Al Khlata glacial deposits in the Oman Mountains and their implications

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Abstract: A thick succession of Al Khlata glacio-lacustrine deposits, including diamictites, crops out in the Wadi Daiqa inlier and there are other possible Al Khlata outcrops in Wadi Amdeh and Wadi al Arabiyin. These outcrops in the Oman Mountains are 100 km north of where the Al Khlata had been thought to pinch out by non-deposition or erosion. Fossil spores and pollen from Wadi Daiqa are highly carbonized having been subject to greenschist facies metamorphism, but are still clearly identifiable as taxa from the Late Carboniferous 2159A zone of the oil-producing areas of interior Oman. This northernmost Al Khlata is sand rich and interpreted to be glacio-lacustrine. Previously the sand-dominated Al Khlata successions north of the Central Oman High have been considered to be glacio-fluvial outwash largely based on their context. The Al Khlata deposits in Wadi Daiqa and the underlying several-kilometre-thick Amdeh succession are preserved in Saih Hatat, probably in a continuation of the Ghaba Salt Basin that itself overlies an accreted terrane from the Pan African orogeny.

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Al Khlata glacial deposits occur widely in the subsurface of interior Oman. They are absent along the easternmost coastal area and were believed absent from northern Oman and the Oman Mountains due to non-deposition. Here we describe a c. 300 m succession of Al Khlata P9 deposits from Wadi Daiqa, and other possible outcrops of Al Khlata lithologies in the Saih Hatat area. The Wadi Daiqa sections are important in being outcrop analogues of sand-prone oil-producing intervals in the subsurface of southern Oman. Unfortunately, the most easily accessible section was flooded with the filling of the Wadi Daiqa water reservoir in 2009. The better-known outcrops at Al Khlata, in the Huqf area, are of younger P5 and P1 age and are predominantly of non-reservoir facies.

History of work on the Permo-Carboniferous Al Khlata Formation in Oman

The first brief description of Gondwanan glacial boulder beds in the Huqf area of Oman were made by Iraq Petroleum Company (IPC) geologists in the 1950s (e.g. Hudson 1958). It was the belief that Wellstead saw equivalent boulder beds in the Oman Mountains in the 1830s which spurred the IPC geologists’ fraught attempt to gain access to Wadi Ma’aidin in 1957 (Heward 2008).

The Al Khlata began to be recognized as an important oil reservoir interval in the subsurface of southern Oman in the mid 1970s, but one that was often impossible to predict over a few hundred metres between oil wells. Regional and field-scale studies were undertaken in support of Petroleum Development Oman’s (PDO) oil exploration and development activities (e.g. Martin & Cooper 1984; Levell et al. 1988; Heward 1990). The value of palynology in helping unravel the complexity of the Al Khlata began to be realized in the mid-1980s when a three-fold subdivision of the formation was established (P9, P5 and P1, Table 1; e.g. Besems & Schuurman 1987; Love 1994). More recent publications on the outcropping and subsurface Al Khlata include those of Al-Belushi et al. (1996), Hartmann et al. (2000), Osterloff et al. (2004), Heward & Al-Ja’aidi (2005), Martin et al. (2008, 2012), Penney et al. (2008, 2011), Stephenson et al. (2008) and Forbes et al. (2010). Much unpublished work lies in oil industry well files and reports.

The Al Khlata has now been encountered in literally thousands of wells drilled for oil or gas over much of interior Oman, and varies in thickness from 0 to >800 m (Fig. 1). The formation has long been thought to pinch out to the north through being at the limit of glacial influence, or thinning against the incipient rift shoulder of the Neotethys (Hughes-Clarke 1988; Levell et al.)

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| Biozone               | PDO Biozone | Production unit | Age                          | Jebel Akhdar         | Saih Hatat   |
|----------------------|-------------|----------------|------------------------------|----------------------|--------------|
| Haushi               |             |                |                              |                      |              |
| Khuff Formation      |             |                | Wordian (Permian) – Early Triassic | Saiq Formation | Saiq Formation |
| Gharif Formation     |             | P1             | Sakmariian – Wordian (Permian) | –                    | –            |
| Al Khlata Formation  | 2141        | P1             | ?Sakmariian (Permian)        | –                    | –            |
|                      | 2165        | P5             | ?Asselian – Sakmariian (Permian) | –                    | –            |
|                      | 2159        | P9             | ?Late Moscovian – Gzhelian (Carboniferous) | –                    | Al Khlata Formation |
| Huqf Supergroup      |             |                |                              |                      |              |
| Hauma Supergroup     |             |                | Early Cambrian – Late Ordovician | –                    | Amdeh Formation |
| Ara Group             |             |                |                              |                      |              |
| Buah Formation       |             |                | Ediacaran – Early Cambrian | Fara Formation      |              |
| Shuram Formation     |             |                | Ediacaran                    | Kharus Formation     | –            |
| Khufai Formation     |             |                | Ediacaran                    | Mai’adin Formation  | –            |
| Masirah Bay Formation|             |                | Ediacaran                    | Hijir Formation      | Hiyam Formation |
| Hadash Formation     |             |                | Ediacaran                    | Masirah Bay Formation | Tawny Dolomite? |
| Abu Mahara Group     |             |                | Cryogenian                   | Ghadir Manqil Formation | Hatat Formation |

The biozones of the Al Khlata (e.g., 2159, 2165, 2141) were named after 1980s computer codes for various palynomorphs, but are now used for the quantitative zonal scheme progressively refined since Besems & Schuurman (1987). These have been subdivided into 2159A & B, 2165A & B, 2141A, B & C (Penney et al. 2008). In day-to-day work with subsurface well data, production intervals (P9, P5 and P1) were established within which samples characteristic of the palynological zones have been analysed or were correlated by wireline logs to wells that have analyses. This nomenclature has been in use by PDO since the mid 1980s.

