Origin of the Mega-Streamlined Morphology in NE Africa and Arabia: Remote Sensing and Field-Based Investigations

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ORIGIN OF THE MEGA-STREAMLINED MORPHOLOGY IN NE AFRICA AND ARABIA: REMOTE SENSING AND FIELD-BASED INVESTIGATIONS

Mohamed Samy Mohamed Elhebery, Ph.D.
Western Michigan University, 2023

Mega-streamlined landforms on Earth and Mars have been attributed to aeolian, glaciogenic, fluvial, and tectonic processes. Identifying the forces that shaped these landforms is paramount for understanding landscape evolution and constraining paleo-climate models and ice sheet reconstructions. Exhumed Late Ordovician glacial deposits and landscape of the North Gondwana are reported here for the first time from SE Egypt. Using field and remote sensing (Advanced Land Observing Satellite [ALOS], Phased Array L-band Synthetic Aperture Radar [PALSAR] radar, multispectral Landsat TM datasets, and digital elevation models [DEMs]) I mapped the distribution of the Late Ordovician glacial features (i.e. deposits and landforms) in the SE Egypt. I identified two main glaciogenic facies in three locations in the SED: (1) massive, poorly sorted, matrix-supported, boulder-rich diamictites in Wadi El-Naam and Korbiai, and (2) more sorted, occasionally bedded outwash deposits in Betan area. Inspection of radar, DEMs, and Landsat OLI images revealed previously unrecognized ENE-trending glacial megalineations (MLs) over the peneplaned Neoproterozoic basement rocks in SE Egypt, whose trends align along their projected extension with those of glacial features (tunnel valleys and striation trends) reported from Saudi Arabia. These glaciogenic features are believed to be largely eroded during the uplift associated with the Red Sea opening, except for those preserved as basal units beneath the Nubia Sandstone Formation or as remnant isolated deposits within paleo-depressions on the basement complex. In the second part of this study, I present field and satellite-based evidence for a Late
Ordovician glacial origin for the ENE-trending mega-streamlined landforms in Arabia, that were interpreted to have been formed by Quaternary aeolian erosion. These streamlined features were exhumed during the Red Sea–related uplift. Then I use Late Ordovician paleo-topographic data to reconstruct the Late Ordovician ice sheet using identified and previously reported glacial deposits and landforms. My reconstruction suggests these glacial features are part of a major, topographically controlled, marine-terminating ice stream, with a minimum length of 1000 km extending from SE Egypt to northern and central Arabia and possibly more than twice this length if the glaciomarine and iceberg deposits in the present-day western Iran are part of this system. These observations support the continuation of the Late Ordovician (Hirnantian) ice sheet from the Sahara into Arabia through SE Egypt, which reinforces models advocating for a single, major, and highly dynamic ice sheet. My results also provide new morphological-based constraints for Late Ordovician climate models.
ORIGIN OF THE MEGA-STREAMLINED MORPHOLOGY IN NE AFRICA AND ARABIA: REMOTE SENSING AND FIELD-BASED INVESTIGATIONS

by

Mohamed Samy Mohamed Elhebery

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Geological and Environmental Sciences
Western Michigan University
August 2023

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ACKNOWLEDGMENTS

All the praise, thanks, and gratitude are to ALLAH, the lord of the worlds, who guided and helped me to bring this work to light. By His grace alone that this work has been completed.

I am deeply grateful to the many individuals who have supported me along my Ph.D. journey at WMU. First and foremost, I owe a debt of gratitude to my advisor, Dr. Mohamed Sultan, for his continuous support, motivation, and patience. This degree would not have been possible without Dr. Sultan's unwavering guidance and support. I feel truly fortunate to have had the opportunity to complete my Ph.D. under his mentorship. Dr. Sultan, I cannot express in words how grateful I am for your patience, guidance, and support, especially during difficult and uncertain times. You have done everything in your power to help me succeed, and I promise to pass on the knowledge and support I have gained from your lab to my future students. May Allah count all of them for your endless good deeds.

I am also extremely grateful to the late Dr. Alan Kehew, a member of my thesis committee, who passed away after making invaluable contributions to this research. Without his kind supervision and guidance, this research would not have been possible. I thank him for his invaluable contribution, insightful remarks, and the books he gave me during his last days at WMU.

I extend my sincere thanks to my thesis committee members, Dr. Peter Voice and Dr. Richard Becker, for their insightful comments, and follow-up on the progress of my research work.
I would also like to express my gratitude to my colleagues in the Earth Science and Remote Sensing Facility (ESRS) for their invaluable support, encouragement, and advice. Being part of the ESRS lab has been an honor and a privilege.

Above all, I want to dedicate this work to the soul of my beloved father, who played a pivotal role in shaping the person I am today. He, and my mother, have instilled in me many values, beliefs, and principles that have been essential to completing this degree and for all my life. Their unwavering support, guidance, and encouragement have been invaluable to me throughout my academic and personal journey. I am forever grateful to my parents, who bore, raised, taught, and loved me, and to my lovely sisters Marwa, Rania, and Doaa and my brother Mustafa, for their love and support.

Finally, I am forever grateful to my wife Gehad, my daughter Mariam, and my son Mousa for their love, understanding, and unwavering support throughout this journey. Without their belief in me, I would never have been able to achieve this milestone. It is time to celebrate this achievement, and I am grateful to share it with you.

Mohamed Samy Mohamed Elhebery
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CHAPTER I: INTRODUCTION

Introduction

Mega-streamlined landforms are widely described in glacial (subglacial MLs; Krabbendam et al. 2016) and eolian (mega-yardangs; Goudie 2007) environments. Given that these kilometer-scale streamlined features are easily identified from satellite images with adequate spatial resolution, their identification and mapping have been facilitated by the introduction of Landsat images in the 1980s (Clark 1993) and enhanced by the deployment of radar-based satellites that are sensitive to subtle topographic variations (Xiong et al. 2017). In this study, I mapped for the first time ENE-trending megalineations (MLs) in SE Egypt and NW Arabia using field observations and remote sensing datasets (Advanced Land Observing Satellite [ALOS], Phased Array L-band Synthetic Aperture Radar [PALSAR] radar, multispectral Landsat TM datasets, and digital elevation models [DEMs]). Since the MLs in SE Egypt are at a high angle to wind directions in Egypt, they cannot be interpreted as being yardangs. A possible alternative origin for these kilometer-scale streamlined features in SE Egypt is a glacial origin during the Late Ordovician. In this study, I will provide lines of evidence in support of the Late Ordovician glacial origin for these landforms. On the other side of the Red Sea, and along the postulated extension of these glacial MLs, similar ENE-trending streamlined ridges in NW Arabia over the Neoproterozoic basement of the Arabian Nubian Shield and the Cambro-Ordovician Saq Sandstone were misinterpreted as mega-yardangs (Brown et al. 1989; Vincent and Kattan 2006; Goudie 2007).

This is the first study that targets the Late Ordovician glaciation in SE Egypt and NW Arabia. Investigating these glacial deposits and subglacial landforms in SE Egypt and NW Arabia will
assist in identifying the Late Ordovician ice sheet occurrences, intensity, dynamics, and continuity across Africa and Arabia.

The Late Ordovician glaciation is one of the most enigmatic climatic events in the Earth’s history. The ice sheet initiation, duration, and extent of glaciation are subjects of debate. Estimates for the duration of Late Ordovician glaciation range from a short-lived (0.5–1 Ma) Hirnantian ice sheet (Brenchley et al. 1994; Sutcliffe et al. 2000) to a ~10 Ma event in which the Hirnantian represented the climax of a much longer glacial period (Finnegan et al. 2011) to a long-lived glaciation that was initiated in the Middle Ordovician (Darriwilian) age (Trotter et al. 2008; Pohl et al. 2016).

Dissertation Framework

Chapter I: this chapter provides an overarching perspective for the present dissertation, introducing the Late Ordovician Landforms in SE Egypt and NW Arabian, which form the focal point of this research. It outlines the dissertation framework and provides an overview of the subsequent chapters, offering readers a clear outline of the research ahead.

Chapters II and III of this thesis are written as independent research studies based on manuscripts, one of which has been published in the Journal of International Geology Reviews (Chapter II; Elhebiry et al., 2020), and the other has been published in the Journal of Earth and Planetary Science Letters (Chapter III; Elhebiry et al., 2022).

Chapter II: in this chapter I identify a previously unrecognized occurrence for the Late Ordovician glaciation in SE Egypt, an apparently significant missing part of the jigsaw puzzle of the Late
Ordovician glaciogenic deposits and exhumed subglacial kilometre-scale, streamlined features including megalineations (MLs) developed on the peneplained pavements of the Neoproterozoic basement complex, using integrated remote sensing interpretations and field studies. Then, I correlate the distribution of the Se Egypt glaciogenic deposits and linear features to those previously reported in other locations in the Sahara and in Arabia to examine the continuity of these features from Africa into Arabia (Elhebiry et al. 2020).

Chapter III: In this chapter, I integrate observations from remote sensing data, field work, and published geological maps to provide evidence of a Late Ordovician glacial origin for the mega-streamlined landforms in Arabia. I then overlay these landforms together with previously reported glacial deposits and landforms on a Late Ordovician paleo-geomorphologic reconstruction to identify one of the largest known terrestrial ice streams, hereafter referred to as the Late Ordovician Arabian Ice Stream (AIS). I show that my findings favor the single major LOIS model. Finally, I explain how these results could be used to constrain Late Ordovician climate models (Elhebiry et al. 2022).

Chapter IV: Provides a summary and conclusion of the thesis.

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CHAPTER II: PALEOZOIC GLACIATION IN NE AFRICA: FIELD AND REMOTE SENSING-BASED EVIDENCE FROM THE SOUTHEASTERN DESERT OF EGYPT

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Abstract

Exhumed Paleozoic glacial deposits and landscape of the North Gondwana are reported here for the first time from the South Eastern Desert (SED) of Egypt. Using field and remote sensing (Advanced Land Observing Satellite [ALOS], Phased Array L-band Synthetic Aperture Radar
mapped the distribution of Paleozoic glacial features (i.e., deposits and landforms) in the SED. Two main glaciogenic facies were identified in three locations in the SED: (1) massive, poorly sorted, matrix supported, boulder-rich diamictites in Wadi El-Naam and Korbiai, and (2) more sorted, occasionally bedded outwash deposits in Betan area. Inspection of radar, DEMs, and Landsat OLI images revealed previously unrecognized ENE-WSW trending glacial megalineations (MLs) over the peneplained Neoproterozoic basement rocks in the central sections of the SED, whose trends align along their projected extension with those of glacial features (tunnel valleys and striation trends) reported from Saudi Arabia. These glaciogenic features are believed to be largely eroded during the uplift associated with the Red Sea opening, except for those preserved as basal units beneath the Nubian Sandstone or as remnant isolated deposits within paleo-depressions on the basement complex. The spatial connection between reported glacial features to the well-defined Late Ordovician deposits in Saudi Arabia and their geographical position favour a Late Ordovician age of the reported glaciogenic features. These observations support the continuation of the Late Ordovician (Hirnantian) ice sheet from the Sahara into Arabia through the SED of Egypt.

