Chapter 22

Evidence for Early and Mid-Cryogenian glaciation in the Northern Arabian–Nubian Shield (Egypt, Sudan, and western Arabia)

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Abstract: Evidence of Early- to Mid-Cryogenian (*c.* 780 Ma and *c.* 740 Ma) glacial activity is summarized for the northern Arabian–Nubian Shield (ANS), including structural framework, stratigraphy, lithological descriptions and relationships with younger and older units, banded iron formation chemostratigraphy, other characteristics, geochronological constraints, and discussion. The ANS is a broad tract of juvenile continental crust, formed from accreted arc-backarc basin terranes developed around the margins of the Mozambique Ocean. As a result, these successions formed in marine environments at some distance from continental margins. Deposits include banded iron formation (BIF) and possibly glacial diamictite scattered over broad regions of the Central Eastern Desert of Egypt, NW Arabia and possible correlative units in NE Sudan. The older (*c.* 780 Ma) examples (Meritri group, NE Sudan; basal Mahd group, Arabia) occur in the central ANS, on the southern flank of an important lithospheric boundary, an ophiolite-decorated suture zone. Mahd group diamictite is thin (1–5 m thick) and rests above the earliest (Cryogenian) ANS unconformity. The Meritri group interval near Port Sudan is much thicker and part of a deformed passive margin. Both Mahd and Meritri group deposits need further study before they are accepted as glaciogenic; confirmation of this interpretation would indicate that Neoproterozoic glacial activity began at least as early as 780 Ma ago. The younger (*c.* 740 Ma) glacial deposits include diamictite and BIF: the Atud diamictite and BIFs of the Central Eastern Desert of Egypt and the correlative Nuwaybah diamictite and BIF of NW Arabia. Northern ANS-BIF is a well-layered chemical sediment of interlaminated hematite-magnetite and jasper. A glacial origin for the Atud-Nuwaybah diamictites is inferred because large clasts and matrix zircons have ages (Palaeoproterozoic and Neoarchean) and compositions (especially quartzite, arkose, and microdiamictite) that require transport from outside the ANS Cryogenian basin. Northern ANS-BIF may also reveal glacial influence, having been deposited in response to reoxygenation of a suboxic ocean. The 740 Ma diamictite and/or BIF may correlate with Tambien Group diamictites in Ethiopia (Miller *et al.* 2011). Northern ANS diamictite and BIF were deposited in an oceanic basin of unknown size, as indicated by association with abundant ophiolites; they are strongly deformed, obscuring many primary features.

There is no strong evidence for or against Ediacaran glaciation in the ANS, largely because the region was uplifted at this time. The *c.* 600 Ma ANS peneplain may have been partly cut by Ediacaran glaciation. Some of the post-accretionary basins of Arabia could preserve glaciogenic deposits of Ediacaran age, but assessing this possibility requires further investigation.

The Arabian–Nubian Shield (ANS) consists of mostly Neoproterozoic outcrops around the Red Sea in NE Africa and West Arabia, exposed by Oligocene and younger uplift and erosion. The ANS is one of the largest tracts of juvenile continental crust of Neoproterozoic age on Earth; its evolution accompanied a supercontinent cycle that defined Neoproterozoic tectonics, beginning with the break-up of the end-Mesoproterozoic supercontinent Rodinia in early Neoproterozoic time (Stern 2008). ANS juvenile crust (intra-oceanic arcs and oceanic plateaux) was generated around and within the Mozambique Ocean and coalesced as this ocean closed (Stern 1994). The tectonic cycle culminated in a protracted collision beginning *c.* 630 Ma, forming the East African Orogen (EAO), an important weld in the end-Neoproterozoic supercontinent of 'Greater Gondwana' (Stern 1994) or 'Pannotia' (Dalziel 1997). In reconstructed Gondwana, the EAO extends from the Mediterranean (Tethys) southward along the eastern margin of Africa and across East Antarctica. Sedimentary evidence of early Cryogenian glacial episodes is likely to be preserved in ANS sequences, because these episodes occurred when ANS crustal components were mostly below sea level (Stern *et al.* 2006). In contrast, evidence of late Cryogenian to Ediacaran glacial episodes may be absent because this was a time of collision and uplift in the ANS. Some evidence for Ediacaran climate may be preserved in post-accretionary basins of Ediacaran age in Arabia (Johnson 2003).

In this chapter we describe possible glaciogenic units from both flanks of the Red Sea in the northern ANS; the interested reader should see the chapter by Miller *et al.* (2011) for an overview of possible glacial deposits from the southern ANS as well as Allen *et al.* (2011*a*, *b*) for chapters covering successions in Oman, to the east of the ANS. The units summarized here include (i) Meritri group metaconglomerate (E. Sudan) and basal Mahd group diamictite (central Arabian Shield); (ii) Atud diamictite (E. Egypt) and Za'am group Nuwaybah diamictite (NW Arabian Shield); and (iii) BIF from E. Egypt, NW Saudi Arabia (Sawawin deposit) and NE Sudan (Fodikwan). Locations of these units are shown in Figure 22.1 and co-ordinates are listed in Table 22.1. We know less about the Meritri group and basal Mahd group and are less confident that they are glaciogenic than we would like to be, but if confirmed, they would be the oldest known Neoproterozoic glaciogenic deposits. These are discussed here to encourage further detailed studies.

The deposits of E. Sudan and the central Arabian Shield have not been the subject of focused sedimentological study. The Meritri group conglomerate of Sudan was first identified and briefly described by Abdelsalam & Stern (1993). The basal Mahd group diamictite was first mentioned by Johnson *et al.* (2003) and then discussed in somewhat greater detail by Stern *et al.* (2006).

