Correlation of the Al Khlata Formation in the Mukhaizna field, Oman, based on a new downhole, cuttings-based palynostratigraphic biozonation

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ABSTRACT

Palynology is the primary method of correlating the subsurface glaciogenic Al Khlata Formation of Oman, due to extreme lateral variability of lithofacies, and poor seismic resolution. Up to now, however, it has been difficult to use cuttings samples because published and in-house palynological zonations rely mainly on quantitative variations in palynomorph groups, and such samples are susceptible to downhole caving. Study of around 400 samples from 12 well sections in the Mukhaizna field in south-central Oman has revealed a small number of palynomorphs that can be used alongside quantitative assemblage character to distinguish five biozones. The biozones are defined downhole using mainly cuttings samples. The top of the highest, Biozone A, is marked by the first downhole increase of Microbaculispora tentula and Cycadopites cymbatus and is associated with high gamma-ray readings indicating the Rahab Member of the Al Khlata Formation. Its quantitative character is similar to the upper parts of Oman and Saudi Arabia Palynological Zone 2 (OSPZ2) as well as the Converrucosisporites confluens Zone of the Collie Basin, Western Australia, and is therefore Sakmarian (Early Permian) in age. The top of Biozone B is distinguished by the first downhole appearance (FDA) of common cavate-zonate spores, and Densoisporites truswellii sp. nov., and is also likely to be Sakmarian in age. It is associated with shaley diamictites and more distal lacustrine mudstones with considerable lateral variability. The top of Biozone C is marked by the FDA of Anapunculisporites concinnus but also contains persistent occurrences of Ahrrensiosporites cristatus, Spelaeotriplites triangulus and Deusilites tentus and is similar to Stage 2 of the Collie Basin and is therefore likely to be Asselian (earliest Permian) in age. It is associated with thick sequences of shaley diamictites that occur throughout the Mukhaizna field with relatively little lateral variability, suggesting very long-lived, large, proglacial or subglacial lakes. A lower subdivision of Biozone C, termed Sub-Biozone C1 is distinguished by very high percentages of cavate-zonate spores. Biozone D, of probable Carboniferous age, is characterised by dominant monosaccate pollen and Punctatisporites, contains small numbers of distinctive spores such as Indotriradites fibrosus sp. nov. and Auroraspora sp. A, and is associated with thick, stacked sandstone sequences and sandy diamictites with extremely high lateral variability. The thickness of the upper biozones, A to C, is relatively constant across the Mukhaizna field, and some consistency in log character is also apparent. However Biozone D varies greatly in thickness and is the most internally heterogeneous in terms of log character. This, and the marked discontinuity in the palynological succession at the Biozone C/D boundary, suggests a possible break in the depositional sequence at the top of Biozone D.

INTRODUCTION AND GEOLOGICAL SETTING

The Al Khlata Formation is present widely in the subsurface of Oman and crops out in the Al-Haushi-Huqf area in the east, but the formation is most productive in terms of hydrocarbons in the south, on the Eastern Flank where numerous locally thick intervals yield oil (Figure 1). The northern extension of the Eastern Flank contains a number of large fields including Rima and Mukhaizna (Figure 1), though the latter is unusual in that its oil is contained in the Gharif Formation rather than the Al Khlata Formation (Bouvier et al., 1995). The Al Khlata Formation is a complex unit consisting of clastic lithologies that range from conglomerates through diamictites, gravels, pebbly sandstones,
siltstones to silty shales (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; Dubreuilh et al., 1992; Roger et al., 1992; Al-Belushi et al., 1996; Angiolini et al., 2003), and its glaciogenic nature was established from facies studies of the outcrop area on the western flank of the Al-Haushi-Huqf Uplift where it rests on striated pavements of the Proterozoic Khufai Formation (Braakman et al., 1982; Al-Belushi et al., 1996; Figure 1).

In the subsurface, the thickness varies from about 100–800 m (Levell et al., 1988; Love, 1994); the variability is largely due to syn-depositional subsidence and erosional palaeorelief of the pre-Al Khlata unconformity (Levell et al., 1988). During its deposition, the infra-Cambrian Ara salt in the South
Oman Salt Basin is believed to have moved diapirically to form salt domes, and developed a series of NS-oriented salt pods. As a result, thick Al Khlata Formation sediments are found in synclines formed by salt withdrawal (Heward, 1990). On the Eastern Flank, thick Al Khlata deposits are also found where salt was apparently dissolved by groundwater syndepositionally (Heward, 1990; Osterloff et al., 2004).

The Al Khlata Formation rests with angular unconformity on Devonian and older rocks (Hughes Clark, 1988). The upper boundary in the subsurface is broadly conformable with the overlying Gharif Formation (Osterloff et al., 2004) and is picked at the base of the lowermost Gharif Formation sandstone unit, overlying the mudstone Rahab Member of the Al Khlata Formation (Figure 2). On logs this boundary is marked by a downhole increase in gamma-ray and sonic, and the separation of the density and neutron logs down-hole (Osterloff et al., 2004). In north-central Oman, the Rahab Member is not distinct, and cannot be picked reliably with logs and is thus mainly identified with a palynostratigraphic proxy.

