A composite stratigraphy for the Neoproterozoic Huqf Supergroup of Oman: integrating new litho-, chemo- and chronostratigraphic data of the Mirbat area, southern Oman

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Abstract: The Huqf Supergroup in Oman contains an exceptionally well-preserved and complete sedimentary record of the Middle to Late Neoproterozoic Era. Outcrops of the Huqf Supergroup in northern and central Oman are now well documented, but their correlation with a key succession in the Mirbat area of southern Oman, containing a sedimentary record of two Neoproterozoic glaciations, is poorly understood. Integration of lithostratigraphic, chemostratigraphic and new U–Pb detrital zircon data suggests that the Mirbat Group is best placed within the Cryogenian (c. 850–635 Ma) part of the Huqf Supergroup. The c. 1 km thick marine deposits of the Arkahawl and Marsham Formations of the Mirbat Group are thought to represent a stratigraphic interval between older Cryogenian and younger Cryogenian glaciations that is not preserved elsewhere in Oman. The bulk of detrital zircons in the Huqf Supergroup originate from Neoproterozoic parent rocks. However, older Mesoproterozoic, Palaeoproterozoic and even Archaean zircons can be recognized in the detrital population from the upper Mahara Group (Fiq Formation) and Nafun Group, suggesting the tapping of exotic sources, probably from the Arabian–Nubian Shield.

The Late Neoproterozoic Era was punctuated by widespread glaciations and large perturbations in the carbon cycle (Hoffman & Schrag 2002; Halverson et al. 2005), which have been associated with the priming of metazoan life in the Ediacaran period (Hoffman et al. 1998; Knoll & Caroll 1999; Knoll 2003; Chen et al. 2004; Condon et al. 2005). The Huqf Supergroup of Oman contains an exceptionally well-preserved record of the time interval from the Cryogenian to the Early Cambrian (Brasier et al. 2000), including a thick succession of glaciogenic and associated non-glacial sedimentary rocks (Le Guerroué 2006a, b) and the extinction of Cloudina and Namacalathus at the Precambrian–Cambrian boundary (Amthor et al. 2003).

As for most Neoproterozoic successions (Evans 2000; Halverson et al. 2005; Etienne et al. 2007), the Huqf Supergroup is inadequately constrained by radiometric ages. Whereas the correlation between the Huqf Supergroup in the Jabal Akhdar of northern Oman and the Huqf region of east–central Oman is now well established, based on lithostratigraphic and chemostratigraphic data (McCarron 2000; Leather 2001; Cozzi & Al-Siyabi 2004; Cozzi et al. 2004a, b; Allen & Leather 2006), the correlation of the Mirbat Group in southern Oman with Neoproterozoic strata elsewhere in Oman and globally has remained speculative (Bell 1993; Brasier et al. 2000; Kellerhals & Matter 2003; Cozzi & Al-Siyabi 2004; Kilner et al. 2005; Bowring et al. 2007).

The excellently exposed Mirbat Group is of particular interest as it records two Neoproterozoic glaciations in an essentially continuous succession, separated by a c. 900 m thick sequence of predominantly marine siliciclastic sedimentary rocks (Kellerhals & Matter 2003; Rieu et al. 2006). It is essential to integrate this succession into the regional stratigraphic context of the Huqf Supergroup to constrain the number and timing of glaciations and to reconstruct a reliable geological history for this part of the Arabian Peninsula.

In this paper we integrate recently collected lithostratigraphic and chemostratigraphic data for the Mirbat Group with (1) subsurface data provided by Petroleum Development Oman (PDO), (2) outcrop data from elsewhere in Oman and (3) the first significant number of U–Pb detrital zircon ages of the Huqf Supergroup. In the light of the new results we attempt to place the Neoproterozoic succession of southern Oman in the broader context of the Huqf Supergroup and in the global framework of Neoproterozoic stratigraphy (Evans 2000; Halverson et al. 2005), and discuss temporal changes in zircon provenance. We propose a new composite stratigraphy of the Huqf Supergroup from crystalline basement to the Early Cambrian.

Geological setting

Neoproterozoic rocks of the Huqf Supergroup crop out extensively in northern (Jabal Akhdar and Saih Hatait), central (Huqf area) and southern (Mirbat area) Oman and are penetrated by many boreholes in the subsurface salt basins of Oman (Figs 1 and 2). In the Jabal Akhdar, two glacial epochs are recorded in...
the Abu Mahara Group, represented by the poorly documented Ghubrah Formation (Brasier et al. 2000) and the sedimentologically better understood Fiq Formation (Rabu 1988; Leather 2001; Leather et al. 2002; Allen et al. 2004). The Fiq Formation comprises <1.5 km of alternating glacial diamictites and interglacial mudstones, siltstones and sandstones restricted to the depocentre of a structurally confined basin, and is overlain by the regionally extensive, sheet-like, c. 1 km thick Nafun Group (Loosveld et al. 1996; McCarron 2000; Cozzi & Al-Siyabi 2004). The Nafun Group contains at its base the $^{13}$C-depleted, transgressive Hadash cap carbonate (Allen et al. 2004) and strongly oversteps basement-cored basin margins, demonstrating major sea-level rise following the deposition of the Fiq Formation. Above the Hadash Formation, the Nafun Group contains two large-scale siliciclastic-to-carbonate cycles, starting with the marine shales and sandstones of the Masirah Bay Formation (Allen & Leather 2006) that pass gradationally up into the prograding carbonate ramp of the Buah Formation (Cozzi & Al-Siyabi 2004; Cozzi et al. 2004a). The overlying Ara Group records segmentation of the regionally extensive Nafun basin into three smaller basins represented by the subsurface salt basins in Oman (Fahud, Ghaba and South Oman Salt Basins). The carbonate–evaporite succession of the Ara Group in the South Oman Salt Basin (Schröder et al. 2003) is time-equivalent to the peritidal carbonate succession in the Huqf area (Nicholas & Brasier 2000), and to the Fara Formation in the Jabal Akhdar. It also spans the Precambrian–Cambrian boundary (Brasier et al. 2000; Amthor et al. 2003). The Ghubrah Formation ($723 +16/−10$ Ma, Brasier et al. 2000; $712 ± 1.6$ Ma, Leather 2001) and Fiq Formation glaciogenic deposits ($<645$ Ma, Bowring et al. 2007) are thought to have formed during the Cryogenian, whereas the Nafun Group has been suggested to cover the whole Ediacaran Period ($c. 635–542$ Ma, Allen & Leather 2006; Le Guerroué et al. 2006b).