The diamictite and banded iron formations to the north in Egypt and NW Arabia (Fig. 22.1) have been studied for some time. The Atud Formation was first described as conglomerate (El-Essawy 1964). Since its first recognition, the Atud Formation has only been recognized in eastern Egypt between 25°N and 26°N. At the type locality near Gebel Atud, it includes schist, metamudstone, and metagreywacke in addition to diamictite, all of which

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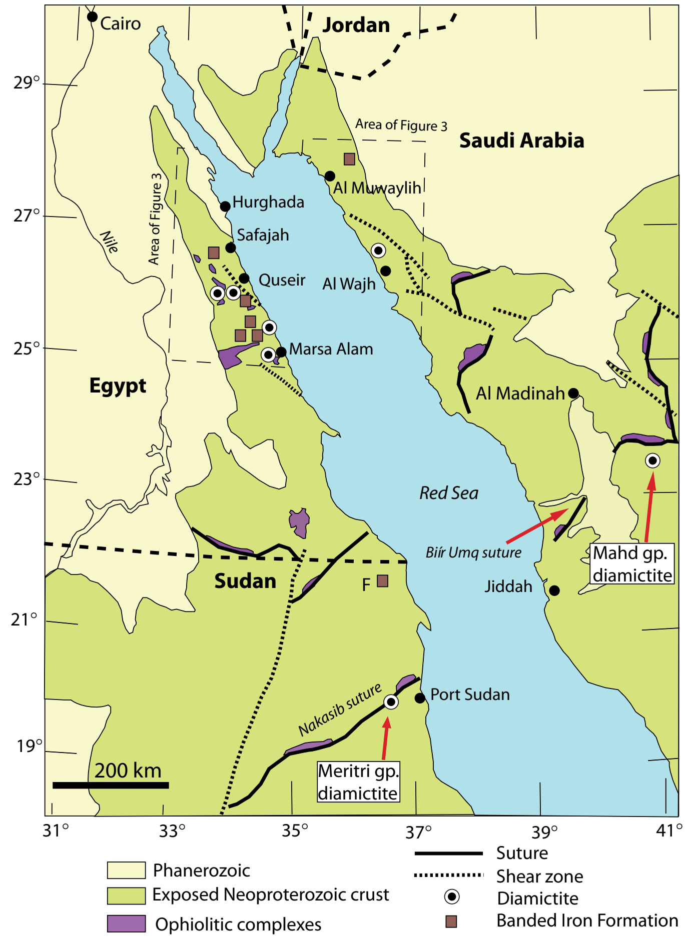

Fig. 22.1. Locality map of the northern ANS showing the approximate locations of geological units described in this chapter. The dark, dashed square designates the area shown in Figure 22.3. Early Cryogenian (*c.* 780 Ma) diamictite sequences (Meritri and Mahd) are confined to the Nakasib and Bir Umq suture areas in the south, whereas Atud and Nuwaybah diamictite and BIF sequences are confined to Egypt and NW Saudi Arabia.

Table 22.1. *Locations of Neoproterozoic deposits of possible glacial origin in the northern ANS*

Nation	Location and lithology	Age (Ma)	Latitude (N)	Longitude (E)
Egypt				
	Wadi Abu Marwat BIF	*c.* 750	26°31′	33°38′
	Wadi Kareim BIF	*c.* 750	25°56′50′	34°02′
	Wadi Kareim diamictite	*c.* 750	25°56′50′	34°02′
	Wadi Muweilha diamictite	*c.* 750	25°52′	34°54′30″
	Wadi El Dabbah BIF	*c.* 750	25°49′	34°09′
	Um Gerifat BIF	*c.* 750	25°40′	34°20′
	Um Ghamis BIF	*c.* 750	25°37′	34°19′
	Wadi Sitra BIF	*c.* 750	25°31′	34°14′
	Wadi Mubarak diamictite	*c.* 750	25°26′	34°34′
	El Hadid BIF	*c.* 750	25°21′	34°08′
	El Imra BIF	*c.* 750	25°17′	34°27′
	Um Nar BIF	*c.* 750	25°16′	34°16′
	Gebel Atud diamictite	*c.* 750	25°01′	34°27′
Saudi Arabia				
	Wadi Sawawin BIF	*c.* 750	27°54′	35°46′
	Nuwaybah diamictite	*c.* 750	26°27′	36°24′
	Mahd diamictite	*c.* 780	23°24′22″	40°46′52″
Sudan				
	Meritri Gp. conglomerate	*c.* 780	19°38′	36°42′
	Fodikwan BIF	–	21°44′	36°42′

suffered greenschist–facies metamorphism (El-Essawy 1964). The term 'conglomerate' is not appropriate for the poorly sorted, matrix-supported deposits of the Atud Formation. These better fit the description of diamictite by Flint *et al.* (1960) as poorly sorted, heterolithic, and very coarse terrigenous sediments. Accordingly, in this chapter we refer to the Atud diamictite (Stern *et al.* 2006).