The Mukhaizna field is situated in the north of the Eastern Flank area (Figure 1) and covers an area of around 350 sq km; heavy oil is present in the Gharif Formation reservoirs (Bouvier et al., 1995). Occidental acquired the Mukhaizna field with the aim of developing large-scale steam injection extraction of heavy oil. The purpose of the palynological subdivision described here is to correlate and describe the Al Khlata Formation below the Gharif Formation, which was targeted to store condensed waste water, produced after heavy oil extraction. A number of wells were drilled in 2005 and 2006 to analyse stratigraphy; and for this study comprehensive suites of cuttings samples and a few sidewall core samples from these wells were combined with samples from earlier wells, including mainly cuttings and sidewall core samples but also very limited sections of core. Four hundred samples from Well Nos. 1–12 (Figure 1) form the database of the study.

The lack of core and sidewall core samples necessitated a different approach to that traditionally used in subsurface Al Khlata Formation palynostratigraphy and within Petroleum Development Oman (PDO; e.g. Penney and Osterloff, 2002; Osterloff et al., 2004), which relies mainly on quantitative characterisation (from core and sidewall core data) of assemblages by assignment of palynomorphs to a small number of suprageneric groups, for example the ‘Horriditriletes Group’ and the ‘Microbaculispora Group’. With such a scheme, there are problems assigning assemblages from cuttings samples. An example is the distinction of the 2159 and 2165 biozones of PDO (Osterloff et al., 2004). In brief, these biozones are defined by the presence of different proportions of monosaccate pollen, Punctatisporites, cavate-zonate spores and Anapiculatisporites concinnus (Osterloff et al., 2004; fig. 7). In core or sidewall core samples such distinctions can be very effective because assemblages can be assumed to be in situ. However, in cuttings samples, all but one of the palynomorph groups or taxa that help to define 2159 and 2165 biozones are likely to have caved from sections above (in which they are common). Thus the proportions of palynomorph groups or taxa in cuttings samples from the lower part of the Al Khlata Formation might be entirely artificial, and are therefore a poor basis for biozonal subdivision.

However there are distinct species which have restricted ranges within the lower parts of the Al Khlata Formation, such as Spelaetritiletes triangulus and Ahrensisoprites cristatus and these are important because if they are present in a cuttings sample, they cannot have caved from above. The first
downhole appearances (FDAs) of such taxa form datums that can be used as an alternative to those based on quantitative character change in assemblages which are susceptible to caving, thus they are key to downhole biozonation based on cuttings. Having said this, the lower parts of the Al Khlata Formation have rather low palynological diversity and downhole events of this type are still rare, even after intensive study; thus, pragmatically, biostratigraphic assignment must also occasionally rely on quantitative differences in assemblages, making core and sidewall core samples critical at certain levels.

**PALYNOLOGICAL SUCCESSION IN MUKHAIZNA FIELD**

Generally the diversity and yield of palynomorphs increases upward through the Al Khlata Formation, probably in response to climatic amelioration following glaciation (Stephenson and Filatoff, 2000; Stephenson et al., 2007), and it is this change which allows palynological characterisation of rock units. The downhole succession represents this amelioration in reverse; the first assemblages encountered in the Al Khlata Formation are diverse, consisting of cheilocardioid spores (e.g. *Microbaculispora* spp. and *Horriditriletes* spp.) and colpate and bisaccate pollen; these are followed by assemblages rich in cavate-zonate spores (e.g. *Cristatisporites* spp., *Lundbladispora braziliensis*, *Vallisporites arcuatus* and *Vallatisporites* spp.) and finally by low-diversity assemblages with common monosaccate pollen (e.g. *Cannanoropollis* spp., *Potonieisporites* spp. and *Plicatipollenites* spp.) and *Punctatisporites* (Figure 3). As discussed above, the biozones are defined using a combination of single taxon-range and quantitative assemblage data, and are a mixture of downhole interval biozones with successive tops defined by FDAs, and downhole acme biozones with tops defined by quantitative changes in a palynomorph group or taxon.

The purpose of this paper is to show how the patterns of occurrence of groups and accessory taxa define the biozones. The work that underpinned the biozonation described here was mainly the documentation of the small number of species restricted to lower parts of the Al Khlata Formation, and these are formally described and illustrated in the appendix (see also Plates 1 to 3). It should be
noted that biostratigraphy of this type, based partly on quantitative trends is not an exact science, and judgement is sometimes required in the positioning of biozonal boundaries. This is also true in the case of reworking of palynomorphs, which is common in glaciogenic sediments (Osterloff et al., 2004). The Al Khlata Formation contains palynomorphs derived by glacial erosion of consolidated hinterland rocks (long-cycle reworked palynomorphs, for example from the Devonian) as well those derived from younger unconsolidated glacial sediments (short-cycle reworked palynomorphs; Stephenson, in press). The latter, which are difficult to distinguish from in situ palynomorphs, make reliable palynozonation difficult without reference to sedimentary facies and appropriate experience concerning which data to use or reject.