**Introduction and Background**

During the Paleozoic, two main glaciation events have been reported from many locations within the Gondwana continent (Eyles 2008; Le Heron et al. 2009; Torsvik and Cocks 2013; Lewin et al. 2018). To date, the duration and the extent of the areas affected by these events are not fully understood. In the Late Ordovician, the Early Paleozoic glaciation was described as a restricted, short-lived (0.5–1 Ma) Hirnantian event (Brenchley *et al.* 1994; Sutcliffe *et al.* 2000), or as part of a longer lived (~10 Ma or more) event in which the Hirnantian glaciation represented the maximum cooling pulse (Saltzman and Young 2005; Finnegan *et al.* 2011). Regardless of whether the Late
Ordovician glaciation was a 1 or 10 Ma event, it was relatively short lived compared to the Late Paleozoic (Permo-Carboniferous event) that lived for tens of millions of years (>70 m. y.) (Eyles 1993; Scheffler et al. 2003; Eyles et al. 2006; Fielding et al. 2008; Isbell et al. 2012).

Many attempts have been made to reconstruct the paleogeographic extension of the Late Ordovician ice sheet (Ghienne 2003; Le Heron et al. 2004; Le Heron and Craig 2008; Torsvik and Cocks 2013; Lewin et al. 2018). Early reconstructions call for an extensive ice sheet across Africa, Arabia, southern Europe, and eastern South America (Ghienne 2003; Le Heron et al. 2004), whereas the more recent models propose separate ice sheets, a large one over North Gondwana and two smaller ice caps in South Africa and South America (Ghienne et al. 2007; Eyles 2008; Le Heron and Craig 2008; Torsvik and Cocks 2013; Lewin et al. 2018). While during the Permo-Carboniferous glaciation event, small isolated ice sheets with more complex distribution were proposed over the Gondwana continent (Eyles 2008; Isbell et al. 2012; Martin et al. 2012; Wopfner 2013; Lewin et al. 2018)

Late Ordovician glaciogenic features (i.e, deposits and landforms) are widely reported from northern Africa, northern Arabia, southern Turkey and western Iran, with largely complete absence of Late Paleozoic records except for the questionable report of Late Paleozoic tillites in the south Western Desert of Egypt (Klitzsch 1983). Both events (Early and Late Paleozoic glaciations) are represented in the northern Central Africa (Niger and Chad), Horn of Africa (Eretria and Ethiopia) and southern Saudi Arabia. While in southern Arabia (i.e, Yemen and Oman) only Permo-Carboniferous glaciogenic deposits have been reported (Figure 1 and references therein). The migration of the glaciogenic deposits south-westward during the Paleozoic glaciation events reflects the southern pole movement across the Gondwana from NW Africa in the Late Ordovician
to central Antarctica during the Permo-Carboniferous glaciation (Scotese and Barrett 1990; Torsvik and Cocks 2013). Throughout the postulated extent of the Ordovician glaciation, especially in northern Gondwana, a wide range of glacial deposits have been reported as well as subglacial landforms including mega-scale glacial lineation (MSGLs), tunnel valleys, and paleo-ice streams (Vaslet 1990; Armstrong et al. 2005; Denis et al. 2007; Le Heron et al. 2009; Ravier et al. 2015).

Figure 1: Location map.

Location map showing the reported Early and Late Paleozoic glacial deposits and landforms. (Late Ordovician: 1 through 28; Permo-Carboniferous from 29 to 38) from the northern Gondwana. (Ghienne and Deynoux 1998); 2. (Ghienne 2003); 3. (Le Heron 2007; Ravier et al. 2015); 4. (Le Heron and Craig 2008); 5. (Ghienne et al. 2007; Ravier et al. 2015); 6. (Lang et al. 2012); 7. (Le Heron et al. 2005); 8. (Le Heron et al. 2006); 9. (Le Heron et al. 2004); 10. (Denis et al. 2007); 11. (Le Heron and Craig 2008); 12. (Klitzsch 1978; Issawi and Jux 1982; Issawi and Osman 1996); 13&14. (Semtner et al. 1994); 15 and 16. (Issawi and Jux 1982); 17. (Kumpulainen et al. 2006; Kumpulainen 2008); 18. (Kumpulainen 2008; Lewin et al. 2018); 19.
In Egypt, the interpretation of the Paleozoic glaciation is controversial. Earlier detailed field studies documented the Late Ordovician glacial diamictites in the Western Desert and fluvioglacial deposits in the North Eastern Desert and in the Sinai Peninsula (Beall and Squyres 1979; Issawi and Jux 1982; Semtner et al. 1994). However, a few regional studies dismissed the presence of the Ordovician glaciation in Egypt (Le Heron et al. 2005; Ghienne et al. 2007; Torsvik and Cocks 2013), while others considered these deposits to have been eroded from the Central Eastern Desert (CED) and the SED during the Cenozoic (Vaslet 1990). One possible explanation for these conflicting analyses is that the regional studies were based on information extracted from regional maps, the majority of which omitted the Paleozoic outcrops, which are limited in distribution. On the other hand, the Permo-Carboniferous glaciation were reported only from the south Western Desert of Egypt (Klitzsch 1983) The stratigraphic position and hence the age of these deposits was later challenged by field and topographic interpretation in Issawi and Osman (1996).

In this study, I report for the first time evidence for the Paleozoic glaciation in the SED. Specifically, I identify glaciogenic deposits and exhumed subglacial kilometre-scale, streamlined features including megalineations (MLs) developed on the peneplained pavements of the
Neoproterozoic basement complex, using integrated remote sensing interpretations and field studies. I provide pieces of evidence that support a probable Late Ordovician (Hirnantian) age for these glaciogenic deposits. I correlate the distribution of the SED glaciogenic deposits and linear features to those previously reported in other locations in the Sahara and in Arabia to examine the continuity of these features from Africa into Arabia. These findings could potentially enhance the current understanding of the continuity of the Late Ordovician ice sheet along north Gondwana (from North Africa into Arabia) and the extension, dynamics, and intensity of the Early Paleozoic glaciation.

**Data and Methods**

Throughout two field trips between 2017 and 2018, I collected field observations of glaciogenic deposits and landforms in SED and described in detail their lithofacies associations. Next, I generated a GIS environment to host all relevant published (e.g., geologic maps) and generated data (field and remote sensing) to integrate observations extracted from these datasets and conduct spatial investigations and analyses. The GIS encompassed the following spatial datasets: (1) field observations, including (a) distribution of the glacial diamicrites at the contact of the Nubian Sandstone with the basement complex in Wadi El- Naam Area, (b) distribution of the remnant glacial diamicrites within the paleo-depressions in the basement complex at Korbiai area, and (c) location of the meltwater outwash deposits in Betan area; (2) published data, including (a) 1:250,000 geologic map (EGSMA 1996), and (b) 1:500,000 (EGPC-Conoco Coral 1987); and (3) remote sensing data, including (a) Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) data that was used for the delineation of large-scale morphological features (e.g., MLs), (b) multispectral images (bands 7, 5, and 3) extracted from Landsat 8 images for the validation of the radar-based MLs distribution, (c) high-resolution (spatial
resolution: up to 30 cm) multispectral base map imagery available on the Arc GIS Online base
map and Google Earth, where both datasets were used for the identification of small-scale glacial
features (e.g., drumlin hills), and (d) ALOS PALSAR digital elevation model (DEM; spatial
resolution: 12.5m) used for 3D visualization and delineation of selected paleo valleys. Radar data
were downloaded from the global (spatial resolution: 25 m) PALSAR-2/PALSAR mosaic that was
generated from the Japanese L-band SAR images (JAXA 2014). All the digital datasets were
generated using ESRI Arc Map V. 10.6.1 software and were co-registered to a unified Universal
Transverse Mercator (UTM) projection (zone 36N) and Datum (WGS-84) in a GIS environment.
The GPlates 2.1 software (GPlates 2018) was used to generate a paleogeographic reconstruction
(using the south polar stereographic) for the reported Late Ordovician glacial deposits and ice flow
directions over the (1° x 1°) Paleo digital elevation model (PaleoDEM) (Scotese and Wright 2018).

**Geologic Setting**

The SED is comprised of outcrops of the Neoproterozoic basement complex, the Paleozoic-
Cretaceous Nubian Sandstone, and Quaternary deposits (Figure 2). The Neoproterozoic basement
complex is part of the Arabian Nubian Shield (ANS), which formed by accretion of the intra-
oceanic island arc, continental microplates, and oceanic plateaus during the closure of the
Mozambique Ocean and the collision between east and west Gondwana (Gass 1981; Kröner et al.
1987; Stern 1994; Abdelsalam and Stern 1996; Johnson and Woldehaimanot 2003; Johnson et al.
2011). The ANS covers extensive areas (~1.5 x 10^6 km^2) on either side of the Red Sea. The
Neoproterozoic outcrops of the Nubian Shield extend in Egypt, Sudan, Eritrea, and Somalia,
whereas those of the Arabian Shield crop out in Saudi Arabia, Jordan, and Yemen. The study area
(~50,000 km^2) occupies large sectors of the SED. East of the study area, Neoproterozoic rocks
form rugged, high relief (up to 1978 m.a.m.s.l at G. Hamata; Said 1962), mountain chains along
the western coastal plain of the Red Sea, whereas west of it, the outcrops are characterized by
lower elevations (450 to 700 m.a.m.s.l) and smoother topography. North of the study area the
Paleozoic-Mesozoic Nubian Sandstone crop out along a sedimentary basin (Wadi Garara and Wadi
Kharit) that extends in a NW-SE-trending direction towards the Nile Valley (Figure 2).

The Paleozoic nomenclature in Egypt is controversial; formation names are not well established,
different names are given to the same formation, and sometimes the same name is assigned to more
than one formation (Klitzsch 1986; Klitzsch and Squyres 1990; Issawi and Osman 1996; Khedr et
al. 2010). In addition, assigned formation names could cover a wide temporal range and spatial
distribution. For example, the term ‘Nubian Sandstone’ encompasses Cambrian to Cretaceous
clastic deposits that are ubiquitous in North Africa and Arabia. Attempts to abolish, modify
(Pomeyrol 1968; Klitzsch and Squyres 1990), or precisely define (Issawi and Jux 1982) the well-
established and widely used inadequate formation names have failed. One example is the term
‘Nubia Sandstone Formation,’ which has been used for the past two centuries (Russegger 1837)
and continues to be used today. I speculate that this is one of the main reasons that a number of
the regional studies concluded that the Late Ordovician glaciation event in N. Africa and Arabia
is absent in Egypt (Sutcliffe et al. 2000; Le Heron et al. 2005; Ghienne et al. 2007) despite the
early, field-based studies that documented upper Ordovician glacial tillite in the Western Desert
and the fluvioglacial deposits in the North Eastern Desert and Sinai (Beall and Squyres 1979;
Issawi and Jux 1982).
Researchers working in the SED face additional difficulties. Published regional (1:250,000 to 500,000) maps (e.g., EGPC-Conoco Coral, 1987; EGSMA, 1996) consider the entire clastic succession, namely the Abu Aggag, Timsah, and Um Barmil Formations, above the basement complex as Upper Cretaceous in age, and in doing so, they ignore the earlier findings that report Paleozoic fossils (Devonian-Carboniferous) in the lower clastic unit (Abu Aggag Formation) in
the SED and east of Aswan (Issawi and Jux 1982; Zaghloul et al. 1983; Issawi and Osman 1996; Khedr et al. 2010).