The differing stratigraphies of the Jebel Akhdar and Saib Hatat windows are quite striking and differences in thickness and lithology continue through the Mesozoic. The equivalence of the Hiyam and Hatat formations of Saib Hatat to the well-established stratigraphy of the Huqf Supergroup is uncertain. It has also not been confirmed, from isotope and other evidence, that the Tawny Dolomite of Le Métour et al. (1986) is indeed a cap carbonate and equivalent to the Hadash Formation.
Fig. 1. Compilation map of Al Khlata distribution in Oman indicating the occurrences described in the Saih Hatat area of the Oman Mountains. Derived from various sources: Al Khlata thickness in South Oman (Osterloff et al. 2004); regional exploration wells penetrating the Al Khlata in the early 1980s (Levell et al. 1988); Al Khlata facies associations and subcrop limit (Sykes & Abu Risheh 1989); interpreted extension of Ghaba Salt Basin beneath the Hawasina nappes (Mount et al. 1998); and approximate line of 55°S palaeolatitude at 300 Ma (Kazimovian: Stampfli & Borel 2004).
The bulk of the evidence from subsurface cores and surface outcrops indicates that the Al Khlata was deposited by meltwaters in lakes, often adjacent to melting ice (Osterloff et al. 2004; Martin et al. 2012). The ice originated from highlands in the SW and advanced repeatedly towards the NE (Heward & Al Ja’adi 2005; Seldon et al. 2010). There is no conclusive evidence from subglacial features or provenance studies that ice advanced towards the SW at any stage, despite the models of Al-Belushi et al. (1996) and Martin et al. (2012). Palynological interpretations imply that deposition occurred at various times during Late Carboniferous–Early Permian time (Table 1, Moscovian–Stephensonian, c. 30 Ma). Eight separate palynological subzones have been recognized, including an interval at the base that is barren or which contains only recycled Devonian floras (Penney et al. 2008, 2011; Stephenson et al. 2008; Forbes et al. 2010). The climate warmed and interglacial floras became more diverse with the passage of time as Oman moved rapidly from a palaeolatitude of c. 55° S to c. 35° S of the equator. Not every penetration of the Al Khlata encounters all the palynological zones; P9 deposits are often confined within underlying topography or limited by later erosion, P5 intervals are also often patchily preserved and the younger P1 intervals are the most continuous and blanket-like (Osterloff et al. 2004; Stephenson et al. 2008).

The thickest and most basal Al Khlata deposits occur along the southeastern edges of the South Oman and Ghaba salt basins where Ara salt was near the surface and dissolved contemporaneously with deposition (Fig. 1). These areas often preserve a more complete sequence of Al Khlata zones and also tend to be shalier overall. The oldest Al Khlata intervals are predominantly sandy with much mature quartz sand reworked from underlying formations of the Haima Supergroup (Table 1). Progressively younger Al Khlata intervals are shalier with thicker, more extensive intervals of rain-out diamictite. In the basinal areas of South Oman the Al Khlata is capped by one or two intervals of ‘varved’ Rahab Shale (Fig. 1). The Rahab shale, with its high gamma-ray and low-density overlying dense diamictites, is normally a readily recognizable interval on wireline logs (Levell et al. 1988; Forbes et al. 2010).

Boulders within the Al Khlata, which can achieve a size of several metres, are either locally sourced sedimentary rocks or further-travelled erratics of granite, volcanic rocks or low-grade metamorphic rocks (Martin et al. 2012). Many Al Khlata boulders and cobbles are quite well rounded, suggesting repeated cycles of transport by ice and water. Some preserve striations that attest to a latest phase of transportation by ice.

The previously known outcrops of the Al Khlata are in the Huqf area from Al Khlata in the south to Haushi in the north and at Qarn Sahmah salt dome to the west (Fig. 1). The best outcrops in wadis around Al Khlata were mapped and 10 shallow-core holes drilled in unpublished PDO work by John Martin in the 1990s. The outcrops and unweathered shallow-cored sections were dated as P5 and P1 (e.g. Besems & Schuurman 1987; Heward & Al-Ja’aidi 2005; Penney et al. 2008; Martin et al. 2012). The boulder spreads at Qarn Sahmah are undated but probably represent a raft of P5 based on comparison to the nearby Qarn Sahmah North-1 well (Heward & Al-Rawahi 2008).

Evidence of Al Khlata outcrops in the Oman Mountains

The first signs that there might be Al Khlata in the Oman Mountains were recognized during a Geological Society of Oman (GSO) field trip to Wadi Amdeh in March 2005. Shallow-marine sediments of the Amdeh Formation were the focus of the excursion but, on a walk back from outcrops in the headwaters of the wadi, orange-coloured diamictites were observed, unexpectedly and rather out of place, in the wadi wall (Follows 2005).

During fieldwork in late 2004 and early 2005 to better constrain the age of Ordovician Amdeh outcrops, samples were taken from dark grey pencil slates of presumed Amdeh age in a side tributary of Wadi Daiqa. These were processed for palynomorphs, and Florentin Paris surprisingly reported the occurrence of carbonized plant material and spores.

During further work in 2007, stratified diamictites with dropstones were found clearly exposed following the passage of the ‘100-year’ floodwaters of cyclone Gonu. Samples were taken for palynology and, with the Wadi Daiqa dams nearing completion and the threat that some of the best outcrops could soon be submerged, a section was logged in December 2008.

Wadi Daiqa

Several hundred metres of Al Khlata succession are present in the interval between the Amdeh 5 and the towering cliffs of Saiq Formation that surround this faulted domal inlier (Fig. 2; Le Métour et al. 1986). The most accessible Al Khlata outcrops were along the main wadi that has now been flooded by the water reservoir; those that remain today are in more rugged terrain. The Al Khlata overlies the Amdeh 5 unconformably without obvious angular
discordance. There is however evidence of normal and reverse movement on fault blocks affecting the Amdeh prior to deposition of the Al Khlata (Fig. 3). The origin of the locally quite intense folding and boudinage of an orthocone limestone bed near the top of the Amdeh succession is currently unclear (slumping, tectonic or glacitectonic?). The Al Khlata varies in thickness up to c. 300 m at different locations around the inlier. It is overlain erosively, but without obvious angular discordance, by an undated interval of coarse-grained, pebbly, feldspathic sandstones and purple siltstones which themselves pass up conformably into the fossiliferous carbonates of the Saiq.