**Biozone A**

The top of Biozone A is defined by the abrupt downhole increase in *Microbaculispora tentula* and *Cycadopites cymbatus* (Figure 4). Often *Botryococcus* also appears at this level. Within Biozone A, *M. tentula* and *C. cymbatus* typically comprise 15–33% of assemblages, and are rare and inconsistent above. This is a very well defined datum in the Mukhaizna field and occurs in all wells that have sufficient sample density to represent it. Other taxa that characterise Biozone A include *Alisporites inarraensis*, *Microbaculispora grandegranulata* and *Vittatina cf. scutata*. A number of the taxa that are common in Biozone A persist lower in the Al Khlata Formation, particularly *M. tentula* which is common in sidewall core and core samples down to Biozone C. In cuttings, Biozone A often contains specimens that have caved from the overlying Lower Gharif Member and basal Khuff Formation.

**Biozone B**

The top of Biozone B is defined by the first appearance of significant numbers of cavate-zonate spores such as *Cristatisporites* spp., *Lundbladispora* spp., *L. braziliensis*, *Vallatisporites* spp., and *V. arcuatus* (Figure 5). Though this is primarily a distinction made on quantitative grounds, it is unlikely to be affected by caving, because very few cavate-zonate spores occur above Biozone B in the Mukhaizna field. Usually cavate-zonate spores constitute around 5–10% of assemblages at the top of Biozone B but increase to levels of 30% or more of palynomorph assemblages in the lower parts of the biozone. A supplementary guide to the top of Biozone B in the Mukhaizna field is the FDA of *Densoisporites truswellii* sp. nov., which is close to the FDA of common cavate-zonate spores (Figure 5). *Punctatisporites* also increases downhole at the top of Biozone B. Other taxa that have FDAs within Biozone B include *Ahrensiisporites cristatus*, *Deusilites tentus* and *Speleotriletes triangulus*. *Brevitriletes cornutus* and *Converrucosisporites confluens* are often common within Biozone B.

**Biozone C**

The top of Biozone C is defined by the FDA of *Anapiculatisporites concinnus*, usually represented by small numbers (Figure 5). This taxon persists downward and is also common in Biozone D. In a few well sections, it is absent, thus a secondary criterion is needed to identify the top of Biozone C, but apart from *A. concinnus*, there are no taxa that have FDAs within Biozone C. At the level of the FDA of *A. concinnus* there is, however, usually an increase in the numbers of cavate-zonate spores such as *Cristatisporites* spp., *Vallatisporites* spp. and *V. arcuatus* from levels of 30% of assemblages in Biozone B to around 40% of assemblages below (Figure 5). This can be used as a supplementary method of identifying the top of Biozone C, though it may be difficult to use in cuttings samples because cavate-zonate spores are common above this level and could, by downward caving, be artificially increased in numbers. Thus a sudden, anomalously large amount of caving, could produce the appearance of a downhole increase in cavate-zonate spores.

**Sub-Biozone C1**

An abrupt change to very abundant cavate-zonate spores (60% or more of assemblages), occurs in many wells within the lower parts of Biozone C (Figure 5), and this can be used to define the top of Sub-Biozone C1. Being defined entirely on quantitative grounds this datum is clearly susceptible to the effects of caving, and is thus erected only at subzonal status. However the presence of the event in a large number of wells, at what appears to be a consistent level based on log character, suggests
Plate 1: Palynomorphs of the Al Khlata Formation in Mukhaizna Field. The locations of specimens are given first by England Finder reference and then by BGS MPK slide code; dimensions of the longest axis of each specimen are also given individually. Slides are held in the Micropalaeontology MPK Collection of the British Geological Survey, Keyworth Nottingham, UK, NG12 5GG. A small number of slides were also registered with the MPA BGS collection and these have MPA codes. (a–c): Microbaculispora tentula, (a) M17/2, MPK 13554, 50 µm; (b) P22, MPK 13555, 50 µm; (c) F9/2, MPK 13555. See facing page for continuation.
Plate 2: Palynomorphs of the Al Khlata Formation in Mukhaizna Field. (a–h, j–l) *Indotriradites fibrosus* sp. nov., (a) E40, MPK 13569, 57 µm; (b) L37, MPK 13570, 58 µm; (c) U24/4, MPK 13571, 60 µm; (d) G23/3, MPK 13572, 58 µm; (e) T15/1, MPK 13573, 72 µm; (f) W23/4, MPK 13574, proximal face missing, 65 µm; (g) M15, MPK 13575, 55 µm; (h) N63, MPA 55885, MPK 13576, 70 µm. (i) *Auroraspora* sp. A, Z11, MPK 13577, 66 µm; (j) detail of proximal face, G23/3, MPK 13572, horizontal field of view 40 µm; (k) detail of distal face, G23/3, MPK 13572, horizontal field of view 40 µm; (l) detail of distal face, T15/1, MPK 13573.