In an effort to address these complexities that are arising from the wide temporal range of ages assigned to the term ‘Nubia Sandstone Formation,’ Khedr et al., (2010) classified the stratigraphic section in the Aswan area to a lower ‘Infra Nubia group’ for the clastic succession from Cambrian to Late Jurassic, the ‘Nubia Group’ for the Late Jurassic to Maastrichtian successions, and the ‘Ultra Nubia Group’ for the Campanian to Paleocene deposits. For the same purpose, and because the Paleozoic glaciation deposits and landforms are the focus of this study, I use the terms ‘preglacial’ for the Cambrian-Ordovician deposits, including the ‘Araba Formation,’ ‘glaciogenic’ for the Late Ordovician deposits, and ‘Post Glacial Nubia Sandstone Formation (PG-NSF)’ for the Paleozoic Nubia Devonian-Carboniferous ‘Abu Aggag Formation’ and the unconformably overlying Mesozoic Nubia of Late Cretaceous ‘Temsah and Um Barmil Formations’.

**Glaciogenic Deposits**

The glaciogenic deposits of the SED were apparently largely eroded during the uplift associated with the Red Sea opening in the Cenozoic that gave rise to the Red Sea Hills. I identified and report a few preserved outcrops that apparently escaped this erosional event. To the west of the Red Sea Hills, I describe remnant Paleozoic glacial deposits that are preserved within paleo-topographic lows in the Betan and Korbiai areas (Figure 2). In Wadi El-Naam these glaciogenic deposits are preserved as a basal conglomeratic unit (diamictite) below the PG-NSF.
Wadi El-Naam

The Wadi El-Naam clastic succession rest over the uneven basement surface and is represented by 1-3m of a paleosol horizon unconformably overlain by massive diamictites (Figure 3(a)). The paleosol layer is largely reddish in colour with yellow to pale brown patches. They consist of 60%–70% angular to sub-angular clasts (size: millimetres to centimetres) within highly altered and oxidized clay matrix. All the clasts were derived from the Neoproterozoic basement. The paleosol layer in Wadi El-Naam separates the underlying Neoproterozoic basement rocks from the Phanerozoic clastic succession and plunges eastward under the Wadi Kharit/Wadi Garara basin (Figure 2).

The overlying diamictite deposits crop out along a 20m high, ENE-trending hill (Figure 3(b)). These outcrops separate the basement (east) from the PG-NSF (west) (Figure 2). The diamictite is massive, polymictic, unsorted, boulder rich, and matrix supported layer. The boulders vary from well-rounded to sub-angular, occasionally with sub-horizontal long axes (Figure 3(c)). The boulders’ diameters vary from a few centimetres to nearly 1 meter. A highly deformed basal layer with rotated clasts about 1m thick is observed at the contact between the diamictite deposits and the underlying basement (Figure 3(d)).

The paleosol layer and similar deposits elsewhere across the ANS could have been the product of the long-lived peneplanation process during the Cambrian and Ordovician period of the recently formed ANS orogenic belt. I interpreted these deposits here as a preglacial deposits that could be correlated with the Araba Formation paleosol reported from the eastern Sinai Peninsula (Issawi et al. 1999; Hassan et al. 2013) and from eastern Aswan (Khedr et al. 2010). While the overlying boulder rich, massive, matrix supported, diamictites can be interpreted as subglacial diamictite
deposits during the late Ordovician glaciation event of the northern Gondwana. The one-meter basal deformed layer with the rotated clasts could indicate a near marginal subglacial basal shear deformation.

**Korbiai**

The deposits in Korbiai area, form small (tens of metres on the side), remnant, isolated outcrops that unconformably overlie the basement rocks. They are composed of several metres (3–5 m; Figure 3(e)), of poorly preserved, massive, unsorted, polymictic, boulder-rich diamictites with matrix support (Figure 3(f)). The clasts sizes vary in diameter from a few centimetres to nearly 1 meter. All the clasts are derived from the basement rocks. One of the outcrops shows clear upward fining of clasts (Figure 3(g)).

These deposits are poorly preserved, yet they can be correlated with the subglacial massive diamictites in Wadi el-Naam area. The outcrops with upward fining clasts could indicate ice retreat deposition conditions.
Field photographs of glacial diamictites in SED from Wadi El-Naam (a, b, c, and d) and Korbiai (e, f, and g). (a) Glacial diamictites [Dmm] unconformably overlying a preglacial paleosol [S] of Cambrian-Ordovician age in Wadi El-Naam drumlin hill. (b) Thick deposits (~20 m) of massive boulder-rich diamictites. (c) Matrix supported, sub-angular to rounded clasts occasionally showing elongation along sub-horizontal axes. (d) Rotated clasts within the glaciotectonite layer at the base of glacial diamictites. (e) Unsorted boulder-rich diamictites [Dmm] overlying an uneven basement surface [B]. (f) Poorly sorted, well rounded to sub-angular, matrix supported diamictites. (g) Fining upward diamictite clasts, which could be indicative of an ice retreat depositional environment.

**Betan**

In the Betan area, some 25 km to the east of the Wadi El-Naam area; a diamictite deposits lies within the basement complex outcrop area and covers a broad low topographic plain (length: 1.5 km; width: 700 m). Several small ancient mining pits (dating from the Predynastic period until the early Arab World; Klemm and Klemm 2013) targeting associated placer gold deposits were observed in the area (Figure 4). The diamictite deposits in the Betan area are rounded to sub-rounded, moderately sorted with occasional well defined horizontal bedding planes. Occasionally, the boulder clasts display elongation (long axes range from 10 to 20 cm long) subparallel to bedding planes (Figure 4).

The relatively wide plain area with well sorted, and well-rounded fabrics east of Wadi El-Naam subglacial diamictites suggest an ice frontal meltwater outwash origin for these deposits. I suggest that the reported glacial deposits from Wadi El Naam, Korbiai and Betan show genetic facies changes from subglacial diamictites in Wadi El-Naam and Korbiai, to ice-proximal meltwater outwash deposits in Betan.
Figure 4: Field photographs.

Field photographs of outwash deposits in a wide plain (area: 0.5 km2) within the basement outcrop area in the Betan area, showing many ancient gold mining pits targeting glacially hosted placer gold deposits. Inset: An ancient pit showing moderately sorted, well rounded clasts with sub-horizontal bedding planes that could indicate deposition in a proximal ice marginal meltwater environment.

**Subglacial Streamlined Features**

The formation of subglacial streamlined landforms is a fundamental process that has been documented in the recent subglacial environments (Menzies 1979; Stokes et al. 2011; Hart et al. 2018). The presence of streamlined features in paleo-glaciers such as those described here are not
only strong evidence for paleo-glacial events, but are also indicative of ice flow directions, ice velocities, and glacier types (Bussett 2010; Krabbendam et al. 2016; Eyles and Doughty 2016). In this section, I provide two additional lines of evidence for the advancing of one of the Paleozoic ice sheets over the SED. These are well expressed MLs and isolated drumlins.

**Megalineations (MLs)**

Mapping of large-scale subglacial features such as MSGGLs was facilitated by the release of Landsat images in the 1970s and 1980s, given the large contiguous areas covered by these scenes and their good spatial resolution (30–70 m; Boulton and Clark 1990; Clark 1993). Since then, a wide range of remote sensing datasets (e.g., ASTER, QuickBird, Google Earth imagery, WorldView-2, ERS 1, lidar, and UAV-captured imagery) have been used for identifying and delineating active and recent (e.g., Cenozoic glaciation) large-scale glacial features (Clark et al. 2000; Glasser et al. 2005; Smith et al. 2006; Ely et al. 2017; Chandler et al. 2018; Sookhan et al. 2018). Similarly, multispectral remote sensing images have been used to map exhumed MSGGLs of the Early and Late Paleozoic glaciations in North Africa (Moreau et al. 2005; Le Heron and Craig 2008; Le Heron 2018).

The early usage of the term ‘MSGGLs’ was to describe linear features over varying lithologies (Boulton and Clark 1990; Clark 1993). However, recently, the term was used exclusively to describe linear glacial features over soft sediments (mainly till) (e.g., Krabbendam and Bradwell, 2011; Spagnolo et al., 2014) and MLs were used to describe kilometre-scale megagrooves and megaridge lineations over hard beds (Bradwell et al. 2008; Krabbendam et al. 2016). In this study, I use the term ‘MLs’ to describe the observed, kilometre-scale, subglacial lineations over the hard beds of the Neoproterozoic basement.
I used the ALOS PALSAR data together with optical datasets (Landsat 8 multispectral images) and digital topography (12.5 m ALOS DEM) to map the MLs in the SED. The ALOS PALSAR is sensitive to roughness and has deep penetration capabilities (up to 2 m; Xiong et al., 2017) in hyper-arid conditions like those of the SED. The use of ALOS PALSAR data enabled the differentiation of linear subparallel, east-northeast—west-southwest trending, basement megaridges with rough surfaces (high backscatter/bright) from intervening subparallel valleys (megagrooves) filled with sands and characterized by smooth surfaces (low backscatter/dark; Figure 5(a,b)). Moreover, it enabled mapping the extension of the megaridges and the intervening megagrooves that were buried under thin veneers of sediments. The overall radar-based distribution of ridges and grooves was corroborated with observations extracted from the multi-spectral Landsat 8 images and ALOS DEM in areas where coverage with wind-blown sands was minimal (Figure 5(c,d)). On the ALOS DEM images, the megaridges and megagrooves appear as topographically high (bright) and low (dark) areas respectively, and on the Landsat images, as low reflectance (dark) and high reflectance areas (bright), respectively. The megagrooves are filled with fine-grained sands and hence have a high reflectance compared to the megaridges that are generally composed of coarse-grained, low reflectance rocks (Sultan et al. 1987; Rivard et al. 1992; Figure 5(c)).

Inspection of the regional ALOS PALSAR mosaic for the study area (Figure 5) shows a previously unrecognized distribution of MLs that covers large areas (length: 200 km; width: 100 km) of the SED. Within this area, sub-parallel megaridges and megagrooves (length: 2 to 40 km; width: 100 to 300 m; depth: few metres to 30 m; separation: 0.4 to 2 km) trend in an ENE-WSW direction (Figure 5). The dimensions of the SED MLs are consistent with those reported from the more recent glaciation events (Bradwell et al. 2008; Krabbendam and Bradwell 2011; Krabbendam et al. 2017).
The fact that the SED MLs do not follow any of the known tectonic trends of the SED suggests that they themselves are not tectonic in origin. This suggestion is further supported by the absence of evidence for extensive brittle and/or ductile, ENE-WSW trending, overprint (e.g., faults, foliation, lineations, etc.) within the areas where the MLs were identified in the SED, had the overprint been tectonic in nature. The SED tectonic trends referred to are: (1) the NW-SE trend related to the Red Sea opening (Oligo-Miocene; Bosworth et al. 2005; Almalki et al. 2015) and the earlier (550–450 Ma) Najd Fault System (Stern 1985; Sultan et al. 1988); (2) the N-S trend of the Hamisana shear zone (Miller and Dixon 1992; Abdelsalam and Stern 1996; de Wall et al. 2001); and (3) the WNW-ESE Allaqi suture zone trend (Abdelsalam et al. 2003; Zoheir and Klemm 2007; Abdeen and Abdelghaffar 2011). The SED MLs are well preserved over peneplained Neoproterozoic outcrops in central SED, gradually fading towards the Red Sea Hills, and none are recognized within the PG-NSF outcrops. This observation together with the identified glacial diamictites at the contact between the Neoproterozoic basement and Paleozoic Nubian Sandstone (Devonian-Carboniferous) favour a glacial origin for these linear features during the Late Ordovician (Hirnantian) glaciation period. The well preserved exposures of the MLs in the central parts of the SED and their absence over the Red Sea Hills suggest they were eroded and exhumed during the Red Sea opening and associated uplift some 25 Ma ago.
Figure 5: Mapping of the MLs in SED.
Mapping of the MLs in SED using ALOS PALSAR, multispectral Landsat 8, and ALOS DEM data. (a) ALOS PALSAR backscatter mosaic for the study area (left) and interpretation map showing the distribution of MLs (right). (b) Left: enlargements of the area covered by the blue boxes in Figure 5(a) showing ENE-WSW trending linear sub-parallel megaridges (bright) and intervening megagrooves (dark). Right: interpretation map showing the distribution of MLs (red lines), which indicate paleo-ice flow directions. (c) Landsat 8 multi-spectral image (RGB, Landsat bands 753) for the area covered by red box in Figure 5(a) showing linear megaridges (dark) and intervening megagrooves (bright) and an interpretation map showing the distribution of MLs (red lines). (d) 3D view (vertical exaggeration: 6x) for the area covered by the red box in
Figure 5(a) with the ALOS PALSAR data draped over the ALOS DEM showing the distribution of megaridges and intervening ENE-WSW oriented megagrooves.

