Palynology and correlation of Carboniferous - Permian glacigene rocks in Oman, Yemen and Pakistan

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Abstract

Palynological assemblages from sections in Yemen and Pakistan are similar enough to allow the application of biozones based on the Pennsylvanian glacigene sediments of interior Oman. Thirty four samples from the upper 84 m of a 125 m thick section of the Tobra Formation at Zaluch Nala, western Salt Range, Pakistan yielded palynomorph taxa including *Microbaculispora tentula*, abundant monosaccate pollen including *Cannanoropollis janakii* and *Plicatipollenites malabarensis*, *Converrucosisporites grandegranulatus*, *Horriditriletes ramosus* and *Horriditriletes tereteangulatus* indicating the late Pennsylvanian Oman 2165B Biozone. Eleven samples from the Yemen Kuhlan Formation, and 22 samples from the underlying Akbarah Formation from approximately 300m of a section near Kuhlan in northwest Yemen, suggest a 2165A Biozone age (also late Pennsylvanian). This correlation indicates the widespread nature of glacial sediments of a narrow biostratigraphic late Pennsylvanian age range (the Oman P5 unit) in basins across part of the north Gondwana margin. New data from three samples from the Tobra Formation at the Choa Road section near Khewra in the eastern Salt Range, Pakistan are assignable to the earliest Permian 2141B Biozone, indicating a possible correlation between the ‘Tobra shale’ and the Rahab Shale Member of Oman, which is considered to mark the final deglaciation sequence in Oman.

Keywords: palynology, Gondwana, Yemen, Oman, Pakistan

1. Introduction

The Pennsylvanian to Cisuralian non-marine, cold-climate sediments of the Gondwana continent are notoriously difficult to correlate both within the continent and with the standard stages (Stephenson et al., 2007; Stephenson 2008). This is because the rocks do not contain the key zonal fossils which are marine (e.g., foraminifera, corals and most importantly conodonts). Thus historically, correlation has relied mainly on palynology. However palynological correlation across Gondwana is difficult, due mainly to disparate stratigraphic and taxonomic methods and different standards of documentation of palynological data used in areas of Gondwana (Stephenson, 2008). Also cold climate palynological assemblages are difficult to compare with those of the palaeoequator which is where the standard stages are based.

Stephenson (2008) assessed palynostratigraphic schemes in the main Gondwana basins and focused on precise basin-to-basin or region-to-region correlations underpinned by careful taxonomy and stratigraphy, giving examples of Arabian to Australian correlation and Australian to South African correlation. He concluded that consolidation of basin-to-basin correlations will probably lead to the most reliable Gondwana–wide correlations. The objective of this study was to test the applicability of a newly-published Oman biozonation across basins in Yemen and Pakistan, to correlate using the biozonation, and thereby understand the age-distribution of glacigene rocks in the three areas (Fig. 1).

The palynology samples described in the paper were prepared by crushing, followed by hydrochloric and hydrofluoric acid treatments (Wood et al., 1996). The post-hydrofluoric acid organic residues were oxidized using Schulze's solution and dilute nitric acid. The slides from Yemen and Pakistan are held in the Collection of the British Geological Survey, Keyworth, Nottingham, UK, NG12 5GG. For details of locations of studied sections see Stephenson et al. (2005) for Oman, Jan and Stephenson (2011) for Pakistan, and Stephenson and Al-Mashaikie (2011) for Yemen. The Choa Road section near Khewra in the eastern Salt Range is at GPS N 32 39 57, E 72 59 08.8.

