An exhumed Paleozoic glacial landscape in Chad

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ABSTRACT
In northern Chad, an outcrop belt of Paleozoic rocks occurs in the Ennedi-Bourkou range. There, satellite image interpretation reveals a series of clearly expressed paleo–ice stream pathways, which are encased in sandstone plateaux. At least five paleo–ice stream pathways are recognized, measuring 5–12 km wide. Each contains well-expressed belts of mega-scale glacial lineations (MSGLs) with occasional drumlins. The paleo–ice stream tracks are confined to present-day low-lying areas, representing ancient valley networks, and have sinuous geometries. The features occur on multiple plateau and/or stratigraphic levels. Their dissection by late Neogene rivers discounts a modern-day origin as eolian features, and offset suites of MSGLs by east–west–striking faults confirms their geologic antiquity. The paleo–ice stream pathways appear to have drained a newly discovered late Paleozoic paleo–ice sheet of probable Visean age that flowed northward toward present-day Libya, with an estimated <250-m-thick tidewater ice margin. This discovery has wide-ranging implications, increasing the known extent of late Paleozoic ice sheets, and potentially their effects on sea-level changes.

INTRODUCTION
The late Paleozoic ice age (LPIA) is an outstanding record across Gondwana (e.g., Eyles, 2008) as diachronous ice sheets grew in response to weathering of the Hercynian mountains (Goddéris et al., 2017). For example, striated pavements formed both on hard bedrock (e.g., in South Australia: Selwyn, 1860; Oman: Braakman et al., 1982; Ethiopia: Bussert, 2010) and on soft substrates (e.g., in Brazil: Trostdorf et al., 2005; Fallgatter and Paim, 2017; Niger: Lang et al., 1991). Recognition in the late 1980s that soft beds deform beneath glaciers and also influence their flow character (Boulton, 1987; Boulton and Hindmarsh, 1987) has had a major impact on the interpretation of ancient glacier beds. It arguably played a key role in the paradigm shift at the turn of the millennium where paleo–ice stream pathways became widely recognized on the basis of mega-scale glacial lineations (MSGLs) and associated structures (Stokes and Clark, 1999, 2001). In the deep time record, the occurrence of ca. 443 Ma MSGLs was first proposed by Moreau et al. (2005) from satellite imagery in Libya. Following this precedent, in this paper I demonstrate the existence of a paleo–ice stream system in Chad of Carboniferous (probably Visean) age (Fig. 1). The evidence comes from freely available satellite imagery (Google Earth data) over the Ennedi-Bourkou range.

The Ennedi-Bourkou range defines the southern flank of the Al Kufrah Basin. No Paleozoic glacially striated surfaces of any type have hitherto been described from this area. In the Libyan portion of the basin, striated surfaces and glacial deposits are recognized in Jabal Azbah at the eastern flank of the basin (Late Ordovician; Le Heron et al., 2010) and in correlative strata in Jabal Eghei to the west (Le Heron et al., 2015). The character of striated surfaces is identical to those reported from more accessible areas (e.g., Deynoux and Ghienne, 2004; Le Heron et al., 2005; Denis et al., 2010; Girard et al., 2015). Apart from large-scale geological maps (Wolff, 1964), the Ennedi-Bourkou range is virgin geological territory.

DATA DESCRIPTION
A series of sandstone plateaux in the Ennedi-Bourkou region of Chad exhibit an array of curvilinear structures on satellite images (Fig. 2). Five main sinuous belts, 5–12 km wide, can be mapped, which together with interstream areas cover a total area of ~6000 km². The belts crosscut Carboniferous (Wolff, 1964) outcrop. They have sharply defined boundaries. There are several examples of “tributary” sets which converge into wider belts northward (Fig. 2). In other examples, some belts of lineaments in present-day valleys (at ~850 m above sea level [a.s.l.]) are deflected around hills at ~1100 m a.s.l. (Fig. 3). Individual belts can be traced and mapped over many tens of kilometers, and exhibit a general north-south trend. In general, the curvilinear structures in the belts are in a different orientation from the regional ENE-WSW trend of linear aeolian dunes (Fig. 2). In oblique view (Fig. 4), satellite image interpretation reveals a series of clearly expressed sandstone plateaux. The curvilinear structures lie on a surface that truncates dipping beds beneath it (Fig. 4A). Considering their lateral extent (Fig. 4B), the belts of curvilinear structures exhibit abrupt lateral terminations. In plan view (Fig. 4C), small oval hills locally sit alongside the curvilinear structures. Some are offset by east-west-striking faults or cut by modern-day wadis. The features occur on multiple sandstone plateaux, yet show comparable orientations (Fig. 4D).