**Drumlin Hills**

As is the case with the MLs, drumlins are considered significant indicators of paleoglacial events and ice flow directions (Boulton and Clark 1990; Kleman and Borgström 1996; Knight and McCabe 1997; Hart 1999; Stokes et al. 2013). In general, in older glaciations, the preservation of drumlin morphology is not expected to be as good as that for MLs, and thus their use as indicators for old glacial events should be treated with caution and only if additional indicators are present. In North Africa, drumlins have been reported from the Late Paleozoic glaciation but not from the Late Ordovician glaciation (Le Heron 2018).

Three elongated oval-shaped hills, here interpreted as ‘exhumed drumlins’ are present at the contact between the PG-NSF and the Neoproterozoic basement. They are 200–300 m in length, 100–150 m in width, 15–25 m in height, and are approximately 100 m apart (Figure 6(a)). They are elongated in an ENE-WSW direction, the direction of the identified MLs.

The southern drumlin hill is completely exposed and is formed of a 1–3 m thick paleosol layer overlain by 18–20 m of boulder-rich glacial diamictites (Figure 3(a)). The other two drumlin hills were covered by a sand veneer sourced from the PG-NSF (Figure 6). The sand-covered drumlins are here interpreted to indicate that these glacial deposits extend beneath the PG-NSF. The presence of these drumlins with the MLs suggest that they represent erosional features (Stokes et al. 2013; Eyles et al. 2016; Sookhan et al. 2018).
Figure 6: Wadi El-Naam drumlin hills.

Wadi El-Naam drumlin hills: (a) Arc GIS base map image for the drumlin hills of Wadi El-Naam, juxtaposed between the basement to the east and PG-NSF to the west. (b) Cross section along the AA’ line.

**Reconstruction of the Paleozoic Glaciation in the SED**

I reported evidence for the distribution of a broad field of MLs over peneplained Neoproterozoic outcrops in the central sections of the SED and a limited number of glaciogenic deposit exposures (3 locations) to the east of the MLs field. The distribution of the MLs and spatial variations of glaciogenic facies in the identified glacial system provide insights into the paleo-geologic setting in the SED.

Schematic cross-sections generated subparallel to the postulated ice flow directions and passing through the identified glaciogenic outcrops (Figure 7). The advocated ice flow directions are subparallel to the identified MLs trends. The profile passes through Wadi El-Naam (west) and
Betan (east) (Figure 7). Distinctive glaciogenic facies variations were recognized along the constructed cross-section. The Betan outwash deposits located to the east of the subglacial diamicrites of Wadi El-Naam (Figure 7) could indicate a paleo-ice margin somewhere between these two outcrops. The MLs trends in combination with the suggested ice margin between Wadi El-Naam and Betan are consistent with west-to-east ice sheet movement and can account for the observed change of glaciogenic deposits from subglacial facies in Wadi El-Naam in the west to meltwater deposits in Betan to the east.

Figure 7: Schematic west-east cross sections.
Schematic west-east cross sections along A-A’ profile (see location in Figure 1). Showing glacial deposits at the base of the Nubia Sandstone Formation and in topographic lows within the basement, the mapped MLs and a glaciogenic facies change from subglacial diamicrites (Wadi El-Naam) to meltwater outwash (Betan), that could indicate the location of the ice margin between W. El-Naam diamicrites and Betan outwash deposits.
Discussion

Evidences for Late Ordovician Age

The debate about the age of the postglacial Abu Aggag Formation, which overlay the reported glaciogenic deposits, between Devonian-Carboniferous based on identification of Paleozoic ichnofossils (*Bifungites*) (Issawi and Jux 1982; Zaghoul et al. 1983; Issawi and Osman 1996; Khedr et al. 2010) and Cretaceous based on their stratigraphic position (Klitzsch 1986; EGPC-Conoco Coral 1987; Klitzsch and Squyres 1990), complicates the definite stratigraphic positioning of the reported glacial features. While the former assignment of Abu Aggag Formation as Devonian-Carboniferous places these glaciogenic deposits in the Late Ordovician glaciation, yet the later (outdated?) interpretation of Abu Aggag Formation as Cretaceous opens the door to either Late Ordovician or Late Paleozoic glaciation. However, the geomorphological and geographical settings of these features suggest evidence in support of a Late Ordovician age. These evidences include: (1) the MLs trends in SED are consistent with the Late Ordovician tunnel valleys and striation trends along their strikes in NW Saudi Arabia (Vaslet 1990; Clark-Lowes 2005) (Figure 8). (2) The Late Paleozoic glaciation has never been reported from north Africa and/or north Arabia except for the glacial tillite in the south Western Desert of Egypt (Klitzsch 1983), deposits that were largely debated in respect to their ages (Issawi and Jux 1982; Issawi and Osman 1996) and their glacial affinities (Le Heron et al. 2009). It is worth mentioning that the Late Paleozoic tillites from south Western Desert (Klitzsch 1983) were excluded from all the newly proposed constructions of the Late Paleozoic glaciation (Fielding et al. 2008; Isbell et al. 2012; Wopfner 2013; Lewin et al. 2018), even including the late Paleozoic ice cap in Chad and Niger (Le Heron 2018). However, these evidences suggest a Late Ordovician age of the glaciogenic deposits in the SED, they do not completely rule out a probable contribution of a younger glacial activity to their
formation and future thermochronometric studies are needed to constrain their age of deposition and their provenance.

Figure 8: Paleo-reconstruction map.
Paleo-reconstruction map (445 Ma) for the reported deposits and striation trends from the northern Gondwana Late Ordovician ice sheet deposits (from Figure 1) plotted over the Gondwana paleogeographic base map (Scotese 2016; Scotese and Wright 2018) using the south polar stereographic projection. (For number references see Figure 1).

**Regional Contribution for the MLs in the Reconstruction of the Late Ordovician Ice Sheet**

Despite the apparent presence of significant paleo-glacial features over the SED and possibly over additional peneplained Neoproterozoic outcrops within the ANS, these features were not recognized by paleo-glaciologists and geomorphologists in the area. For example, many of the
paleo-glaciological maps mark all the ANS as an eroded area that is not expected to preserve any paleo-geomorphological features (Vaslet 1990; Le Heron et al. 2005). This could be related to a prevailing opinion that the modern landscape in the Eastern Desert and the ANS is the product of Cenozoic geological and climatic processes, namely the Red Sea-related rifting and uplift tectonics and the alternating wet and dry periods during the Pleistocene (Abotalib et al. 2016). The shoulders of the rift along the Red Sea, Gulf of Suez, and the Dead Sea transform fault were elevated by as much as 4 km, exposing the crystalline basement and the overlying thick (up to 2.5 km) sedimentary successions to extensive erosion (Bosworth et al. 2005; Almalki et al. 2015).

There seems to be a consensus that pre-Jurassic (Gondwana breakup) erosional surfaces are rare in Afro-Arabia, and if preserved, they would have been exhumed from beneath a sedimentary cover (Partridge and Maud 1987; Burke and Gunnell 2008). This model explains the Late Ordovician subglacial erosional and depositional features and landscapes in the study area. I attribute the preservation of the identified glacial features (MLs, drumlins, diamictites within basement paleo-topographic lows) in the SED to their burial under the overlying Nubian sequences since the Devonian Period (Abu Aggag Formation) and their exhumation during the Red Sea opening and associated uplift. The uplift of the basement complex gave rise to the Red Sea hills and eroded away basement rock and much of the overlying sedimentary sequences including the glacial deposits. The identified glacial features were locally exhumed where the PG-NSF sequences were eroded away but not the underlying glacial deposits and features. This apparently occurred in the remnant diamictite units deposited within paleo-depressions in the basement (e.g., Betan and Korbiai), as drumlins at the contact between PG-NSF and the uplifted basement (e.g., Wadi El-Naam), and as MLs over the peneplained basement, away from, but proximal to, the Red Sea Hills.
Despite the fact that many well-preserved striated surfaces, MSGLs, and tunnel valleys have been reported from Early and Late Paleozoic glaciations related to Paleozoic sedimentary outcrops proximal to the Neoproterozoic ANS basement outcrops (Clark-Lowes 2005; Moreau et al. 2005; Ghienne et al. 2007; Le Heron and Craig 2008; Le Heron 2018; Tofaif et al. 2018), none have been identified from the basement itself. One exception is the interpretation of a few Late Paleozoic glacially, striated pavements in Ethiopia (Bussert 2010). My findings suggest that glacial features similar to the ones reported in this study may have gone undetected in the ANS and additional paleo-geomorphological investigations along the exhumed Neoproterozoic ANS are recommended.

**Implications**

The reported glacial deposits and subglacial landforms in the SED have paleo-glaciological significance. Identifying MLs and glacial deposits in the SED is important for deciphering the Late Ordovician ice sheet progression, intensity, dynamics, and continuity across Africa and Arabia. It will also assist in developing comprehensive reconstructions of the ice sheet history. This research adds a previously unrecognized occurrence for the Late Ordovician glaciation in the SED, an apparently significant missing part of the jigsaw puzzle of the Late Ordovician glaciation. The inferred ice flow directions in the SED of Egypt are consistent with the trends of tunnel valleys and striations within these valleys in Saudi Arabia (Figure 1; Vaslet 1990; Clark-Lowes 2005). This observation further supports the previously hypothesized connection of the northern Gondwana ice sheet in the Sahara, Egypt, and Saudi Arabia (Vaslet 1990; Ghienne et al. 2007; Le Heron et al. 2009). These findings in the SED of Egypt could also assist in addressing one of the apparent unresolved questions pertaining to the number of cycles of the Late Ordovician glaciation. Four cycles of ice advances/retreats were reported from eastern Libya (Le Heron and
Craig 2008), but only two from Saudi Arabia (Vaslet 1990; Tofaif et al. 2018). The identified ice margin in the SED suggests that at least one of the four ice sheet advances did not reach Arabia. This interpretation is consistent with the presence of three facies of glacial deposits within the tunnel valleys of Saudi Arabia (Clark-Lowes 2005), one of which is proglacial and glaciomarine in origin and is probably related to the SED ice margin.