Structural framework

The Meritri group conglomerate (Sudan) is preserved within the B'ir Umq-Nakasib Suture Zone, whereas the Mahd group diamictite (Saudi Arabia) is preserved just south of this suture zone. This is one of the longest and best-defined ophiolite-decorated suture zones in the ANS (Johnson *et al.* 2003) and extends (with the Red Sea closed) ENE–WSW over 600 km from the Nile in Sudan into the central Arabian Shield. The suture zone itself consists of rocks that originated in a variety of juvenile oceanic environments and include strongly deformed ophiolite nappes, and metavolcanic, metasedimentary, and intrusive rocks. Dating of the ophiolites, volcanic rocks, and pre- and syntectonic plutons indicates that oceanic magmatism in the region was active *c.* 870–830 Ma, whereas suturing occurred *c.* 780–760 Ma (Hargrove III *et al.* 2006). Structural complexities (folding, faulting, shearing, etc.) are especially severe for the Meritri group, which is part of a southwards-directed nappe stack (Fig. 22.2a), discussed in the following section (Abdelsalam & Stern 1993). The Mahd group diamictite is less folded and faulted because it lies south of the suture zone.

The Atud and Nuwaybah diamictites and associated BIF in Egypt and NW Saudi Arabia are also folded and faulted. BIF is strongly deformed although much of this deformation may have occurred as a result of slumping of dense, weak sediments in a tectonically unstable basin. BIF and surrounding sediments are metamorphosed to greenschist facies. Tectonic deformation began as a result of collision between arc terranes prior to *c.* 680 Ma (Ries *et al.* 1983). Other deformation resulted from pervasive left-lateral strike-slip shearing along the Najd fault system, which was active during Ediacaran time (Sultan *et al.* 1988). Najd deformation was a far-field manifestation of collision between fragments of east and west Gondwana (Abdelsalam & Stern 1997). Najd faulting imparted a penetrative shear fabric to most Cryogenian supracrustal units in Egypt and NW Arabia.

Stratigraphy

Cryogenian supracrustal sequences in the northern ANS are dominated by variably deformed immature clastic metasediments (greywackes) and metavolcanic rocks; rare sedimentary carbonates also occur. Cryogenian stratigraphic reconstructions are complicated because of strong deformation as well as the presence of several accreted terranes (Johnson & Woldehaimanot 2003). Cryogenian metasedimentary successions are also lithologically monotonous. Distinctive units such as sedimentary carbonates are uncommon, although these become increasingly important in the ANS farther south in Sudan, Eritrea, Ethiopia, and SW Arabia. As a result, ANS Cryogenian supracrustal units often lack a useful formal stratigraphic framework. This is especially true for Egypt, where Stern (1981) informally divided the Cryogenian supracrustal succession of the Central Eastern Desert into a basal 'older (ophiolitic) metavolcanics', 'metasediments', and 'younger (arc-like) metavolcanics'. Egyptian Cryogenian successions are unconformably overlain by Ediacaran clastic sediments of the Hammamat Group and the Dokhan Volcanics. A similar situation exists for Sudan. In contrast, there are a plethora of stratigraphic names for Cryogenian supracrustal successions of Saudi Arabia, largely based on the results of quadrangle mapping.

