A high resolution palynozonation for the Pennsylvanian to Lower Permian Al Khlata Formation, south Oman

Randall A. Penney, Consultant Palynologist, XGL/31, Petroleum Development Oman LLC, P.O. Box 100, Muscat Post Code 113, Sultanate of Oman. Email: randall.ra.penney@pdo.co.om

Michael H. Stephenson, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK. Email: m.stephenson@bgs.ac.uk.

Issam Al Barram, XGL/3X, Petroleum Development Oman LLC, P.O. Box 100, Muscat Post Code 113, Sultanate of Oman. Email: Issam.I.Barram@pdo.co.om

Key words: Al Khlata Formation, Pennsylvanian, Lower Permian, Palynology, High Resolution Biozonation, Gondwana Correlation.

ABSTRACT

Palynology is the main method of correlating the subsurface glaciogenic Al Khlata Formation of Oman, due to extreme lateral variability of facies, and poor seismic resolution. The chief operating company in Oman, Petroleum Development Oman, has developed a robust in-house palynozonation through almost 40 years of exploration and production based on thousands of samples and hundreds of well sections. In this paper the formal definitions of the biozones are published, and the biozones are correlated in detail with faunally-calibrated palynological biozones in Western Australia, thereby allowing correlation with the standard Russian stages. Seven biozones are distinguished. The oldest, biozones 2159A and B, of probable late Pennsylvanian age, are characterised by low diversity assemblages of *Punctatisporites* and monosaccate pollen, with Biozone 2159A having a lower proportion of monosaccate pollen than Biozone 2159B. Biozone 2165A, of probable Asselian age, is characterised by common cingulicamerate spores and *Microbaculispora* Group; while Biozone 2165B contains in addition to the above, common *Horriditriletes* Group, and is likely to be Asselian-Sakmarian in age. Biozone 2141A is characterised by common taeniate and non-taeniate bisaccate pollen and *Cycadopites cymbatus*, particularly toward the top; and the succeeding 2141B by common *Microbaculispora* Group and *C. cymbatus*. Biozones 2141A and B are believed to be Sakmarian in age. The youngest, Biozone 2141C, is characterised by *Microbaculispora* and *Horriditriletes* Group with the former being more abundant. The seven-fold subdivision is a considerable improvement on previous palynozonations of the Al Khlata Formation, which only allowed three or four-fold subdivisions; however, there still remain considerable uncertainties in dating the lowest biozones, 2159A and B. Improvements in dating of Al Khlata Formation sediments are most likely to come from palynological correlation with radiometrically- or faunally dated sequences in South America, eastern Australia and southern Africa.

INTRODUCTION

Pennsylvanian to Lower Permian rocks crop out over relatively small areas of central Saudi Arabia, the Wajid outcrop area in southwestern Saudi Arabia, and in the Haushi-Huqf outcrop area in Oman (Text-Figure 1), but are present widely in the subsurface, where they form important hydrocarbon reservoirs (McGillivray and Husseini, 1992; Hughes Clarke, 1988). The main formations of the region containing Pennsylvanian to Lower Permian sequences are the Al Khlata and Gharif formations in Oman, and the Unayzah Formation in Saudi Arabia.

The Al Khlata Formation consists of a complex package 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). The glaciogenic nature of the Al Khlata Formation was established from studies of the outcrop area on the western flank of the Haushi-Huqf Uplift where striated pavements of the Precambrian Khufai Formation have been found (Braakman et al., 1982; Al-Belushi et al., 1996). Hughes Clarke (1988) credited Levell et al. (1982) with the definition of the type section of the Al Khlata Formation, which is located at Wadi Al Khlata near the Haushi-Huqf Uplift (57°25’46”E, 19°46’43”N; Text-Figure 1) where it is about 100 m thick. The subsurface reference section of the Al Khlata Formation was defined in Rahab-2 well, south Oman (55°06’32”E, 18°01’09”N) where the formation is more than 246 m thick (Hughes Clarke, 1988; Mohammed et al., 1997). In the subsurface of south Oman, the thickness of the Al Khlata Formation varies from about 100 to 800 m (Levell et al., 1988; Love, 1994; Knight and Hartkamp-Bakker, 1998). The variation of thickness is largely the result of syn-depositional subsidence and erosional palaeorelief on the pre-Al Khlata unconformity (Levell et al., 1988; Knight and Hartkamp-Bakker, 1998). During its deposition, the infra-Cambrian Ara salt in the South Oman Salt Basin moved diapirically to form salt domes, and developed a series of NS-oriented salt pods.

As a result, thick Al Khlata sediments are found in synclines formed by salt withdrawal. On the Eastern Flank, thick Al Khlata Formation deposits are also found where salt was apparently syndepositionally dissolved by groundwater (Heward, 1990; Osterloff et al., 2004).

The Al Khlata Formation is present throughout the central interior of Oman south of the Oman Mountains, and west of the Huqf Axis high (Text-Figure 1). It rests with angular unconformity on Devonian and older rocks (Hughes Clark, 1988). The upper boundary of the subsurface Al Khlata Formation is described by Mohammed et al. (1997) as broadly conformable with the overlying Gharif Formation. This lithological boundary is generally picked at the base of the lowermost Gharif sandstone, overlying the upper Rahab Member of the Al Khlata Formation. On electric logs this boundary is marked by a downhole increase in gamma ray, 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 the boundary is mainly identified via palynostratigraphical proxy.

Petroleum Development Oman has used palynology extensively for correlating the subsurface Al Khlata Formation, such that at present it is the chief method used due to extreme lateral variability of facies (and therefore of the wireline logs), and poor seismic resolution. Historically PDO have identified important palynomorphs by code numbers rather than Linnaean binomials, for example the colpate pollen taxon *Cycadopites cymbatus* is known by the code 2141. Where a taxon is taken as marker or index for a biozone, its code is used also to denote that biozone. Hence the original 2141 Biozone in its broadest terms was characterised by the common occurrence of *Cycadopites cymbatus*. The system in various forms has been in operation for nearly 40 years in PDO, and has proved to be extremely robust having been developed from a database of thousands of samples and hundreds of well sections. However, although its basic characteristics have been illustrated (Osterloff et al.

2004, fig. 7), formal definitions of the biozones have not been published. The biozones have also not been correlated in detail with other biozones of Gondwana. Thus the main purpose of this paper is to define and correlate the biozones. For continuity and simplicity, the nomenclature for biozones used internally in PDO is retained.

PALYNOLOGICAL SUCCESSION

Generally the diversity and yield of palynomorphs increases upsection through the Al Khlata Formation, probably in response to climatic amelioration, related to global post glacial warming and the northward movement of the Arabian Plate between the Pennsylvanian and Early Permian (Stephenson and Filatoff 2000; Stephenson et al., 2005; 2007). The earlier assemblages are characterised by common monosaccate pollen and *Punctatisporites* Group, while later assemblages are of greater diversity including cingulicamerate and cheilocardioid spores, and colpate and bisaccate pollen. The biozones are of the acme type with bases defined by quantitative changes in a palynomorph group or taxon. In this paper we will list the constituents of the groups and then show how the patterns of occurrence of groups define the biozones. The composition of the groups and authors of taxa are given in Table 1. Along with groups, certain taxa are also important, for example *Anapiculatisporites concinnus*, *Cycadopites cymbatus*, and *Kingiacolpites subcircularis.* Key taxa and groups are illustrated in Plates 1 and 2.

BIOZONATION

Methodology. Percentage proportions of taxon groups and species are central to the method of biozonation, and proportions quoted in this paper are averages gained from many hundreds of well analyses involving thousands of samples (Table 2). PDO in-house procedures suggest that counts of approximately 150 to 200 specimens per slide are adequate to represent true proportions. Three reliability categories are applied: ‘poor’ (total count 50 - 74 specimens), ‘fair’ (75 – 99 specimens) and ‘good’ (over 100 specimens). Samples with counts of less than 50 are designated non-diagnostic and therefore are not used in biozonation, except in the case of 2159, where a tentative assignment is allowed with counts of between 25 and 50. Samples from cored well sections are the main basis of the biozonation, though sidewall core samples are used in important sections where core is not available.

It should be noted that biostratigraphy of this type, based mainly 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. 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, 2008). 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.

2159A Biozone. The lowest biozone of the Al Khlata Formation has a cored reference section in Marmul-6H1 well between 920.39 to 902.77m (Text-Figure 2). The primary diagnostic criterion is the abundance of the *Punctatisporites* Group which constitutes up to 100% of assemblages. Taxa of the Monosaccate Group constitute less than 5% of assemblages. Below the base of the biozone, samples contain non-diagnostic assemblages or are barren with sparse reworking of Devonian to Lower Palaeozoic spores, cryptospores or acritarchs. Rarely *Anapiculatisporites concinnus, Aratrisporites saharaensis, Brevitriletes* spp., and members of the Cingulicamerate Group such as *Vallatisporites arcuatus* occur as do algal palynomorphs such as *Botryococcus*, *Tetraporina* spp. and *Tasmanites*. Apart from the reference section, this biozone is well represented in the cored interval from Qata-9 (Text-Figure 2). However, in uncored sections it is usually identified from spot sidewall samples such as exemplified in Rima-65 (see also Text-Figure 2).

There is a transition between 2159A and the succeeding Biozone 2159B, with the result that the boundary between the zones is difficult to position precisely. In the transition section, the percentage of monosaccate pollen fluctuate on average between 5% and 10% with the balance of the assemblage consisting mainly of the *Punctatisporites* Group (Qata-9, Text-Figure 2).