The majority of the identified paleo-ice streams are confined to the Saharan ice sheet (western part of the northern Gondwana ice sheet; Moreau et al. 2005; Le Heron and Craig 2008; Ravier et al. 2015); however, the presence of ENE-WSW trending MLs and drumlins in the SED and tunnel valleys along their projected extension in Saudi Arabia support models (Stokes and Clark 1999; Winsborrow et al. 2010) that advocate the presence of paleo-ice stream in the eastern part of the northern Gondwana. Further studies will be needed to map the suggested paleo-ice stream.

The reported glacial deposits and subglacial landforms from the SED have economic significance as well. Wet-based glacial deposits, such as those reported for the SED, could potentially form significant mineral placer deposits by glacial meltwater (Eyles 1995; Eyles and De Broekert 2001); ice sheets must have advanced and/or retreated over rich mineralized terrains, which is the case with the ANS. The glaciogenic deposits and de-glaciated organically enriched shales (hot shales) can act as reservoir and source rocks, respectively (Husseini 1990; Bell and Spaak 2007; Le Heron et al. 2009; Huuse et al. 2012). Thus, the south Western Desert, northern Sudan, and the structurally controlled Nubia basins in the Eastern Deserts could be potential targets for early Paleozoic reservoirs as an extension of the known Paleozoic reservoirs in Algeria, Libya, north western Desert and Saudi Arabia (Le Heron et al. 2009; Huuse et al. 2012; Bosworth et al. 2015).
Summary

Exhumed subglacial paleo-landscapes and glaciogenic deposits of the Paleozoic glaciation over the northern Gondwana continent were reported here for the first time from the SED of Egypt. The glaciogenic deposits unconformably overlie the Neoproterozoic basement rocks and are overlain by the PG-NSF. Most of these glacial deposits were largely eroded away during the Tertiary uplift associated with the Red Sea opening, except for those basal units beneath the PG-NSF, which now crop out as remnant isolated paleo-valley fillings within the basement complex (e.g., Betan) and at its contact with the overlying early Paleozoic sequences (e.g., Wadi El-Naam). Two main glaciogenic facies deposits were recognized at three sites: (1) massive, polymictic, poorly sorted, matrix-supported, boulder-rich diamictites in Wadi El-Naam and Korbiai, and (2) moderately sorted, occasionally bedded meltwater outwash deposits in Betan area.

Inspection of radar backscatter images, Landsat 8 multispectral images, and digital topography revealed previously unrecognized MLs covering large areas (length: 200 km; width: 100 km) in the SED. The MLs appear as sub-parallel, ENE-WSW trending megaridges and megagrooves (length: 2 to 40 km; width: 100 to 300 m; depths few metres to 30 m); their trends are consistent with those reported for the Late Ordovician tunnel valleys in Saudi Arabia and for striations within these valleys (Vaslet 1990; Clark-Lowes 2005). Three ENE-WSW trending, oval, elongated hills, here interpreted as ‘drumlins,’ (length: 200–300 m, width: 100–150 m, height: 15–25 m) were exhumed in Wadi El-Naam at the contact between the PG-NSF and the Neoproterozoic basement. An inferred ice-margin from the observed west-to-east variations in the glaciogenic facies; subglacial ice-proximal diamictites were identified in Wadi El-Naam and meltwater outwash deposits in Betan.
Acknowledgments

The authors thank Professor John Menzies for his contribution in identifying and interpreting the paleosol layer and Mr. Eid Nour, Mr. Nasser Awad and Shiekh Sir El-Khatam (the head of the Ababda tribe) for facilitating fieldwork. We extend our gratitude to the William Bosworth and an anonymous reviewer for their constructive comments that significantly improved this work, along with Robert Stern for editorial handling for the manuscript.
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CHAPTER III: RED SEA TECTONICS UNVEIL ONE OF THE LARGEST KNOWN TERRESTRIAL ICE STREAMS: NEW CONSTRAINTS ON LATE ORDOVICIAN ICE SHEET DYNAMICS

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https://doi.org/10.1016/j.epsl.2022.117531

Abstract

Mega-streamlined landforms on Earth and Mars have been attributed to aeolian, glaciogenic, fluvial, and tectonic processes. Identifying the forces that shaped these landforms is paramount for understanding landscape evolution and constraining paleo-climate models and ice sheet reconstructions. In Arabia, east-northeast trending, kilometer-scale streamlined landforms were interpreted to have been formed by Quaternary aeolian erosion. I provide field and satellite-based evidence for a Late Ordovician glacial origin for these streamlined landforms, which were exhumed during Red Sea–related uplift. Then I use Late Ordovician paleo-topographic data to reconstruct the Late Ordovician ice sheet using identified and previously reported glacial deposits and landforms. This reconstruction suggests these glacial features are part of a major,
topographically controlled, marine-terminating ice stream, with a minimum length of 1000 km extending from the southeast Egypt to northern and central Arabia and possibly more than twice this length if the glaciomarine and iceberg deposits in the present-day western Iran are part of this system. These results support models that advocate for a single, major, and highly dynamic ice sheet and provide new morphological-based constraints for Late Ordovician climate models.

**Introduction**

The Late Ordovician glaciation remains one of the most enigmatic climatic events in the Earth’s history. The ice sheet initiation, duration, and extent of glaciation are subjects of debate. Estimates for the duration of Late Ordovician glaciation range from a short-lived (0.5–1 Ma) Hirnantian ice sheet (Brenchley et al., 1994; Sutcliffe et al., 2000) to a ~10 Ma event in which the Hirnantian represented the climax of a much longer glacial period (Finnegan et al., 2011) to a long-lived glaciation that was initiated in the Middle Ordovician (Darriwilian) age (Pohl et al., 2016; Trotter et al., 2008).

Two models were proposed for the distribution of the Ordovician ice sheet(s): (1) a single, major ice sheet over Gondwanaland extending across North Africa, Arabia, South Africa, and South America (Pohl et al., 2016; Porębski et al., 2019; Torsvik and Cocks, 2013), or (2) small ice caps in South Africa and South America separated from the northern ice sheet in North Africa and Arabia (Ghienne et al., 2007; Le Heron and Dowdeswell, 2009). Late Ordovician glacial deposits and landforms are reported from North Africa, Arabia, southern Europe, South Africa, and South America (Elhebiry et al., 2020; Ghienne et al., 2007; Le Heron and Dowdeswell, 2009). However, their localized and dispersed nature (Pohl et al., 2016) hinder proper reconstruction of the ice sheet extent and the development of a comprehensive understanding of Late Ordovician glaciation.
The vast extent of the Late Ordovician ice sheet (LOIS), with its Cenozoic-style climatic cyclicity (Ghienne et al., 2014) and its voluminous continental ice accumulations exceeding those of the Last Glacial Maximum (Finnegan et al., 2011) suggest a highly dynamic ice sheet with significant outlet glaciers and ice streams. However, the reported Late Ordovician ice streams (Le Heron et al., 2009) are confined to the Saharan (western) part of the LOIS (Figure 9A) and are limited in number compared to those reported from recent ice sheets (e.g., the 117 ice streams in the Laurentide Ice Sheet (Margold et al., 2015)).

Ice streams—focused, fast-flowing ice conduits—are the “arteries” of ice sheets from which most (up to 90%) of the ice mass is discharged (Bell and Seroussi, 2020; Krabbendam et al., 2016; Stokes and Clark, 2001). Identifying the position, extent, and length of paleo ice streams and the factors controlling their distribution is fundamental for reconstructing paleo ice sheets and delineating their geometries and dynamics. Fortunately, paleo ice streams left behind clues (mega-streamlined morphologies) that are preserved for hundreds of millions of years (Stokes and Clark, 2001). Nevertheless, not all mega-streamlined landforms are glacial in origin (Krabbendam et al., 2016; Moreau et al., 2005); multiple erosional processes such as aeolian and fluvial processes (Abotalib et al., 2016) or tectonic and magmatic activities (Ernst et al., 2001) could have played a role in their formation.

Despite the early discoveries of surface exposures of Late Ordovician glacial deposits in Arabia (McClure, 1978; Vaslet, 1990) and the recent reports of glacial deposits from borehole data in the area (e.g., Alqubalee et al., 2021; Craigie et al., 2016; Melvin, 2015) (Figure 9), no evidence for ice streams have been identified. The delineation of ice streams from surface and subsurface glacial deposits is hindered by the complex nature of the ice sheet dynamics and by the wide range
of lithofacies assemblages left behind. Thus, mapping glacial landforms remains an effective, and widely used, tool for identifying and delineating the distribution of ice streams (Chandler et al., 2018; Krabbendam et al., 2016; Stokes and Clark, 2002).

Recently, Late Ordovician glacial deposits and exhumed subglacial mega-lineations (MLs) and landforms were reported from southeast Egypt over the Neoproterozoic basement rocks of the Arabian Nubian Shield (Elhebiry et al., 2020). On the other side of the Red Sea, and along the postulated extension of the newly reported glacial MLs, similar east-northeast–trending streamlined ridges in northwest Arabia over the Neoproterozoic basement of the Arabian Nubian Shield and the Cambro-Ordovician Saq Sandstone were interpreted as mega-yardangs formed by wind erosion (Brown et al., 1989; Goudie, 2007; Vincent and Kattan, 2006).

In this study, I integrate observations from remote sensing data, field work, and published geological maps to provide evidence of a Late Ordovician glacial origin for the mega-streamlined landforms in Arabia. I then overlay these landforms together with previously reported glacial deposits and landforms on a Late Ordovician paleo-geomorphologic reconstruction to identify one of the largest known terrestrial ice streams, hereafter referred to as the Late Ordovician Arabian Ice Stream (AIS). I show that my findings favor the single major LOIS model. Finally, I explain how these results could be used to constrain Late Ordovician climate models.