The Neoproterozoic sedimentary succession in the Mirbat area (Qidwai et al. 1988; Platel et al. 1992a, b; Kellerhals & Matter 2003; Rieu et al. 2006) (Fig. 2) was formerly referred to as the Mirbat Sandstone Formation, comprising a Lower, Middle and Upper Member. Based on distinct lithological differences and the
large-scale genetic stratigraphic framework, it is been proposed to informally revise this nomenclature. The former Mirbat Sandstone Formation is referred to here as the Mirbat Group and the former members are raised to formation status and named the Ayn, Arkahawl and Marsham Formations, in ascending stratigraphic order. A newly recognized stratigraphic unit at the top of the Mirbat Group is introduced as the Shareef Formation.

The Mirbat Group unconformably overlies 0.7–1.0 Ga crystalline and metamorphic basement (Gass et al. 1990; Worthing 2005; Mercolli et al. 2006) and is eroded at the top by a sub-Cretaceous unconformity (Fig. 2). The Ayn Formation, at the base of the Mirbat Group, is preserved within several palaeovalleys eroded into basement rocks and comprises ~400 m thick glacially influenced basin-margin deposits (Rieu et al. 2006). It consists of intervals of glacimarine rain-out diamictite and sediment gravity flow deposits, alternating with fluvial and deltaic sandstones and conglomerates. The overlying marine succession (Arkahawl and Marsham Formations) is laterally continuous throughout the outcrop area, with a basal cap carbonate that transgresses over the basement highs that flanked the previous depocentre. The lower part of the Arkahawl Formation is characterized by coarse-grained turbidite complexes, fining up into distal marine siltstones and mudstones. These siltstones and mudstones pass up into the shallow marine and fluvial deposits of the Marsham Formation, which are thought to record eustatic sea-level drawdown heralding the second glacial epoch represented by the scarcely preserved, glacially influenced diamictites of the Shareef Formation.

Integration of outcrop and subsurface data

Neoproterozoic rocks of the Huqf Supergroup in the subsurface have been extensively drilled by PDO and the correlation between the laterally extensive Nafun Group in the Jabal Akhdar, the Huqf area and in the subsurface is well established (McCarron 2000; Cozzi & Al-Siyabi 2004; Cozzi et al. 2004a, b; Allen & Leather 2006) (Figs 2 and 3). The outcrop–subsurface correlation within the underlying Abu Mahara Group is, however, relatively poorly understood (Loosveld et al. 1996). This is partly due to the small number of boreholes that penetrate the Abu Mahara Group and to the relatively poor quality of the seismic data below the Ara salt. The Abu Mahara Group in the subsurface is composed largely of coarse-grained siliciclastic and volcaniclastic deposits filling roughly NE–SW-trending basins that have been tentatively interpreted as restricted, fault-bounded rift basins (Rabu 1988; Loosveld et al. 1996). Although the Fiq Formation was probably deposited in a rift (Allen et al. 2004), the geodynamic context of the Abu Mahara Group as a whole is unknown.

Near the Mirbat area (Fig. 3), few boreholes penetrate the Abu...
Fig. 3. Correlation between the Nafun Group in outcrops and the subsurface, and the proposed stratigraphic position of the Mirbat Group in the framework of the Huqf Supergroup. Well data from Petroleum Development Oman (PDO) and carbon isotopic data (expressed as $\delta^{13}C$ % VPDB) from PDO (TM-6 well) and Burns & Matter (1993), Allen et al. (2004), Cozzi et al. (2004a) and Le Guerroué et al. (2006b) (Huqf and Jabal Akhdar). Ba, Birba; Bh, Buah; Hd, Hadash; Kf, Khufai; MB, Masirah Bay; Mhm, Marsham; Srf, Shareef.
Mahara Group. The overall stratigraphy of the Arkahawl and Marsham Formations compares well with that of the Abu Mahara Group in borehole GM-1, 80 km north of the outcrops of the Mirbat Group (Fig. 3). The Abu Mahara Group in GM-1 overlies crystalline basement and contains at the base a 250 m thick unit of predominantly siltstones and sandstones and minor shales, which may represent the more distal equivalent of the predominantly coarse-grained turbiditic sandstones in the lower half of the Arkahawl Formation in the Mirbat Group. As in the Arkahawl Formation, the sandstones in GM-1 pass up into a thick (c. 300 m) succession of predominantly siltstones and shales. The overlying 30 m interval of well-sorted, fine-grained sandstones in GM-1 may correlate with the base of the Marsham Formation in outcrop, which would require the overlying siltstones and shales in GM-1 to represent a more distal equivalent of the predominantly shallow marine sandstones of the Marsham Formation. At the top of the Abu Mahara Group in GM-1 is a 30 m thick unit of reddish sandstones containing rock fragments and purple-coloured sandy diamictites. This unit is correlated with the top of the Mirbat Group at outcrop, where red sandstones of the Marsham Formation are overlain by purple-coloured sandy diamictites of the Shareef Formation. It is not known to the Mirbat area is in harmony with the overall NW-directed palaeocurrents recorded in the Mirbat Group, to be published elsewhere. The lack of coarse-grained Ayn-equivalent glacial deposits at the base of GM-1 may be the result of restricted preservation of the Ayn Formation in palaeovalleys, as is the case in the outcrops of the Mirbat area, with thicknesses of the Ayn Formation varying between 0 and c. 400 m.