2159B Biozone. The reference section is the cored Marmul-6H1 interval from 901.8 to 870.5m (Text-Figure 2), and the main feature that distinguishes 2159B from 2159A is the increase in the proportion of the Monosaccate Group to greater than 10% of assemblages with a proportional decrease in *Punctatisporites* Group. 2159B Biozone is also more diverse than 2159A in containing *Anapiculatisporites concinnus* (usually less than 5% of the assemblage), *Aratrisporites saharaensis, Apiculiretusispora* spp., *Brevitriletes* spp., *Cyclogranisporites* spp., *Densosporites* spp. (including *D. rotundidentatus*), *Dibolisporites, Wilsonites australiensis*, *Spelaeotriletes* spp. (including *S. triangulus*), *Vallatisporites arcuatus* and *Verrucosisporites andersonii.* Overall there is an increase in the Monosaccate Group upsection through the biozone and this group may be locally very abundant (up to 70% of assemblages) at the top of the biozone (Rima-65, Text-Figure 2). Apart from the reference section, this biozone is well represented in cored intervals within Al Burj-36 and Rima-65.

2165A Biozone. The reference section is the Wadi Al Khlata Borehole-5 between 27.0 and 17.75m. The primary diagnostic criteria are (1) the Cingulicamerate Group constitutes up to approximately 30% of the assemblages (mainly *Vallatisporites arcuatus*, *Lundbladispora braziliensis* and *Cristatisporites* spp.); and (2) the *Microbaculispora* Group constitutes approximately 5% of assemblages, although it can be rare or absent locally (Text-Figure 3). The *Punctatisporites* and Monosaccate groups may also be abundant. *Anapiculatisporites concinnus* is present, usually comprising less than 5% of the assemblage, and the *Horriditriletes* and Bisaccate groups are usually rare or absent. Diversity is relatively high in comparison with 2159A, with *Ahrensisporites cristatus* 1979, *A. saharaensis*, *Apiculiretusispora* spp., *Cyclogranispotites* spp., *Densosporites* spp., *D. disfacies*, *W. australiensis* and *V. andersonii* present (Text-Figure 3). Apart from the cored reference section, this biozone is well represented in sidewall sampled intervals within Dimeet-1 and Al Burj-23 (Text-Figure 3).

2165B Biozone The reference section is Wadi Al Khlata Borehole-5 from 16.73 to 14.45m. The primary diagnostic criteria are (1) *Horriditriletes* Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) *Microbaculispora* Group constitutes usually around 3 to 5% of assemblages but can be occasionally absent. The Cingulicamerate Group may constitute 20 to 30% or more of assemblages. (mainly *Lundbladispora* spp., *Cristatisporites* spp. and *Vallatisporites arcuatus*). The *Punctatisporites* Group is usually less frequent than in the underlying biozones. *Cycadopites cymbatus*, *Granulatisporites* *confluens, Converrucosisporites grandegranulatus, Marsupipollenites* spp. and the *Vittatina* and Taeniate Bisaccate groups appear towards the top of this biozone (Text-Figure 3, 5). Apart from the reference section, this biozone is well represented in the cored interval within Amal-9 and sidewall sampled sections from Dimeet-1 and Al Burj-23 (see also Text-Figure 3).

2141A Biozone. The reference section is Nimr-46 cored interval between 934.59 to 897.1m. The primary diagnostic criteria are: (1) non-taeniate and taeniate bisaccate groups together represent more than 10% of the assemblages; and (2) *Cycadopites cymbatus* is rare towards the base but increases to 5 to 10% of assemblages towards the top. The proportions of the Cingulicamerate Group vary considerably but are usually lower than those of 2165A or B biozones. The proportion of *Punctatisporites* Group continues to decrease so that percentages are lower than in 2165B. *Horriditriletes* Group usually represents 10% but can be up to 20% of assemblages, and the *Microbaculispora* Group is approximately 3 to 5% of assemblages but can be occasionally absent. Taxa or groups that occur rarely include *Kingiacolpites subcircularis* and the *Vittatina* Group, *Brevitriletes cornutus, Dibolisporites disfacies*, *Densosporites* spp. (including *Densosporites rotundidentatus*), *Verrucosisporites* spp., *Botryococcus, Deusilites tentus*, *Tetraporina* spp. and *Tasmanites* (Text-Figure 4). Apart from the reference section, this biozone is well represented in the cored intervals of Rahab-2 and Wadi Al Khlata Borehole-2 (Text-Figure 4).

2141B Biozone. The reference section is Rahab-2 between 1008.32 and 992.14 m. The primary diagnostic criteria are (1) The *Microbaculispora* Group represents greater than 10% and can constitute up to 60% of assemblages, in addition the *Microbaculispora* Group is more abundant than the *Horriditriletes* Group; (2) *Cycadopites cymbatus* makes up 5 to 10% of assemblages; and (3) the Cingulicamerate Group are extremely rare or absent. The Non-Taeniate Bisaccate Group exceeds the Taeniate Bisaccate Group. Taxa that occur rarely include *Kingiacolpites subcircularis*, *Deusilites tentus*, *Tetraporina* spp. and *Tasmanites*. Apart from the reference section, this biozone is also well represented in the cored interval of Rahab-28 (Text-Figure 4).

2141C Biozone. The reference section is Rahab-2 between 982.38 and 964.7m. The primary diagnostic criterion is that the *Microbaculispora* Group represents more than 10% of assemblages, but the *Horriditriletes* Group exceeds it in proportion, reaching 30% or more. *Cycadopites cymbatus* and the Non-Taeniate Bisaccate Group are variable but usually common to abundant, reaching abundances of 60% or more of assemblages. The Taeniate Bisaccate Group represents 5 to 20% of assemblages but is always less abundant than the non-taeniate taxa. The accessory taxa are broadly the same as those in 2141B. Working downhole, however, the first appearances of *Vittatina* cf. *scutata* and *Converrucosisporites grandegranulatus* are characteristic of this biozone. Apart from the reference section, this biozone is also well represented in the cored interval of Rahab-28 (Text-Figure 4).

CORRELATION WITH ARABIA AND WESTERN AUSTRALIA

Besems and Schuurman (1987) and Love (1994) produced palynostratigraphical schemes for Oman (Text-Figure 6). The former authors, working on outcrops of the Al Khlata Formation in east-Central Oman, recognised two distinct palynological assemblages. Assemblage Group A is dominated by zonate, trilete 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 correlates with 2165A and B, and Assemblage Group B with 2141A. The boundary between Assemblage Groups A and B coincides with that between 2165B and 2141A, because both are defined on the increase of bisaccate pollen to approximately 10%.

Love (1994) described four palynological assemblages from the entire subsurface Haushi Group. The *Potonieisporites* Assemblage is reportedly low in diversity containing simple trilete spores and monosaccate pollen such as *Potonieisporites*. His succeeding *Microbaculispora* Assemblage was correlated to Besems and Schuurman's Assemblage Group A (Text-Figure 6) and his third assemblage, the *Cycadopites cymbatus* Assemblage to Besems and Schuurman's Assemblage Group B. Based on the data of Besems and Schuurman (1987) which show percentages of approximately 10% Cingulicamerate Group in Assemblage Group B, we correlate that biozone with the 2141A Biozone proposed here. Thus only the lower part of the *Cycadopites cymbatus* Assemblage of Love (1994) correlates with Assemblage Group B. As a whole the *Cycadopites cymbatus* Assemblage correlates with 2141A to C because the eponymous taxon and the Bisaccate Group are common throughout those biozones. Love's *Kingiacolpites subcircularis* Assemblage, which is not dealt with here, is equivalent to zones immediately overlying 2141C.

The field scale biozonation of Stephenson and Osterloff (2002) was primarily aimed at high resolution correlation of the Lower Gharif Member and Rahab Shale. The lowest *Microbaculispora tentula* Biozone correlates with 2141B because it is primarily characterised by high numbers of that taxon (>10% of assemblages). The succeeding *Converrucosisporites* sp. A - *Microbaculispora grandegranulata* Biozone correlates to the 2141C Biozone because it is based on the presence of common coarsely ornamented cheilocardioid spores reaching approximately 5% (Text-Figure 6).

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*, thus it correlates with 2159A and B biozones. The base of OSPZ2 is defined on the first occurrence of *Microbaculispora tentula* and *Horriditriletes* spp. thus this horizon correlates approximately with the base of 2165A. The upper parts of OSPZ2 are characterised by rising numbers of *C. cymbatus, M. tentula* and coarsely ornamented cheilocardioid spores and thus correlate with the interval 2165B to 2141C.

In this paper we correlate with Western Australia primarily because these sequences have been documented in detail including quantitative data, allowing correlation with the present biozones which are defined with quantitative criteria. Also Western Australia has the most comprehensive marine faunal record which has allowed the palynological succession to be correlated with the standard Russian sequence (Archbold 1999; Stephenson 2008).