2. The Oman sequence and the Al Khlata Formation biozonation

Pennsylvanian to Cisuralian rocks of the Al Khlata Formation crop out at the Haushi-Huqf outcrop area in Oman but are present widely in the subsurface, where they form important hydrocarbon reservoirs (Hughes Clarke, 1988). The Al Khlata Formation ranges from conglomerates through diamictites, gravels, pebbly sandstones, siltstones to silty shales (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; 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 on the Precambrian Khufai Formation have been found (Fig. 2; Braakman et al., 1982; Al-Belushi et al., 1996). The type section of the Al Khlata Formation is located at Wadi Al Khlata near the Haushi-Huqf Uplift (57°25'46"E, 19°46'43"N) where it is about 100 m thick (Levell et al., 1988) and there is a subsurface reference section 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). 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). 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). During its deposition, the Cambrian Ara salt in the South Oman Salt Basin moved diapirically to form salt domes. As a result, thick Al Khlata Formation 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 (for details of locations see Penney et al., 2008; Heward, 1990; Osterloff et al., 2004). These long periods of subsidence have lead to the most complete record of Pennsylvanian to Cisuralian glaciations in Arabia and to the most complete palynological record, with the result that the palynological succession of Oman forms the standard with which other less complete successions are correlated. The assemblages have been described in great detail before (e.g. Besems and Schuurman, 1987; Love, 1994; Stephenson and Filatoff, 2000; Stephenson and Osterloff, 2002; Stephenson, 2004; Stephenson et al., 2003; 2005; 2007;) but in general the diversity and yield increases up 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 (Stephenson et al., 2005). The earliest assemblages (e.g. 2159) are characterised by common monosaccate pollen and *Punctatisporites*, while later assemblages are of greater diversity including cingulicamerate and cheilocardioid spores, and colpate and bisaccate pollen (e.g. 2141; see Penney et al., 2008). Biozones were defined in the Al Khlata Formation by Penney et al. (2008) on the basis of quantitative changes in defined palynomorph groups (Table 1) and on the ranges of certain distinctive taxa, for example *Anapiculatisporites concinnus, Cycadopites cymbatus*, and *Kingiacolpites subcircularis*. The details of the biozones and how they are applied are given by Penney et al. (2008), however for the reader's convenience a summary of the relevant biozones is given here.

The primary diagnostic criteria of the 2165A Biozone are (1) the Cingulicamerate Group (Table 1) 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. Distinctive accessory taxa include *Ahrensisporites cristatus* and *Wilsonites australiensis*. The 2165B Biozone is defined according to: (1) the *Horriditriletes* Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) the *Microbaculispora* Group constitutes usually around 3 to 5% of assemblages but can be absent. *Cycadopites cymbatus*, *Converrucosisporites confluens, C. grandegranulatus, Marsupipollenites* spp. and the *Vittatina* and Taeniate Bisaccate groups appear towards the top of this biozone. *Spelaeotriletes triangulus* is also present. The 2141A Biozone is defined according to: (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. Taxa or groups that occur rarely include *Kingiacolpites subcircularis* and the *Vittatina* Group, *Brevitriletes cornutus*, *Dibolisporites disfacies*, *Verrucosisporites* spp., *Botryococcus*, *Deusilites tentus*, *Tetraporina* spp. and *Tasmanites*. Other distinctive accessory taxa include *Converrucosisporites confluens* and *Vittatina* cf. *scutata*. In the 2141B Biozone, the *Microbaculispora* Group (mainly *M. tentula*) become very common (10-60% of assemblages), and *Cycadopites cymbatus* is also common (5-10% of assemblages). In addition, the Cingulicamerate Group is very rare or absent. Accessory taxa include *Converrucosisporites confluens* and *Vittatina* cf. *scutata*.

3. Yemen; Akbarah and Kuhlan formations

The Pennsylvanian glacigene sediments of Yemen are represented by the Akbarah and overlying Kuhlan formations (Stephenson and Al-Mashaikie, 2010; 2011). The type section of the Kuhlan Formation is close to the village of Kuhlan, northwest Yemen, about 70 km northwest of Sana'a city, and is there underlain by the Akbarah Formation (Fig. 2). The Kuhlan Formation consists of yellowish-brown, pinkish and red, massive, cross-bedded, medium to fine-grained sandstone units, which are interbedded with thick, fissile and stratified siltstone/shale beds of grey to red colour (Kruck and Thiele, 1983; Al-Mashaikie 2005). The Akbarah Formation at Kuhlan is in two parts (Stephenson and Al-Mashaikie, 2011). The lower part is composed of thick sandstone beds fining upwards to siltstone and thick fissile shale. These units are interbedded with massive and stratified diamictite beds. Dropstones are embedded within the sandstone and the shale beds, and their size decreases upward illustrating increasingly distal conditions. This part is broadly interpreted to be of glacial origin. The upper part is composed of several cycles beginning with beds of thin, fine-grained sandstone fining upwards to thick fissile shale beds, interpreted to be of marine origin (Stephenson and Al-Mashaikie, 2011). Eleven samples from the Yemen Kuhlan Formation, and 22 samples from the underlying Akbarah Formation from 180m of the Kuhlan section were analysed by Stephenson and Al-Mashaikie (2011). The Kuhlan Formation assemblages contain common indeterminate monosaccate pollen, *Cristatisporites* spp., *Cannanoropollis janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp. Other taxa include *Brevitriletes cornutus*, *B. parmatus*, *Dibolisporites disfacies*, *Horriditriletes uruguaiensis*, *H. ramosus*, *Lundbladispora braziliensis*, *Microbaculispora tentula*, *Spelaeotriletes triangulus*, *Vallatisporites arcuatus* and *Verrucosisporites andersonii*. Rarer taxa include *Ahrensisporites cristatus*, *Anapiculatisporites concinnus* and *Wilsonites australiensis.* The ranges and quantitative character of selected taxa are shown in Fig. 3 and selected taxa are illustrated in Fig. 4. The Akbarah Formation assemblages are broadly similar (Stephenson and Al-Mashaikie, 2011) in being dominated by indeterminate monosaccate pollen, *Cristatisporites* spp., *Cannanoropollis janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp.