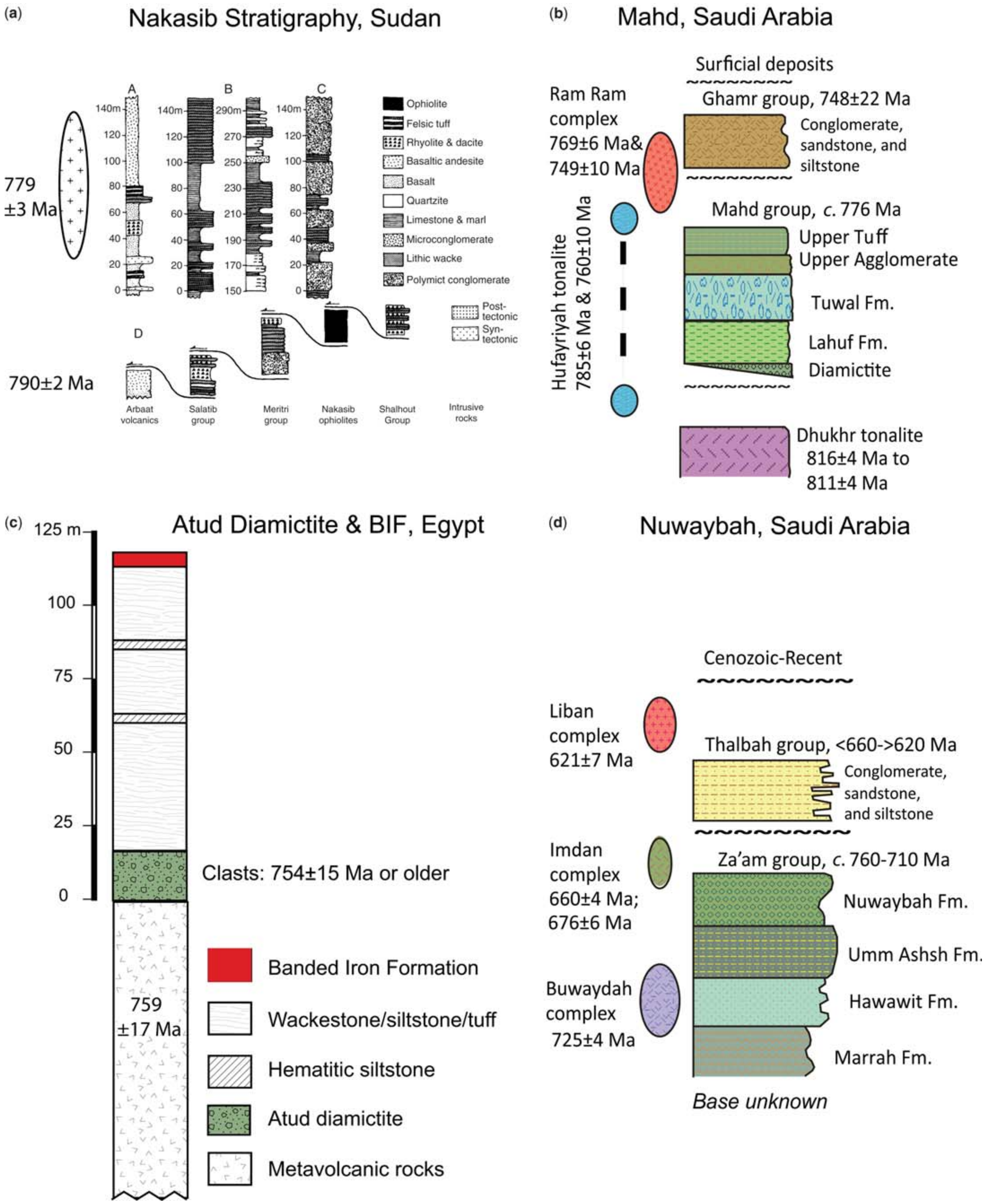

Fig. 22.2. Stratigraphic summaries of possibly glaciogenic Cryogenian units described in this chapter, locations presented in Table 22.1. (**a**) Stratigraphic chart for possibly glaciogenic conglomerates of the Meritri group, Nakasib suture, NE Sudan. Column A is a measured section for the lower part of the Arba'at volcanic rocks along Khor Arba'at. Column B is a representative section for the sedimentary part of the Salatib group along Khor Salatib. Column C is a representative section for diamictite of the Meritri group along Khor Meritri. Column D summarizes the stacking order observed in the nappes of the Nakasib suture (from Abdelsalam & Stern 1993). (**b**) Simplified stratigraphic column for Mahd group rocks showing stratigraphic position of basal diamictites (after Lowther 1994). (**c**) Simplified stratigraphic column for Atud diamictite and associated BIF in Wadi Kareim, Central Eastern Desert of Egypt, from Ali *et al.* (2010). (**d**) Simplified stratigraphic column for Nuwaybah diamictite in NW Saudi Arabia (after Davies 1985).

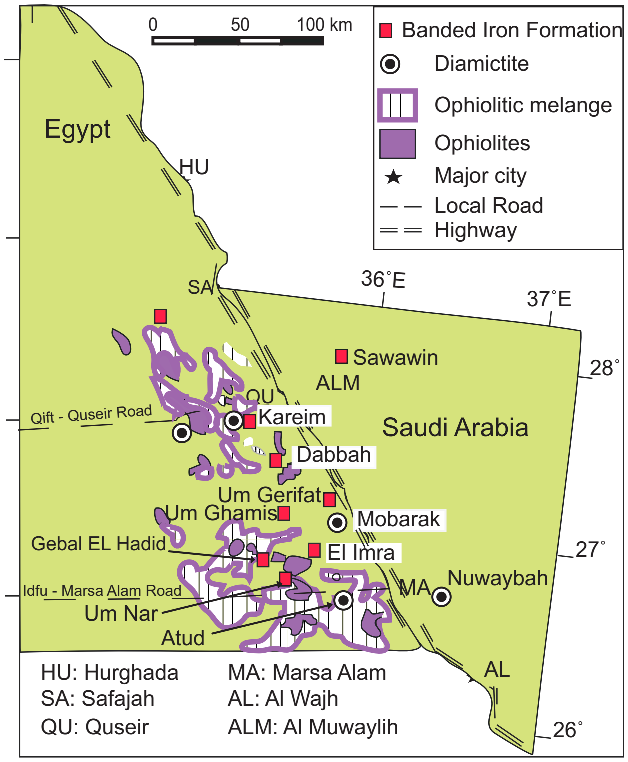

Fig. 22.3. Location of the Atud and Nuwaybah diamictite and associated BIF, as well as ophiolitic rocks in Egypt and Saudi Arabia, northern ANS, with the Red Sea closed. Diamictites in this area are thought to be early Cryogenian in age. See Figure 22.1 for regional location (modified after Ali *et al.* 2010) and Table 22.1 for geographical coordinates of sites.

Meritri group metaconglomerate of possible glacial origin in E. Sudan is associated with five informal groups, separated by thrusts so that original depositional relationships are unresolved (Fig. 22.2a). The *c.* 2-km-thick Arbaat (metavolcanic) group lies at the base of the succession and appears to be autochthonous. Subsequent units are thrust southwards on top of the Arbaat group and one another and include from the base: the Salatib group, a 1.2-km-thick succession of clastic metasediments, carbonates, conglomerate and felsic tuffs, the Meritri group composed of coarse conglomerate, lithic greywacke, limestone, red sandstone and felsic metavolcanics, the Nakasib ophiolite and at the top, the arc-like Shalhout group (Fig. 22.2a; Abdelsalam & Stern 1993). Lateral variations within the Meritri group show changes from granitic-clast dominated in the east to volcanic-clast dominated in the west.

Diamictite at the base of the *c.* 780 Ma Mahd group (Fig. 22.2b) unconformably overlies diorite and tonalite of the *c.* 810 Ma Dhukhr batholith, indicating an episode of possibly glacial erosion at *c.* 780–810 Ma (Johnson *et al.* 2003). Continuity of unit to the north is truncated by terrane boundary; possible continuity to the south and east is unknown. The basal Mahd group unconformity is one of the oldest unconformities known in the ANS. Another early Cryogenian unconformity, which might be related to the basal Mahd group unconformity, is found farther south in the Arabian Shield, between plutonic rocks of the *c.* 800 Ma An Nimas batholith and metamorphosed conglomerate, limestone, and sandstone of the 780–795 Ma Hali group (Cooper *et al.* 1979). This encourages speculation that heretofore unrecognized Cryogenian glacial deposits might exist in the southern Arabian Shield.