The palynostratigraphy of Australasian pre-glacial and periglacial sediments is known in less detail than that of later Australasian sequences (Kemp et al. 1977). Amongst published studies, Kemp et al. (1977) and Powis (1984) give generalised details on Australian Stage 1 and 2 biozones (Text-Figure 6). Data from single sequences or small groups of sequences within this interval were supplied by Truswell (1978), Backhouse (1991, 1993) and Jones and Truswell (1992). The unpublished doctoral thesis of Powis (1979) concerning the pre-glacial and periglacial sediments of the Canning Basin, Western Australia provides perhaps the most comprehensive survey of the palynostratigraphy of such sediments. Powis (1984) defined the base of Stage 2 as the level of the collective first appearance of *Microbaculispora tentula*, *Horriditriletes ramosus* and *Horriditriletes tereteangulatus*, and Jones and Truswell (1992) correlated their *Microbaculispora tentula* Biozone with Stage 2 of Powis (1984). Thus, the base of 2165A correlates with the bases of Stage 2 of Powis (1984) and the *Microbaculispora tentula* Biozone of Jones and Truswell (1992).

Backhouse (1991, 1993) reported that *C. confluens* occurs first toward the top of eastern Australian Stage 2, and this order of first occurrence is also evident in Oman, where *C. confluens* occurs stratigraphically well above the first occurrences of *M. tentula* and *H. ramosus*. Hence, 2165A and B correlate in part with ‘Stage 2’ sensu Backhouse. *Converrucosisporites confluens* occurs first between 2165B and 2141B thus the *C. confluens* Biozone of Backhouse (1991) correlates with those south Oman biozones. The presence of large, heavily-ornamented cheilocardioid spores such as *Converrucosisporites* sp. A and *Verrucosisporites* cf. *naumovae* in 2141C may suggest that this biozone correlates with the *Pseudoreticulatispora pseudoreticulata* Biozone of Backhouse (1991).

An advantage of correlation between south Oman biozones and Western Australia is that the calibration by marine fauna available in the latter area can be applied in south Oman. Backhouse (1991) considered his Stage 2 to be ?Asselian in age, while the *Pseudoreticulatispora pseudoreticulata* biozone was considered Sakmarian. The *Converrucosisporites confluens* Biozone appears to straddle the boundary between Asselian and Sakmarian (see Backhouse, 1991, fig. 10). By correlation therefore, 2165A and B are likely to be Asselian in age, while 2141A to C are likely Sakmarian. A single faunal calibration is available in Oman, since the Haushi limestone (of the Lower Gharif Member) which overlies the Al Khlata formation, contains definite Sakmarian fusulinids (Angiolini et al. 2006; Text-Figure 6). Age assessments for biozones 2159A and B are less certain since

Western Australian faunal calibration does not reach below Stage 2 of Powis (1984) or Backhouse (1991). However, Jones and Truswell (1992) considered their *Asperispora reticulatispinosus* Biozone to be uppermost Westphalian D (Late Moscovian based upon the assessment of Davydov et al., 2004) to Autunian or Early Asselian in age, and a similar age is therefore adopted for 2159A and B for the present.

CONCLUSIONS

Palynology is the main method of correlating the subsurface glaciogenic Al Khlata Formation of Oman, due to extreme lateral variability of facies, and poor seismic resolution. Over many years a robust seven-fold in-house PDO palynozonation has been developed and in this paper the formal definitions of the biozones are published, and the biozones are correlated. Ages applied to the upper five biozones are the most precise that can presently be offered, through correlation with recently faunally-dated palynological biozones in Western Australia. The dates thereby gained are consistent with the single faunal tie-point given by fusulinids in the Haushi limestone of the Lower Gharif Member, which shows that the entire Al Khlata Formation is Sakmarian or older. Age assessments for biozones 2159A and B are less certain since Western Australian faunal calibration does not reach below Stage 2 of Western Australia. Further improvements in dating of Al Khlata Formation sediments are most likely to come from palynological correlation with radiometrically- or faunally dated sequences in South America, eastern Australia and southern Africa (see Stephenson, 2008).

ACKNOWLEDGEMENTS

The authors are grateful to the management of Petroleum Development Oman and the Oman Ministry of Oil and Gas for permission to publish this paper. M. H. Stephenson publishes with the permission of the Director, British Geological Survey. XXXXXX are thanked for reviewing and improving the paper.

REFERENCES

AL-BELUSHI, J. D., GLENNIE, K.W., and WILLIAMS, B.P.J.

1996 Permo-Carboniferous Glaciogenic Al Khlata Formation, Oman: a new hypothesis for origin of its glaciation. *GeoArabia*, 1: 389-404.

ANGIOLINI, L., STEPHENSON, M.H., and LEVEN, Y.

2006 Correlation of the Lower Permian surface Saiwan Formation and subsurface Haushi Limestone, central Oman: *GeoArabia*, 11: 17-38.

ANGIOLINI, L., BALINI, M., GARZANTI, E., NICORA, A., and TINTORI, A.

2003 Gondwanan deglaciation and opening of Neotethys: the Al-Khlata and Saiwan formations of Interior Oman. *Palaeogeography Palaeoclimatology Palaeoecology*, 196(1-2): 99-123.

ARCHBOLD, N.W.

1999 Permian Gondwana correlations: the significance of the western Australian marine Permian: *Journal of African Earth Sciences*, 29: 63-75.

BACKHOUSE, J.

1991 Permian palynostratigraphy of the Collie Basin, Western Australia. *Review of*

Palaeobotany and Palynology, 67: 237-314.

BACKHOUSE, J.

1993 Palynology and correlation of Permian sediments in the Perth, Collie and Officer basins. *Geological Survey of Western Australia Report* 34: 111-128.

BESEMS, R.E., and SCHUURMAN, W.M.L.

1987 Palynostratigraphy of Late Paleozoic glacial deposits of the Arabian Peninsula with special reference to Oman. *Palynology*, 11: 37-53.

BRAAKMAN, J., LEVELL, B. MARTIN, J. POTTER, T.L., and VAN VLIET, A.

1982 Late Palaeozoic Gondwana glaciation in Oman. *Nature,* 299: 48-50.

DAVYDOV, V., WARDLAW, B.R., and GRADSTEIN, F.M.

2004 The Carboniferous Period *In*: Gradstein, F.M., Ogg, J.G., and Smith, A.G. (eds) *A geologic time scale 2004*, Cambridge University Press, p.222-248.

DUBREUILH, J, BECHENNEC, F., BERTHIAUX, A , LE METOUR, J., PLATEL, J.-P., ROGER, J., and WYNS, R.

1992 *Geological map of Khaluf*, Sheet NF 40-15, scale 1:250,000 and explanatory notes. Directorate General of Minerals, Oman Ministry of Petroleum and Minerals, Muscat.

HEWARD, A.P.

1990 Salt removal and sedimentation in Southern Oman. *In*: Searle, A.H.F. and Ries, A.C. (eds), The Geology and Tectonics of the Oman Region, *Geological Society Special*

Publication No. 49: 637-652.

HUGHES-CLARKE, M.W.

1988 Stratigraphy and rock unit nomenclature in the oil producing area of interior Oman. *Journal of Petroleum Geology*, 11: 5-60.

JONES, M.J., and TRUSWELL, E.M.

1992 Late Carboniferous and Early Permian palynostratigraphy of the Joe Joe Group, southern Galilee Basin, Queensland, and implications for Gondwana stratigraphy. *Bureau of Mines and Mineral Resources Journal of Australian Geology and Geophysics*, 13: 143-185.

KEMP, E.M.,. BALME, B.E., HELBY, R.J., KYLE, R.A., PLAYFORD, G., and. PRICE, P.L.

1977 Carboniferous and Permian palynostratigraphy in Australia and Antarctica: a review. *Bureau of Mines and Mineral Resources Journal of Australian Geology and Geophysics*, 2: 177-208.

KNIGHT, R.W., and HARTKAMP-BAKKER, C.

1998 An integrated Stratigraphical Review of the Al Khlata Formation (South Oman). *Petroleum Development Oman Exploration Report* 386.

LEVELL, B.K., BRAAKMAN, J..H. and. RUTTEN, K.W.

1982 Oil bearing sediments of Gondwana glaciation in Oman. *American Association of Petroleum Geologists Bulletin*, 72(7): 775-796.

LOVE, C.F.

1994 The palynostratigraphy of the Haushi Group (Westphalian-Artinskian) in Oman. *In*: M.D. Simmons (ed.), *Micropalaeontology and Hydrocarbon Exploration in the Middle East*. Chapman and Hall, London, p. 23-39.

McGILLVARY, J.G., and HUSSEINI, M.I.

1992 The Palaeozoic petroleum geology of central Arabia. *American Association of Petroleum Geologists Bulletin* 76(10): 1473-1490.

MOHAMMED, A.R., HUSSEY, J.A., and REINDL, E.

1997 Catalogue of Oman Lithostratigraphy, *PDO Exploration Report* 389.

OSTERLOFF, P.L., PENNEY, R., AITKEN, J., CLARK, N., and. Al-HUSSEINI, M.

2004 Depositional sequences of the Al Khlata Formation, subsurface Interior Oman. *In*: Al-Husseini, M.I. (ed.), Carboniferous, Permian and Triassic Arabian Stratigraphy. *GeoArabia Special Publication* 3, Gulf PetroLink, Manama, Bahrain, p. 61-81.

POWIS, G.D.

1979 *Palynology of the Late Palaeozoic glacial sequence, Canning Basin, Western Australia*. Unpublished. Ph.D. thesis, University of Western Australia, Perth, Australia.

POWIS, G.D.

1984 Palynostratigraphy of the Late Carboniferous sequence, Canning Basin, W. A. *In*: Purcell, P.G. (ed.), The Canning Basin, Western Australia. *Proceedings of the Geological Society of Western Australia/PESA Symposium, Perth,* 1984, p. 429-438.