Plate 1 (Continued):
13556, 50 µm. (d) *Cycadopites cymbatus*, N6/4, MPK 13557, 75 µm. (e) *Deusilites tentus*, O68/1, MPK 13558, 80 µm. (f–g) *Ahrensisporites cristatus*, (f) K19, MPK 13559, 65 µm; (g) U26, MPK 13560, 85 µm. (h–i) *Spelaeotriletes triangulus*, (h) G8/2, MPK 13561, 92 µm; (i) O22/3, MPK 13562, 90 µm. (j–k) *Anapiculatisporites concinnus*, (j) O61/2, MPK 13563, 35 µm; (k) L66/1, MPA 55875, MPK 13564, 35 µm. (l–m) cavate-zonate spore group: (l) *Vallatisporites* sp., V7/2, MPK 13565, 80 µm; (m) *Cristatisporites* sp., C29, MPK 13566, 65 µm. (n–o) monosaccate pollen group: (n–o) *Potonieisporites* spp., (n) W14/4, MPK 13567, 130 µm; (o) K19, MPK 13568, 130 µm.
that it may be used within the Mukhaizna field, though its utility beyond the boundaries of the field is doubtful. Sub-Biozone C1 is associated with a rock unit with a distinctive log character having a wide separation between gamma-ray and neutron porosity, probably representing a highly argillaceous diamictite (Figure 5). Such a close connection between lithology and palynological character is sometimes given as evidence of facies control of the distribution of palynomorph assemblages, in which case the assemblage type could be questioned as a viable basis for biozonation. However the assemblage appears so far to have a consistent stratigraphic position and is maintained until evidence to the contrary, an example of which would be an assemblage of Sub-Biozone C1 type associated with wide gamma-ray - neutron separation at an anomalous stratigraphic level.

Plate 3

Plate 3: Palynomorphs of the Al Khlata Formation in Mukhaizna Field. (a–j) *Densoisporites truswelli* sp. nov.; (a) E29, MPK 13579, 56 µm; (b) X62/1, MPK 13579, 58 µm; (c) K52/3, MPA 55890, MPK 13580, 50 µm; (d) O46, MPA 55890, MPK 13581, 56 µm; (e) S52/2, MPK 13582, 60 µm; (f) S53, MPK 13583, 62 µm; (g) P85/1, MPK 13614, 60 µm; (h) P53/4, MPK 13615, 65 µm; (i) V50/1, MPK 13616, 60 µm; (j) L33/3, MPK 13617, 62 µm; (k) detail of distal surface, L33/3, MPK 13617, horizontal field of view 40 µm; (l) detail of proximal surface, L33/3, MPK 13617, horizontal field of view 40 µm.
Figure 4: Characteristics of Biozone A in selected wells in the Mukhaizna field. Well 5 and 12 indicate two possible Rahab Member cycles.
Biozone D

The top of the lowest biozone of the Al Khlata Formation, Biozone D, is marked by a distinct drop in assemblage diversity and palynomorph yield, and by the first appearance of assemblages dominated by Punctatisporites spp. (mainly P. gretensis forma minor and P. lucidulus) and monosaccate pollen (mainly Potonisporites spp.) to around 50% and 30% of assemblages, respectively (Figure 6). Sidewall core samples also reveal that below the top of Biozone D, cavate-zonate spores become extremely rare to absent (Figure 6). Neither of these criteria for identifying the top of Biozone D can be used without some sidewall core sample coverage since downhole caving from biozones B and C can affect proportions of cavate-zonate spores, Punctatisporites spp. and monosaccate pollen in cutting samples. Biozone D has low diversity and thus has very few taxa that are restricted to it and which can be used to characterise it. However Indotriradites fibrosus sp. nov. has an FDA consistently within the upper part

Figure 5: Characteristics of biozones B and C, and Sub-Biozone C1 in selected wells in the Mukhaizna field.
of Biozone D, is relatively common, and is the only cavate-zonate spore taxon restricted to the lower parts of the Al Khlata Formation. It occurs in core and sidewall core samples in Biozone D in Well No. 5 and appears to be particularly significant in shales above the thickest Biozone D age sandstones in the Mukhaizna field, for example in Well Nos. 2 and 5 (Figure 6). *Auroraspora* sp. A is also most common in Biozone D, though it also may occur rarely in the lower part of Biozone C. Below Biozone D, all wells have a palynologically barren section (Figure 6) between the last palynologically-productive sample and the lower boundary of the Al Khlata Formation (as picked on logs), varying between 85m and 50m thick. In cuttings samples this barren section cannot usually be identified because of downhole caving.