Sedimentology

The Al Khlata sequence exposed in the wadi is 235 m thick and comprises three lithofacies: white quartzose sandstones, yellow-brown weathered diamictites and dark grey shales with orange-pink coloured ironstones (Figs 4 & 5).

The sandstones are predominantly coarse-grained tabular bodies with a porous ‘honeycomb’ texture. They are quite different to the compact fine-grained quartzites of the Amdeh 5 Member which often contain scattered moulds of crinoid columnals and are capped by brown weathering shell beds. The Al Khlata sandstones are locally pebbly to bouldery with subangular clasts of Amdeh quartzite, siltstones, vein quartz and red chert. The base of the first main sandstone interval is sharp and tongues of sand continue from the base downwards in a progradational arrangement into the underlying stratified sandy diamictite (Figs 4c & 5). The base of the second major sandstone unit contains large rafts of diamictite presumably eroded from below. The sandstones are stratified and often appear to show low-angle wavy climbing-ripple or dune cross-stratification (Fig. 4e). The macroscopic pores are often tabular, centimetre-scale and pick out sedimentary stratification.

In thin-section the sandstones are medium- to coarse-grained quartz arenites that are well compacted with sutured grain-to-grain contacts. There is a primary cement of small carbonate rhombs. The honeycomb porosity is clearly secondary and the timing of its creation is currently unknown. The composition and paragenesis of these Al Khlata sandstones appears comparable with that of...
described by Hartmann et al. (2000) for the salt basin areas of interior Oman, except for the rapid burial and subsequent rebound these rocks have experienced since the Late Cretaceous.

Diamictites occur at the base of the section and again at 110 m (Fig. 5). They vary from sandy to silty and stratified to massive (Fig. 4c, d). The stratified diamictites have millimetre–centimetre-thick sandstone beds that extend laterally over tens of metres. Coarser grains within the tongues of sand are often millet-seed in shape. Dropstones vary from granule to small boulder size and some show evidence of surface striations. The clasts are mainly of Amdeh lithologies, cherts and occasional granitic erratics (Fig. 4d). One grey horizon in the lower stratified diamictite contained probable macroscopic plant debris. Occurrences of plant remains are rare in the Al Khlata at outcrop or in cores from the subsurface of interior Oman.

Grey siltstones and pencil slates with ironstone nodules and bands cap the measured section, and it was these that first yielded evidence of carbonized plant remains and spores in 2005. Due to the presence of a strong cleavage it is difficult to discern any primary sedimentary features. These outcrops have been subject to greenschist facies metamorphism during Late Cretaceous subduction of the Oman margin (Le Métour et al. 1986). No work has been done on the ironstones to determine their mineralogy or diagenesis, but there is evidence from other outcrops in the Wadi Daiqa inlier that they formed sufficiently early to be reworked as clasts.

The diamictites with dropstones are the most diagnostic facies and clearly indicate rain-out in a standing body of water from an ice margin or from icebergs (Miller 1996; Eyles & Eyles 2010). The tongues of sand that pass laterally into thin laminated sandstone beds within the stratified diamictite probably represent event or seasonal underflows into a glacial lake. Small-scale deformation with backward rotation of laminae on the progradational foresets is due to slumping on unstable slopes.

The thicker intervals of sandstone and sparsely pebbly sandstone are more problematic in showing predominantly horizontal or low-angle wavy stratification, partly from climbing ripples or dunes. They do not contain the abundant trough or tabular cross-stratification and sorted pebble fabrics that would be expected from glacio-fluvial rivers (Miller 1996; Eyles & Eyles 2010; Miall 2010). These laterally extensive, tens-of-metres-thick, relatively tabular units are interpreted as lobes of a
Fig. 4. Al Khlata outcrops in Wadi Daiqa (58°49′15.04″E, 23°04′48.29″–45.15″N) now flooded by the lake. (a) Panorama of sandy basal part of the sequence. Youngs to the right, viewed towards the SSE. ‘X’ is at c. 100 m on the logged section (Fig. 5). (b) Panorama of shaler upper part of the sequence. Youngs to the right, viewed towards the SE. Beds are quite tabular over the extent of the outcrop. Sand unit in centre is 45 m thick. (c) Stratified sandy diamictite with dropstones and a tongue of darker sand. Tongues of sand indicate progradation towards the NW. Hammer handle is 28 cm. (d) Stratified sandy diamictite with dropstones including a granite cobble. Lens cap is 5 cm. (e) Typical honeycomb texture of the sandstones picking out climbing ripple cross-stratification (type B of Ashley et al. 1982). Plant leaves are c. 10 cm long. (f) Grey pencil shales (slates) with 5–10 cm thick horizons of orange-coloured ironstone.
Fig. 5. Measured section through the Al Khlata sequence shown in Figure 4 and located on Figure 2. The locations of palynological samples are indicated.
Table 2. Palynological counts of Wadi Daiqa field samples. The shaded columns are from samples taken slightly further upstream from the measured section.