ROGER, J.,. CHEVREL, S,. PLATEL, J.-P., BECHENNEC, F., DUBREUILH, J.,. LE

METOUR, J., and Wyns, R.

1992 *Geological map of Mafraq*, Sheet NF 40-11, scale 1:250,000 and explanatory notes. Directorate General of Minerals, Oman Ministry of Petroleum and Minerals, Muscat.

STEPHENSON, M.H.

2008 in press A review of the palynostratigraphy of Gondwanan Late Carboniferous to Early Permian glacigene successions. *Geological Society of America Special Paper*.

STEPHENSON, M.H., and FILATOFF, J.

2000 Correlation of Carboniferous-Permian palynological assemblages from Oman and Saudi Arabia. *In*: S. Al-Hajri and B. Owens (eds.), *Stratigraphic palynology of the Palaeozoic of Saudi Arabia. GeoArabia* Special Publication No. 1, Gulf PetroLink, Bahrain, p. 168-191.

STEPHENSON, M.H., and OSTERLOFF, P.L.

2002 Palynology of the deglaciation sequence represented by the Lower Permian Rahab and Lower Gharif members, Oman. *American Association of Stratigraphic Palynologists, Contribution Series* 40: 1-41.

STEPHENSON, M. H., OSTERLOFF, P. L., and FILATOFF, J.

2003 Integrated palynological biozonation of the Permian of Saudi Arabia and Oman: progress and problems. *GeoArabia*, **8**: 467-496.

STEPHENSON, M.H., LENG, M.J., VANE, C.H., OSTERLOFF, P.L., and ARROWSMITH, C.

2005 Investigating the record of Permian climate change from argillaceous sediments, Oman. *Journal of the Geological Society,* London, 162: 1-11.

STEPHENSON, M.H., ANGIOLINI, L., and LENG, M.J.

2007 The Early Permian fossil record of Gondwana and its relationship to deglaciation: a review. *In*: M. Williams, A.M. Haywood, F.J. Gregory and D.N. Schmidt (eds.) *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies.* The Micropalaeontological Society, Special Publications. The Geological Society, London, p. 103–122.

TRUSWELL, E. M.

1978 Palynology of the Permo-Carboniferous in Tasmania: an interim report. *Bulletin of the Geological Society of Tasmania*, 56: 1-39.

FIGURE CAPTIONS

Fig. 1. South Oman study area indicating locations of 2159, 2165 and 2141 palynozonal correlation lines.

Fig. 2. South Oman 2159 palynozonal correlation example; (left to right) Marmul-6 well reference section and Qata-9, Al Burj-36 and Rima-65 well sections.

Fig. 3. South Oman 2165 palynozonal correlation example; (left to right) Dimeet-1, Al Burj-23, Amal-9 well sections and Wadi Al Khlata (short) Borehole-5 reference section.

Fig. 4. South Oman 2141 palynozonal correlation example; (left to right) Rahab-28 well section, Rahab-2 reference section, Nimr-46 and Wadi Al Khlata Borehole-2 well sections.

Fig. 5. Haushi Palynozonation scheme displaying palynomorphs groups, key and main accessory taxa.

Fig. 6. Correlation chart with Arabia and Australia.

Table 1. Composition of taxon groups used in palynozonation.

Table 2. Summary of main biozone characteristics.

Plate 1. Representative palynomorphs from the Cingulicamerate, *Horriditriletes*, *Microbaculispora*, *Punctatisporites* groups and other 2159 biozonal taxa from the Al Khlata Formation, South Oman. Magnification X600. All slides are held in the collection of Petroleum Development Oman, Muscat.

1 - 4. *Microbaculispora* Group. 1,2 *Microbaculispora tentula* Habhab-2 1200.41m core, M39/4and X31/3 ; 3 *Converrucosisporites grandegranulatus* Habhab-2 1205.42m core, P28/4; 4 *Converrucosisporites confluens* Habhab-2 1205.42m core, C24/3.

5, 8 and 9 Other 2159 Zonal Taxa. 5 *Anapiculatisporites concinnus* Habhab-2 1207.50m core, K21/4; 8 *Wilsonites australiensis*; 1202.70m core, N39/4; 9 *Dibolisporites* sp. 1202.70m core, H25.

6, 7 *Horriditriletes* Group; 6 Habhab-2 1197.60m core, P32 and 7 Nimr-38H1 914.48m core, N30.

10 – 15 Cingulicamerate Group. 10 *Lundbladispora* sp. Wadi Al Khlata Borehole #5 17.70m; 11, 13 and 15 *Cristatisporites* spp. Habhab-2 1207.50m core, B37/4 and 1202.70m core, O17/3, Nimr-38 914.48m core, D29/3 ; 12 *Lundbladispora* sp. Habhab-2 1200.41m core, W34/1 ; 14 *Vallatisporites arcuatus* Nimr-38 914.48m core, P32.

16 – 18 *Punctatisporites* Group. 16, 17 *Calamospora* spp. Habhab-2 1213.52m core, T26/0; 1197.60m core, C44/1. 18 *Punctatisporites gretensis* Habhab-2 1216.50m core, K31/1.

Plate 2. Representative palynomorphs from the Non-Taeniate Bisaccate, Taeniate Bisaccate and Monosaccate Groups, colpate pollen and algal taxa. Magnification X600,

Slide repository as for plate 1.

1 – 6 Colpate pollen taxa: 1 and 2 *Cycadopites cymbatus* Habhab-2 1200.41m, R35/4 and 1200.41m, K46/0; 3 *Striasulcites* sp.; Habhab-2, 4 and 5 *Marsupipollenites* spp. Habhab-2H1 1213.52m , Q26 and Saih Rawl-8 2961.38m, V44/4; 6 *Kingiacolpites subcircularis* Amal South-5 1450.05m, C25/3.

8, 9 Algae: ?*Tetraporina* spp., 8 Habhab-2 1207.50m, E21/3; 9 Wadi Al Khlata Borehole #2, 14.40m M39/4.

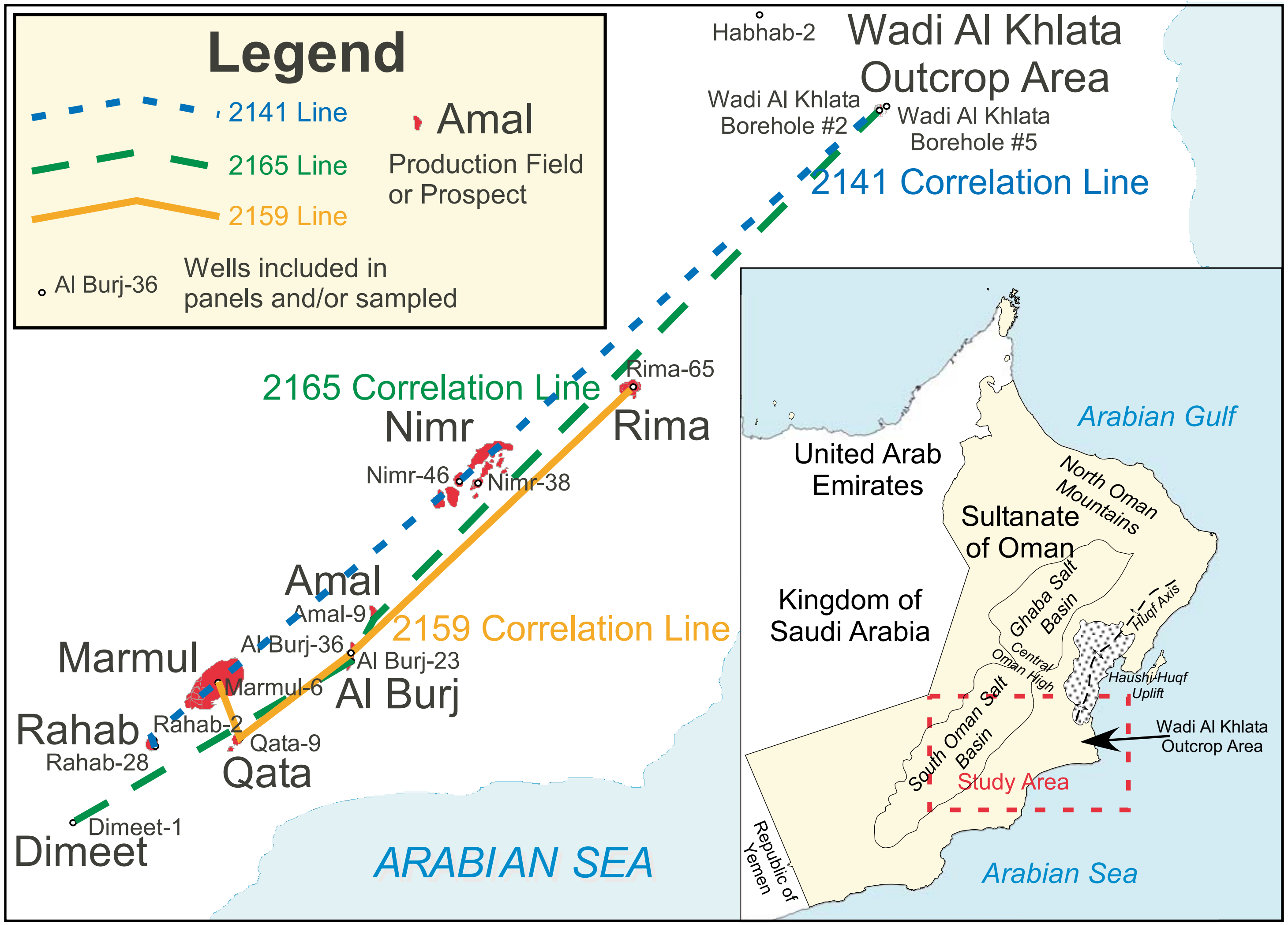
7, 10 Non-Taeniate Bisaccate Group: 7 *Alisporites* sp. Habhab-2 1200.41m, X38; 10 *Alisporites indarraensis* Amal-9 1298.45m, K39/1.