**Figure 6:** Characteristics of Biozone D and the ‘barren zone’ in selected wells in the Mukhaizna field.
CORRELATION WITH PDO AND OTHER OMAN BIOZONES

Petroleum Development Oman biozones for the Al Khlata Formation have not been formally defined or described, but basic details and a chart relating to the Rima field, 50 km to the south of the Mukhaizna field, are given by Osterloff et al. (2004, fig. 7), which allow comparisons to be made. Biozone A is closely similar to Rima field Biozone 2141B in that both appear to be marked by downhole increases in Microbaculispora and C. cymbatus, while Biozone B is similar to 2141A since both are marked by downhole increases in cavate-zonate spores, and 2165 is similar to Biozone C because both are marked by the FDA of Anapiculatisporites spp. (Figure 7). In parts of south Oman, assemblages containing common cavate-zonate spores and Horriditriletes spp. are designated 2165B (R.A. Penney, personal communication, 2007), though they are missing in Rima field (Osterloff et al., 2004; fig. 7) and in Mukhaizna field suggesting that 2165B sediments were either not deposited or were eroded before the deposition of 2141A or Biozone B sediments. Osterloff et al. (2004) consider there to be evidence for numerous other smaller unconformities within sequences assigned to the PDO 2165 Biozone. Biozone 2159 is marked by downhole increases in Punctatisporites along with a general dominance of that taxon alongside monosaccate pollen, and very little else. Thus Biozone 2159 compares closely with Mukhaizna field Biozone D. This also implies that Biozone C and Sub-Biozone C1 are together equivalent to PDO Biozone 2165A. Osterloff et al. (2004) suggested that 2159 Biozone may be subdivided into two subzones, an upper 2159B and a lower 2159A. The subdivision is based mainly on proportions of monosaccate pollen to Punctatisporites spp. While this may be applicable in core or sections with dense sidewall core samples, caving within Mukhaizna field wells which are mainly represented by cuttings samples, makes such a subdivision (into, for example, an upper and lower Biozone D) impossible because the proportions of the two main constituents may be entirely related to degree of caving rather than in situ trends. Cuttings samples from lower parts of the sequence are also sometimes difficult to assign with confidence because they may be (a) barren pre-Al Khlata Formation sediments with caving, (b) barren lowest Al Khlata Formation sediments with caving, or (c) low-yielding genuine Biozone D in situ assemblages.

Besems and Schuurman (1987) and Love (1994) have produced palynostratigraphical schemes for Oman (Figure 7). The former authors, working on outcrops of the Al Khlata Formation in eastern Central Oman, recognised two distinct palynological assemblages. Assemblage Group A is dominated

| System/stage | Arabian Peninsula Stephenson et al. (2003) | PDO Biozones | Oman | Western Australia Zones, Backhouse (1991) | Powis (1984) |
|--------------|------------------------------------------|---------------|------|------------------------------------------|--------------|
|             | Stratigraphy | Love (1994) | Besems and Schuurman (1987) | Mukhaizna Biozones |               |
| Permian      | L. Ghairi Member | OSPZ2 | 2141B | Assemblage Group B | S. fusus |
| Sakmarian    | | | C. cymbatus Assemblage | Biozone A | P. pseudo. |
| Asselian     | Unayzah B | 2141A | Assemblage Group B | Biozone B | |
|              | Unayzah B | 2165B | Microbaculispora Assemblage | Assemblage Group A | C. confluens |
|              | Unayzah C | 2165A | | | Stage 2 |
| Carboniferous| OSPZ1 | 2159 | Potonieisporites Assemblage | Biozone C | Stage 2 sensu Backhouse (1991) |
|              | | | | | Stage 1 |

Figure 7: Correlation of Mukhaizna field biozones.
by cavate-zonate spores and Assemblage Group B is characterised by taeniate and non-taeniate bisaccate pollen. The quantitative data of Besems and Schuurman (1987; text-figures 3-7), which comes from a very small number of sample horizons suggests that Assemblage Group A of Besems and Schuurman (1987) correlates with Mukhaizna field Biozone C, and Assemblage Group B with Mukhaizna field Biozone B (Figure 7).

Love (1994) described four palynological assemblages from the entire subsurface Haushi Group. The Potonieisporites Assemblage is reportedly low in diversity containing simple trilete spores (mainly Punctatisporites) and monosaccate pollen such as Potonieisporites, thus it correlates with Mukhaizna field Biozone D. His succeeding Microbaculispora Assemblage records the first uphole appearance of M. tentula and other taxa and is similar to Biozone C, while the Cycadopites cymbatus Assemblage correlates partly with biozones A and B (Figure 7).