| Co-ordinates WGS84 | WDAK01/07 | WDAK02/07 | WDAK03/07 | WDAK04/07 | WDAK05/07 | WDAK06/07 | WD2004-10 | DX 10 (7) |
|--------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Longitude/Latitude | 58°49'13.94"E | 58°49'14.02"E | 58°49'03.01"E | 58°49'13.94"E | 58°49'07.64"E | 58°48'52.43"E | 58°49'05.34"E | 58°49'05.58"E |
|                     | 23°04'48.23"N | 23°04'47.80"N | 23°04'47.26"N | 23°04'48.23"N | 23°04'46.64"N | 23°04'52.54"N | 23°04'52.58"N | 23°04'55.31"N |
| PDO biozone          | ?2159A    | ?2159A    | ND        | ?2159A    | ?2159A    | ?2159A    | 2159A     | 2159A     |
| Taxon               |           |           |           |           |           |           |           |           |
| Anapiculatisporites | 1         | 0.56      | 1         | 0.53      | 1         | 0.53      |           |           |
| concinnus           |           |           |           |           |           |           |           |           |
| Aratrisporites      |           |           |           |           |           |           |           |           |
| saharaensis         | ?         |           |           |           |           |           |           |           |
| Bissacates          | 4         | 2.26      | 5         | 2.66      | 2         | 1.69      | 2         | 0.70      |
| Brevitriletes spp.  |           |           |           |           |           |           |           |           |
| Cingulicavati       |           |           |           |           |           |           |           |           |
| Cristatisporites    | 2         | 1.13      | 1         | 0.53      |           | 1         |           |           |
| Indotriradites fibrosus | 1     | 0.53      |           |           |           |           |           |           |
| Microbaculispora    |           |           |           |           |           |           |           |           |
| Monosaccates        | 164       | 92.66     | 152       | 98.70     | 25        | 100.00    | 180       | 95.74     |
| Punctatisporites    | 2         | 1.13      |           |           |           |           |           |           |
| ? Wilsonites        | 164       | 92.66     | 152       | 98.70     | 25        | 100.00    | 180       | 95.74     |
| australiensis       |           |           |           |           |           |           |           |           |
| R. lepidophytus     | 4         | 2.26      | 1         | 0.65      |           |           |           |           |
| (rwkd)              |           |           |           |           |           |           |           |           |
| Spores unspecified  | 1         | 0.65      |           |           |           |           |           |           |
| Total counts        | 177       | 100.00    | 154       | 100.00    | 25        | 100.00    | 188       | 100.00    |

*Collected in 2004.
†Collected in 2005.
‡Punctatisporites group includes mainly P. gretensis and P. lucidulus + Calamospora spp.
subaqueous fan where highly sediment-charged meltwaters disgorge into a glacial lake. Climbing ripple or dune cross-stratification is typical of glacial deposits where highly sediment-charged currents decelerate under conditions of waning flow (Rust & Romanelli 1975; Eyles & Eyles 2010).

In the absence of sedimentary features, the grey siltstones and slates are interpreted to represent quiet periods of lake deposition with suspended sediment settling through the water column. The evidence that the lake was probably glacial comes from equivalent sections and an overlying sandy diamictite that occurs elsewhere in the inlier.

**Palynology**

Eight samples, collected on four occasions between 2004 and 2007, were processed and analysed (Fig. 6, Table 2). All yielded highly carbonized, poorly preserved assemblages in line with the degree of metamorphism these rocks have been subjected to. The youngest samples (2004–10 and DX 10; Fig. 5) are directly assignable to PDO palynomorph zone 2159A (Table 1; Penney et al. 2008, 2011). The lower five samples are more heavily carbonized and lack monosaccate pollen. They are questionably assigned to the 2159A zone. Although the sixth sample (AK03/07) contains some Punctatisporites-like opaque shapes, is below the limit of reliability to assign a zone and is designated Non Diagnostic (ND). Given that most of the samples come from the logged section and contain similar assemblages, it can be assumed that they are all approximately the same age and fall within the same palynomorph zone. It should be noted that within the 2159 zone, there is an overall decrease in the proportion of Monosaccate pollen from the top to the base (Penney et al. 2008). This is in accordance with the samples from the logged section (Fig. 5, Table 2). Over 90% of the assemblage consists of the Punctatisporites spp. Group, which typically includes the smooth-walled genera Calamaspora, Punctatisporites and Retusotriletes. The other significant taxonomic group is monosaccate pollen (Monosaccites), which constitute less than 5% of the assemblages and was not recorded in samples WDAK01/07 through WDAK06/07. At the levels of carbonization shown by the samples, it is difficult to distinguish genera let alone attempt speciation. Other notable palynomorphs include Anapiculatisporites concinnus, Cristatisporites ssp., Vallatisporites ssp. (including Vallatisporites arcuatus) and Indotriradites fibrosus. The gross proportions of the main taxonomic constituents are sufficient to position these samples within the PDO zonation scheme and all taxa encountered are in accordance with the 2159A zonal assignment. Occurrences of the Devonian spore Retispora lepidophyta are considered reworked and, indeed, this taxon is frequently encountered in lower Al Khlatla sequences.

Stephenson et al. (2008) established a ‘first-appearances’ zonal scheme for the subsurface Al Khlatla based on drill cuttings from wells in the Mukhiazn field of southern Oman. This is a practical alternative to the quantitative scheme of Penney et al. (2008) based on core and sidewall samples. Comparison of the Wadi Daiqa assemblage with Stephenson et al. data is difficult, except for the occurrence of I. fibrosus which is a notable constituent of their earliest datable Al Khlatla Biozone D.

**Palynological correlation and dating**

Relatively little raw palynological data is published from age-equivalent Gondwana sequences worldwide, particularly sequences with dated marine or volcanic intercalations. Some of the most detailed data published are from Eastern Australia. Jones & Truswell (1992) provide palynological percentages for taxa recovered from core in the Joe Joe Group of the southern Galilee Basin, Queensland. They subdivided their sequence into five Oppel-zones.
ranging in age from Namurian (Carboniferous) to early Tastubian (Early Permian). Plotting the percentages and re-grouping the taxonomy to be equivalent to the Penney et al. (2008) scheme reveals these assemblages range approximately from 2159A to ?2165 zones. There are differences in detail between the Eastern Australian and the North Oman outcrop data, but the overall assemblages are strikingly similar. This detailed core data can be fitted within the surrounding Eastern Australian zonation (Norvick 1974, 1981; Price 1976, 1983; Kemp et al. 1977), which is in turn correlated with the Western Australian zonation from the Canning Basin (Powis 1979, 1984; Backhouse & Mory 2011) where the 2159 zone approximates to Stage 1 of the Stephenson et al. (2003) Arabian Plate OSPZ1.

