft sediments, which accumulated during the preceding intra/interglacial. The width of the ice stream is traced by associated flanking lateral moraines implying a limited lateral extent of the glacier during this cycle. On satellite images, these structures are discernible as distinctive ridges in the present day geomorphology. Given that uplift and erosion affected the Ennedi Plateau on a regional scale in a uniform way, denudation exhumed ice stream pathways of at least two glacial periods and removed possible traces of Advance 2 (Fig. 5E & F).

4.2. Glacial cycles

Because GLs show different orientations on each plateau level, we propose that each plateau preserves a separate phase of glacial erosion. Therefore, GLs in the Palaeozoic record cannot be seen in terms of scaled-up, self-similar versions of smaller scale lineations as previously suggested by Le Heron (2018). This suggests that the different flow sets represent individual events rather than a single advance that led to their formation. Instead, on the basis of the crosscutting relationships of the GLs, we suggest three discrete glacial cycles to be recognised (see Fig. 2).

It is unclear, without detailed fieldwork in the region, whether the GLs at the lowermost elevations are oldest or youngest. Support for the former interpretation might come from the similar geomorphology of the Late Ordovician record at the Libyan–Algerian border, whereby younger glacial rocks onlap lower and older glacially striated surfaces (e.g. Moreau et al., 2005). This idea is supported by several tens of metres of intervening stratigraphy between the subglacial surfaces on the Ennedi Plateau. Markedly, this interpretation works in the opposite sense to that of many modern Alpine landscapes, which carved terraces deeper and deeper levels (Reitner et al., 2012). The timeframe over which these cycles developed and their connection to potential global sea level cycles observed at low palaeo-latitudes (e.g. Davies, 2008)