OSPZ1, the lowest of the Arabian regional biozones (Stephenson et al., 2003), is characterised by assemblages dominated by Punctatisporites, Retusotriletes and bilaterally and radially symmetrical monosaccate pollen, which also contain Anapiculatisporites concinnus, therefore it correlates with Mukhaizna field Biozone D. The base of OSPZ2 is defined on the first uphole occurrence of M. tentula and Horriditriletes spp., thus this horizon correlates approximately with the base of Biozone C, though this horizon is difficult to establish in the downhole Mukhaizna field scheme. The upper part of OSPZ2 is characterised by rising numbers of C. cymbatus and M. tentula and therefore correlates with biozones A and B (Figure 7).

**CORRELATION AND STRUCTURE OF THE AL KHLATA FORMATION IN MUKHAIZNA FIELD**

Correlation with PDO biozones and within the Mukhaizna field allows some observations to be made about the structure and form of the Al Khlata Formation in the Mukhaizna field. A correlation of the biozones (Figure 8) indicates considerable differences in thickness, with the thinnest (Biozones A, B and C) in the upper parts, and the thickest (Biozone D) at the base. This probably reflects the decrease in diversity downhole providing fewer FDA datums to allow subdivision. Biozones also vary in thickness across the Mukhaizna field, particularly Biozone D, reflecting either differences in sedimentation rates or unconformities and disconformities. Core is only available in one small interval within Biozone D of Well No. 5, thus little is known directly of lithologies in the Mukhaizna field; however comparison with other similar sequences has allowed limited calibration so that a few lithologies can be identified from logs with reasonable certainty. Thus Biozone A is closely associated with mudstones with high gamma-ray levels whose stratigraphic position and field wide distribution indicate the presence of the Rahab Member, a unit associated with widespread deglacial lakes in south Oman (Stephenson and Osterloff, 2002).

Biozone A is the least densely sampled of the biozones but within its span in several well sections (e.g. Well Nos. 5 and 12; Figure 4), two or more gamma-ray peaks occur, suggesting more than one generation of lake deposits, or lake development arrested periodically by coarser sediment input. This accords with interpretations of the Rahab Member, which is associated with 2141B of PDO, the correlative of Biozone A in other parts of south Oman (e.g. Nimr and Rima fields; Osterloff et al., 2004; Love, 1994). In these fields two to three subdivisions of the Rahab Member are applied. Biozone B is associated with arenaceous and argillaceous diamictites and occasional sandstones, sometimes with very abrupt vertical changes in lithology (e.g. Well Nos. 3, 8 and 9; Figure 8), as well as considerable horizontal variability (compare for example Well Nos. 3 and 4 which are less than 2 km apart; Figures 1 and 8).

Biozone C/C1 sequences are less variable than those of B, consisting of great thicknesses of mainly argillaceous diamictites, interspersed with thinner arenaceous diamictites, and occasionally sandstones, all with relatively little lateral variability (compare for example Well Nos. 2, 3, 4 and 5; Figure 8). Sub-Biozone C1 is commonly associated with very fine-grained diamictites with very high gamma-ray levels (e.g. Well Nos. 2 and 3; Figure 8). The distribution of argillaceous diamictites suggests that Biozone C/C1 times in Mukhaizna field were characterised by widespread subglacial or proglacial lakes.
The most abrupt change in depositional and palynological style occurs between biozones C/C1 and D. The latter varies considerably in thickness, being thicker in the south, and is characterised by extreme vertical and lateral variability of argillaceous and arenaceous diamictites, as well as thick - probably stacked - sandstone units. The chief palynological differences are in diversity and quantitative character. The lower parts of Biozone C (Sub-Biozone C1) have very high numbers of cavate-zonate spores (up to 80% of assemblages from highly productive samples), while sidewall and core samples from Biozone D indicate an almost complete lack of such spores (Figure 6). Diversity and palynological yield are also much lower in Biozone D. It is not possible to be certain of an
unconformity, nor estimate the duration of any sedimentary hiatus because the ranges of the species and palynomorph groups from biozones C/C1 and D are not accurately known with respect to the standard Carboniferous and Permian scales established in Russia. However the rate of change in assemblages suggests that part of an otherwise rather gradual palynological succession is missing, implying an unconformity or disconformity. Thus there is some palynological evidence for at least two unconformities within the Al Khlata Formation in Mukhaizna field, between biozones B and C/C1 (suggested by the absence of the equivalent of 2165B Biozone; Figure 7), and between biozones C/C1 and D.