Very little detail is published for locations closer to Oman apart from the Stephenson et al. (2003) Arabian Plate zonation, which is based upon the ranges of key taxa. These authors do not provide quantitative data apart from quoting a reference section in the Southern Saudi Arabian well Mukassir-1 and mentioning that the smooth-walled spores Punctatisporites and Retusotriletes account for up to 50% of the assemblages in the lowest (OSPZ1) zone. Additional palynological data is provided from Saudi and Oman sections in Stephenson & Filatoff (2000), but this is from the overlying Stage 2 equivalent latest Carboniferous (Pennsylvanian) to Permian intervals. Stephenson & Al-Mashaikie (2011) provide raw palynological data from outcropping Akbarah and Kuhlan formations of NW Yemen. Only the lowermost samples of the Akbarah Formation display any resemblance to the 2159 zone, counts are extremely low and correlation with 2159 is doubtful.

The main difficulty in more precisely dating the Al Khaltara is the absence of marine fossils or radiometric dates. There is also a lack of reliable age dating for Stage 1 in the Eastern Australian sequences. Only spore and pollen assemblages can be used to correlate and compare sections. The occurrence of monosaccate pollen indicates an age no older than Namurian (Mississippian) and, based upon comparison with the Australian sequences and applying the Davydov et al. (2004) assessment, an age no older than Moscovian is inferred for the 2159A zone. Stephenson (2009) described younger Gondwanan floras from Namibia that occur in a succession containing ash layers that have been radiometrically dated. He concludes that the Oman 2165 zone may be Carboniferous rather than Permian (Asselian), with the implication that the 2159 zone may be somewhat older than previously thought. It should also be noted that regionally the full stratigraphical extent of the basal Al Khaltara cannot be determined due to the absence of in-situ palynofloras. Only reworked Devonian and earlier palynomorphs are encountered (Penney et al. 2008).

**Other outcrops in the Wadi Daiqa inlier**

Al Khaltara outcrops have also been examined around the northern flank of the inlier. Similar outcrops occur on the southern side but have not been visited since the main valley was flooded due to the difficulty of access.

The most complete c. 300 m section of Al Khaltara is found in the NW area of the inlier (Fig. 7). Here a >100 m thick, coarse-grained, basal sandstone with prominent wavy-horizontal bedding and granular honeycomb texture is overlain by grey pencil slates with ironstone horizons, as in the measured section (Fig. 7a–d). The basal sandstone shows a weathering pattern typical of those with carbonate cement. Siltstones towards the base of the pencil slates contain scattered grains of medium-grained sand and at least one horizon has possible burrows. A distinctive 15 cm bed of ironstone-cemented sandstone within the slates is full of medium- to coarse-grained well-rounded, recycled, sand grains.

An overlying sand package occurs that was not exposed in the measured wadi section. Its base is conglomeratic with cobbles and boulders of a variety of lithologies including ironstone, granite, carbonates and vein quartz. It passes up into

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**Fig. 7.** Al Khaltara and possible Gharif outcrops elsewhere in the Wadi Daiqa inlier (58′49′03″E, 23′05′36″N). For location see Figure 2. (a) Panorama viewed to the north of cliffs of Al Khaltara, Gharif and Saiq. The Al Khaltara comprises two cliff-forming sandstone intervals, a lighter bedded one and a darker more massive one. Pencil slates separate the two sandstone intervals but are eroded out towards the right. The lowermost Al Khaltara cliff is >100 m high. The locations of photos below are indicated in upper case letters. (b) Conglomeratic Al Khaltara sandstone erosively overlying laminated siltstones. Note the small injection feature to the left. Hammer handle is 28 cm. (c) Wavy horizontal bedding at 15–25 cm spacing dominates the basal part of the main sandstone cliff. (d) Interval of grey pencil shales (slates) and orange-coloured ironstone beds separating the two Al Khaltara sandstones. The bushes are c. 1.5 m high. (e) Stratified sandy diamictite towards the top of the second Al Khaltara sandstone interval. The granite cobble is 17 cm in longest diameter. (f) Interbedded white and purple, pebbly feldspathic sandstones with purple siltstones of possible Gharif age occurring between the Al Khaltara and the Saiq. The bushes are c. 1.5 m high. (g) Laminated Al Khaltara flaggy sandstones erosively overlain by a conglomerate of possible Gharif age containing orange-coloured ironstone cobbles. Hammer handle is 28 cm.
compact finer-grained sandstone that lacks honeycomb texture, into a stratified sandy diamictite (Fig. 7e) and is capped by flaggy sandstone with sole-marks, load structures and current ripples (basal part of Fig. 7g). This upper sandstone-sandy diamictite package is erosively based and cuts out the pencil slate interval to amalgamate with the basal sandstone (Fig. 7a). The presence of ironstone clasts, presumably derived from the pencil slates below, suggests that the ironstones formed near surface and soon after deposition.

Outcrops further east are of the basal diamictite and the basal thick sandstone (Fig. 8). Quite intense deformation of unknown origin affects the uppermost Amdeh 5 and basal diamictite in some locations. The basal sandstone exhibits the characteristic porous honeycomb texture and general lack of distinctive sedimentary structures. Cross-bedding occurs locally (Fig. 8c). Several different types of macroscopic honeycomb porosity are possibly evident; some may be from dissolution of a carbonate cement, some from the removal of centimetre-size lithic clasts and others appear to have a tectonic alignment. Outcrops still further east on Figure 2 show only a few tens of metres of compact quartzose sandstones, lacking the porous honeycomb texture, and at times resemble sandy diamictite (Fig. 8e). This sandstone may represent the upper sandstone-diamictite package, with the basal sandstone presumed absent (or it would have been a more prominent topographic cliff-former as elsewhere). This might suggest the thickest Al Khlata succession in the Wadi Daiqa inlier is confined within underlying topography, as is commonly the case in the subsurface of interior Oman.