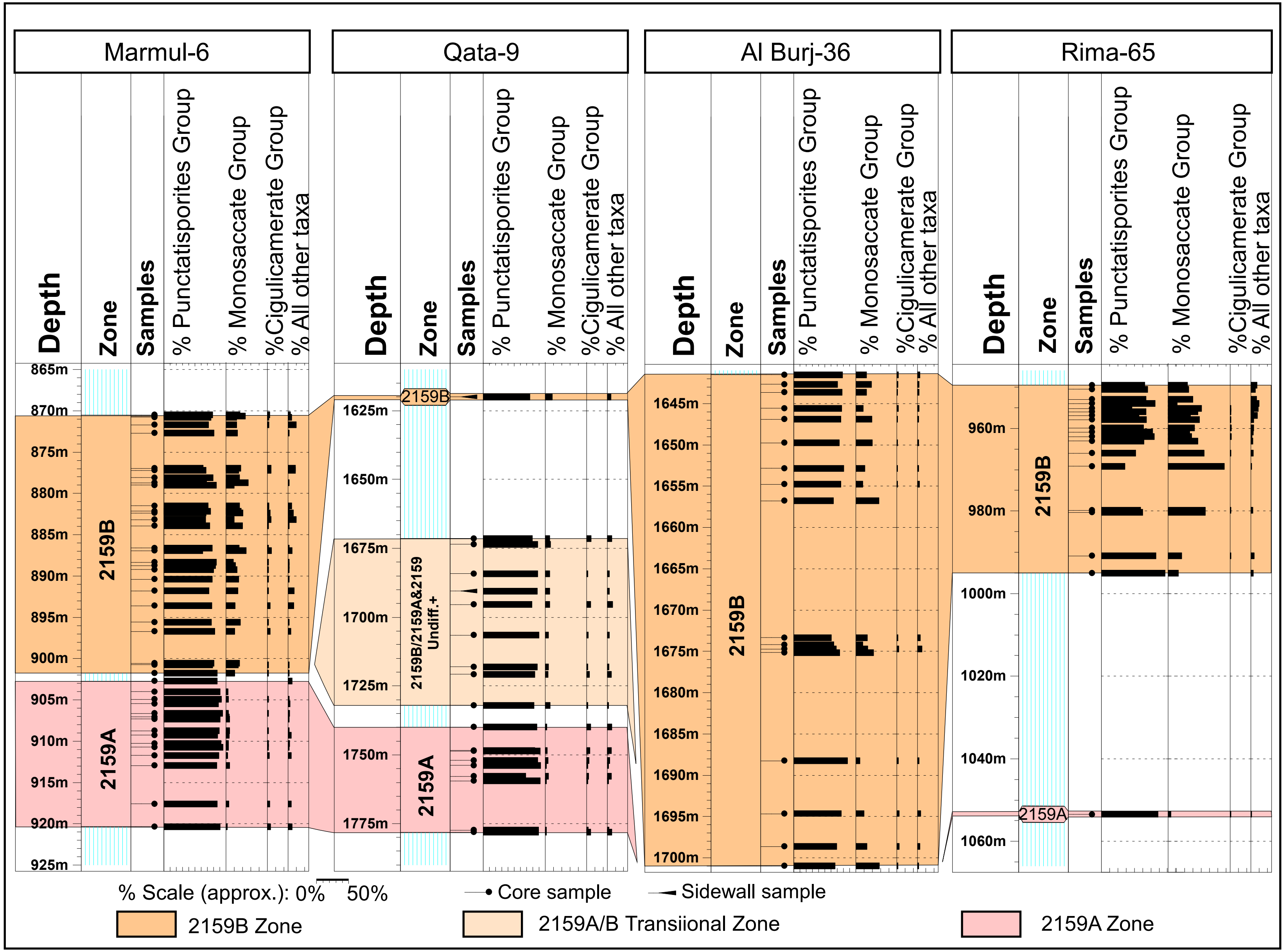
11 – 14 Taeniate Bisaccate Group: 11 *Striatoabieites multistratiatus* Rima-69 975m, O38/4; 12 *Vittatina saccata* Habhab-2 1207.50m, Q35/2; 13 *Protohaploxypinus amplus* Habhab-2 1205.42m, B23/3; 14 *Strotersporites* sp. cf. *indicus* Habhab-2 1200.41m, F29/4.

15, 16 Monosaccate Group: 15 *Caheniasaccites* cf. *ovatus* Nimr-38 901.03m, S36/4; 16 *Potonieisporites* sp. Nimr-38 901.03m, D28.

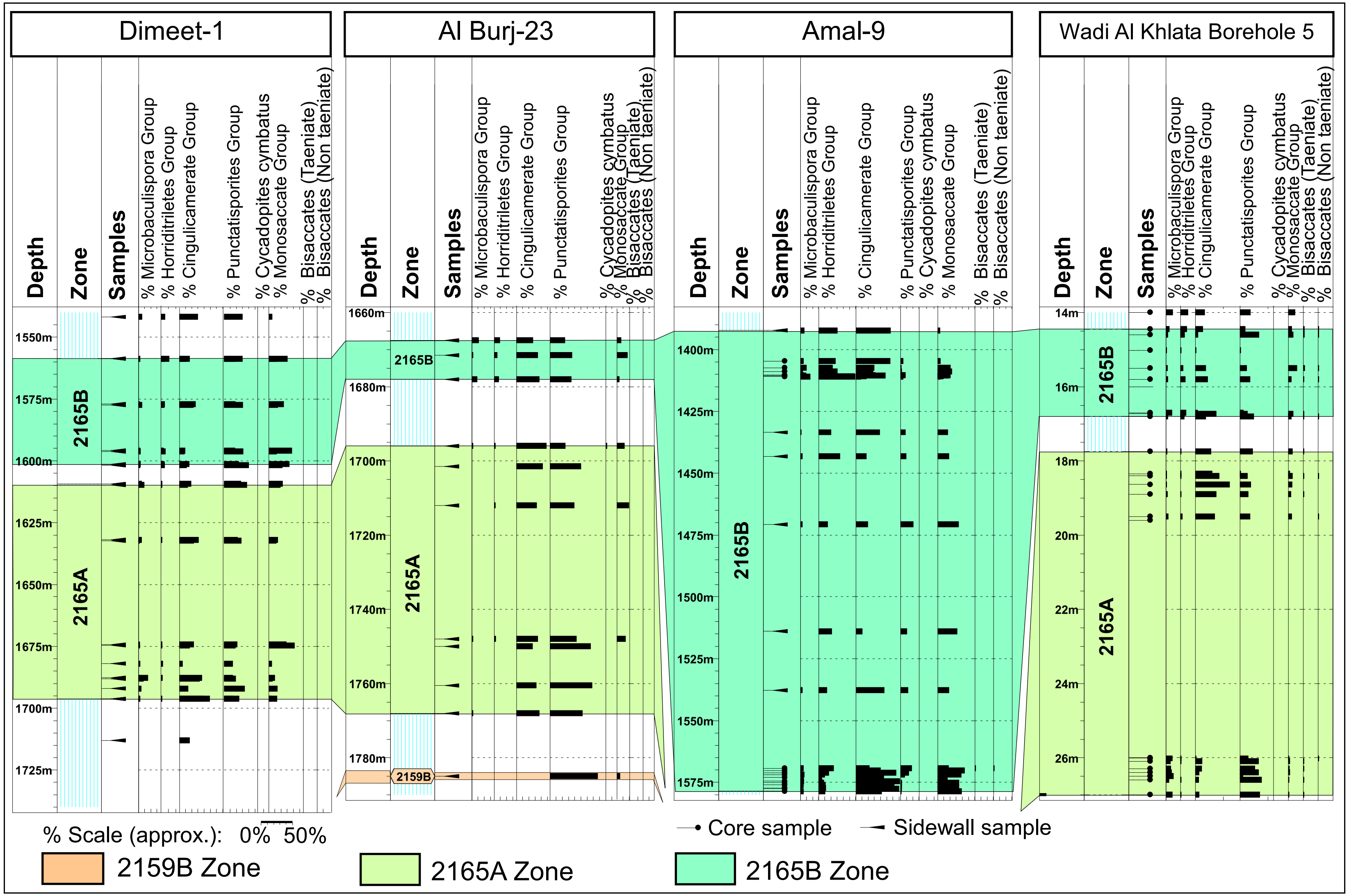
17, 20, 21 Taeniate Bisaccate Group: 17 *Strotersporites indicus* Nimr-39, 914.48m, M24; 20 *Protohaploxypinus* cf. *goraiensis* Nimr-38, 913.68m, O34/2; 21 *Complexisporites polymorphus* Habhab-2 1205.42m, M22/3.