Figure 8: Correlation of biozones across the Mukhaizna field. Line of section shown in Figure 1; Well 11 not included. For Well Nos. 2 and 5, lithology reconstructed from neural network analysis of electric logs.
CORRELATION WITH ARABIA AND WESTERN AUSTRALIA

It is generally difficult to correlate Gondwana palynological assemblages precisely to those of the Russian type areas because of the scarcity of marine fauna in Gondwana, and the dissimilarity with assemblages of these type areas which are paleoequatorial (Stephenson et al., 2003, 2007; Stephenson, in press). Thus the Carboniferous – Permian boundary cannot be directly correlated in Gondwana by palynology (Stephenson, in press). To apply standard chronostratigraphic names, a two-stage correlation is required with an intermediate location which has marine faunas that are either equivalent to those of the Russian stages or similar enough to allow correlation (Stephenson et al., 2003; Stephenson, in press). Western Australia is an example of an intermediate area that is ideal for correlation of Mukhaizna field assemblages for two reasons. Firstly, because the palynological succession there has been documented in detail, including quantitative data, and secondly, Western Australia has the most comprehensive of the Gondwana marine faunal records. This has allowed the palynological succession there to be correlated with the standard Russian sequence. Thus, by this correlation approach the application of standard Russian stage names in the Al Khlata Formation is possible.

Kemp et al. (1977) and Powis (1984) gave details on Stage 1 and 2 biozones of Western Australian pre-glacial and periglacial sediments. Data from single sections or small groups of sections within this interval were also supplied by Backhouse (1991, 1993) and Powis (1979). Powis (1984) defined the base of Stage 2 as the collective first uphole appearance of *M. tentula*, *Horriditriletes ramosus* and *Horriditriletes teretangulatus*, thus the base of Biozone C correlates with the base of Stage 2 (Figure 7). Backhouse (1991) reported that *C. confluens* occurs first uphole toward the top of Stage 2, and this order of first uphole occurrence is also evident in Oman, where *C. confluens* occurs stratigraphically well above the first uphole occurrences of *M. tentula* and *H. ramosus*. Hence Biozone C correlates in part with ‘Stage 2’ sensu Backhouse. *Converrucosisporites confluens* occurs within the equivalent of biozones A to B (and above) elsewhere in south Oman (Stephenson, 1998; unpublished data) and thus the *C. confluens* Biozone of Backhouse (1991) correlates with those Mukhaizna biozones. Backhouse (1991) considered his Stage 2 to be ?Asselian in age, while the *C. confluens* and *Pseudoreticulatispora pseudoreticulata* biozones were considered to be Sakmarian. By correlation, therefore, Biozone C is likely to be Asselian in age, while biozones A and B are likely Sakmarian (Figure 7). The age of Biozone D may be Carboniferous (Figure 7).

APPENDIX 1: SYSTEMATIC PALYNOLOGY

**Genus Indotriradites Tiwari emend. Foster 1979**

*Indotriradites fibrosus* sp. nov. (Plate 2, a–h, j–l)

**Holotype:** (held in the collection of the British Geological Survey): Plate 2, Figure d, j, k.

**Paratype:** Plate 2, Figure e, l.

**Type locality:** Al Khlata Formation, Mukhaizna field, Oman. Slide MPK 13572.

**Derivation of name:** after the fibrous appearance of the zona.

**Diagnosis:** Spores, radial, trilete; amb rounded triangular with smooth or dentate margin. Intexinal body indistinct, thin, sometimes folded independently of the exoexine, laevigate. Laesurae distinct, sometimes prominent; straight; extend to the margin of the spore body though thickening on the zona may appear to extend the laesurae to the zona margin; lips prominent, 1–2 µm wide. Proximal face planar; exoexine laevigate or finely punctate, thin. Distal face planar to slightly convex; exoexine thin, punctate; ornamented with small, unevenly distributed irregularly shaped projections or small (<1 µm) verrucae, coni and grana; or occasionally scabrate. Exoxinal zona wide approximately a third of the radius of the spore; thin and delicate. Inner part thick, prominent, standing above the plane of the proximal surface. This part is marked with many small surface pits or shows evidence...
of internal voids less than 1 µ in diameter at different levels within the exoexine. Raised thickened area often appears as a dark ring, and is 2–5 µm wide. Outer part of zona thinner, planar, with a characteristic fibrous appearance due to the presence of many radial thickenings that project outward from the inner zona, on the proximal and distal surface. The thickenings are 1 µm wide, 3–5 µm long; in most cases reaching around half of the way across the outer zona. Few projections reach the zonal margin. Most specimens have 20 to 30 radial thickenings around the circumference. Where thickenings are of abnormal length or are distributed densely, they have prominent bulbous termini. The outer zona is usually laevigate and thin. In a few specimens a discontinuous thickening occurs at the zonal margin, less than 1 µm wide.

Dimensions: 50(58)70 µm; 20 specimens. Holotype 58 µm.

Comparison: Most similar to *Indotriradites niger* and *Kraeuselisporites* sp. of Segroves (1970). The former has coarser distal ornament as well as being described by Segroves (1970) as being distally ‘microreticulate’; the latter is similarly microreticulate and has concentration of spinae and coni at the inner edge of the zona. A specimen assigned by MacRae (1988; pl. 10, fig. 4) to *Cirratriradites africanensis* is similar to *I. fibrosus* sp. nov. but *C. africanensis*, according to Hart (1963), is ornamented with small densely packed coni and grana. The description and illustration of *C. africanensis* provided by Hart (1963) are not sufficient to allow further comparison.