**Geological Evolution**

Four main lithologic packages (Neoproterozoic basement complex, Paleozoic sedimentary succession, Cenozoic Harrat basalts, and Quaternary An Nafud dunes; Figure 9C) cover the study area. The Neoproterozoic basement complex was formed by arc accretionary processes during an extensive, prolonged (~300 My) orogeny forming the Arabian Nubian Shield (Stern, 1994). The
elevated land of the new orogenic belt triggered intensive continental weathering and peneplanation processes, which resulted in thick clastic sedimentary successions of the Cambrian Siq Sandstone, the Cambro-Ordovician Saq Sandstone, and the Ordovician Qasim Formation (Konert et al., 2001) (Figure 9). Northwest Arabia was then uplifted and deposition was interrupted during the Middle to Late Ordovician in response to far-field effects of the Taconic orogeny, which incised valleys and canyons (paleo-valleys) within the Qasim Formation and exposed the underlying Saq Sandstone and basement complex (Laboun, 2013). Following the Taconic orogeny, the LOIS extended across north Gondwana, including the study area (Elhebiry et al., 2020; Vaslet, 1990), and eroded and polished the Neoproterozoic basement and the Saq Sandstone, forming subglacial streamlined landforms, and tunnel valleys. The glacial and preglacial deposits filled the preglacial paleo-valleys can be differentiated from the glacial tunnel valleys. The latter are parallel to the reported glacial striation trends (N70E), whereas the former have sinuous to irregular shapes suggesting a preglacial paleo-valley incision morphology (Figure 9c). The ice sheet retreated, sea levels rose, and Early Silurian shale was deposited over glacial sequences; together, they formed a glaciogenic petroleum system (Huuse et al., 2012; Le Heron et al., 2009). The Gondwana continent witnessed a second, longer (>70 My), Permo-Carboniferous glacial event, that was reported in southern, but not northern Arabia (Elhebiry et al., 2020). Gondwana migrated in a northwest direction across the south pole that moved from northwest Africa in the Late Ordovician to central Antarctica during the Permo-Carboniferous (Scotese and Barrett, 1990; Torsvik and Cocks, 2013). While the Gondwana continent was moving during the Paleozoic and Mesozoic Eras, northwest Arabia was stationed in a near-shore location (i.e., coastal plains to continental shelf) where thick, shallow-to-slightly-deep marine clastic deposits were laid down over the Late Ordovician glacial deposits and landforms. Paleozoic rocks are exposed today in an arcuate belt
around the margin of the Neoproterozoic basement (Laboun, 2013) and can be divided into: (1) pre-glacial deposits comprising Cambrian to Ordovician Siq and Saq Sandstones and Qasim Formation; (2) glacial deposits (Zarqah and Sarah Formations); and (3) post-glacial deposits. The Late Ordovician glacial deposits and landforms were buried by the thick Paleozoic and Mesozoic post-glacial deposits until the onset of Red Sea–related uplift in the Cenozoic, when the shoulders of the Red Sea rift were elevated and the crystalline basement and the overlying thick sedimentary successions including the glacial deposits were exposed (Bosworth et al., 2005). Red Sea rifting was accompanied by emplacement of flood basalts (Harrat) along the eastern flank of the rift starting some 30 Ma and extending into the Holocene epoch (Stern and Johnson, 2010). During the Pleistocene, the climate of northwest Arabia alternated between dry and wet periods (Abotalib et al., 2019), where wind erosion prevailed during the dry periods forming the great An Nafud dunes, and lake deposits were laid down within interdune depressions during the wet periods (Rosenberg et al., 2013). The prolonged geological evolution of the northwest Arabia region suggests a complex landscape evolution, and thus interpretation of the formation mechanisms of different landforms must be considered with caution and should take the geological evolution of the area into account.
Figure 9: Location and geologic maps.

Location and geologic maps for the Late Ordovician glacial deposits and landforms. (A) Location map showing the reported Late Ordovician glacial deposits, landforms, and paleo ice streams (M.S. Elhebiry et al., 2020; Le Heron et al., 2009; and references therein), as well as subsurface glacial deposits in Arabia (Alqubalee et al., 2021; Craigie et al., 2016; Melvin, 2015). (B) Enlargement of the area covered by the central box in Fig. 9A showing the distribution of MLs and glacial deposits recently mapped in the SED (Elhebiry et al., 2020). (C) Simplified geologic map for northwest Arabia, showing the MLs trends, structural trends, tunnel valleys (T.V.) and paleovalleys (P.V.). Note that the MLs were not reported over the post-Ordovician
rock units in southeast Egypt and northwest Arabia. The exhumed MLs extended for 600 km along their strike on both sides of the Red Sea (~200 km in southern Egypt and 400 km in northern Arabia).

Materials and Methods

A threefold methodology was adopted. First, I mapped the megalineations (MLs) and extracted their morphometric parameters (length/width ratio) using the following remote sensing products: (1) multispectral Landsat 8 images (bands 7, 5, and 3) to map the large-scale morphological trends (ridges/valleys) over the basement and Saq Sandstone; (2) Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) data downloaded from the global PALSAR-2/PALSAR mosaic (25 m spatial resolution) to validate the Landsat-based MLs distribution, especially in areas with mega-ridges (rough surface: high backscatter, bright) alternate with valleys partially filled with sand and silt (low backscatter, dark); (3) high-resolution (spatial resolution: up to 30 cm) multispectral base map imagery available on the Arc GIS Online base map and Google Earth to map smaller linear features over the Saq sandstone and to obtain high resolution topographic profiles (Figures 10C, D, E and F), the ALOS PALSAR DEM (spatial resolution: 12.5 m) to delineate and visualize (in 3D) the mega-ridges and to map the distribution of dunes (linear and barchan) and infer wind directions (Figure 11B), and Shuttle Radar Topography Mission (SRTM) DEM mosaics (spatial resolution: 30 m) to enable 3D visualization in areas where the ALOS PALSAR DEM is not available (Figure 11A).
Figure 10: East-northeast–trending streamlined features in northwest Arabia.

East-northeast–trending streamlined features in northwest Arabia. (A) Landsat 8 multi-spectral image (RGB, Landsat; bands 7, 5, and 3) showing the east-northeast–trending MLs over the Cambro-Ordovician Saq Sandstone. (B) Landsat 8 multi-spectral image showing the east-northeast trending MLs over the Neoproterozoic basement. (C) Google Earth image over area
outlined by box "C" in Figure 10A showing sub-parallel ENE-oriented megagrooves incised in a granitic body. (D) Google Earth image over area outlined by box “D” on Figure 10A showing ENE-trending, parabolic U-shaped valley, incised in Neoproterozoic metavolcanics and a N-S-trending hanging valley on its northern side. (E) Topographic profile along the cross-section B-B’ in Figure 10C showing the depth and width of the sub-parallel steep-sided megagrooves (negative topography) separated by megaridges. (F) Topographic profile along cross-section A-A’ in Figure 10D showing the depth and width of the U-shaped valley. Locations of Figure 10A and 10B are shown in Figure 9.

Second, I compiled and integrated observations and evidences in support of a glaciogenic origin of the mapped MLs in Egypt and Saudi Arabia from satellite data, field surveys in the Eastern Desert of Egypt, geologic maps, and field-based glacial lithofacies in Saudi Arabia (Ekren et al., 1987; Janjou et al., 1997, 1996; Vaslet et al., 1994).

Third, I generated a GIS platform to host all relevant data in a unified geographic projection (datum WGS-84: using ESRI ArcMap V. 10.6.1) to facilitate the spatial correlation of mapped and reported glacial deposits. The GIS encompasses the following spatial datasets: (1) published data including geologic maps (scale: 1:1250,000 and 1:1000,000) and the associated field observations and explanatory notes (Ekren et al., 1987; Janjou et al., 1997, 1996; Vaslet et al., 1994), (2) mosaics of the remote sensing data sets and the interpreted east-northeast MLs, (3) structural trends extracted from the 1:250,000 quadrangle maps, and (4) reported Late Ordovician glacial deposits, landforms, striation trends, and ice streams.

Fourth, I used the GPlates software to generate a Late Ordovician (450 Ma) reconstruction that displays the distribution of the mapped MLs in northwest Arabia and southeast Egypt, as well as the previously reported striation trends, tunnel valleys, subglacial, and glaciomarine deposits in
the Arabian part of the ice sheet. All these elements were plotted onto a paleo-topographic map initiated using Paleo-Digital Elevation Model data sets (Paleo-DEM, 1° x 1° resolution) (Scotese and Wright, 2018).

**Results and Discussion**

**Shape and Distribution of Megalineations**

Landsat 8 multispectral images, together with ALOS PALSAR radar and digital elevation model (DEM) (SRTM 30 m and ALOS 12.5 m) data were utilized to map the streamlined MLs over the Neoproterozoic basement and the Saq Sandstone in northwest Arabia (Figures 10A and B). The PALSAR data, with its deep penetration capabilities (up to 2 m), and sensitivity to roughness (Xiong et al., 2017) was particularly useful in mapping the MLs in areas proximal to dunes. MLs were found to extend over the Neoproterozoic basement and the pre-glacial Saq Sandstone along an east-northeast trend for ~400 km. The MLs over the Neoproterozoic basement display the following morphometric parameters: subparallel valleys (mega-grooves; negative topography) separated by parallel ridges extending for tens of kilometers, a few hundreds of meters wide, and tens of meters tall (Figures 10C and E), with length-to-width ratios from 50:1 to >100:1. Some megagrooves show a U-shaped valley morphology (Figures 10D and F). The MLs extend over crystalline basement units of varying compositions, textures, and modes of emplacement and deposition (e.g. massive, foliated, intrusions, volcanics, and metasediments (Brown et al., 1963); Figure 10). The MLs over the Saq Sandstone north and east of the basement MLs have similar orientation, but display different morphometric parameters (length: 1–6 km; width: few hundred meters and up to 1 km; height: 5–50 m; length/width ratio: ~10:1; Figure 9C). The consistency of ML trends, but not their morphologies, over both the crystalline rocks and Paleozoic sandstones,
indicates bedrock control on mega-lineated landform distribution. Similar bedrock controls on morphometric parameters of subglacial landforms are documented in recent glacial landforms (Krabbendam et al., 2016). The regional morphometric parameters of the MLs could have been modified by recent wind regimes.

**Origin of the Megalineations**

The east-northeast trends of the streamlined MLs differ from the reported northerly and northwesterly structural trends for the basement (Stern and Johnson, 2010) in the area (Figure 9C), which rules out a possible tectonic origin for these MLs. This inference is further supported by the absence of northeast trending deformation in the mapped area on both sides of the Red Sea (Brown et al., 1963; Elhebiry et al., 2020; Stern and Johnson, 2010), except for local E-W trending dike swarms and a few late-stage faults with the same orientation (Duncan et al., 1990) (Figure 9). Also, the fact that the mapped MLs maintain consistent trends for hundreds of kms over crystalline rocks of varying compositions, textures, and modes of emplacement and deposition argues against structural control of the MLs orientation by specific internal features of rock units (e.g., bedding orientations, fracture patterns, foliations, or other linear fabrics).

Earlier studies which considered these streamlined landforms as mega-yardangs (Brown et al., 1989; Goudie, 2007; Vincent and Kattan, 2006) were biased by the presence of transverse barchan dunes along and orthogonal to the extension of the MLs in the northern part of the study area (Figure 11A). Here, I provide evidence in support of a Late Ordovician glacial origin of these streamlined landforms and argue against an aeolian origin. First, the streamlined beds are sub parallel to the prevailing wind directions (southwest to northeast; inferred from the barchan dunes orientation in An Nafud desert) in the northern part of the study area (Goudie, 2007; Vincent and
Kattan, 2006) (Figure 11A), but not in the central and southern sections, where the MLs are at high angles to the prevailing wind direction (from northwest to southeast; inferred from the longitudinal dune trends; Figure 11B). Second, the mapped MLs were identified over the preglacial rock units (Neoproterozoic basement and the Cambro-Ordovician Saq Sandstone) but not over glacial or post-glacial deposits (Figures 9C, 11C and 11D). Third, the morphometric parameters (elongation ratios 10 to >100) of the MLs are similar to those reported for subglacial MLs over hard beds (Krabbendam et al., 2016) but different from the ratios reported for yardangs (3.5 to 5) (Ghodsi, 2017; Goudie, 2007). Also, their morphology over the basement (parallel U-shaped valleys interpreted here as glacial mega-grooves; Figures 10C, D, E and F) is different from the morphology of yardangs (parallel ridges), a difference that was realized by Brown et al. (1989) and led them to classify them as trough yardangs instead of normal yardangs. Fourth, yardangs are formed over soft beds and are largely composed of fluvial/lacustrine sediments (Ding et al., 2020; Goudie, 2007). To the best of my knowledge, the only exception comes from a questionable remote sensing–based study in which mega-yardangs were reported over crystalline basement in Namibia (Ding et al., 2020; Goudie and Viles, 2015). Fifth, the mapped MLs are parallel to the reported glacial striation and tunnel valley trends (Vaslet, 1990) and align with recently reported Late Ordovician MLs in southeastern Egypt (Elhebiry et al., 2020) (Figure 9B). Sixth, numerous well documented, small-scale, glacial features (e.g. striated and grooved glacial surfaces, roche moutonnées, and tunnel valleys) are found within the area where the MLs are mapped (Janjou et al., 1997; Vaslet, 1990; Vaslet et al., 1994). The trends of the reported glacial striations in the study area (N75°E to N58E; Senalp and Al-Laboun, 2000; Vaslet, 1990) align with those of the mapped MLs. The above-mentioned observations are consistent with a glacial origin for the MLS and the presence of Neoproterozoic basement cobbles and boulders (up to 1 m in diameter) within the
lower tillite layer of the glacial deposits of Sarah Formation in the eastern part of the shield (Janjou et al., 1997; Vaslet, 1990) is consistent with the LOIS being in direct contact with the crystalline basement.