though monosaccate pollen, *Microbaculispora tentula*, and *Critstatisporites* spp. are more common in the Kuhlan Formation.

4. Pakistan; Tobra Formation

The Pennsylvanian to Cisuralian succession of the Salt Range, Pakistan consists of the Tobra and Dandot formations (Jan and Stephenson, 2011). The Tobra Formation, consisting of boulder beds and conglomerates, was long known as the Talchir boulder beds (e.g. Noetling, 1901) because of its similarity to beds of that name in peninsular India. However the unit was designated the Tobra Formation by Kummel and Teichert in 1970 and correlated with the Talchir Stage of India. Its type locality is near Tobra Village in the eastern Salt Range, where its thickness is 20 m (Shah, 1977). The Tobra Formation was interpreted as glaciogenic by Wynne (1878, 1886) and Koken (1907). At the Zaluch Nala gorge (Fig. 2) in the western Salt Range, Teichert (1967) reported the thickness of the Tobra Formation to be 122 m and divided the formation into three members, A, B and C, all of diamictite facies type. In Zaluch Nala and in the Khisor Range to the west, the Tobra Formation is unconformably overlain by the Warchha Formation, a medium- to coarse-grained, purple, arkosic sandstone interpreted as an arid climate deposit (Ghazi and Mountney, 2009). In the eastern Salt Range, the Tobra Formation, for example at the Choa Road section near Khewra, is however conformably overlain by the Dandot Formation (Fig. 2; Shah, 1977). The Dandot Formation consists of pale grey to olive-green sandstone with scattered pebbles up to 10 cm in diameter, or pebbly beds with subordinate dark grey and greenish splintery shales (Shah, 1977), as well as *Eurydesma* and *Conularia* (Pascoe, 1959; Jan and Stephenson, 2011).

The palynomorph assemblages of the Tobra Formation at Zaluch Nala, studied by Jan and Stephenson (2011) can be divided into two. The lower assemblages between 84 and 73 m (5 samples), are dominated by the *Punctatisporites* Group of Penney et al. (2008; Table 1) constituting an average 20% of the assemblages. Cingulicamerate spores (Penney et al. 2008) represent 18% of the assemblages (*Cristatisporites crassilabratus, Cristatisporites* spp., *Lundbladispora braziliensis*, *Vallatisporites arcuatus* and *Vallatisporites* spp.). Indeterminate spores also make up 18% of the lower assemblages. The monosaccate pollen *Cannanoropollis janakii*, *Plicatipollenites malabarensis*, *Potonieisporites novicus* and *Potonieisporites* spp. make up 6% of these lower assemblages. The *Horriditriletes* Group (*Horriditriletes tereteangulatus*, *Horriditriletes ramosus* and *Horriditriletes uruguaiensis*) and the *Microbaculispora* Group (mostly *Microbaculispora tentula*) make up 1% each. The upper assemblages between 47 and 4 m (24 samples), are dominated by the *Punctatisporites* Group which makes up on average 17% of the assemblages, followed by the cingulicamerate spores, which represent 13% on average. The *Horriditriletes* Group makes up 11% of the upper assemblages and the *Microbaculispora* Group (*Microbaculispora tentula* and *Converrucosisporites grandegranulatus*) represents 4%. *Brevitriletes cornutus*, *Brevitriletes parmatus* and *Brevitriletes leptoacaina* are generally rare. Radially- and bilaterally-symmetrical monosaccate pollen are represented by poorly-preserved common *Barakarites* cf. *rotatus* and *Plicatipollenites malabarensis*. *Cannanoropollis janakii* is also present. Taeniate and non-taeniate bisaccate pollen are represented by *Hamiapollenites* spp., *Limitisporites rectus*, *Protohaploxypinus* cf. *hartii* and *Striatopodocarpites* spp. The ranges and quantitative character of selected taxa are shown in Fig. 5 and selected taxa are illustrated in Fig. 4.