Overlying the Al Khlata on the northern flanks of the Wadi Diaqa inlier is a >50 m interval of pebbly coarse-grained cross-bedded feldspathic sandstones and mottled purple siltstones and shales (Figs 7a, f & 8f). The base is locally conglomeratic, including distinctive slabs of orange ironstone (Fig. 7g). Fossil tree trunks are present at several locations in the uppermost sandstones, poorly preserved by iron and silica (Fig. 8g). These sandstones pass gradationally up into the orange weathering basal interval of the Saiq Formation. Bioturbation is present in thinner finer-grained sandstones towards the top of the succession.

This interval is distinctive for its coarse grain size, feldspar content, its purple siltstones, cross-stratification and the occurrence of fossil wood. These features and its gradational passage into the overlying Saiq are evidence that the interval possibly represents the Upper Gharif. Middle and Upper Gharif sandstones are typically richer in feldspar than the Al Khlata (Hartmann et al. 2000) and fossil wood is widespread in the uppermost Gharif in the Huqf outcrop area (Berthelin et al. 2004; Heward & Al-Ja’aidi 2005; Matysová et al. 2010). Shales with mature seasonal palaeosols and grey plant beds, typical of the Upper Gharif in interior Oman, are however absent.

Wadi Amdeh

An outcrop of diamictite c. 145 m by 175 m occurs anomalously in the upper reaches of Wadi Amdeh. It was made obvious and accessible by a graded road bulldozed through to Wadi Tayin, but that road is now in disrepair. The outcrop appears to be a small pull-apart basin related to the intersection of NNE–SSW and WNW–ESE faults within a sequence mapped as Amdeh 5 (Fig. 9; Villey et al. 1986). No other evidence of diamictite or similar anomalous lithology has been found in the vicinity, particularly at the unconformity between the Middle Ordovician Amdeh 5 and the Middle Permian Saiq formations.

The outcrop consists of grey, massive, silty diamictite with a bright orange oxidized margin (Fig. 10a). Contacts appear to be faulted and at two locations there is evidence of injection of diamictite into the Amdeh. The thickness of diamictite is unknown and the only variation appears to be a reduction in maximum clast size from boulder to cobble grade towards the SE. Clasts are of sedimentary lithologies, derived from the Amdeh (including

Fig. 8. Al Khlata and possible Gharif outcrops elsewhere in the Wadi Daiqa inlier (58°49′44″E, 23°07′20″N). For location see Figure 2. (a) Panorama viewed towards the NW of a cliff of Al Khlata sandstone underlain by an interval of yellow diamictite of varying thickness. The locations of photos (b–d) are indicated in upper case letters. Lateral variations in sequence and block faulting are again apparent in the underlying Amdeh 5. The dark sandstone interval in the Amdeh 5, lower right, is c. 15 m thick. (b) Weathered massive sandy diamictite with granule and pebble-sized dropstones. Hammer handle is 4 cm wide. (c) Trough cross-stratified Al Khlata sandstone in fallen block from cliff above. Hammer head is 18 cm. (d) Elongate tabular pores picking out stratification in Al Khlata sandstone. Hammer handle is 28 cm. (e) Poorly sorted pebbly sandstone, verging on sandy diamictite, from near the base of the Al Khlata in outcrops to the right of the wadi at the right of A (58°50′E, 23°05′51″N). Hammer head is 18 cm. (f) Coarse-grained possibly Gharif sandstone with abundant white kaolinite from the alteration of feldspar (58°50′01″E, 23°05′54″N). Hammer handle is 4 cm wide. (g) Partly weathered-out iron-silicified tree trunk in coarse-grained feldspathic sandstone of possible Gharif age (58°50′07″E, 23°05′53″N). Hammer handle is 28 cm.
boulders containing the trace fossil *Skolithos* and also erratic non-Amdeh carbonate clasts. No clasts of vein quartz or igneous material have been observed to date. Clasts vary from subrounded to subangular and occasionally preserve surface striations (Fig. 10c). The carbonate clasts are at least in part limestone, some show what appear to be ooids and others are fossiliferous with large bivalve and gastropod fossils or fossil moulds. Large platy fossils resembling pitta bread but with curved internal septa are yet to be identified (Fig. 10e). Notably, the fossiliferous clasts contain no obvious macroscopic crinoid, coral, bryozoan or foraminiferal debris.

In thin-section the fossiliferous carbonate clasts are highly recrystallized with ghosts of mollusc shells. In less recrystallized sections, probable peloids are apparent and also possible microcrystalline ghosts of productid spines. What appeared to be ooids in the field are spherulitic arrangements of dolomite rhombs in a sparry calcite matrix. Al-Hajri (2009) additionally reports fragments of echinoid plate and spine, coral and fusulinid in thin-sections and the minerals calcite, dolomite, goethite, quartz, albite and chlorite from x-ray diffraction analyses. The fusulinid, apparently from the matrix of the oxidized diamicite, resembles the genera *Sphaerulina* of uppermost Early–Late Permian age (E. Leven, pers. comm. 2012).

Samples of diamicite for palynology were collected by Graham Booth in 2008 and processed without yielding anything identifiable, not even carbonized structured organic matter. Additional material was reprocessed in 2012, again without success. Giles Miller dissolved large pieces of fossiliferous carbonate clasts in acetic acid in the search for conodonts, again without success. Conodonts are normally found in c. 60% of limestones of Cambrian–Carboniferous age.