On the other side of the Red Sea, in the southern Eastern Desert of Egypt (SED), similar MLs were reported by in my previous research (Elhebiry et al., 2020) (Figure 9B). The MLs of the SED extend for over 200 km in an east-northeast-direction, a direction orthogonal to the reported north to south wind trajectories (Brookes, 2003). The streamlined landforms display morphometric parameters (megagrooves: length 10s km; width 100s m; and depth 10s m) and field relations over Neoproterozoic crystalline basement, but not over post-Ordovician deposits similar to those in northern Arabia (Elhebiry et al., 2020).

Several outcrops of glacial deposits (i.e., diamictites) and features (i.e., glacial polished pavement) were observed in the SED, in areas where MLs were mapped. Those include massive, unsorted, boulder-rich (up to 1 meter in diameter) and matrix-supported diamictites that unconformably overlie the crystalline basement (e.g, Wadi El-Naam, and Korbiai areas; Figures 12A and B). Most of those deposits were eroded during Red Sea-related uplift, but a few were preserved in paleo-topographic depressions above basement rocks (e.g, Betan area: Figure 12C). Again, these observations from the SED and those reported from northern Arabia are consistent with the LOIS being in direct contact with the crystalline basement of the Arabian-Nubian Shield.

The pre-Gondwana breakup (pre-Jurassic) morphological features and landforms were thought to be less likely to be preserved and exposed in Afro-Arabia especially in tectonically active areas as the Red Sea rift (Burke and Gunnell, 2008). My observations, however, indicate that Late Ordovician MLs were protected by the overlying thick Paleozoic clastic sedimentary cover until
the Cenozoic when the Red Sea–related uplift began. Uplift led to exhumation of the basement complex and the overlying sedimentary sequences (removing 5–15 km) and landforms along the Red Sea shoulders (Almalki et al., 2015; Bosworth et al., 2005). No MLs were recognized over the rugged basement outcrops near the rift shoulders on both sides of the Red Sea, possibly due to deeper erosion. A few tens of kilometers away on both sides of the Red Sea, Late Ordovician landforms are exposed on gently dipping Neoproterozoic peneplains (Figures 9B and 9C) but remained buried underneath the overlying Paleozoic clastic successions a few hundred kilometers further away (Figure 9) (Elhebiry et al., 2020). These observations support a Late Ordovician glacial erosional origin for the streamlined features, which were later exhumed by the Red Sea–related uplift. Many of the streamlined features over the Saq Sandstone in the northern part of the study area were polished and widened by wind erosion.
Figure 11: DEMs and radar images.

DEM and radar images showing the orientation of the MLs, barchan and longitudinal dunes. (A) SRTM DEM data over the northern part of the study area showing sub-alignment of the streamlined features with the wind direction (southwest to northeast; inferred from the distribution of the barchan Nafud dunes). (B) ALOS DEM (12.5 m resolution) over the eastern sections of the study area showing wind directions (northwest to southeast; inferred from the longitudinal dune elongation direction) that are at high angles to the MLs trends (east-northeast). (C) ALOS PALSAR image showing the Sarah Formation (bright areas outlined by red lines) overlying the MLs; the radar data enables differentiation of linear ridges with rough surfaces (bright, high backscatter) from the valleys floored with fine-grained sand (dark, low backscatter). (D) Interpretation map of 2E. Sarah Formation paleo-valleys display inverted topographies (Janjou et al., 1997; Vaslet, 1990) and act as corner reflectors that are characterized by high radar backscatter (bright areas). Locations of Figures 11A to 11D are shown in Figure 9C.
Figure 12: Field photographs.

Field photographs for glacial deposits over the Neoproterozoic basement of the Arabian-Nubian Shield in the SED of Egypt. (A) Thick glacial deposits (~15m) of massive, unsorted, boulder-rich, and matrix supported diamictites unconformably overlying the basement rocks in Wadi El-Naam area, SED, Egypt. (B) Contact between the basement (B) and the overlying unsorted, matrix-supported glacial and boulder rich glacial diamictites, Korbiai area. (C) Glacial
diamictites preserved in the paleo-topographic depressions (area ~ 0.5 km²) within the Neoproterozoic basement in Betan area. Locations of Figures 12A–12C are shown in Figure 9B.

**Late Ordovician Arabian Ice Stream (AIS)**

The identification of Paleozoic ice streams has been almost exclusively based on the presence of long subglacial bed forms (elongation ratio 10–100) (Moreau et al., 2005). The presence of long bed forms is indicative of fast ice flow (Stokes and Clark, 2002), yet they do not fully portray the extent and type of the ice stream in question. This is especially true for Paleozoic ice streams, where many of the streamlined beds may have not been completely preserved or might not be exposed. To address this issue, I first reconstruct the distribution of the mapped glacial MLs and the reported glacial deposits in the Late Ordovician using a paleo-geomorphologic (paleo-DEM) dataset (445 Ma; resolution: 1° × 1°; Supplementary materials) (Scotese and Wright, 2018), then identify the factors (e.g., topographic focusing and calving margins) that control the extension and the distribution of ice streams in recent analogues (Margold et al., 2015; Stokes et al., 2016; Winsborrow et al., 2010), and finally use these factors to map ice stream landforms and predict their projected extension in areas where streamlined morphologies are not exposed.

Mapping of the MLs indicates exposed extension of a major ice stream from southern Egypt to northwest Arabia, approximately 1000 km in length. Inspection of the spatial distribution of the mapped MLs and reported glacial deposits over the reconstructed paleoDEM data (Figure 13A) indicates that the mapped MLs align with glaciomarine and iceberg deposits in the present-day western Iran (Ghavidel-syooki et al., 2011; Figure 9), which are characterized by lithofacies indicative of deposition hundreds of kilometers over the continental shelf of the paleo-Tethys. Such extensive ice advancement into the ocean, in recent analogues occurs along the termination
Thus, my model indicates the presence of an impressive ice stream extending over a distance of 1000 km from southeastern Egypt into northern and central Saudi Arabia across the Arabian Peninsula, and possibly for an additional 2000 km, and terminating in the paleo-Tethys (Figure 13A). The proposed distribution of the AIS is supported by the following observations. First, the initiation of the ice stream in southern Egypt is based on the presence of a high topographic obstacle (>2000 m) (Pohl et al., 2014; Scotese, 2016; Scotese and Wright, 2018) which apparently impeded the west-to-east advancement of the LOIS south of the identified ice stream and focused ice flow at the ice stream location (Figure 13A), a phenomenon known as topographic focusing (the most influential control on recent ice streams) (Margold et al., 2015; Stokes and Clark, 2001) is further supported by the presence of Late Ordovician glacial deposits in Eritrea and Ethiopia (west; Figure 9A) (Bussert, 2010; Lewin et al., 2018) and their absence in southern and central Arabia (east; Figures 9C and 11). Second, subglacial meltwater routing along the proposed east-northeast–trending AIS is supported by the presence of tunnel valleys trending in similar directions (Vaslet, 1990) and by the presence of glacial gold placer deposits that were formed by the action of subglacial pressurized meltwater in southern Egypt (Elhebiry et al., 2020). Third, the proposed extent of the ice sheet hundreds of kilometers over the continental shelf in Late Ordovician paleogeographical maps (Figure 13A) is supported by the discovery of glaciomarine and iceberg deposits to the east of the ice stream (present-day location in western Iran; Figure 9) (Ghavidelsyooki et al., 2011) that indicate the presence of a calving margin at the AIS terminal. The paleoslopes measurements reported from the incisions in the Dargaz Formation in western Iran (Ghavidel-syooki et al., 2011), are consistent with the orientation of the tunnel valleys (Vaslet, 1990) and the proposed AIS in Saudi Arabia. Additional evidence in support of the inferred
distribution of the AIS comes from the Hirnantian graptolite assemblages recovered from the Dargaz Formation in western Iran, where many occurrences of *Normalograptus ajjeri*, and only a few of *Normalograptus persculptus*, were reported (Ghavidel-syooki et al., 2011), a pattern that is diagnostic of graptolite associations from North African and Arabian Ordovician rocks (Ghavidel-syooki et al., 2011).

Additional subsurface data pertaining to the thickness of the glacial deposits is needed to validate the potential extension of the AIS from central Arabia to present-day western Iran, where thick glacial deposits within the deep troughs of the ice stream are to be expected. If the presence of such thick glacial deposits along the postulated extension of the AIS was validated, then the identified glacial features in southeast Egypt and Arabia could be part of an extensive, topographically controlled, marine-terminating Late Ordovician ice stream in excess of 2500 km in terrestrial extent and up to 500 km on the continental shelf (Figure 13a). Figure 13a shows the proven extension of the AIS for 1000 km in southeast Egypt and Arabia based on the distribution of MLs (Figure 13a; solid lines) and its potential extension for an additional 2000 km to present-day west Iran (Figure 13a; dashed lines). The latter (extension of the AIS) is a research topic that merits additional investigations. If the glaciomarine and iceberg deposits in the present-day western Iran were proven to be part of the AIS system, its length will be more than twice that of the longest Quaternary ice streams (Figure 13B). The Quaternary Laurentide Ice Sheet has the longest known ice streams, extending for ~1000 to 1300 km (e.g., M’Clure Strait and Hudson Strait, Canada). I suggest that the AIS was a long-lived ice stream; the presence of MLs and subglacial landforms over crystalline hard beds, which is the case with the AIS, has been cited as evidence for long-lived ice streams (Krabbendam et al., 2016). The extensive erosion associated with glacial processes in the upstream section of the AIS could explain the absence of Cambro-
Ordovician sediments on the western, but not the eastern, side of the Arabian Nubian Shield.