The Tobra Formation is exposed beneath the Dandot Formation at the Choa Road section near Khewra in the eastern Salt Range (Fig. 2 (g); GPS N 32 39 57, E 72 59 08.8). At this locality, the Tobra Formation is approximately 9m thick and consists, at the base, of clast– and matrix–supported conglomerate; and towards the top of mudstones which contain occasional dropstones. Two palynological samples were collected from the matrix of the conglomerate and one from the upper mudstone. The palynomorph assemblages of three samples contain common *Alisporites indarraensis*, *Cycadopites cymbatus*, *Horriditriletes* spp., and *Microbaculispora tentula*, as well as rare *Brevitriletes cornutus*, *Converrucosisporites confluens*, *Microbaculispora grandegranulata*, *Verrucosisporites andersonii*, and *Vittatina* cf. *scutata* (Figs. 6, 7).

5. Correlation and conclusions

Palynological assemblages from sections in Yemen and Pakistan are similar enough to allow the application of biozones based in the Carboniferous-Permian glacigene sediments of interior Oman (Fig. 8). The commonness of the *Horriditriletes* Group (see text-figure 3 of Penney et al., 2008) suggests that the upper assemblages of Zaluch Nala (Pakistan) correspond to the 2165B Biozone of south Oman, probably below the stratigraphical level where *Converrucosisporites confluens* appears first; the lower assemblages are tentatively correlated with 2165A Biozone (for details see Jan and Stephenson, 2011). The 2165 A and B biozones correspond to the Al Khlata AK P5 Production Unit of Petroleum Development Oman (Penney et al., 2008).

In the Yemen Akbarah and Kuhlan formations, the presence of common cingulicamerate spores (e.g. *Cristatisporites* spp.) and monosaccate pollen, and the presence of *Brevitriletes cornutus*, *B. parmatus, Deusilites tentus, Dibolisporites disfacies*, *Microbaculispora tentula* and *Verrucosisporites andersonii*, as well as the presence of *Anapiculatisporites concinnus* and *Spelaeotriletes triangulus* suggest a range within the 2165A to 2141A biozones (Fig. 8). However the presence of *Ahrensisporites cristatus* and *Wilsonites australiensis* indicates that the section is most likely of 2165A age.

This correlation (Fig. 8) indicates the widespread nature of glacial sediments of a narrow biostratigraphic age range (the Oman AK P5 Production Unit) in basins across part of the north Gondwana margin. Unpublished work by Jan (2011) in other parts of the Salt and Khisor ranges in Pakistan, although not fully representing the full extent of Upper Carboniferous stratigraphy, do not show the presence of the oldest Oman AK P1 Production Unit of 2159 Biozone age. Similarly, the Akbarah Formation at Kuhlan in Yemen rests on metamorphosed basement. It is interesting to speculate on the apparent absence of the oldest Oman P1 Production Unit in these parts of Yemen and Pakistan. This may relate to the fact that salt withdrawal and dissolution was more common in south Oman (Heward, 1990), creating the accommodation space for these earliest of Arabian Carboniferous glacial sediments.

The Tobra Formation in Zaluch Nala, Pakistan lacks the deglaciation sequence of 2141 A and 2141B Biozone age that is common in Oman (see for example Stephenson et al., 2007). This is an indication of either non-deposition during the deglaciation period, or erosion associated with the unconformity between the Tobra Formation and the overlying red bed Warchha Formation (Jan and Stephenson, 2011). However the three samples from the Tobra Formation at the Choa Road section in the eastern Salt Range are assignable to the 2141B Biozone of Penney et al. (2008). In Oman, the 2141B Biozone is closely associated with the Rahab Shale Member, a widespread shale facies in South Oman which is considered to represent the final Permian deglaciation in the form of a large melt-out lake (Stephenson et al. 2005; Fig. 8). It is interesting to speculate whether the 'Tobra shale' correlates with the Rahab Shale Member.

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References

Al-Belushi, J.D., Glennie, K.W., Williams, B.P.J., 1996. Permo-Carboniferous Glaciogenic Al Khlata Formation, Oman: a new hypothesis for origin of its glaciation. GeoArabia 1, 389-404.