The age of the Wadi Amdeh diamicite outcrop cannot at present be established with certainty, nor can the source of the fossiliferous carbonate clasts, in an area of Oman where there are no known carbonate units preserved between the Ediacaran Hiyam Formation and the Permian Saiq Formation (Table 1). The Hiyam is mainly dolomite, but there is a member at the top that is a dolomitic limestone with stromatolites and cherts. The few fossil fragments identifiable from thin-sections provide conflicting evidence of Carboniferous–Permian age. Conglomerate layers occasionally occur in the Amdeh 5 and in the Saiq, but these are of different character to the diamicite (Le Métour et al. 1986; Villey et al. 1986).
Fig. 10. (a) Diamictite outcrop at the head of Wadi Amdeh (58°23′5.66″E, 23°13′54.19″N) viewed towards the NE. (b) Diamictite with subrounded boulders and cobbles of sedimentary lithologies in a green-grey silty matrix. Hammer head, on boulder just left of centre, is 18 cm. (c) Probable striations on surface of quartzite clast. Lens cap is 5 cm. (d) Thick-shelled, recrystallized c. 5 cm bivalve fossils in limestone clast. (e) Molluscs and large platy fossils of unknown affinity in a limestone clast. These platy fossils are tabular not tubular and contain curved internal septa. Lens cap is 5 cm.
Fig. 11. (a) Quartzose sand unit c. 30 m thick between the Amdeh 5 and Saiq at Hayl Al Quwasim (58°59′7.58″E, 23°02′46.40″N); (b) Clastic interval underlying the Saiq at the entrance to the Wadi Mijlas gorge (58°47′43.1″E, 23°15′31.9″N). Person, circled, is 1.6 m tall. (c) Residual Al Khala boulders, including frequent granitic boulders, at Wadi Al Khala North (57°25′5.04″E, 19°46′26.41″N) and (d) near Saiwan (Haushi, 57°37′8.02″E, 20°52′7.20″N).
Given the proximity to the dated Al Khleta outcrops in Wadi Daiqa, it seems probable that this outcrop of diamictite represents a small faulted inlier of Al Khleta. It is unlikely that the diamictite represents the Late Ordovician Hirnantian glaciation as such direct products of glaciation are not known in Oman or this far east in Arabia (Le Heron et al. 2009; Forbes et al. 2010). It is unlikely to be a diamictite of some other submarine mass-flow origin given the shallow-marine context of the Amdeh 5, the boulder size of some of the clasts, the presence of striated clasts and the polymict nature of the clasts.

Other neighbouring localities

The Hayl al Quwasim inlier occurs 15–20 km ESE of the Daiqa inlier (Fig. 1). In Wadi al Arabiyin there is a 30-m-interval of white coarse-granule-grade pebbly sandstone occurring between Amdeh 5 and grey bioturbated carbonates of the basal Saq (Fig. 11a). Cross-stratification is present with a palaeocurrent towards the WNW. Coarse-grained sandstones are found at other locations on the NE margin of the inlier with vivid red and purple colouration similar to some oxidized outcrops of Al Khleta in the Huqf area (e.g. at Shab Nakhad, Fig. 1). The sandstones at Hayl al Quwasim differ from those in the underlying Amdeh in their grain size, colour and lack of shell beds. Their age is unclear, but there is a strong possibility they are Al Khleta deposits; further detailed mapping may discover diamictites and other lithologies typical of glacial depositional systems.

At the landward entrance to the Wadi Mijlas gorge, 20 km NNW of Wadi Daiqa, there is a c. 50 m clastic interval between the Amdeh 5 and the Saq formations that is faulted and cut by a dolerite intrusive. The clastic interval comprises mainly purple mottled siltstones, channelized coarse-grained cross-stratified feldspathic sandstones and, nearer the base, beds of boulder conglomerate with Amdeh-like clasts and an irregularly bedded quartzose sandstone (Fig. 11b). Le Métour et al. (1986) include this interval in the Amdeh 5 but it is very different to the shales, quartzites and shell beds typical of this member. There is no evidence of diagnostic Al Khleta lithologies, such as diamictite or rapidly deposited sandstones with climbing-ripple cross-strata, and the age of this heterogeneous interval is uncertain. The upper coarse-grained cross-stratified feldspathic sandstones and purple mottled siltstones resemble those at Wadi Daiqa except that the proportion of purple siltstones is higher here and no evidence of fossil wood has yet been observed.

Regional context and implications

The only published Oman-wide facies map of the Al Khleta is that of Sykes & Abu Risheh (1989). This pre-dates the general use of palynological zonation and lumps the whole formation together. They distinguish two overall facies associations: a heterogeneous formation with thick diamictites, sandstones, siltstones and shales; and a predominantly sandy formation with thick sandstones and only occasional thin interbeds of diamictite and shales. The heterogeneous association and the overlying Rahab Shale occur largely south of the Central Oman High and the sandy association occurs to the north and west (Fig. 1). This distribution is also described in Hughes-Clarke (1988) and Heward (1990), and representative logs of these associations are shown in Forbes et al. (2010, Rahab and Hajal versus Saih Rawl). The associations were broadly thought to be those of glacial lakes and outwash-rivers, respectively, although in detail there is likely to have been much interplay and erosion during multiple periods of ice advance and retreat. The sandy association is much less understood, sampled and cored than the heterogeneous formation as it does not contain hydrocarbons, except at the top in a few fields in the Ghaba Salt Basin and the Sahmah area. The Unayzah C of eastern central Saudi Arabia has similar, clean, low gamma-ray log signatures as the sandy association (Melvin & Sprague 2006; Melvin et al. 2010). There, sandstone sequences 0–150 m thick are interpreted as glacio-fluvial although there is no direct evidence of glacial conditions (e.g. diamictites, erratic boulders) and they lack the abundant cross-bedding which might be expected from such outwash river deposits. If the Unayzah C and sandy association are equivalent, it could imply broad regional depositional systems.
Typical field occurrences of Al Khleta ‘boulder beds’ in the Huqf and at Qarn Sahmah are illustrated in Figure 11c–e. The lack of evidence of Al Khleta deposits or boulder remnants in the Jebel Akhdar area of the Oman Mountains is depicted by Figure 11f, g.

The Wadi Daiqa outcrops are glacio-lacustrine and the 10 to >100 m sandstone units have characteristics of mass-flow deposits rather than those of glacial rivers. They call into question just how much of the sandy Al Khleta in northern Oman is glacio-fluvial outwash and how much was sand deposited in lakes. The diancites in Wadi Daiqa were deposited from ice at a palaeolatitude of c. 53° S, not quite as far north as the most northerly diancites in the younger Unayzah B of central Saudi Arabia (Melvin & Sprague 2006). Melvin et al. (2010) now report much higher palaeolatitudes (mean of c. 75° S) from palaeomagnetic measurements on core samples from the Unayzah B. Cross-bedding is not abundant in the Al Khleta outcrops in the Oman Mountains and what there is shows generally northerly directed palaeocurrents (NE–NW).