The thin dolomite bed overlying the Abu Mahara Group in GM-1 is interpreted as equivalent to the Hadash Formation (cap carbonate of the Fiq glacigenic deposits in the Jabal Akhdar), marking the base of the overlying Nafun Group. By virtue of this correlation, the whole Mirbat Group can be considered equivalent to the Abu Mahara Group (Fig. 3). The poorly preserved glacigenic diamictites of the Shareef Formation in the Mirbat area correlate to the base of the 1.5 km thick glacigenic Fiq Formation in the Jabal Akhdar of northern Oman. As a consequence, the glacigenic Ayn Formation is thought to correspond to the relatively poorly documented, but well dated, diamictites of the Ghubrah Formation in the Jabal Akhdar region.

The Abu Mahara Group is also recognized in boreholes HT-1 and LH-1, where it comprises >0.6 km of interbedded diamictites, sandstones and shales, capped by a c. 5 m thick cap dolostone (Fig. 3). Because in HT-1 there is no evidence for a second cap carbonate overlying the lowermost diamictites, the whole succession below the cap dolostone is interpreted to represent a single, though composite, glacial epoch, equivalent to the Fiq Formation in the Jabal Akhdar (Fig. 3). Borehole LH-1 is located in a structurally complex area just west of the South Oman Salt Basin and several thrust faults complicate correlation with the Huqf Supergroup elsewhere in Oman. Although the stratigraphy overlying the diamictites is poorly defined, it broadly resembles that of the Nafun Group. Moreover, the similarity of the carbon isotopic signature of the cap dolostone in LH-1 to that of the Hadash Formation in the Jabal Akhdar (Fig. 3) and the presence of zircons as young as 645 Ma near the top of the diamictite unit (U–Pb age; Bowring et al. 2007) reinforce the correlation of these diamictites with the glacigenic deposits of the Fiq Formation. The relatively poor development of the Fiq-equivalent diamictites in GM-1 (few tens of metres) compared with the HT-1 and LH-1 wells (Fig. 3) and the outcrops in the Jabal Akhdar may be due to large local differences in subsidence related to the location of syndepositional fault blocks.

**Cap carbonates**

Although the exact number and extent of Neoproterozoic glaciations is still controversial (Kennedy et al. 1998; Evans 2000; Etienne et al. 2007), it is widely recognized that some differences exist between younger and older Cryogenian cap carbonates from Canada, Australia and Namibia (Kennedy et al. 1998; Hoffman & Schrag 2002; Halverson et al. 2004, 2005). In contrast to their end-Cryogenian counterparts, older Cryogenian (‘Sturtian’) cap carbonates are commonly argillaceous limestones instead of dolostone, they are thinner than end-Cryogenian caps and the declining arm of the δ13C anomaly typical of end-Cryogenian caps is not present. Instead, δ13C values rise with stratigraphic height starting from values of around −3‰ to −2‰ at the base, and reach much higher values (+5‰) than found in end-Cryogenian caps, which typically recover to 0‰ (Kennedy et al. 1998; McKirdy et al. 2001; Yoshioka et al. 2003; Halverson et al. 2005). As the cap carbonate of the Ayn Formation in the Mirbat Group is predominantly limestone and shows an upward increase in δ13C from −3.5‰ to +5.8‰, it is more similar to older Cryogenian than to end-Cryogenian cap carbonates elsewhere (Fig. 4). A regressive trend, typical of some
older Cryogenian cap carbonates is, however, missing. The Hadash Formation cap carbonate overlying the Fiq glacigenic deposits in the Jabal Akhdar and subsurface, on the other hand, is a dolostone grading upward into shales and has δ¹³C values typically between −7‰ and −4‰ at the base, increasing upward to values typically between −4‰ and −1‰ (Allen et al. 2004). Thus the Hadash Formation cap carbonate resembles end-Cryogenian (‘Marinoan’) cap carbonates elsewhere (Fig. 4). There is no field evidence for an older Cryogenian cap carbonate in northern Oman, which may be due to removal by erosion below the Saqlah volcanic and volcaniclastic rocks at the base of the Fiq Formation (Le Guerroué et al. 2005).

Detrital zircon ages

As a test of the proposed correlations, detrital zircon populations from the Mirbat Group are compared with those of the Abu Mahara Group and of the basal Nafun Group in the Jabal Akhdar and Huqf regions. Details of analytical methods are available online at http://www.geolsoc.org.uk/SUP18271. A hard copy can be obtained from the Society Library. In total, 1057 new U–Pb zircon ages were produced by laser ablation inductively coupled plasma mass spectrometry (ICP-MS). In all samples the zircon population is dominated by 700–900 Ma (Neoproterozoic) ages, but the Nafun and upper Abu Mahara (Fiq Formation) Groups also contain Mesoproterozoic and Palaeoproterozoic zircons. Zircons as young as ∼600 Ma are present in the Nafun Group (Figs 5 and 6; Table 1).

Fig. 5. (a–g) Concordia diagrams showing all data that are <25% discordant and with 2σ errors <20% for 235U/207Pb and <10% for 238U/206Pb. Data point relative-error ellipses are at 2σ.