18, 19, 22, 23 Monosaccate Group: 18 ?*Divarisaccus* sp. Habhab-2 1216.50m, C19/2; 19 *Florinites flaccidus* Habhab-2 1205.42m, R24/2; 22 *Plicatipollenites malabarensis* Habhab-2 1197.60m, D39/4; 23 *Barakarites* cf. *rotatus* Habhab-2 1218.82, W26/3.

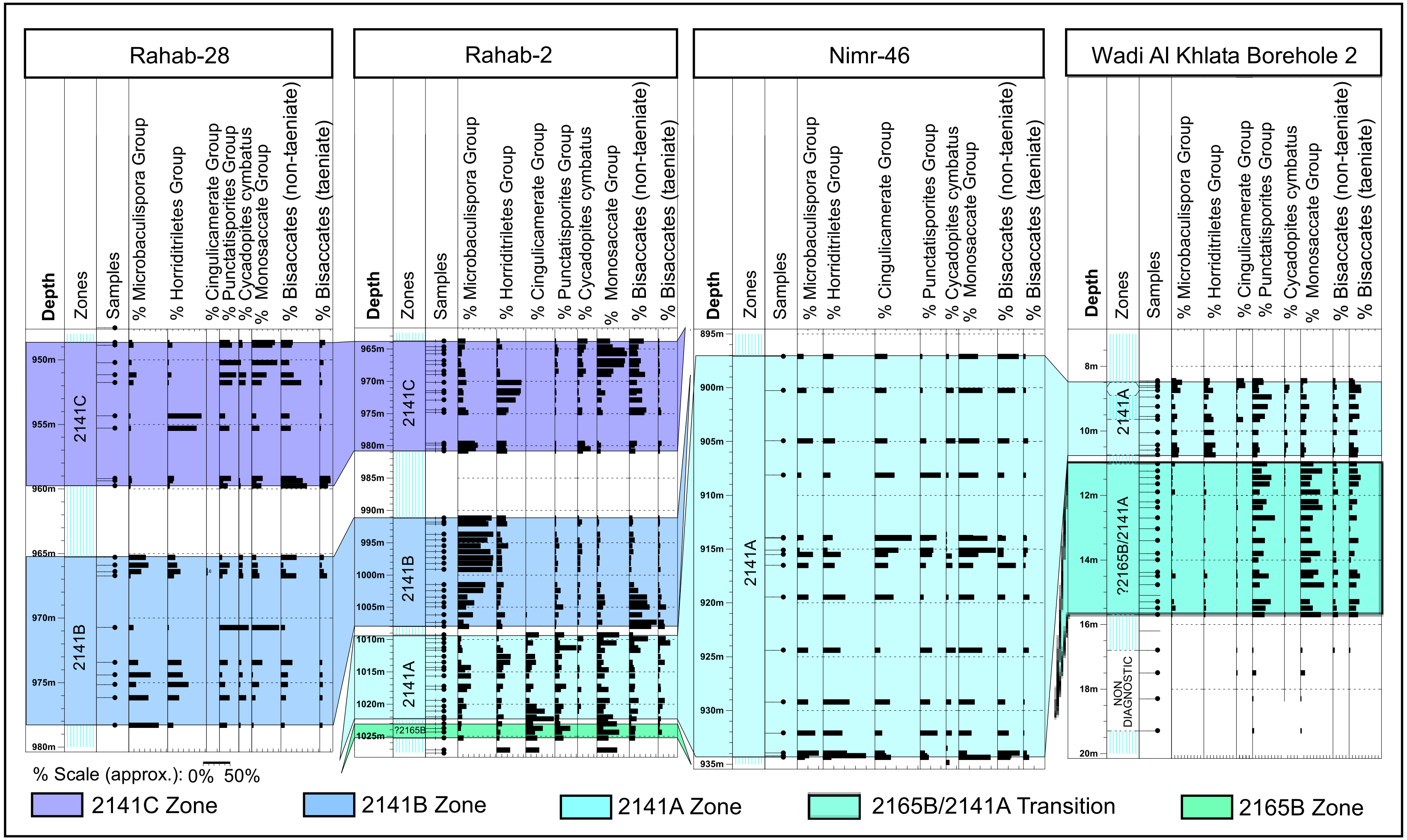

Legend
2141 Line
2165 Line
2159 Line
Amal
Production Field or Prospect
Al Burj-36
Wells included in panels and/or sampled
Habhab-2
Wadi Al Khlata Outcrop Area
Wadi Al Khlata Borehole #2
Wadi Al Khlata Borehole #5
2141 Correlation Line
2165 Correlation Line
Rima-65
Nimr
Rima
Nimr-46
Nimr-38
Amal
Amal-9
2159 Correlation Line
Marmul
Al Burj-36
Al Burj-23
Marmul-6
Al Burj
Rahab
Rahab-2
Rahab-28
Qata-9
Qata
Dimeet-1
Dimeet
ARABIAN SEA
Arabian Gulf
United Arab Emirates
North Oman Mountains
Sultanate of Oman
Kingdom of Saudi Arabia
Ghaba Salt Basin
Huqf Axis
Central Oman High
Haushi-Huqf Uplift
South Oman Salt Basin
Wadi Al Khlata Outcrop Area
Study Area
Republic of Yemen
Arabian Sea

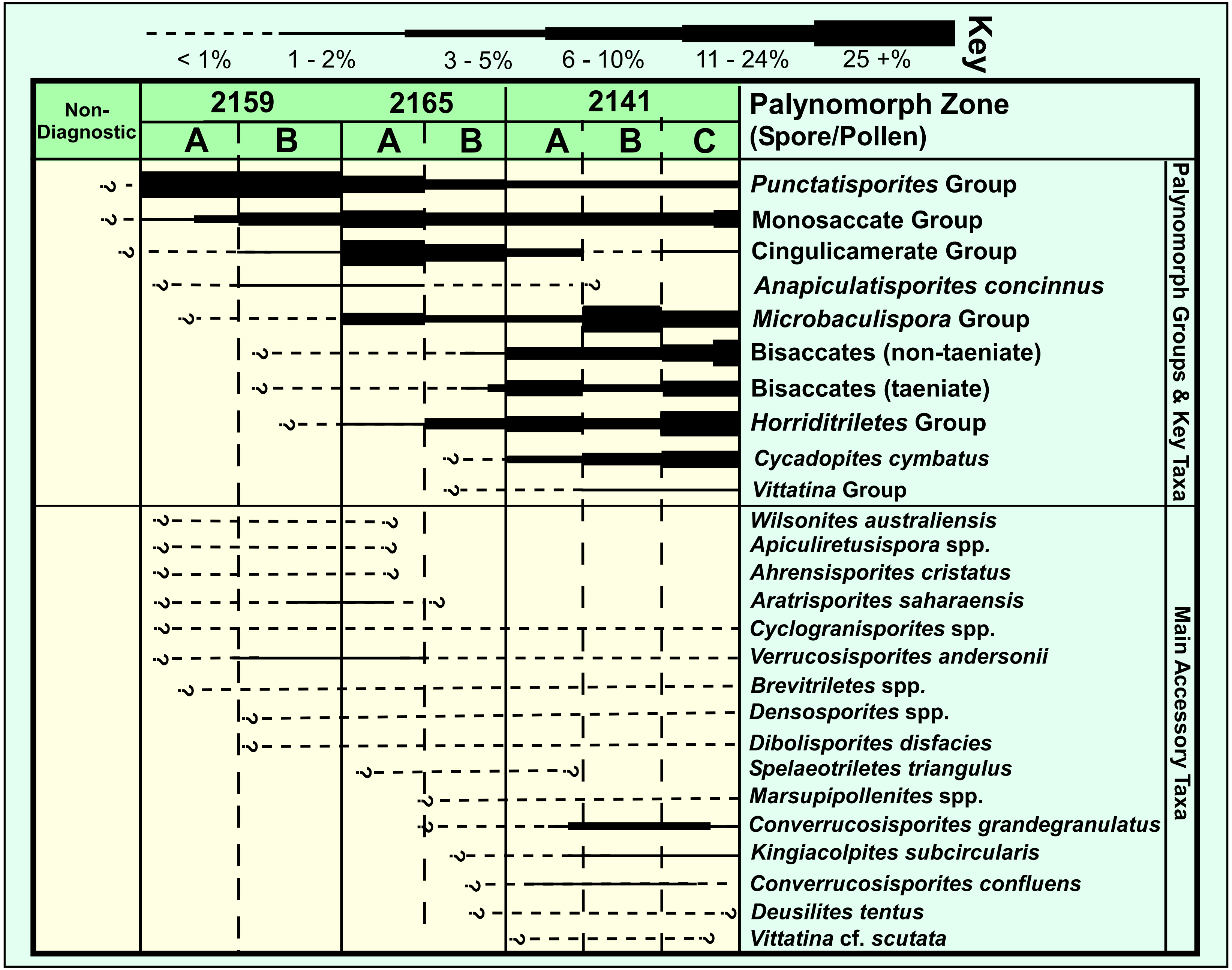


Marmul-6
Qata-9
Al Burj-36
Rima-65
Depth
Zone
Samples
% Punctatisporites Group
% Monosaccate Group
%Cigulicamerate Group
% All other taxa
2159B
2159A
2159B/2159A&2159 Undiff.+
865m
870m
875m
880m
885m
890m
895m
900m
905m
910m
915m
920m
925m
1625m
1650m
1675m
1700m
1725m
1750m
1775m
1645m
1650m
1655m
1660m
1665m
1670m
1675m
1680m
1685m
1690m
1695m
1700m
960m
980m
1000m
1020m
1040m
1060m
% Scale (approx.): 0% 50%
Core sample
Sidewall sample
2159B Zone
2159A/B Transiional Zone
2159A Zone