The question remains why c. 300 m of Al Khleta deposits are preserved in the Eastern Oman Mountains 100 km north of where many workers thought they had never been deposited and, if they had been, they would have subsequently been eroded (e.g. Levell et al. 1988; Blendinger et al. 1990; Al-Belushi et al. 1996).

In seminal work for PDO, Stuart-Smith et al. (2007) identified a number of basement terranes in Oman assembled during the Pan African orogeny at c. 730 Ma. They described how the South Oman and Ghaba salt basins overlie a NE-trending belt of accreted ophiolitic and magmatic arc terrane at the margin of the Eastern Arabian craton. They noted that subsidence and the creation of accommodation space was always greater in the South Oman and Ghaba salt basins than in areas outside, such as the Fahud Salt Basin that overlies more stable continental crust, hence the thicker sections of Huqf, Ara and Haima successions. The terrane boundaries were often the locus of faulting during subsequent periods of deformation. These accreted Pan African terranes continue under the Late Cretaceous Hawsina nappes and probably hold keys to the differing geology of Saih Hatat compared to Jebel Akhdar (Table 1). The equivalence of the Hatat and Hijam formations to the Huqf Supergroup in Jebel Akhdar, the Huqf and the subsurface of interior Oman is poorly understood, partly due to the strong overprint of Late Cretaceous deformation and metamorphism in Saih Hatat. Allen (2007) omits these formations from his excellent synthesis of the Huqf in Oman. The absence of regional folding and the relatively constant level of erosion of these Neoproterozoic deposits in Saih Hatat, pre-Amdeh, is quite different to the tight, 3–5 km wavelength Cambrian-aged folding and exposure of many different Huqf formations pre-Saiq in Jebel Akhdar (J.-P. Breton, pers. comm. 2004). Mount et al. (1998) interpreted from seismic, structural and geological evidence that the Ara salt of the Ghaba Salt Basin extended some distance beneath the Hawasina thrust front (Fig. 1). The preservation of >3.4 km of Amdeh in Saih Hatat (Lovelock et al. 1981) is comparable with thicknesses of Cambro-Ordovician sediments in the Ghaba Salt Basin (Mount et al. 1998). The Amdeh Formation is entirely missing from Jebel Akhdar. It comes as little surprise then to find Al Khleta sediments preserved in the Saih Hatat area and missing from Jebel Akhdar and one wonders to what extent accommodation space (for the Amdeh, Al Khleta and Upper Gharif) and the block faulting pre-Al Khleta were generated by salt movement or removal. There are however no obvious signs of evaporites or residues lying between the Hijam and the Amdeh in the outcrops examined by the authors, or reported in the regional mapping of Villey et al. (1986) and Le Métour et al. (1986).

Martin et al. (2008) speculated on whether the Gondwanan ice sheets or ice lobes moved through the low-lying basinal areas and how adjacent areas were affected by ice. It is interesting that the northern limit of the heterogeneous association of Sykes & Abu Risheh (1989) is shown extending further north along the axis of the Ghaba Salt Basin than the Central Oman High (Fig. 1). The striated pavements on the carbonates of the Khufai and Buah formations to the tight, 3–5 km wavelength Cambrian-aged folding and exposure of many different Huqf formations pre-Saiq in Jebel Akhdar (J.-P. Breton, pers. comm. 2004). Mount et al. (1998) interpreted from seismic, structural and geological evidence that the Ara salt of the Ghaba Salt Basin extended some distance beneath the Hawasina thrust front (Fig. 1). The preservation of >3.4 km of Amdeh in Saih Hatat (Lovelock et al. 1981) is comparable with thicknesses of Cambro-Ordovician sediments in the Ghaba Salt Basin (Mount et al. 1998). The Amdeh Formation is entirely missing from Jebel Akhdar. It comes as little surprise then to find Al Khleta sediments preserved in the Saih Hatat area and missing from Jebel Akhdar and one wonders to what extent accommodation space (for the Amdeh, Al Khleta and Upper Gharif) and the block faulting pre-Al Khleta were generated by salt movement or removal. There are however no obvious signs of evaporites or residues lying between the Hijam and the Amdeh in the outcrops examined by the authors, or reported in the regional mapping of Villey et al. (1986) and Le Métour et al. (1986).

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Conclusions

Sand-rich Al Khleta deposits outcrop extensively in the Wadi Daiqa inlier in the interval between the
Ordovician Amdeh and Permian Saiq formations. Evidence to date is that these are glacio-lacustrine deposits of Late Carboniferous P9 age (2159A palynomorph zone, no older than ?Late Moscovian). It is possible that other outcrops of the Al Khlata are present in Wadi Amdeh and Wadi al Arabiyin. There is no evidence yet that Jebel Akhdhar was ice covered or Al Khlata sediments were ever deposited there. Ice tongues may have moved through basinal areas. Jebel Akhdhar does not appear to have been a significant source area for Gharif sediments either, in contrast to the area east of the Huqf outcrops that was a major source of feldspathic sand.

Fossiliferous carbonate clasts in diamictite from Wadi Amdeh possibly indicate the presence of a yet-to-be-recognized Palaeozoic carbonate formation in northern Oman.

Overlying the Al Khlata in Wadi Daiqa and the Wadi Miṣjas gorge there is an interval of coarse-grained cross-bedded feldspathic sandstones and purple siltstones that is undated but has some features in common with the uppermost Gharif of the Huqf outcrops.

The presence of thick Amdeh, Al Khlata and ?Gharif sequences in Saih Hatat is probably due to the continuation of the Ghaba Salt Basin under the Hawasina and Semail nappes. No direct evidence of salt or salt residue has yet been reported.

The different Neoproterozoic and Palaeozoic stratigraphies between Saih Hatat and Jebel Akhdhar possibly stems from their different underlying basement assembled during the Pan African orogeny.

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