Distinguishing features: Amongst the cavate-zonate spores of the Al Khlata Formation, *I. fibrosus* sp. nov. is distinct in displaying very little morphological variation. It is also unusual in that it is most common in the lowest part of the unit, where cavate-zonate spores are otherwise extremely rare in the Mukhaizna field. The taxon is distinguished most readily by its wide ‘fibrous’ zona with a dark ring on the inner margin.

**Genus Densoisporites** Weyland & Krieger emend. Dettmann 1963

*Densoisporites truswellii* sp. nov. (Plate 3, Figs. a–l)
1992 *Densoisporites* sp. Jones and Truswell: p. 175; fig. 12, X-Y.
1998 *Densoisporites* sp. Jones and Truswell - Stephenson: p. 82: pl. 44, figs. a-b

Holotype: (held in the collection of the British Geological Survey): Plate 3, Figure g.

Paratype: Plate 3, Figures j, k, l.

Type locality: Al Khlata Formation, Mukhaizna field, Oman. Slide MPK 13614.

Derivation of name: in honour of the palynologist Elizabeth Truswell.

Description: Spores, radial, trilete; amb very rounded triangular. Intexinal body distinct, outline conforms with overall outline of spore, eccentrically placed; intexine thin, laevigate, commonly folded concentrically at the margin of the body. Laesurae distinct, sinuous; with raised lips <2 µm wide at the proximal pole, thinner away from the pole. Laesurae extend 70% of spore radius; often do not reach the inner margin of the cingulum. Proximal face planar but for raised lips; exoexine finely micropunctate. Distal face slightly convex; exoexine thin, finely micropunctate. Exoexinal cingulum thick, 3-8 µm wide, narrows at the apices; very finely spongy/micropunctate. Intexine-exoexine separation equatorial, variable; 1-8 µm when viewed in proximodistal orientation.

Dimensions: 51(55)65 µm, 29 specimens. Holotype 60 µm.

Comparison: Differs from the closest form, *Lundbladispora braziliensis*, in having a narrow cingulum and lacking a thin membraneous zona.

Distinguishing features: Spongeous exoexine and narrow cingulum.
Genus *Auroraspora* Hoffmeister et al. emend. Richardson 1960

*Auroraspora* sp. A (Plate 2, i)

**Description:** Spores, radial, trilete; amb circular to irregular due to folding. Intexinal body distinct, circular, dark in colour; intexine thin (<1 µm), laevigate, nearly always eccentrically placed in the exoexinal body. Intexinal body varies in size relative to the total diameter of the exoexinal body (from 40–60% of the total diameter). Proximal exoexinal folds often radiate from the proximal exoexine roots; more rarely circumpolar proximal intexinal folds occur associated with the proximal exoexine roots. Exoexinal body circular in proximodistal view. Exoexinal body flaccid, exoexine 1–2 µm thick, bearing a distinctive, fine, well-defined reticulation.

**Dimensions:** 45(50)69 µm, 8 specimens.

**Comparison:** This taxon is similar to *Playfordiaspora cancellosa*. However the latter has more regular polygonal lumina than *Auroraspora* sp. A.

**Distinguishing features:** Well-defined reticulation on flaccid outer layer; radiating proximal folds.

**APPENDIX 2: FULL AUTHOR CITATIONS OF TAXA**

- Ahrensisporites cristatus Playford and Powis, 1979
- Alisporites indarraensis Segroves, 1969
- Anapiculatisporites concinnus Playford, 1962
- Auroraspora sp. A
- Breccitrites cornutus (Balme and Hennelly) Backhouse, 1991
- Curratriradites africanaensis Hart 1963
- Cycladopites cymbatus (Balme and Hennelly) Segroves, 1970
- Converrucosisporites confluentus (Archangelsky and Gamers) Playford and Dino, 2002
- Densoisporites trusvelli sp. nov
- Deusilites tentus Hender and Nygreen, 1967
- Indotriradites niger (Segroves) Backhouse 1991
- Indotriradites fibrosus sp. nov.
- Lundbladispora braziliensis (Pant and Srivastava) Marques-Toigo and Pons, 1976
- Microbaculispora grandegranulata Anderson, 1977
- Microbaculispora tentula Tiwari, 1965
- Playfordiaspora cancellosa (Playford and Dettmann) Maheshwari and Banerji 1975
- Punctatisporites tretensis forma minor Hart, 1965
- Punctatisporites lucidulus Playford and Helby, 1968
- Speleotriletes triangulus Neves and Owens, 1966
- Vallatisporites arcuatus (Marques-Toigo) Archangelsky and Gamers, 1979
- Vittatina cf. V. scutata (Balme and Hennelly) Bharadwaj, 1962

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