Mirbat Group, southern Oman

The sampled stratigraphic intervals include the Ayn, Arkahawl, Marsham and Shareef Formations (Fig. 2). Samples of the Ayn Formation come from three diamictite units (D1, D2 and D3 of Kellerhals & Matter 2003) in Wadi Autunt and are vertically separated from each other by c. 100 m. The sample of the Arkahawl Formation is derived from turbiditic sandstones in Wadi Himuna, about 75 m above the top of the Ayn Formation. From the Marsham Formation two samples (vertically separated by 50 m) were collected near Jabal Shareef from sandstones comprising shoreface facies. Diamictites of the Shareef Formation were sampled in the same section, as well as in a section 3 km to the NE. The Arkahawl and Marsham Formations, which represent the ‘interglacial’ period between the Ayn and Shareef glaciations, are treated as one stratigraphic interval and their zircon ages have been pooled to obtain a statistically significant number of ages (Vermeesch 2004).

The stratigraphic units of the Mirbat Group contain remarkably similar detrital zircon populations, comprising zircons almost exclusively of Neoproterozoic age (Figs 5 and 6). When only the most concordant data and those with the lowest analytical errors are considered (filter 2), main peaks in the Ayn Formation are revealed at c. 722, 810 and 840 Ma (Fig. 6). A single zircon yields an age of c. 1060 Ma. In the Arkahawl and Marsham Formations only the c. 810 Ma and c. 840 Ma peaks are present, whereas in the Shareef Formation the zircon population is dominated by c. 870 Ma ages with only a small ‘shoulder’ at c. 810 Ma. All zircons that yield ages <722 Ma are >10% discordant and have 2σ errors >10% (Fig. 5), which precludes assigning any precise geological significance to them. The maximum age constraint for the depositional age of the Ayn Formation and the overlying part of the Mirbat Group is therefore provided by the c. 722 Ma sub-population in the Ayn Formation. This sub-population is represented by four grains, which have a mean age of 722 ± 19 Ma (Table 1). This age is in agreement with the constraints provided by the 700–750 Ma age of the underlying basement based on Rb–Sr, K–Ar and Sm–Nd whole-rock and mineral analyses (Gass et al. 1990; Worthing 2005; Mercoll et al. 2006), but is considered to be more robust.

Abu Mahara Group, northern Oman

All three stratigraphic units of the Abu Mahara Group in the Jabal Akhdar, which include the Ghubrah Formation, Saqlah Member and Fiq Formation, have been sampled (Fig. 2). The Ghubrah Formation sample was derived from a thin (centimetrescale) graded siltstone 1 m above the thin ash bed dated previously by Brasier et al. (2000), Leather (2001) and Bowring et al. (2007). The Saqlah sample was taken from interbedded debris-flow deposits and laminated carbonates and siltstones, c. 15 m below pillowed basalts in Wadi Mistal. The Fiq Formation was sampled at three localities in Wadi Mistal and Wadi Sahtan. The Wadi Mistal and Wadi Sahtan sections are separated laterally by 40 km and are thought to comprise sediment derived from opposite flanks of the Fiq graben (Allen et al. 2004). In total, eight samples were taken so that at each side of the basin the basal, middle and upper parts of the 1.5 km thick Fiq succession are represented.

Zircons of the Ghubrah Formation sample are predominantly Neoproterozoic in age. In addition, about 40% yield ages significantly younger than the reported age of the underlying ash bed, most of which are >10% discordant and/or have 2σ errors >10%, precluding the assignment of geological significance to
their ages. Discordant \(^{238}\text{U}^{207}\text{Pb}\) zircon ages as young as 600 Ma, as a result of lead loss, are also common in the underlying ash bed. When only the most concordant data and those with the lowest analytical errors are considered (filter 2) (Table 1), the youngest sub-population that can be distinguished and assigned geological significance has a peak at 710 Ma, which is in excellent agreement with the reported U–Pb ages of the underlying ash bed of \(723 \pm 16\) Ma (Brasier et al. 2000) and \(712 \pm 1.6\) Ma (Leather 2001). One younger zircon that yields an age of \(658 \pm 29\) Ma also passes the second filter. However, no geological significance can be inferred from a single age that is 9% discordant. A sub-population that is distinctly older that the underlying ash bed makes up 10% of all analysed zircons. The ages in this sub-population range from 750 to 910 Ma, but only two of them pass filter 2 (760 and 810 Ma). No reliable peak ages can therefore be defined for these older grains, but it may nevertheless be concluded that a significant Neoproterozoic detrital component older than the ash bed is present in this sample.

All zircons of the Saqlah unit yield Neoproterozoic ages. When only the most concordant data and those with the lowest analytical errors are considered (filter 2), a main peak is revealed at 860 Ma, and three subordinate peaks and ‘shoulders’ occur at 730, 815 and 910 Ma (Fig. 6). Ten zircons yield ages between 589 and 714 Ma, which are not assigned any geological significance because of either discordance of >10% or 2σ errors >10%. The youngest sub-population in this sample that is assigned geological meaning is composed of three zircons of 721 ± 25, 725 ± 19 and 740 ± 21 Ma (Table 1). Because of their overlapping errors they form a single sub-population with a mean age of 729 ± 24 Ma. It should be noted, however, that the two youngest grains have ages similar to the U–Pb age of the Ghubrah tuffaceous ash reported by Brasier et al. (2000). There is therefore a possibility that they have been reworked into younger deposits.

Because of the absence of significant differences between the zircon ages of the different samples of the Fiq Formation (i.e. from Wadi Sahtan and Wadi Mistal), they have been treated together. The majority of the zircons (94%) in the Fiq Formation are of Neoproterozoic age, 5% of Palaeoproterozoic age, and less than 1% of late Mesoproterozoic and late Archean age (Figs 5 and 6). When only the most concordant data and those with the lowest analytical errors are considered (filter 2), main age peaks occur at 790–810 Ma and 840–860 Ma with ‘shoulders’ at 700–720 Ma and 750 Ma. Older sub-populations include two late Mesoproterozoic zircons of 1050 Ma, 12 middle Palaeoproterozoic grains between 1730 and 1965 Ma with a main peak at 1880 Ma, and two early Palaeoproterozoic to Archean zircons of 2330 and 2550 Ma, respectively. The youngest zircon that passes filter 2 has an age of 675 ± 17 Ma, but is 6.8% discordant and is undistinguishable from the 700–720 Ma population (Table 1). The maximum age of the Fiq Formation is therefore constrained to 2550 Ma.