DATA INTERPRETATION
The curvilinear structures are interpreted as MSGLs, recognized by their aspect ratio of >10:1 (Stokes and Clark, 1999), sharply defined belts of which are classic diagnostic indicators of paleo–ice stream pathways (Stokes and Clark, 2001). The associated oval hills are interpreted as drumlins, part of the same continuum of subglacial bedforms (Ely et al., 2016), which together represent erosional features (Eyles et al., 2016).
The network of paleo–ice streams, occupying present-day lows, also represents a series of ancient valleys. The local deflection of MSGLs around hills (Fig. 3) points to nunataks, with a maximum 250 m elevation difference between glacier bed and hill top. A glacial origin is preferred over a tectonic explanation on account of the sinuous nature of the belts over a wide plateau, and by considering analogous but older Late Ordovician paleo–ice stream systems (e.g., Moreau et al., 2005; Ghienne et al., 2007; Le Heron and Craig, 2008; Denis et al., 2010; Le Heron, 2016; Moreau and Ghienne, 2016). To the north of Ennedi-Bourkou, there is an extensive eolian deflation surface (e.g., Griffin, 2006). However, the dissection of the networks of MSGLs by wadis discounts a modern-day origin as eolian features. The truncation of successions of dipping strata (Fig. 4A) by the MSGL-bearing surfaces is strongly suggestive that they are of erosional character. The local offset of the MSGLs by east-west–striking faults (Figs. 2, 4C, and 4D) confirms their geological antiquity. In terms of MSGLs on multiple plateaux (Fig. 4D), there are analogs from the Late Ordovician record (Moreau et al., 2005). Two interpretations are possible: (1) they represent successive glacial cycles and the repeated occupation of the same paleodepression by ice streams, and (2) MSGLs formed by large-scale intraformational detachments and shearing of the deforming bed. In the latter model, MSGLs are seen as scaled-up versions of soft-sediment striated surfaces (Sutcliffe et al., 2000; Deynoux and Ghienne, 2004; Le Heron et al., 2005; Denis et al., 2010).

**IMPLICATIONS**

Based on my interpretations, I present the first documented case of paleo–ice stream flow sets from the LPIA, the first evidence for late Paleozoic glaciation in Chad, and one of the strongest lines of evidence for late Paleozoic glaciation in the Sahara. Visean (Lower Carboniferous) diamicites were recorded from Gilf El Kebir, Egypt (Klitzsch, 1983), although Le Heron et al. (2009) questioned their glaciogenic affinity. More compelling evidence came from the Air Plateau, Niger, where Lang et al. (1991) documented convincing striated pavements, dropstone-bearing laminites, erratics, kame terraces, and eskers in strata of Visean age. Striations supported a northwest to northeast ice flow. In Chad, we propose that ice flowed to the northwest on account of tributary systems joining trunk ice streams in the same direction (Fig. 2). In Chad, the age of the structures is constrained by them crosscutting Carboniferous strata: based on comparison to similar relations in Niger, it seems likely that they are also of Visean age. I thus present a tentative paleogeographic reconstruction (Fig. 5) showing a north-central African ice sheet draining to the north.

A tidewater terminus in northern Chad is supported by a close match to the paleoshoreline of Torsvik and Cocks (2013) for the immediately preceding Tournaisian time slice (350 Ma). Thus a significant ice sheet at temperate paleolatitudes (~50°N on recent reconstructions; Montañez and Schmieder, 2007; Poulson, 2013; Fig. 5) can be interpreted. Given this, it is likely that the ice streams were either initiated or sustained by calving at the margin (Fig. 5) (e.g., Winsborrow et al., 2010). No evidence for eskers or other fluvial channels (apart from modern wadis) occur in the paleo–ice stream tracks, thus implying that there was no role for preexisting drainage in promoting fast ice flow (cf. Livingstone et al. [2017] for the Humboldt Glacier, North Greenland). The low estimated thickness of the ice based on the presence
of nunataks (<250 m) is also consistent with the ice streams occupying an ice-marginal domain, probably also supported by the oblique branching of ice stream tracks at the large scale (Fig. 2). The waxing and waning of the ice sheet would have influenced far-field cyclothem development on Laurentia (e.g., Davies, 2008).

Because diamictite distribution may not accurately reflect the size of LPIA ice sheets (Gonzalez-Bonorino and Eyles, 1995), paleo–ice stream systems such as those in Chad provide a high-quality check on ice sheet dimensions. Together, the occurrence of paleo–ice streams and inter-stream areas over ~6000 km² of desert, together with previously published glacial evidence from Niger (Lang et al., 1991), testify to an ice sheet of significant size.

CONCLUSIONS

The sandstone plateaux in the Ennedi-Bourkou range of Chad are characterized by curvilinear MSGLs. Beyond demonstrating the first evidence for LPIA glaciation in Chad, the exhumed glacial landscape provides the first substantive geomorphic evidence for LPIA paleo–ice streams and demonstrates the existence of a major paleo–ice sheet. Further belts of paleo–ice streams may await discovery in the late Paleozoic record.

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