Dimeet-1
Al Burj-23
Amal-9
Wadi Al Khlata Borehole 5
Depth
Zone
Samples
% Microbaculispora Group
% Horriditriletes Group
% Cingulicamerate Group
% Punctatisporites Group
% Cycadopites cymbatus
% Monosaccate Group
% Bisaccates (Taeniate)
% Bisaccates (Non taeniate)
2165B
2165A
2159B
1550m
1575m
1600m
1625m
1650m
1675m
1700m
1725m
1660m
1680m
1720m
1740m
1760m
1780m
1400m
1425m
1450m
1475m
1500m
1525m
1575m
14m
16m
18m
20m
22m
24m
26m
% Scale (approx.): 0% 50%
Core sample
Sidewall sample
2159B Zone
2165A Zone
2165B Zone


Rahab-28
Rahab-2
Nimr-46
Wadi Al Khlata Borehole 2
Depth
Zones
Samples
% Microbaculispora Group
% Horriditriletes Group
% Cingulicamerate Group
% Punctatisporites Group
% Cycadopites cymbatus
% Monosaccate Group
% Bisaccates (non-taeniate)
% Bisaccates (taeniate)
2141C
2141B
2141A
?2165B
?2165B/2141A
NON DIAGNOSTIC
% Scale (approx.): 0% 50%
2141C Zone
2141B Zone
2141A Zone
2165B/2141A Transition
2165B Zone


Key
< 1%
1 - 2%
3 - 5%
6 - 10%
11 - 24%
25 +%
Non-Diagnostic
2159
2165
2141
A
B
A
B
A
B
C
Palynomorph Zone (Spore/Pollen)
Palynomorph Groups & Key Taxa
Punctatisporites Group
Monosaccate Group
Cingulicamerate Group
Anapiculatisporites concinnus
Microbaculispora Group
Bisaccates (non-taeniate)
Bisaccates (taeniate)
Horriditriletes Group
Cycadopites cymbatus
Vittatina Group
Main Accessory Taxa
Wilsonites australiensis
Apiculiretusispora spp.
Ahrensisporites cristatus
Aratrisporites saharaensis
Cyclogranisporites spp.
Verrucosisporites andersonii
Brevitriletes spp.
Densosporites spp.
Dibolisporites disfacies
Spelaeotriletes triangulus
Marsupipollenites spp.
Converrucosisporites grandegranulatus
Kingiacolpites subcircularis
Converrucosisporites confluens
Deusilites tentus
Vittatina cf. scutata

System/stage		Arabian faunal content	Stephenson et al., 2003, Arabian Peninsula (Strat)	Stephenson et al., 2003, Arabian Peninsula (Biozone)		Stephenson and Osterloff, 2002, Oman	Oman, Love, 1994	Oman, Besems and Schuurman, 1987	This study	Eastern Australian zones, Jones and Truswell, 1992	Powis, 1984	Western Australia zones, Backhouse, 1991
Permian	Sakmarian	↑ **Stratigraphic range of *P.* ex gr. *karapetovi karapetovi* in Haushi limestone**	**L. Gharif Mb.**	OSPZ3	c	***C. pox***	*K. subcircularis* Assemblage					
					b	***U. oman.***						
					a	***A. indarra.***						*S. fusus*
				OSPZ2		***Conv. sp. A M. grande***	*C. cymbatus* Assemblage		2141C	***V. pseudo.***		*P. pseudo.*
			Al Khlata Fm.			***M. tentula*** ?			2141B	*Microbaculispora tentula* Biozone = eastern Australian Stage 2	Stage 2	*C. confluens*
								Ass. Group B	2141A			
	Asselian						*Microbaculispora* Assemblage	Assemblage Group A	2165B			Stage 2 *sensu* Backhouse (1991)
?	?								2165A			
Pennsylvanian	**?Late Moscovian - Gzhelian**			OSPZ1			*Potonieisporites* Assemblage		2159B	***? Asperispora reticulatispinosus* Biozone**	Stage 1	
									2159A			

Group	**Main genera**	**Main species**
'Punctatisporites' Group	*Punctatisporites, Calamospora*, *Cyclogranisporites, Retusotriletes*	*Punctatisporites gretensis*, *Punctatisporites gretensis* forma *minor*, *Punctatisporites lucidulus*
'Cingulicamerate' Group	*Vallatisporites, Densoisporites, Lundbladispora, Cristatisporites, Indotriradites*	*Vallatisporites arcuatus, Vallatisporites* cf. v*allatus*, *Lundbladispora braziliensis*, *Densoisporites solidus*, *Cristatisporites crassilabratus*.
Microbaculispora' Group	*Microbaculispora, Converrucosisporites Granulatisporites*	*Microbaculispora tentula*, *Converrucosisporites grandegranulata*, *Converrucosisporites confluens*.
'Horriditriletes' Group	*Horriditriletes, Lophotriletes*	*Horriditriletes ramosus, Horriditriletes tereteangulatus, Horridtriletes uruguaiensis, Lophotriletes sparsus*
'Monosaccate' Group	*Barakarites, Cannanoropollis, Plicatipollenites, Caheniasaccites, Potonieisporites*	*Barakarites rotatus*, *Caheniasaccites ovatus*, *Plicatipollenites malabarensis*, *Potonieisporites braziliensis, Potonieisporites novicus*
Bisaccate (Non taeniate) Group	*Alisporites*, *Limitisporites, Platysaccus*, *Sulcatisporites*, *Sahnites*	*Alisporites indarraensis*, *Sahnites gondwanensis*
Bisaccates (Taeniate) Group	*Complexisporites, Protohaploxypinus*, *Striatoabieites*, *Striatopodocarpites, Strotersporites*	*Complexisporites polymorphus*, *Protohaploxypinus limpidus*, *Protohaploxypinus amplus*, *Striatoabieites multistriatus*, *Striatopodocarpites cancellatus*, *Strotersporites* cf. *indicus.*
'Vittatina' Group	*Circumstriatites, Marsupipollenites, Pakhapites, Vittatina, Striasulcites*	*Vittatina subsaccata*, *Vittatina* cf. *scutata, Circumstriatites talchirensis*, *Marsupipollenites striatus*, *Pakhapites fusus*, *Striasulcites tectus*

Biozone	**Main characteristics**
2159A	Abundance of *Punctatisporites* Group which constitutes up to 100% of assemblages. Taxa of the Monosaccate Group constitute less than 5% of assemblages.
2159B	Increase in the proportion of the Monosaccate Group to greater 10% of assemblages such that *Punctatisporites* spp. does not exceed 90% of assemblages.
2165A	(1) the Cingulicamerate Group constitutes up to approximately 30% of the assemblages; and (2) the *Microbaculispora* Group constitutes approximately 5% of assemblages.
2165B	(1) *Horriditriletes* Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) *Microbaculispora* Group constitutes usually around 3 to 5% of assemblages.
2141A	(1) non-taeniate and taeniate bisaccate groups together represent more than 10% of the assemblages; and (2) *Cycadopytes cymbatus* is rare towards the base but increases to 5 to 10% of assemblages towards the top of the biozone.
2141B	(1) The *Microbaculispora* Group represents greater than 10% and can constitute up to 60% of assemblages, in addition the *Microbaculispora* Group is more abundant than the *Horriditriletes* Group; (2) *Cycadopytes cymbatus* makes up 5 to 10% of assemblages; and (3) the Cingulicamerate Group are extremely rare or absent.
2141C	The *Microbaculispora* Group represents more than 10% of assemblages, but the *Horriditriletes* Group exceeds it in numbers, reaching 30% or more.

APPENDIX

The following is a complete listing of all taxa mentioned in the text of this paper including their full author citations.

Ahrensisporites cristatus Playford & Powis 1979
Alisporites indarraensis Segroves 1970
Anapiculatisporites concinnus Playford 1962
Apiculiretusispora spp.
Aratrisporites saharaensis Loboziak et al., 1986
Barakarites rotatus (Balme & Hennelly) Bharadwaj & Tiwari 1964
Brevitriletes cornutus (Balme & Hennelly) Backhouse 1991
Caheniasaccites ovatus Bose & Kar 1966
Circumstriatites talchirensis Lele & Makada 1972
Converrucosisporites confluens (Archangelsky & Gamerro) Playford & Dino 2002
Converrucosisporites grandegranulatus (Anderson) Lindström 1995
Cristatisporites crassilabratus Archangelsky & Gamerro 1979.
Cycadopites cymbatus (Balme & Hennelly) Segroves 1970
Densoisporites rotundidentatus Segroves 1970
Densoisporites solidus Segroves 1970
Densoisporites sp. Jones & Truswell 1992
Deusilites tentus Hemer & Nygreen 1967
Dibolisporites disfacies Jones & Truswell 1992
Florinites flaccidus Menéndez & Azcuy 1973
Horriditriletes ramosus (Balme & Hennelly) Bharadwaj & Salujah 1964
Horriditriletes tereteangulatus (Balme & Hennelly) Backhouse 1991
Horriditriletes uruguaiensis (Marques-Toigo) Archangelsky & Gamerro 1979
Kingiacolpites subcircularis Tiwari & Moiz 1971
Lophotriletes sparsus Singh 1964
Lundbladispora spp.
Lundbladispora braziliensis (Pant & Srivastava) Marques Toigo & Pons 1976
Marsupipollenites striatus (Balme & Hennelly) Foster 1975
Microbaculispora tentula Tiwari 1965
Pakhapites fusus (Bose & Kar) Menéndez 1971
Plicatipollenites malabarensis (Potonié & Sah) Foster 1975
Potonieisporites brasiliensis (Nahuys et al.) Archangelsky & Gamerro 1979
Potonisporites novicus Bharadwaj 1954.
Protohaploxypinus amplus (Balme & Hennelly) Hart 1964
Protohaploxypinus cf. goraiensis (Potonié & Lele) Hart 1964
Punctatisporites gretensis Balme & Hennelly 1956
Punctatisporites gretensis forma *minor*, (Balme & Hennelly) Hart 1965
Punctatisporites lucidulus Playford & Helby 1966
Sahnites gondwanensis (Mehta) Pant 1955
Spelaeotriletes triangulus Neves & Owens 1966
Striatoabieites multistriatus (Balme & Hennelly) Hart 1964
Striasulcites tectus Venkatachala & Kar 1968
Strotersporites cf. *indicus* Tiwari 1965
Vallatisporites arcuatus (Marques-Toigo) Archangelsky & Gamerro 1979
Vallatisporites cf. *vallatus* Hacquebard 1957
Verrucosisporites andersonii Backhouse 1988