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![Figure 6](attachment:image.png)

**Fig. 6.** Frequency distribution diagrams for detrital zircons. Grey areas are based on data produced by filter 1 (<25% discordant; 2σ errors <20% for \(^{235}\text{U}^{207}\text{Pb}\) and <10% for \(^{238}\text{U}^{206}\text{Pb}\)); the black lines are based on data produced by filter 2 (<10% discordant; 2σ errors <10% for \(^{235}\text{U}^{207}\text{Pb}\) and \(^{238}\text{U}^{206}\text{Pb}\)). Number of analyses (n) produced with filters 1 and 2 are displayed outside and inside parentheses, respectively. Peaks ages are in Ma. The stratigraphic position of the Mirbat Group is based on the lithostratigraphic and chemostratigraphic correlations shown in Figures 3 and 4.
to 700–720 Ma, similar to the age of the tuffaceous ash bed in the underlying Ghubrah Formation, and is consistent with both a ‘Marinoan’ (terminating at 635 Ma in Namibia and South China, Hoffmann et al. 2004; Condon et al. 2005) and ‘Sturtian’ (c. 658 Ma in Australia, Fanning & Link 2006; Kendall et al. 2006; lasting until 670 Ma in Idaho, Fanning & Link 2004) affinity for the Fiq Formation glaciogenic deposits. Bowring et al. (2007) discovered detrital zircons as young as 645 Ma from core taken with the estimated depositional age of the base of the Masirah Bay Formation at 635 Ma and its top at 609 Ma (Table 1). Although it is dangerous to assign geological significance to populations defined by single grains, the similarity of these ages to a 600–640 Ma sub-population suggests that the Fiq Member is older than 640 Ma.

Nafun Group, northern and central Oman

The Masirah Bay Formation sample was collected from the Khufai Dome, Huqf region (Fig. 2) within tidal sandstones (unit D of Allen & Leather 2006) about 200 m above the Hadash Formation. Detrital zircon data from the top Khufai Formation and base Shuram Formation are from Le Guerroué et al. (2006a).

The Masirah Bay Formation sample contains zircons of which 89% are of Neoproterozoic age, 10% of Palaeoproterozoic age and <1% of Mesoproterozoic age (Figs 5 and 6). When only the best data are considered (filter 2), a major peak is revealed at 825 Ma with a ‘shoulder’ at 800 Ma. Older sub-populations include a single Mesoproterozoic zircon of 1215 Ma and six Palaeoproterozoic zircons ranging in age from 1785 to 2490 Ma. The two youngest zircons that pass filter 2 yield ages of 606 ± 9 Ma and 664 ± 16 Ma (Table 1). Although it is dangerous to assign geological significance to populations defined by single grains, the similarity of these ages to a 600–640 Ma sub-population in the overlying Khufai Formation (Le Guerroué et al. 2006a) indicates that the maximum age of deposition of the Masirah Bay Formation is 600–640 Ma. This age is consistent with the estimated depositional age of the base of the Masirah Bay Formation at c. 635 Ma and its top at 609 ± 9 Ma, inferred from thermal subsidence modelling and global chemostratigraphic correlations (Le Guerroué et al. 2006b).

Published detrital zircon ages (51 in total) at the top of the Khufai Formation in the Huqf region and at the base of the

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Table 1. U–Pb laser ablation ICP-MS ages of detrital zircons produced by filter 2 (<10% 2σ errors for 7/35 and 6/38 and <10% discordant)

| Formations          | 7/35 age | 1σ | 6/38 age | 1σ | 7/6 age | 1σ | % Disc. | 7/35 age | 1σ | 6/38 age | 1σ | % Disc. |
|---------------------|----------|----|----------|----|---------|----|---------|----------|----|----------|----|---------|  
| Ayn Formation       |          |    |          |    |         |    |         |          |    |          |    |         |  
| 812                 | 10       | 12 | 114      | 5.8| 1.0     |    | 9.8     |          |    |          |    |         |  
| 819                 | 29       | 11 | 110      | 9.8| 0.7     |    | 2.1     |          |    |          |    |         |  
| 784                 | 29       | 10 | 112      | 3.4| 3.4     |    | 5.2     |          |    |          |    |         |  
| 788                 | 18       | 7  | 72       | 1.1| 1.1     |    | 3.6     |          |    |          |    |         |  
| 795                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  
| 877                 | 30       | 15 | 164      | 4.3| 4.3     |    | 2.2     |          |    |          |    |         |  
| 787                 | 30       | 15 | 120      | 2.2| 2.2     |    | 1.2     |          |    |          |    |         |  
| 786                 | 18       | 7  | 72       | 1.1| 1.1     |    | 4.0     |          |    |          |    |         |  
| 785                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  
| 784                 | 29       | 11 | 110      | 9.8| 0.7     |    | 2.1     |          |    |          |    |         |  
| 789                 | 18       | 7  | 72       | 1.1| 1.1     |    | 3.6     |          |    |          |    |         |  
| 795                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  
| 877                 | 30       | 15 | 164      | 4.3| 2.2     |    | 1.2     |          |    |          |    |         |  
| 787                 | 30       | 15 | 120      | 2.2| 2.2     |    | 1.2     |          |    |          |    |         |  
| 786                 | 18       | 7  | 72       | 1.1| 1.1     |    | 4.0     |          |    |          |    |         |  
| 785                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  
| 784                 | 29       | 11 | 110      | 9.8| 0.7     |    | 2.1     |          |    |          |    |         |  
| 789                 | 18       | 7  | 72       | 1.1| 1.1     |    | 4.0     |          |    |          |    |         |  
| 795                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  
| 877                 | 30       | 15 | 164      | 4.3| 2.2     |    | 1.2     |          |    |          |    |         |  
| 787                 | 30       | 15 | 120      | 2.2| 2.2     |    | 1.2     |          |    |          |    |         |  
| 786                 | 18       | 7  | 72       | 1.1| 1.1     |    | 4.0     |          |    |          |    |         |  
| 785                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  
| 784                 | 29       | 11 | 110      | 9.8| 0.7     |    | 2.1     |          |    |          |    |         |  
| 789                 | 18       | 7  | 72       | 1.1| 1.1     |    | 4.0     |          |    |          |    |         |  
| 795                 | 27       | 11 | 102      | 5.9| 5.9     |    | 8.1     |          |    |          |    |         |  