Al-Mashaikie, S.Z.A.K., 2005. Lithofacies and petrography of siliciclastic red bed sequences: a new lithostratigraphic concept of the early Mesozoic Kuhlan Formation (NW Yemen). Freiberger Forschungshefte, C507: Palaontologie, Stratigraphie, Fazies 13, 27-47.

Angiolini, L., Balini, M., Garzanti, E., Nicora, A., Tintori, A., 2003. Gondwanan deglaciation and opening of Neotethys: the Al Khlata and Saiwan formations of interior Oman. Palaeogeography, Palaeoclimatology, Palaeoecology 196, 99-123.

Angiolini, L., Gaetani, M., Muttoni, G., Stephenson, M. H., Zanchi, A., 2007. Tethyan oceanic currents and climate gradients 300 m.y. ago. Geology 35, 1071–1074.

Besems, R.E., 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., Van Vliet, A., 1982. Late Palaeozoic Gondwana glaciation in Oman. Nature 299, 48-50.

Ghazi, S., Mountney, N.P., 2009. Facies and architectural elements of a meandering fluvial succession: The Permian Warchha Sandstone, Salt Range, Pakistan. Sedimentary Geology, 221, 99-126.

Heward, A., 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.H., 1988. Stratigraphy and rock unit nomenclature in the oil-producing area of Interior Oman. Journal of Petroleum Geology 11, 5-60.

Jan, I.U., Stephenson, M.H., 2011. Palynology and correlation of the Upper Pennsylvanian Tobra Formation from Zaluch Nala, Salt Range, Pakistan. Palynology 35, 212–225

Jan, I.U. 2011. Unpublished PhD thesis, University of Leicester, UK.

Koken, E., 1907. Indisches Perm und permische Eiszeit. Neues Jahrbuch für Geologie und Paläontologie, Festband, 446-546.

Kruck, W., Thiele, J., 1983. Late Palaeozoic glacial deposits in the Yemen Arab Republic. Geologisches Jahrbuch, Reihe B 46, 3–29.

Kummel, B., Teichert, C., 1970. Stratigraphy and Paleontology of the Permian-Triassic Boundary Beds, Salt Range and Trans-Indus Ranges, West Pakistan. In: Kummel, B., Teichert, C., (Eds.), Stratigraphic Boundary Problems: Permian and Triassic of West Pakistan. University Press of Kansas, Department of Geology Special Publication 4, 2-110.

Levell, B.K., Braakman, J.H., Rutten, K.W., 1988. Oil-bearing sediments of Gondwana glaciation in Oman. AAPG Bulletin 72, 775-796.

Love, C.F., 1994. The palynostratigraphy of the Haushi Group (Westphalian-Artinskian) in Oman. In: Simmons M.D (Ed.), Micropalaeontology and Hydrocarbon Exploration in the Middle East. Chapman and Hall, 23-39.

Noetling, F., 1901. Beiträge zur Geologie der Salt Range, insbesondere der permischen und triassischen Ablagerungen. Neues Jahrbuch für Mineralogie, Geologie und Paläontologie 14, 369-471.

Osterloff, P., Al-Harthy, A., Penney, R., Spaak, P., Williams, G., Al-Zadjali, F., Jones, N., Knox, R., Stephenson, M.H., Oliver, G., Al-Husseini, M.I., 2004. Depositional sequence of the Gharif and Khuff formations, subsurface Interior Oman. In: Al-Husseini M.I. (Ed.), Carboniferous, Permian and Early Triassic Arabian Stratigraphy. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, 83-147.

Pascoe, E.H., 1959. A manual of the geology of India and Burma. India Government Press Calcutta. II 484-1338.

Penney, R.A., Al Barram, I., Stephenson, M.H., 2008. A high resolution palynozonation for the Al Khlata Formation (Pennsylvanian to Lower Permian), South Oman. Palynology 32, 213-231.

Shah, S.M.I., 1977. Stratigraphy of Pakistan. *Geological Survey of Pakistan Memoir* 12, 26.

Stephenson, M.H., Filatoff, J., 2000. Correlation of Carboniferous-Permian palynological assemblages from Oman and Saudi Arabia. In: Al-Hajri, S. & Owens, B. (eds.) Stratigraphic palynology of the Palaeozoic of Saudi Arabia, Gulf Petrolink, Bahrain GeoArabia Special Publication No. 1, 168-191.

Stephenson, M.H., 2004. Early Permian Spores from Oman and Saudi Arabia. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 185-215.