The Atud diamictite is a distinctive lithology found in the Egyptian metasedimentary succession. This has been reported from four areas in the Central Eastern Desert of Egypt: Wadi Kareim, Wadi Mobarak, Wadi Muweilih, and the type locality east of Gebal Atud (Table 22.1, Fig. 22.3). The Wadi Kareim occurrence is especially significant (Figs 22.2c & 22.3), because this is the only locality where the Atud diamictite is found in clear stratigraphic relationship with BIF. The diamictite is part of a supracrustal succession in which metavolcanic rocks are conformably overlain by immature metasedimentary rocks (*c.* 100 m thick of wackestone-sandstone, siltstone and diamictite) and BIF. Metavolcanic rocks at the base of the section are *c.* 100 m thick and are truncated below by a thrust fault. Egyptian diamictite and BIF are found in regional association with Cryogenian ophiolites, a tripartite association that indicates that both sedimentary units were deposited in an oceanic basin. Deformation obscures small-scale lateral variations of the Atud Diamictite; the BIF is restricted to the Central Eastern Desert of Egypt, with nine occurrences between 25°15′N and 26°35′N (Fig. 22.3, Table 22.1).

In NW Saudi Arabia, the diamictite and BIF are geographically separate parts of the Za'am group, the oldest known unit in the Midyan terrane. The diamictite (Nuwaybah Formation) is in the upper part of the Zaam group, which is an assemblage of basaltic, andesitic, and subordinate rhyolitic flows and tuffs, abundant volcaniclastic sandstone and siltstone, and volcaniclastic conglomerate (Fig. 22.2d). The Zaam group was deformed and metamorphosed (greenschist facies) prior to *c.* 660 Ma, and neither original top nor bottom is exposed. It is overlain unconformably by the younger Thalbah group. The significance of the basal Thalbah group unconformity is unknown but could correspond to Cryogenian glacial erosion. The lateral extent of the Nuwaybah diamictite is not yet known.

Further north, in Wadi Sawawin, the BIF-bearing succession consists of Ghawjah Formation metavolcanic rocks overlain by Silasia Formation metasedimentary rocks. Ghawjah metavolcanic rocks are correlated with the 'younger metavolcanic' rocks of Egypt. The Silasia Formation consists of *c.* 1-km-thick immature clastic metasedimentary rocks with BIF-bearing units near the top; the sequence is intruded by diabase sills. The stratigraphic and age relationships shown by the successions at Wadi Kareim and Wadi Sawawin are remarkably similar except that the diamictite is absent from the latter succession.

Possible glaciogenic deposits and associated strata

(A1) *Meritri group metaconglomerate, E. Sudan*

Abdelsalam & Stern (1993) inferred that the original thickness for the Meritri group in Khor Meritri was *c.* 2 km. They subdivided the group into four formations comprising, from oldest to youngest: conglomerate (possibly glaciogenic); lithic greywacke; intercalated limestone, red sandstone and felsic tuff; and felsic volcanic rocks. The coarsest clastic beds are made up of abundant polymict conglomerate intercalated with minor lithic greywacke and limestone. The polymict conglomerate is matrix supported, with the matrix made up of lithic greywacke and minor carbonate. Clasts include granite, granodiorite, diorite, rhyolite, ignimbrite and carbonate as well as subordinate clastic metasediments. Intermediate to felsic volcanic clasts become more abundant to the west. In the NE, along Khor Meritri, plutonic clasts are most abundant, comprising *c.* 50% of total clasts, whereas volcanic clasts are *c.* 35% and clasts of metasediments make up *c.* 15%. Abdelsalam (pers. comm. 2007) measured 76 of these clasts, finding a maximum size of $70 \times 40 \times 35\ cm^3$ (clasts are deformed and stretched); clasts >40 cm are common. The lithic greywacke unit is made up of lithic greywacke intercalated with minor felsic volcanic layers and limestones. Locally the lithic greywacke grades into conglomerate with smaller clasts of mostly felsic volcanic rocks. Sedimentary structures include graded bedding in the sandstone, cross-bedding and channels. Channel structures and cross-bedding indicate that the palaeocurrent direction was from SE to NW.

(A2) *Basal Mahd group diamictite, central Arabian Shield*

Although dominated by volcanic rocks, the Mahd group has a 1–5-m-thick diamictite resting on the unconformity. The diamictite is matrix-supported, with a dark-grey, immature, arkosic matrix containing abundant, angular to sub-angular clasts (up to 30 cm across) of granitic and felsic volcanic rocks.

(B1) *Atud diamictite, E. Egypt*

The Atud diamictite consists of massive poorly sorted and rounded clasts, from gravel to boulder, in a sheared grey matrix. Atud clasts include quartzite, highly altered granitoid, and a distinctive arkosic breccia (microdiamictite) (Ali *et al.* 2010). Clasts and matrix zircons in the Atud diamictite are dominated by *c.* 750 Ma granitic rocks and microdiamictite but with a significant amount of Palaeoproterozoic and Neoarchean granitic rocks and quartzite (Ali *et al.* 2010).