For Ayn, Saqlah and Fiq Formations, ages >800 Ma are not shown. Italic lettering indicates ages that form the youngest sub-population in each unit. The complete dataset is provided in the Supplementary Publication (see p. 000).
Shuram Formation in the Jabal Akhdar are represented by 90% Neoproterozoic and 10% Palaeoproterozoic ages (sensitive high-resolution ion microprobe (SHRIMP) II $^{238}$U/$^{206}$Pb ages) (Le Guerroué et al. 2006b) (Fig. 6). In the Khufai Formation, the Neoproterozoic sub-population contains peaks at 600–640, 720, 800 and 825 Ma. Three Palaeoproterozoic grains are present of 1822, 2042 and 2473 Ma. Detrital zircons at the base of the Shuram Formation contain Neoproterozoic sub-populations with peaks at 755, 800, 850 and 885 Ma. Three Palaeoproterozoic zircons of 1820, 2040 and 2470 Ma occur. It should be noted, however, that in the study of Le Guerroué et al. (2006b) a statistically low number of zircons was used ($n = 20–31$) and that, as a result, significant additional sub-populations may not have been encountered (Vermeesch 2004).

Comparison of detrital zircon populations

When the detrital zircon populations of the Abu Mahara and Nafun Group samples in the Jabal Akhdar and Huqf areas are compared (Fig. 6), two main trends are observed. The first trend is an increase of old grains with stratigraphic height, from no Palaeoproterozoic zircons in the Saqlah sample, to 5% in the upper Abu Mahara Group (Fiq Formation) and to 10% in the Nafun Group (Masirah Bay, Khufai and Shuram Formations) samples. The second trend shows a decrease in the ages of younger sub-populations from 700–720 Ma in the Abu Mahara Group, to 600–645 Ma in the Nafun Group. In this sense the Mirbat Group is distinctly different from the Nafun Group and more similar to the Abu Mahara Group (Saqlah and Fiq), because both older (Palaeoproterozoic) and younger (600–650 Ma) sub-populations are absent in the Mirbat Group. Although the older sub-population present in the Fiq Formation is not found in the sample of the Shareef Formation, it should be noted that as a result of a sub-Cretaceous unconformity only the lowermost 50 m of the latter are exposed, and that the analysed sample therefore may not be representative of the unknown amount of the Shareef stratigraphy that is missing. Moreover, taking into account that the Fiq Formation samples were taken over 1.5 km of stratigraphy, of which the stratigraphically lowest come from 100 m above the base of the Fiq Formation, comparison of the Fiq and Shareef detrital zircon populations is problematical. Taken together, the geochronological results fit with the proposed correlations within the Huqf Supergroup shown in Figure 3.

A composite stratigraphy of the Huqf Supergroup and global correlation

Using the correlation between the Mirbat Group and the rest of the Huqf Supergroup presented here, it is possible to construct a composite stratigraphic column from 0.7–1.0 Ga crystalline basement to the Precambrian–Cambrian boundary, containing two distinct and well-documented Cryogenian glacial intervals (the Ayn–Ghubrah and Fiq–Shareef glaciations) and three major Neoproterozoic negative carbon excursions (Fig. 7).

If our correlation of the Mirbat Group with the Huqf Supergroup is correct (Fig. 3), the Arkahawl and Marsham Formations of the Mirbat Group fill in the stratigraphic gap between the older (Ayn–Ghubrah) and younger (Fiq–Shareef) Cryogenian glaciations, which has not been preserved elsewhere in this part of the Arabian Peninsula as a result of a regional unconformity below the Saqlah Member in the Jabal Akhdar region of northern Oman. The Arkahawl and Marsham Formations may then be equivalent to other Cryogenian ‘interglacial’ successions such as, for example, the Twitya and Keele Formations in the Windemere Supergroup of NW Canada (Narbonne & Aitken 1995; Day et al. 2004), the Rasthof and Ombaatjie Formations of northern Namibia (Hoffman & Schrag 2002) and the Tindelpina and Etina Formations of the Central Flinders Range in Australia (Preiss & Forbes 1981; Sohl et al. 1999).

Taking into account the 723 +16/−10 Ma (Brasier et al. 2000) and 712 ± 1.6 Ma (Leather 2001) U–Pb ages for the tuffaceous
ash interbedded with the Ghubrah Formation diamictites, and the 722 ± 19 Ma maximum age of the Ayn Formation glacigenic deposits, we infer a glacial epoch at 710–720 Ma in the Oman region. If this is correct, the Ayn–Ghubrah glaciation is significantly older than the Sturtian glaciation in Australia indicated by U–Pb dating of zircons from tuffs interbedded with diamictites (<658 Ma, Fanning & Link 2006) and as inferred from post-glacial shales (643.0 ± 2.4 Ma and 657.2 ± 5.4 Ma) dated using Re–Os (Kendall et al. 2006). Consequently, either the ‘Sturtian’ glacial epoch lasted from c. 720 to 660 Ma, or the Ayn–Ghubrah glaciation is older than the Sturtian of Australia and the interval 720–660 Ma was characterized by a number of different, possibly diachronous, glaciations.