Verrucosisporites cf. *naumovae* Hart 1963
Vittatina cf. *scutata* (Balme & Hennelly) Bharadwaj 1962
Vittatina subsaccata Samoilovich 1953
Wilsonites australiensis Playford & Helby 1968

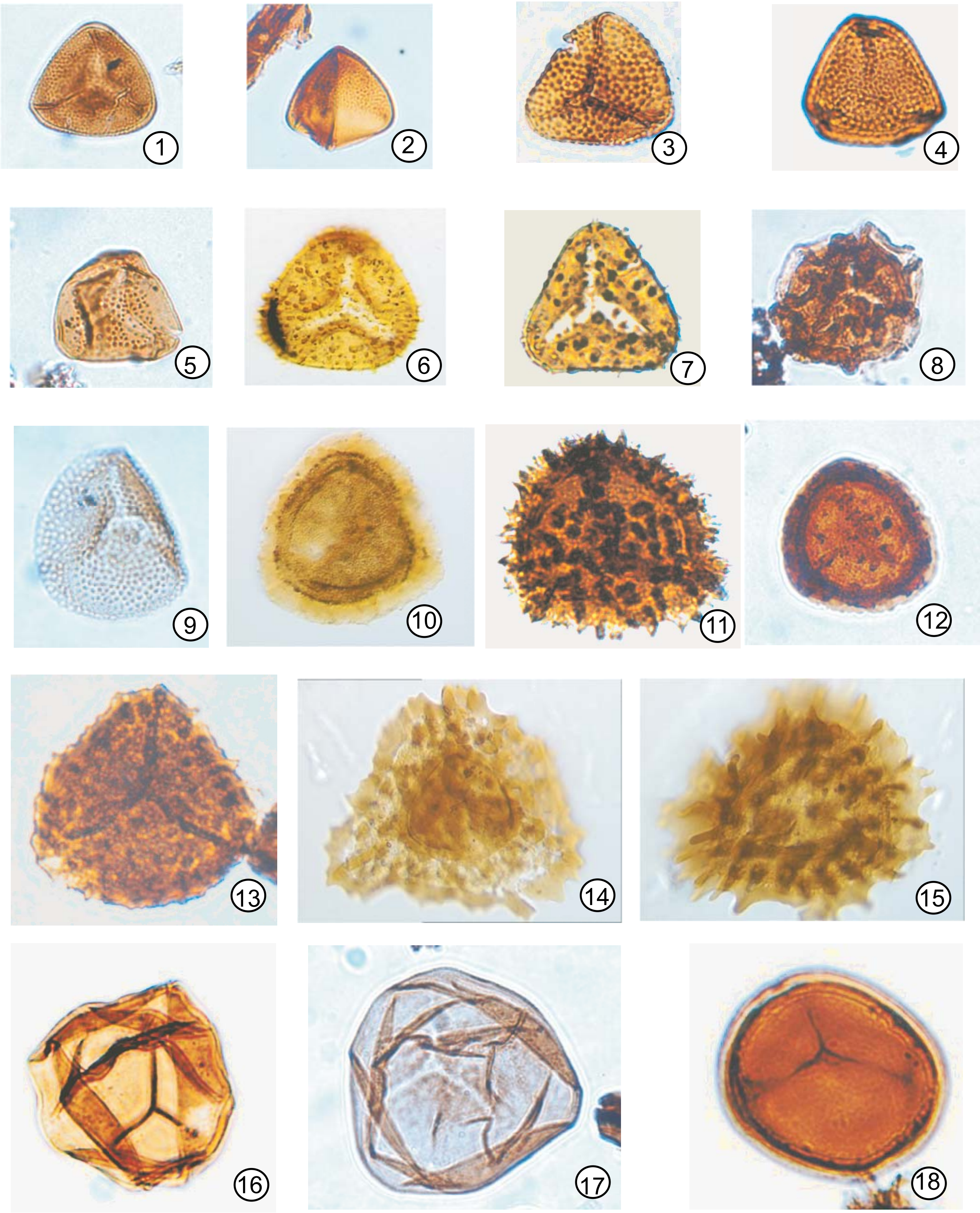


PLATE 1; Penney, Stephenson and Al Barram

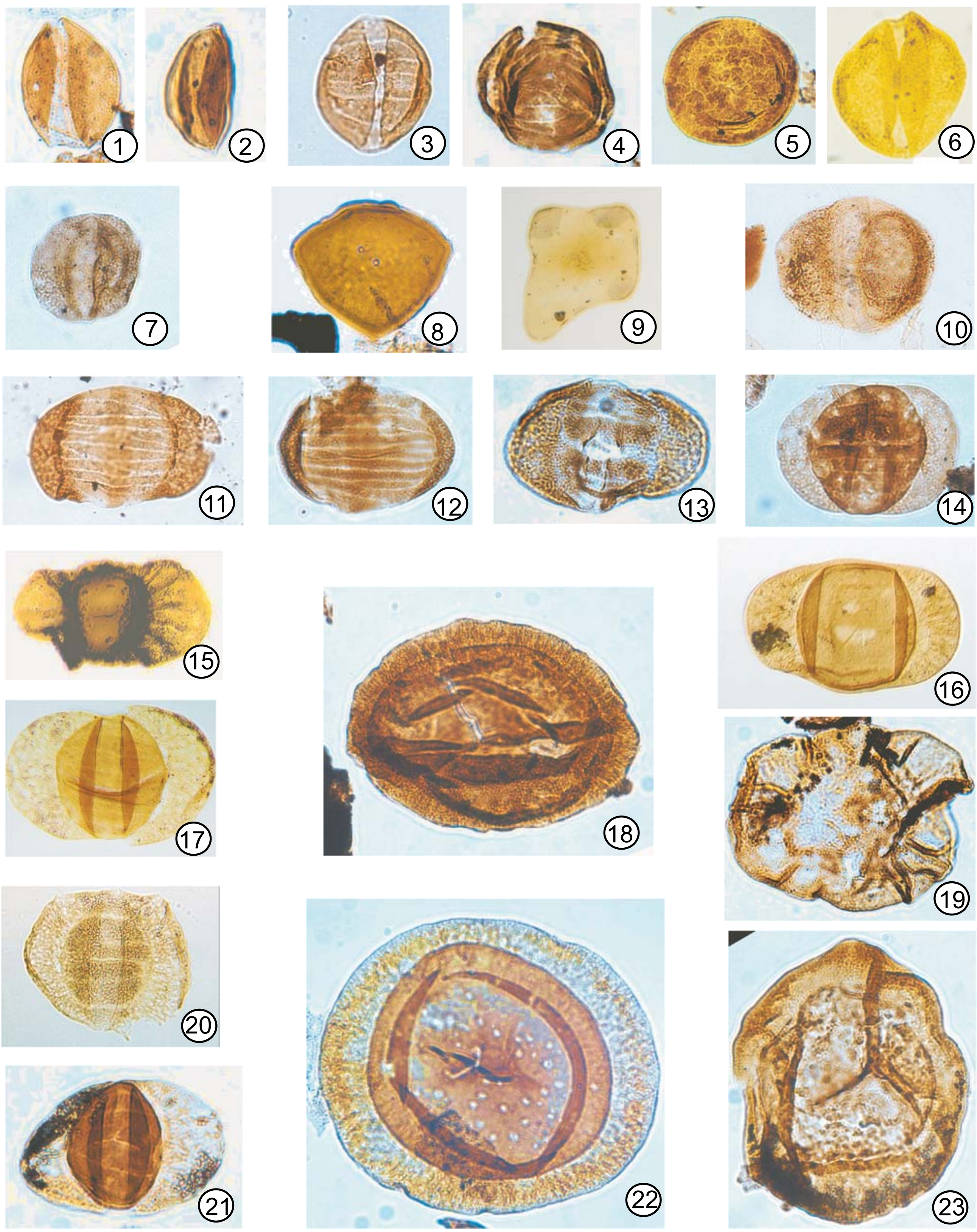


PLATE 2; Penney, Stephenson and Al Barram