We have also examined Atud diamicite from the eastern half of the Wadi Mobarak belt in Egypt. Basement exposures around Wadi Mobarak are dominated by highly deformed ophiolitic fragments of serpentinites, metagabbro, and greenschist-facies mafic metavolcanic rocks, whereas the sedimentary sequence includes tuff, shale, schist and Atud diamictite (Akaad *et al.* 1995). Diamictite clasts are similar to those observed in Wadi Kareim.

(B2) *Nuwaybah Formation (Za'am group) diamictite, NW Saudi Arabia*

The Nuwaybah locality is located within the Al Wajh quadrangle in the northwestern part of the Arabian Shield. The diamictite locality we studied is beautifully exposed in a roadcut along the Red Sea highway (Table 22.1). Clasts and matrix zircons in the Nuwaybah diamictite are dominated by *c.* 750 Ma granitic rocks and distinctive arkose/micro-diamictite but with a significant amount of Palaeoproterozoic and Neoarchaean granitic rocks and quartzite (Ali *et al.* 2010), similar to lithologies and ages of the Atud diamictite in Egypt.

(C1) *Banded iron formation (BIF), E. Egypt*

BIF of early Cryogenian age is found in the Central Eastern Desert of Egypt, with nine occurrences between latitudes 25°15′ and 26°35′N. The Fodikwan BIF in NE Sudan may be related (Table 22.1, Fig. 22.1), but more work is needed to test this possibility. BIF occurs as fairly regular bands interbedded with metasediments and metavolcanics in a zone that originally had a stratigraphic thickness of 100–200 m, within which the aggregate BIF thickness is about 10–20 m (Sims & James 1984). Egyptian BIF is mostly an oxide facies, consisting of interlaminated hematite and jasper, and containing 40–46% Fe (Sims & James 1984). In several locales, BIF-bearing metasediments are intruded by metadiabase sills.

(C2) *Silasia Formation BIF, NW Saudi Arabia*

BIFs in NW Saudi Arabia occupy a more restricted region than do their Egyptian counterparts. Arabian BIF occurs within the Silasia Formation, which, like the Egyptian section, consists of volcanogenic greywackes that appear to rest conformably on metavolcanic rocks (Ghawjah Formation). The exposed thickness of the Silasia Formation is estimated to be *c.* 1160 m in the reference area of Wadi Sawawin (Goldring 1990). Arabian BIF is mostly present as an oxide facies, consisting of interbedded hematite and jasper, and containing 40–46% Fe (Goldring 1990). Similar to the Egyptian section, the Silasia Formation is intruded by metadiabase sills up to 100 m thick.

Boundary relations with overlying and underlying non-glacial units

(A1) *Meritri Group metaconglomerate, E. Sudan*

Contacts with underlying and overlying units are faulted.

(A2) *Basal Mahd Group diamictite, central Arabian Shield*

Contacts with underlying units are unconformable. Contacts with overlying units are conformable.

(B1) *Atud diamictite, E. Egypt*

Contacts with underlying units are only clear at Wadi Kareim, where they appear conformable.

(B2) *Nuwaybah Formation (Za'am group) diamictite, NW Saudi Arabia*

The basal contact of the Nuwaybah Formation is thought to be conformable on the underlying Umm Ashsh Formation (part of the Za'am group). The top of the Formation is obscured by granite intrusions and by an angular unconformity with younger sedimentary rocks (Thalbah group).

(C1) *BIF, E. Egypt*

This BIF is found in conformable stratigraphic relationship with underlying immature, possibly tuffaceous greywackes. It is associated with metavolcanic rocks and intrusive diabase.

(C2) *Silasia Formation BIF, NW Saudi Arabia*

The BIF-bearing sediments are conformable above metavolcanic rocks of the Ghawjah Formation. The top of the formation is not exposed at the Sawawin locality because it is intruded by metadiorite.

Chemostratigraphy

This section is applicable only for the BIF. There are no significant carbonate sediments in the region, although these become increasingly important to the south (in Sudan, S. Saudi Arabia, Eritrea, and Ethiopia, see Allen *et al.* 2011*a*, *b*; Miller *et al.* 2011). NW Saudi Arabia (Sawawin) BIF has been sampled systematically and stratigraphically, in order to identify the nature of its sources (Mukherjee 2008). Samples of Egyptian BIF were also studied in order to understand regional variations. Rare earth elements (REE) are particularly useful for studying the BIF because these record the composition of equilibrium seawater that the BIF precipitated from.

REE patterns for the Sawawin BIFs are similar to a mixture of modern shallow suboxic seawater (German *et al.* 1991; Webb & Kamber 2000) with low-T hydrothermal vent fluid solution (Bau & Dulski 1999) suggesting a dominant hydrothermal input of REEs and by analogy Fe into the BIFs (Mukherjee 2008). BIF iron input sources are isotopically dominated by hydrothermal vent fluids but continental runoff is also significant as revealed by Ce/Ce* and Eu/Eu* (Mukherjee 2008).

Other characteristics

Gold mineralization may be associated with BIF at Abu Marawat (Botros 2002). BIF here occurs as sharply defined horizons within a volcanic-sedimentary succession, which is regionally metamorphosed into greenschist facies. Gold concentrations of up to 2.15 ppm occur in the BIF, either enclosed in the flaky hematite crystals of hematite-rich layers or as fine inclusions in magnetite-rich bands.

El-Habaak & Mahmoud (1995) identified spherical bodies as *Eosphaera tyleri* in jasper-rich layers from Wadi Kareim BIF, Egypt. Those occur as more or less clear spherules of quartz surrounded by thin veneers of very fine hematite granules. They recognized two distinct varieties of *E. tyleri*, one of which is *c.* 15 mm in diameter and the other *c.* 60 mm; El-Habaak & Mahmoud (1995) suggested that biological activity played a role in spherule formation and BIF deposition.