It has been suggested that the Ayn glaciation analogs to those of the Fiq Formation in northern Oman, and that the Arkahawl and Marsham Formations of the Mirbat Group are equivalent to the Ediacaran Masirah Bay Formation forming the lower part of the Nafun Group (Bell 1993; Kilner et al. 2005). Although negative δ 13C excursions similar to the −12‰ δ 13C values recorded in the Shuram Formation of the Nafun Group have elsewhere been tentatively associated with the Gaskiers glaciation (Halverson et al. 2005) at around 582 Ma (Bowring et al. 2003), neither glacial deposits nor a major unconformity have been recorded in the well-exposed shallow-water sections in the Huqf region that could correlate to the Shareef glaciation recorded in Mirbat (Gorin et al. 1982; Cozzi & Al-Siyabi 2004; Cozzi et al. 2004a, b; Le Guerroué et al. 2006a, b). This lack of evidence for glaciation, however, could be explained by non-preservation of glacigenic sediments and the difficulty of recognition of synglacial unconformities in platformal areas, as is demonstrated in the Otavi platform of northern Namibia at the level of the Ghaub glaciation (Hoffman & Schrag 2002) and in the Windermere Supergroup of the McKenzie Mountains at the level of the Icebrook glaciation (Narbonne & Aitken 1995). Consequently, it is most plausible to correlate the Mirbat Group with the Abu Mahara Group, but it is not possible to fully dismiss the possibility that the Ayn and Shareef glaciations of the Mirbat area correlate with the Fiq glaciation and Khufai–Shuram boundary, respectively, elsewhere in Oman.

Source regions for detrital zircons and palaeogeography

Local sources

In all samples the detrital zircon populations are dominated by Neoproterozoic ages that are in good agreement with the age range of local basement rocks where exposed. The basement ages in the Mirbat area (0.7–1.0 Ga) are reflected well in the peaks of the detrital zircon ages of the Mirbat Group (Fig. 3). In the Mirbat area, the most precise age of the group of late intrusions comes from the Leger Granite (726 ± 0.4 Ma U–Pb age; Bowring et al. 2007). Although there is no stratigraphic contact between the Mirbat Group and the Leger Granite, the 722 ± 19 Ma sub-population of zircons in the Ayn Formation may have been derived from this or associated intrusions, suggesting that the Leger Granite intruded prior to deposition of the Ayn Formation and was exhumed shortly after. This sub-population is similar in age to the zircons found in tuffaceous ashes of the Ghubrah Formation in northern Oman.

Peaks in the detrital zircon ages of the Masirah Bay and Khufai Formations in the Huqf region at 800 and 825 Ma (Fig. 3) are identical to the ages of nearby granitoids and volcanioclastic rocks at Al-Jobah (U–Pb ages, Leather 2001; Allen & Leather 2006). Other dated basement outcrops in Oman include the 780 Ma granites on the Juzor al Hallaniyat Islands (Rb–Sr age, Platel et al. 1992c) and 825–830 Ma granitic intrusions in the Jabal Ja’alan region in northern Oman (U–Pb ages, Pallister et al. 1990) (Fig. 1). The c. 710 Ma peaks that are observed in the Ghubrah and Fiq Formation detrital suites are interpreted to reflect reworking of Ghubrah-aged volcanic material. The two youngest zircons in the Saqlah Member (721 ± 25 Ma, 725 ± 19 Ma) may have a similar provenance.

The younger, 600–650 Ma zircon populations found in the Nafun Group and the very top of the Fiq Formation in the Lahan well in southern Oman (Le Guerroué et al. 2006a; Bowring et al. 2007), may indicate syn- or post-tectonic igneous and volcanic activity in Oman between 600 and 640 Ma. However, no primary igneous rocks of this age have been dated in Oman. The only evidence for possible syntectonic volcanism of northern Oman is the presence of pillow basalts in the Saqlah Member (Rabu 1988; Allen et al. 2004; Le Guerroué et al. 2005).

Exotic sources and changing palaeogeography

The admixture of older, predominantly Palaeoproterozoic zircons in the Fiq Formation and Nafun Group indicates a change in provenance that may reflect progressive erosion and exhumation of deeper Precambrian crystalline basement. The ages and geochemistry of exposed basement suggest a Neoproterozoic island-arc origin for the Oman basement (Le Metour et al. 1995; Worthing 2005; Mercolli et al. 2006). As an alternative, the small proportion of older zircons may have been derived from exotic sources outside present-day Oman. Palaeocurrent directions in the Masirah Bay Formation indicate that sediment was locally derived from the east (Allen & Leather 2006), but the location of the major sources during deposition of the overlying part of the Nafun Group is unclear. It is generally accepted that by the end of the Neoproterozoic Era Oman was part of east Gondwana (Dalziel 1997; Meert & Van der Voo 1997; Meert 2003), which is thought to have formed through a series of island-arc continents in the Arabian–Nubian Shield region, starting as early as 800 Ma, followed by the accretion of a number of continental blocks. However, given the limited data about the position of Oman with respect to these areas during most of the Neoproterozoic, it is not easy to judge from which area sediment may have been delivered to Neoproterozoic basins in Oman. Possible ‘exotic’ Palaeoproterozoic sources that, at least by the end of the Neoproterozoic, were located relatively close to Oman include parts of Saudi Arabia, Yemen, Sudan and India (Fig. 8).