**Ice Sheet Reconstruction**

Continental ice sheets are significant components of paleoclimatic models. In deep-time climate modelling, the surface air temperatures, continental ice volume, atmospheric circulation, ice-ocean interactions, and CO$_2$ threshold values for glacial onset are affected by the change in the ice sheet extent and ice surface elevations that are largely controlled by ice stream geometry and distribution (Pohl et al., 2016). Ordovician climate models showed that the ice stream distribution and topographic elevations can exert significant controls on ice volume estimates, where the addition of ice streams reduced the estimated ice volume by some 40% (Pohl et al., 2016). A northern ice sheet model covering north Gondwana (Africa-Arabia) with small isolated ice caps in southern Africa and South America was proposed by Le Heron and Dowdeswell (2009); they based their model on limited sedimentary fluxes that were estimated from the ice streams of the Saharan part of the ice sheet only. The stability of mid-latitude ice caps was challenged by recent climatic models for the Late Ordovician that called on a single major ice sheet covering Gondwanaland from the pole to tropics and extending from North Africa–Arabia to South Africa and South America (Pohl et al., 2016; Torsvik and Cocks, 2013). These findings of a major AIS support the single major LOIS models and is inconsistent with others that call on a smaller ice sheet in northern Gondwana. I cite two lines of evidence. First, the earlier estimates for the ice volume of the smaller ice sheet were based on the cumulative ice stream fluxes from Saharan ice streams only (Le Heron and Craig, 2008; Le Heron and Dowdeswell, 2009). Adding a new major long-lived ice stream, namely the AIS and possibly others yet to be discovered, will significantly increase the estimates of ice stream fluxes and ice sheet volumes. Second, a correlation has been recognized between the volume of ice sheets and the length of their ice streams; the larger the volume of ice, the longer
their ice streams (Margold et al., 2015; Stokes et al., 2016; Winsborrow et al., 2010). Thus, the
great extent of the AIS—a minimum of 1000 km and possibly more than twice the length of the
longest of the Quaternary ice sheets—supports an extensive Late Ordovician ice sheet compared
to Quaternary ice sheets.

The eastern Gondwana peripheral glacial and glacio-marine occurrences from the Late Ordovician
ice sheet in western Iran and southern Turkey were thought to have originated from isolated and
elevated ice caps over the Arabian Nubian Shield (Ghavidel-syooki et al., 2011) or from an ice
lobe connected with the main LOIS (Ghienne et al., 2010). This reconstruction indicates a similar
origin for the western Iran glacio-marine deposits; it originated from the main ice sheet and was
transported by the AIS (Figure 13). The reconstruction also supports the connection between the
Saharan and Arabian part of the Late Ordovician ice sheet given juxtaposition of the MLs in Africa
and Arabia and the alignment of their trends.

This Late Ordovician ice sheet reconstruction suggests extensive mid-latitude (~ 40°) calving
margins at the front of the AIS in the continental shelf of northeast Gondwana (Figure 13A). This
suggestion is consistent with the newly reported Late Ordovician iceberg deposits from the
subtropical shelf of Baltica sourced from the Northern African–Arabian margin (Porębski et al.,
2019). Moreover, the presence of the AIS calving margins in the eastern margin of Gondwana
resolves the dilemma raised from the fact that the isopach map of the Late Ordovician dropstones
in Baltica shelf indicates southeast sourced icebergs that were driven northwestward and supports
the suggested cold water linkage between the Arabian margins and Baltica as a “source to sink”
route for the Late Ordovician eastern margin icebergs (Porębski et al., 2019).
Figure 13: Reconstruction and delineation of the AIS in the Late Ordovician.

Reconstruction and delineation of the AIS in the Late Ordovician: (A) A detailed paleo-geomorphological reconstruction for the eastern part of the LOIS and the AIS. All topographic features interpreted from the (1° × 1°) PaleoDEM data (Scotese and Wright, 2018). The map indicates the topographic controls for the identified MLs, and the marine terminations of these features. The southern boundary of the AIS was constrained by the location of a topographic high (the Arabian-Nubian shield), whereas the northern margin is not well-defined. Inset map shows paleo-reconstruction for the reported deposits and striation trends from the LOIS plotted over the Gondwana paleo-geographic base map (Scotese, 2016). (B) Correlation between the size of the AIS from LOIS and Hudson Strait Ice Stream (HSIS) and M’Clure Strait Ice Stream
(MSIS) of the Laurentide Ice Sheet (Margold et al., 2015), the largest known terrestrial ice streams and the Recovery Ice Stream (RIS), the largest from the Antarctic ice sheet.

**Implications**

Most of the subglacial landforms of the Paleozoic ice sheets are not preserved or are unexposed. The MLs, although indicative of the presence of ice streams, do not on their own provide a comprehensive understanding of the ice sheet dynamics and extent (Le Heron and Craig, 2008). My Late Ordovician reconstruction for landforms and striation trends and their spatial correlations with paleo-topographic datasets address—at least in part—these apparent shortcomings. It allows the identification of topographic controls and provides a more realistic distribution and extent for the Late Ordovician ice streams. These findings potentially provide additional constraints and refinements for a wide range of Late Ordovician climate models; the presence of extensive ice streams, similar to the one described here (the AIS) provides evidence for a highly dynamic LOIS. The major calving margins identified in eastern Gondwana in front of the AIS confirm the recently suggested Late Ordovician counterclockwise ocean circulation northwestward from Arabia (source) to Baltica (Porębski et al., 2019) as a new constraint for Late Ordovician climate models.

My findings show that subglacial AIS-related MLs were misclassified as mega-yardangs and raise the question of whether similar misinterpretations could have been made in other parts of the arid and hyper-arid world, and possibly on Mars, where MLs are much less likely to be obscured or modulated by tectonic activities. Ice streams could have carved mega-lineated flutes in Martian outflow channels during earlier warmer climatic periods (Lucchitta et al., 1981; Pacifici et al., 2009). The long glacial cycles due to the Earth’s high amplitude obliquity modulation in the
Ordovician (>10^6 yr) (Ghiennie et al., 2014) that compared well with the Martian amplitude modulation (Ward and Rudy, 1991) and the presence of the large polar landmass of Gondwana raises the suggestion that the AIS-related landforms could be a better analogue to Martian glacial landforms than Quaternary landforms (Lucchitta, 2001).

The identified AIS could have significant implications for hydrocarbon exploration. Oil and gas are produced from the Late Ordovician ice stream deposits in the Saharan part of the LOIS (Libya and Algeria) (Huuse et al., 2012; Le Heron et al., 2009). Significant untapped hydrocarbon reserves could reside within the AIS given its large size and its voluminous sedimentary flux. Ordovician glacial deposits have been considered as potential hydrocarbon producing reservoirs in Arabia, yet most of the studies of the glaciogenic outcrops were focused on the sedimentary facies, depositional architecture, and glaciogenic reservoir characteristics (Alqubalee et al., 2021; Craigie et al., 2016; Melvin, 2015; Michael et al., 2018). No attempts were made to identify the Ordovician ice streams and understand the LOIS dynamics and geometry as a primary source for the glacial and proglacial deposits. (Michael et al., 2018; Tofaif et al., 2018). Most of the subsurface exploration for these deposits were misguided by the north to northwest oriented pre-Ordovician paleo-valleys (Figure 9c) in northern Arabia (far from the AIS) that were filled by glaciogenic deposits (Craigie et al., 2016; Michael et al., 2018). To date these efforts have not been successful. Instead, I suggest that oil and gas exploration efforts should target the identified track of the AIS underneath the Arabian Shelf. The latter could represent an alternative profitable exploration target.
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CHAPTER IV: SUMMARY AND CONCLUSIONS

Exhumed subglacial paleo-landscapes and glaciogenic deposits of the Late Ordovician glaciation over the northern Gondwana continent were reported here for the first time from the southeastern Desert of Egypt. The glaciogenic deposits unconformably overlie the Neoproterozoic basement rocks and are overlain by the PG-NSF. Most of these glacial deposits were largely eroded away during the Tertiary uplift associated with the Red Sea opening, except for those basal units beneath the PG-NSF, which now crop out as remnant isolated paleo-valley fillings within the basement complex (e.g. Betan) and at its contact with the overlying early Paleozoic sequences (e.g. Wadi El-Naam). Two main glaciogenic facies deposits were recognized in three sites: (1) massive, polymictic, poorly sorted, matrix-supported, boulder-rich diamicrites in Wadi El-Naam and Korbiai, and (2) moderately sorted, discontinuously bedded meltwater outwash deposits in Betan area.

Inspection of radar backscatter images, Landsat 8 multispectral images, and digital topography revealed previously unrecognized MLs covering large areas (length: 200 km; width: 100 km) in the SED. The MLs appear as subparallel, ENE-WSW trending megaridges and megagrooves (length: 2 to 40 km; width: 100 to 300 m; depths up to 30 m); their trends are consistent with those reported for the Late Ordovician tunnel valleys in Saudi Arabia and for striations within those valleys. Three ENE-WSW trending, oval, elongated hills, here interpreted as drumlins (length: 200–300 m, width: 100–150 m, height: 15–25 m) were exhumed in Wadi El-Naam at the contact between the PG-NSF and the Neoproterozoic basement. An ice margin was inferred from the observed west to east variations in glaciogenic facies: subglacial diamicites in Wadi El-Naam, and meltwater outwash deposits in Betan.
In the second part of this study, I extend the study area to NW Arabia. Using similar methodology of integrated field and remote sensing data sets, I provide field and satellite-based evidence for a Late Ordovician glacial origin for the ENE-trending mega-streamlined landforms in Arabia, that were interpreted to have been formed by Quaternary aeolian erosion.

In NW Arabia, MLs were found to extend over the Neoproterozoic basement and the pre-glacial Saq Sandstone with ENE trend for ~400 km. The MLs over the Neoproterozoic basement display the following morphometric parameters: subparallel mega-grooves separated by parallel ridges extending for tens of kilometers, a few hundreds of meters wide, and tens of meters tall, with length-to-width ratios from 50:1 to >100:1. Some megagrooves show a U-shaped valley morphology. The MLs over the Saq Sandstone north and east of the basement MLs have similar orientation, but display different morphometric parameters (length: 1–6 km; width: few hundred meters and up to 1 km; height: 5–50 m; length/width ratio: ~10:1). The morphometric parameters (elongation ratios 10 to >100) of the MLs are similar to those reported for subglacial MLs over hard beds. Our results show that subglacial MLs were misclassified as mega-yardangs and raise the question of whether similar misinterpretations could have been made in other parts of the arid and hyper-arid world, and possibly on Mars, where MLs are much less likely to be obscured or modulated by tectonic activities.

Then I use Late Ordovician paleo-topographic data to reconstruct the Late Ordovician ice sheet using identified and previously reported glacial deposits and landforms. My reconstruction suggests these glacial features are part of a major, topographically controlled, marine-terminating ice stream, with a minimum length of 1000 km extending from SE Egypt to northern and central Arabia and possibly more than twice this length if the glaciomarine and iceberg deposits in the
present-day western Iran are part of this system.

The proposed distribution of the AIS is supported by the following observations: (1) the initiation of the ice stream in southern Egypt is based on the presence of a high topographic obstacle (>2000 m) which apparently impeded the west-to-east advancement of the LOIS south of the identified ice stream and focused ice flow at the ice stream location, a phenomenon known as topographic focusing. (2) Subglacial meltwater routing along the proposed east-northeast–trending AIS is supported by the presence of tunnel valleys trending in similar directions and by the presence of glacial gold placer deposits that were formed by the action of subglacial pressurized meltwater in southern Egypt. (3) The proposed extent of the ice sheet hundreds of kilometers over the continental shelf in Late Ordovician paleo-geographical maps is supported by the discovery of glaciomarine and iceberg deposits to the east of the ice stream that indicate the presence of a calving margin at the AIS terminal. These observations support the continuation of the Late Ordovician (Hirnantian) ice sheet from the Sahara into Arabia through SE Egypt, which reinforces models advocating for a single, major, and highly dynamic ice sheet. My results also provide new morphological-based constraints for Late Ordovician climate models.

The identified AIS could have significant economic implications for hydrocarbon exploration. Oil and gas are produced from the Late Ordovician ice stream deposits in the Saharan part of the LOIS (Libya and Algeria), given the large size of the AIS and its voluminous sedimentary flux, significant untapped hydrocarbon reserves could reside along the course of the subsurface extension of the ice stream.