The Mahd group basal diamictite is overlain by hypabyssal intrusive to volcaniclastic rocks (caldera complex) that hosts a major epithermal gold deposit (Mahd adh Dhahab Mine). The age of gold mineralization is not known with certainty, but is likely to have been syngenetic with Mahd Group igneous activity (*c.* 760–*c.* 780 Ma; Hargrove III *et al.* 2006). The deposit consists of quartz veins and stockwork that contains copper, zinc, iron, and lead sulphides and very fine-grained gold and silver (averaging 5–30 mm), mostly as tellurides, associated with the sulphides (Moore 1979).

Palaeolatitude and palaeogeography

Extensive deformation and metamorphism makes palaeomagnetic determinations unreliable, and for this reason few have been carried out (Reischmann *et al.* 1992).

Geochronological constraints

(A1) *Meritri Group metaconglomerate, E. Sudan*

The age of the Meritri group is constrained by the age of underlying metavolcanics and intrusive plutonic rocks, reported by Stern & Abdelsalam (1998). Conventional multigrain analyses of two size fractions of zircons separated from a metarhyolite lava of the apparently underlying Arba'at Formation yielded a nearly concordant age of 790 ± 2 Ma. The supracrustal sequence, including the Meritri group, was intruded by the Arba'at quartz diorite, which yielded a single fraction, nearly concordant U–Pb zircon age of 779 ± 3 Ma (Stern & Abdelsalam 1998). Faulting leads to uncertainties about the exact relationship between the intrusion and Meritri group, but these ages suggest that deposition of the Meritri diamictite may be constrained between 779 ± 3 and 790 ± 2 Ma.

(A2) *Basal Mahd Group diamictite, central Arabian Shield*

The age of this diamictite is constrained by the age of subjacent and superjacent igneous rocks. The Dhukhr complex, which unconformably underlies the diamictite, has robust conventional multigrain U–Pb zircon crystallization ages of 811 ± 4 Ma (Stoeser & Stacey 1988) and 816 ± 4 Ma (Calvez & Kemp 1982). The Hufayriyah batholith, which also unconformably underlies the Mahd group *c.* 60 km north–NE of the diamictite locality, has a U–Pb zircon SHRIMP age of 785 ± 6 Ma (Hargrove III *et al.* 2006). Rhyolite in the Mahd group upsection from the basal diamictite has been dated by U–Pb zircon SHRIMP techniques at 777 ± 5 Ma (Hargrove III *et al.* 2006). In addition to the U–Pb zircon SHRIMP age, the Hufayriyah batholith also yields a conventional multigrain U–Pb zircon age of 760 ± 10 Ma (Calvez & Kemp 1982); this result may represent a younger pulse of Hufayriyah intrusion and is not necessarily a robust constraint on the age of rocks at the base of the Mahd group.

(B1) *Atud diamictite, E. Egypt*

The age of this unit is constrained to be younger than both the age of the underlying metavolcanics (Fig. 22.2c) and the age of the youngest clast within the diamictite. Ali *et al.* (2009) report a SHRIMP U–Pb zircon ion probe age of *c.* 750 Ma for the metavolcanics that lie beneath the Atud diamictite at Wadi Kareim. One metavolcanic sample yielded a weighted mean ^{206}Pb–^{238}U age of 769 ± 29 Ma.

As noted above, the Atud diamictite at Wadi Kareim is dominated by Cryogenian clasts and matrix material but contains abundant clasts of Palaeoproterozoic and Neoarchaean granitic rocks and pre-Neoproterozoic quartzite. Clasts in the diamictite are as young as 754 ± 15 Ma (Ali *et al.* 2010). Because of stratigraphic relationships shown on Figure 22.2c, the maximum age of *c.* 750 Ma for the metavolcanics and 754 ± 12 Ma for the Atud diamictite at Wadi Kareim also provides a maximum age for BIF deposition at this locality (Ali *et al.* 2009, 2010).

Geochronological data support the inference that clasts in the Atud diamictite sample much older rocks than are exposed in the Eastern Desert of Egypt and so must have been transported some distance. Two granitic cobbles from NW of Marsa Alum (also referred to as the Wadi Mobarak metasedimentary unit) yielded highly discordant conventional multigrain U–Pb zircon upper intercept ages of 1120 and 2060 Ma (Dixon 1981). Dixon (1979) obtained a discordant U–Pb zircon upper intercept of 2.3 Ga for a granitic cobble from Atud conglomerate outcrops west of Quesir. SHRIMP geochronological studies by Ali *et al.* (2010) confirm and extend Dixon's conclusions that many Atud clasts are pre-Neoproterozoic.

(B2) *Nuwaybah Formation (Za'am Group) diamictite, NW Saudi Arabia*

Like the Atud diamictite, this unit is dominated by Cryogenian material but contains abundant clasts of Palaeoproterozoic and Neoarchaean granitoids and quartzite. The youngest clasts in the Nuwaybah diamictite yield SHRIMP U–Pb zircon ages of 765 ± 22 Ma (Ali *et al.* 2010). Another clast is an arkose with a SHRIMP U–Pb zircon age of 766 ± 5 Ma, which we interpret as the age of the basement supplying the arkose, which was rapidly eroded and deposited, lithified, and re-eroded, all apparently within a very few millions of years.