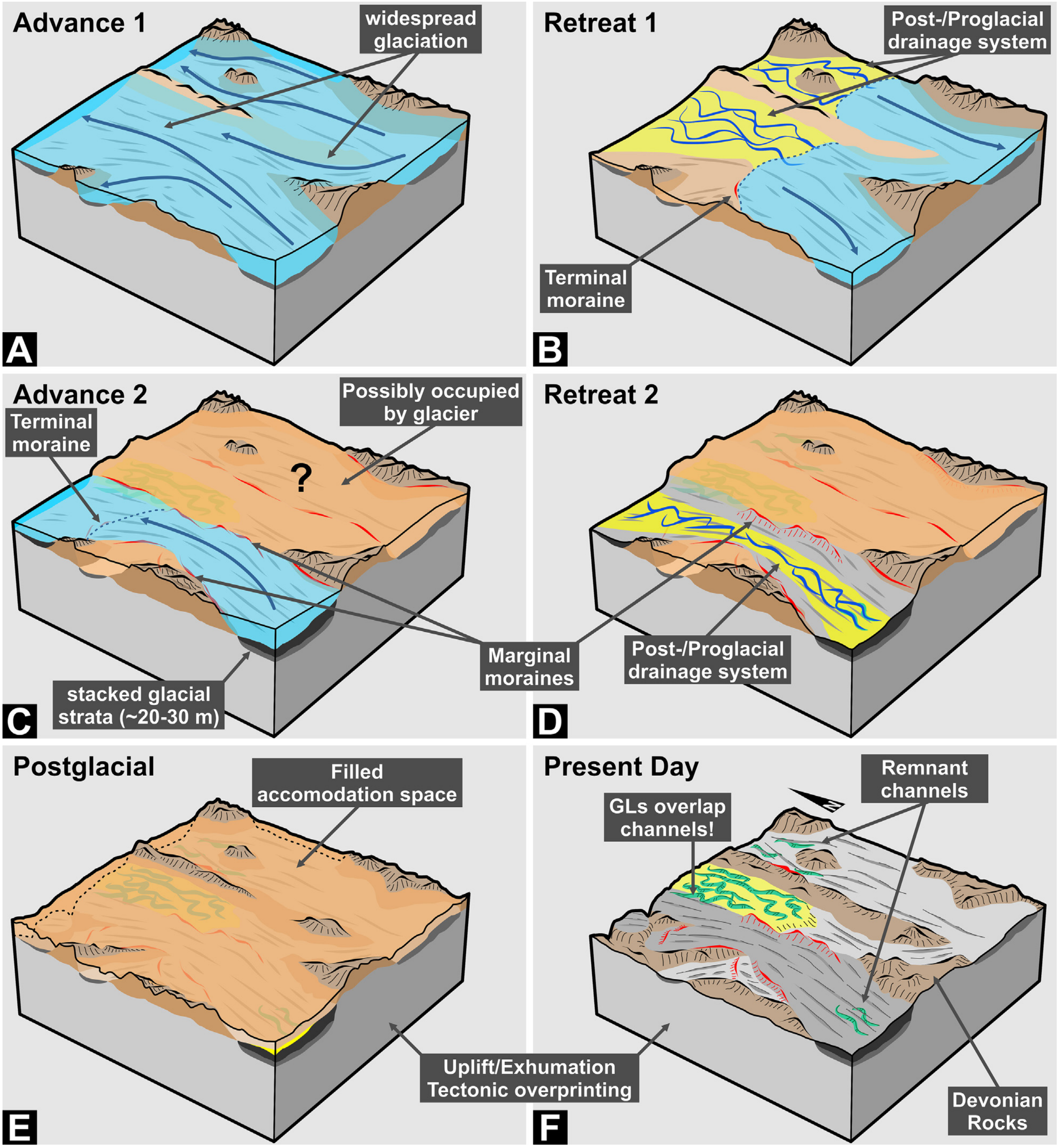

Fig. 5. Temporal and spatial evolution (A–F) of the area containing the channels (note Fig. 3). Step A: Earlier advance with widespread glaciation during the LPIA. Step B: Development of a glaciofluvial drainage system that is associated with ice retreat and predates Advance 2 of step C. Note that channel remains do also occur in the eastern ice stream in Fig. 3. Step C: Subsequent advance of ice that potentially occupies former glacier-pathways. Glacier is overriding glaciofluvial channel system (possible traces of ice streams within this advance might have been eroded). Step D: Postglacial drainage system of a later retreat-phase (note channel remains in the ice stream in Fig. 1). Step E: filled accommodation space (note that this stage symbolises a stretch of several million years), affected by denudation via uplift leading to F. Step F visualises present day morphology and exhumed facies associations. Light grey: subglacial facies of an earlier advance, dark grey: exhumed subglacial facies of a later advance, red: ridge-like structures potentially representing terminal and marginal moraines, yellow: (glacio) fluvial facies postdating individual advances, green: channels, light blue: glacier, and orange: sedimentary rocks.

requires further study. Thus, attempts to correlate the phases recognised in our geomorphological analyses to cycles recognised in the Dwyka Group at the other end of the continent (South Africa: Dietrich and Hofmann, 2019) are premature.

4.3. The role of meltwater

The lateral relationships between the subglacial landsystem and proglacial landsystem are notable for two reasons. Firstly, except for a few channels crosscutting the youngest GLs, channel belts and GL belts occur in mutually exclusive, N–S oriented zones. This suggests that the meltwater system was initially controlled by strongly focussed, regional pathways that ran broadly parallel to regional ice flow. Furthermore, this relationship implies that palaeo-ice stream trajectories had minimal influence upon the meltwater systems (channel belts) that subsequently developed, and rather a tendency for the channel belts' former ice stream occupied areas. This would amplify the earlier suggestions of Le Heron (2018) that, given the likely occurrence of a coastline to the north of the study area (Torsvik and Cocks, 2013) the ice stream system did not primarily evolve in response to a topographic (basement) control, but rather by e.g. iceberg calving at the ice front (Winsborrow et al., 2010). Given the remoteness of the area and the continuing lack of access, additional controls on meltwater pathways as a result of basement heterogeneity must remain conjectural.

To the authors' knowledge, the landsystem described herein is the only known example of this age showing subglacial and proglacial deposits side-by-side with mappable relationships. The outcrop quality of the sedimentary record of the LPIA in SW Africa is excellent, with some outcrops of soft-sediment striated surfaces permitting detailed drone survey and insight into cyclic subglacial processes (Le Heron et al., 2019), however features such as striated pavements are highly fragmentary. In regions with similar mesa topography to northern Chad, such as the Mariental area of Namibia which also has an excellent record of LPIA glaciation (striated surfaces, boulder pavements, dropstone-bearing sediments: Stollhofen et al., 2000 and references therein), there is no evidence for similar structures on satellite images. In Uruguay, compelling evidence for erosional bedforms such as roches moutonées cut into crystalline basement is apparent on satellite images (Assine et al., 2018; Isbell et al., 2023), but features that might record subglacial (e.g. eskers) to proglacial meltwater release are conspicuously absent. The basal LPIA unconformity in Oman is locally striated in the Huqf, and this also lacks evidence for associated channel systems, rather being directly overlain by lacustrine deposits (Martin et al., 2012). None of these locations exhibit the range of structures, so widely preserved over a large area as the Ennedi Plateau.

5. Conclusions

- The Ennedi Plateau records a world-class example of a Late Palaeozoic landscape that shows the transition from a subglacial landsystem to a proglacial landsystem. On the basis of satellite image interpretation, the glacial record of northern Chad is now known to be of much greater lateral extent than previously thought (approximately 20.000 km^2 in this study vs. the 6000 km^2 in Le Heron, 2018);
- The first full map of the Chadian glacial landsystem is presented, with an extensive network of palaeo-ice streams, flow sets, and an exceptionally well-preserved suite of palaeo-channel belts;
- Mapping reveals that glacial lineations occur on three separate stratigraphic levels, some of which have clearly different flow-orientations and crosscutting relationships. This demonstrates the time-transgressive development of palaeo-ice streams, and allows a glaciation consisting of three individual cycles to be differentiated. Crosscutting relationships between GLs on individual glacial surfaces are also observed;
- Palaeo-channels of subaerial origin exhibit complex, crosscutting relationships, which testify to multiple phases of cut and fill. The palaeo-channels are in inverted relief, whose character is explained through a simple burial and diagenetic model rather than the need to appeal to an esker origin. Collectively, the wide range of channel geometries and relationships permits insight into the drainage patterns on a sandur in front of the Ennedi ice sheet.

Data availability

Data is fully available in the public domain, and can be.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All data are freely available to the public via Bing Maps (Microsoft Corporation, 2023).

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