The nearest pre-Neoproterozoic crystalline and metamorphic source terranes to the present west of Oman that can be identified as possible sources for the old detrital zircons ages in the Huqf Supergroup are in Saudi Arabia and northern Somalia (Fig. 8). Agar et al. (1992) reported 1.6–1.8 Ga and 2.4–2.6 Ga gneisses in the southern Afif terrane in Saudi Arabia from a combination of U–Pb zircon and Sm–Nd model ages. In the Khida area in Saudi Arabia c. 1630 and 1660 ± 10 Ma granites occur (U–Pb; Stacey & Hedge 1984; Whitehouse et al. 2001a). In northern Somalia granitoids of 1.4–1.8 Ma occur (Pb–Pb zircon ages, Kröner & Sassi 1996) in the Qabri Bahar–Mora complexes, which have been suggested to correlate to Precambrian terranes in southern Yemen (Whitehouse et al. 1998; Whitehouse et al. 2001b). However, only few pre-Neoproterozoic zircon ages have been reported from Yemen, between 2.6 and 3.0 Ga (U–Pb zircon; Whitehouse et al. 1998), mainly older than those found in the Huqf Supergroup. Furthermore, detrital zircons in the late
Neoproterozoic or Early Cambrian Hammamat Group in Egypt and in >750 Ma sedimentary rocks in the Khida province, Saudi Arabia, contain pre-Neoproterozoic zircon populations broadly similar to those of the Huqf Supergroup with peaks at 1.7–1.9 Ga and 2.4–2.6 Ga (Khida province) (U–Pb ages, Whitehouse et al. 2001a) and at 1.8–2.0 Ga and 2.3–2.6 Ga (Hammamat Group) (U–Pb; Wilde & Youssef 2002), testifying that these old sources were exposed in the Arabian Nubian Shield area in Neoproterozoic to Early Cambrian times. Farther away, detrital zircons in paragneisses in Sudan contain 1.2, 1.7, 2.0, 2.4 and 2.6 Ga subpopulations (Pb–Pb; Stern et al. 1994). Old zircons of the Huqf Supergroup may also have been derived from sources located towards the present-day SE of Oman, such as the Indian shield. Granitic basement of 1.6–1.7 Ga and 2.5 Ga has been reported from Rajasthan province (Pb–Pb zircon ages; Wiedenbeck et al. 1996; Roy 2001; Mondal et al. 2002). In addition, detrital zircons in Palaeoproterozoic and Cambrian sediments in the Lesser Himalaya, thought to be derived from the Indian Shield, show a spread in pre-Neoproterozoic ages that fits well with that of the Huqf Supergroup, including a few 1.1–1.2 Ma ages and a peak from 1.6 to 2.6 Ga (U–Pb; DeCelles et al. 2000; Myrow et al. 2003), further testifying to the availability of Mesoproterozoic and Palaeoproterozoic detrital sources in this region.

If the old zircons found in the Fiq Formation and Nafun Group are in fact derived from sources outside Oman, it is possible that their admixture with locally derived zircons reflects the accretion of Oman to an older block of continental crust situated to the west in present-day coordinates. Accretion of Oman in the time period between deposition of the Ghubrah and Fiq sediments could not only account for the difference in detrital zircon populations, but also for the angular unconformity that separates the Ghubrah Formation from the overlying stratigraphy.

Summary and conclusions

The Huqf Supergroup of Oman comprises an exceptionally complete record of the late Neoproterozoic Era, but the correlation of Neoproterozoic outcrops in northern and central Oman with those of the Mirbat Group in southern Oman has until now been poorly understood. Integration of recently collected lithostratigraphic and chemostratigraphic data for the Mirbat Group with subsurface and outcrop data from elsewhere in Oman, and with new detrital zircon U–Pb ages, suggests that the Mirbat Group is most satisfactorily correlated with the Cryogenian Abu Mahara Group of the Huqf Supergroup. This interpretation is based on: (1) the close match between the Mirbat Group and Abu Mahara Group stratigraphy in the subsurface of southern Oman, but distinct differences from the laterally persistent siliciclastic–carbonate cycles in the Nafun Group throughout Oman; (2) the difference in carbon isotopic and lithological characteristics of the cap carbonates overlying the Ayn and Fiq glacial deposits, but their similarity to older Cryogenian and end-Cryogenian cap carbonates elsewhere around the world, respectively; (3) distinct differences between the detrital zircon populations of the lower Nafun Group and those of the Arkahawl and Marsham Formations, but their resemblance to detrital zircons from pre-Fiq stratigraphy. The proposed correlations are also in agreement with maximum constraints on the ages of deposition. A composite stratigraphic column (Fig. 7) for the Huqf Supergroup from ≥725 Ma basement to the Precambrian–Cambrian boundary is proposed. This composite column contains two well-documented glacial intervals and three negative carbon isotopic excursions. Based on these correlations the Arkahawl and Marsham Formations of the Mirbat Group fill the stratigraphic gap between the Ghubrah and Fiq glaciations recognized in northern Oman.

Detrital zircons in the Abu Mahara, Mirbat and lower Nafun
Groups are dominantly Neoproterozoic in age and were derived from local basement. The admixture of older detrital zircons, for which no source is known to exist in Oman, in the Fiq Formation and the Nafun Group may have resulted from exhumation of deep crystalline Precambrian basement in Oman, or more probably, the expansion of drainage basins into an older block of continental crust joined to the Oman plate. The latter possibility could have resulted from accretion of Oman to another tectonic block sometime around 650 Ma during the assembly of eastern Gondwana, which could not only explain the observed provenance change, but also the widespread unconformity between the Fiq–Saqlah and the underlying stratigraphy in northern Oman. Consequently, a paradox emerges that the presumably extensional basins that accommodated the Fiq Formation evolved at a time when collisional tectonics dominated the eastern margin of the Arabian–Nubian Shield.

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