The formation has a minimum age of deposition constrained by the age of intrusions in the Zaam Group near the diamictite. These include the Buwaydah complex, dated by the conventional U–Pb zircon method at 725 ± 4 Ma (Hedge 1984) and the Imdan complex, dated by the SHRIMP U–Pb zircon method at 676 ± 6 Ma (15 data points (Kennedy *et al.* 2011) and conventional U–Pb zircon method at 660 ± 4 Ma (Hedge 1984). Zaam Group felsic tuff 175 km SE of the diamictite locality yields U–Pb zircon SHRIMP ages of 711 ± 10 Ma and 708 ± 4 Ma (Kennedy *et al.* 2004, 2005). However, the stratigraphic relationship between the diamictite and these tuffs is poorly understood, thus the significance of these data for constraining the depositional age of the diamictite is not clear.

(C1) *BIF, E. Egypt*

BIF age is best known from Wadi Kareim, where ages of conformably underlying metavolcanics and diamictite indicate that it is younger than *c.* 750 Ma (Ali *et al.* 2009, 2010), but perhaps not much younger.

(C2) *Silasia Formation BIF, NW Saudi Arabia*

The Silasia Formation, which hosts this BIF, is intruded by plutonic rocks of the Muwalylih suite, dated by U–Pb zircon techniques at 710–725 Ma (Hedge 1984). Unfortunately, Hedge (1984) did not provide analytical details, the number of zircon populations or statistics about the results (uncertainty and mean square of the weighted deviates). Ali *et al.* (2011) report a U–Pb zircon ion probe weighted mean $^{206}Pb/^{238}U$ age of 763 ± 25 Ma for Ghawjah metavolcanics beneath the BIF. Silasia Formation was deformed and then intruded by Sawawin complex diorite, which yields a U–Pb zircon concordia age of 661.5 ± 2.3 Ma (Ali *et al.* 2011). Silasia Formation BIF is thus $< 763 \pm 25$ Ma, probably *c.* 750 Ma, similar in age to Egypt BIF.

Discussion

The foregoing summary indicates that there is compelling evidence of a *c.* 740 Ma age glaciation and plausible evidence of a *c.* 780 Ma glaciation in the northern ANS. Indistinguishable bracketing ages of the Meritri group (790 ± 2 Ma to 779 ± 3 Ma) and Mahd group (785 ± 6 Ma to 777 ± 5 Ma) indicate that deposition of these units may have occurred about the same time. A glaciogenic interpretation for *c.* 780 Ma Mahd-Meritri groups might help explain the enigmatic Bitter Springs $\delta^{13}C$ excursion of approximately the same age, thought to be associated with glaciation but for which no definitive evidence of glaciation has been identified to date (Halverson *et al.* 2005, 2007). The association of the Mahd diamicite with the oldest unconformity known from the Arabian Shield is also consistent with a glacial interpretation and is tentative evidence of a *c.* 780 Ma local continental glaciation, probably sourced to the south (present coordinates). Certainly, more work is needed to map, study sedimentology and stratigraphy, date clasts and matrix, and examine intervening sedimentary and possible igneous environments of Mahd and Meritri groups deposits.

Evidence for a *c.* 740 Ma glaciation is found in the ophiolite-Atud diamictite-BIF basin and includes far travelled exotic clasts (based on age and composition) and association of diamictite with BIF. By virtue of their age, these deposits may correlate with early Cryogenian glaciogenic successions elsewhere (Fairchild & Kennedy 2007). The Atud-Nuwaybah diamictite may be strictly correlative, with similar ages of deposition, clast lithology and distribution of Cryogenian, Palaeoproterozoic and Neoarchaean clast ages (Ali *et al.* 2010). The association of diamictite with BIF is consistent with the genetic coupling suggested by Snowball Earth concepts (Hoffman 2005), although alternative interpretations exist. Based on similar age constraints (the youngest detrital zircons in the Ethiopian diamictites are also *c.* 0.75 Ga), Atud diamictite may also be broadly synchronous with Negash and Shiraro diamictites in northern Ethiopia (Avigad *et al.* 2007; Miller *et al.* 2003, 2011). Neoproterozoic diamictites from the ANS (this chapter and Miller *et al.* 2011) do not seem to correlate directly with diamicitites of the Abu Mahara Group of the Huqf Supergroup, Oman, which are younger in age (700–735 Ma) and are dominated by *c.* 860 Ma zircons that are not common in the Atud/Nuwaybah diamictites (Rieu *et al.* 2007).

Because pre-Neoproterozoic basement is unknown in Egypt east of the Nile, Dixon (1981) concluded that these clasts were derived from older crust to the west or south, perhaps from the Saharan Metacraton (Abdelsalam *et al.* 2002). Dixon (1979) suggested that Atud clasts were transported such great distances by ice rafting, but other possible explanations (e.g. meteorite impact ejecta blanket, far-travelled submarine debris flow) are possible.

There is controversy regarding how the Egyptian BIFs formed, although ideas published in the geological literature were mostly developed prior to the Snowball Earth hypothesis (Fairchild & Kennedy 2007). Sims & James (1984) suggested that BIF formed as chemical precipitates during lulls in dominantly subaqueous, calc-alkaline volcanism, apparently within an intraoceanic island-arc environment. The close association in time and space between volcanic activity and deposition of the BIF suggests a genetic relation (Sims & James 1984).

Finally, it should be noted that there is no strong evidence for or against an Ediacaran glaciation in the ANS. The ANS peneplain may have been partly cut during this time, but regional uplift resulted in generally poor preservation (Stern *et al.* 2006). Some of the post-accretionary basins of Arabia may preserve glaciogenic deposits of Ediacaran age, but focused investigations are needed to establish or refute this possibility (Johnson 2003).

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