Stephenson, M.H., 2008. A review of the palynostratigraphy of Gondwanan Late Carboniferous to Early Permian glacigene successions. In: C.R. Fielding, T.D. Frank and J.L. Isbell (Eds.), Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper 441, 317-330.

Stephenson, M.H., 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 no. 40, p. 1-41.

Stephenson, M.H., Al-Mashaikie, S.Z.A.K., 2010. New age for the lower part of the Kuhlan Formation, northwest Yemen. GeoArabia 15, 161-170.

Stephenson, M.H., Al-Mashaikie, S.Z.A.K., 2011. Stratigraphic Note: Update on the palynology of the Akbarah and Kuhlan formations, northwest Yemen. GeoArabia 16, 17-24.

Stephenson, M.H., Al Rawahi, A., Casey, B. 2008. Correlation of the Al Khlata Formation in the Mukhaizna field, Oman, based on a new downhole, cuttings-based palynostratigraphic biozonation. GeoArabia 13, 15-34.

Stephenson, M.H., Angiolini, L., Leng, M.J., 2007. The Early Permian fossil record of Gondwana and its relationship to deglaciation: a review. In: Williams, M., Heywood, A.M., Gregory, F.J., Schmidt, D.N., (Eds.). Deep-Time perspective on Climate Change: Marrying the signal from Computer Models and Biological Proxies. The Micropalaeontological Society, Special Publications. The Geological Society, London, 169-189.

Stephenson, M.H., Leng, M.J., Vane, C.H., Osterloff, P.L., Arrowsmith, C., 2005. Investigating the record of Permian climate change from argillaceous sediments, Oman. Journal of the Geological Society, London 162, 641–651.

Stephenson, M.H., Osterloff, P.L., Filatoff, J., 2003. Palynological biozonation of the Permian of Oman and Saudi Arabia: Progress and challenges. GeoArabia 8, 467-496.

Teichert, C., 1967. Nature of the Permian glacial record, Salt Range and Khisor Range, West Pakistan. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 129, 167-184.

Torsvik, T.H., Van der Voo, R., 2002. Refining Gondwana and Pangea palaeogeography: estimates of Phanerozoic non-dipole (octupole) fields. Geophysical Journal International 151, 771–794.

Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Chapter 3. Palynological techniques - Processing and microscopy. In: J. Jansonius and D.C McGregor (Eds.), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists Foundation 1, p. 29-50.

Wynne, A.B., 1878. On the geology of the Salt Range in Punjab. Geological Survey of India Memoir 14, 1-313.

Wynne, A.B., 1886. On a facetted and striated pebbles from the Olive group conglomerate of Cliel Hill in the Salt Range of the Punjab, India. Geological Magazine 3, 492-494.

Figure Captions

Figure 1. Locations of studied sections on reconstruction of Gondwana after Angiolini et al. (2007). 1, Yemen; 2, Interior Oman; 3, Salt Range, Pakistan. For details of locations of studied sections on modern maps see Stephenson et al. (2005) for Oman, Jan and Stephenson (2011) for Pakistan, and Stephenson and Al-Mashaikie (2011) for Yemen. The Choa Road section near Khewra in the eastern Salt Range is at GPS N 32 39 57, E 72 59 08.8.

Figure 2. a) The Al Khlata Formation in Wadi Al Khlata, Oman showing diamictite overlying the striated surface of the Khufai Formation; b) Al Khlata Formation diamictite in Wadi Al Khlata; c) view of the Kuhlan and Akbarah formations at the type section of the Kuhlan Formation, Yemen; d) contact between Akbarah (lower) and Kuhlan (upper) formations; e) contact between the Tobra and Warchha formations, Khisor Range, Pakistan; f) view of the Tobra and Wargal formations, Zaluch Nala, western Salt Range, Pakistan; g) the Choa Road section near Khewra, eastern Salt Range, Pakistan; h) diamictite facies in the Tobra Formation of the Choa Road section.

Figure 3. Distribution of selected palynomorph groups and taxa from the Yemen Kuhlan and Akbarah formations, Kuhlan, northwest Yemen. For details of section and lithology, see Stephenson and Al-Mashaikie (2011). Blue squares indicate barren samples.

Figure 4. Selected palynomorphs from the Kuhlan and Akbarah formations, and the Tobra Formation, Zaluch Nala. Scale bars for each specimen. MPA and MPK numbers are British Geological Survey Collection codes. a) *Converrucosisporites grandegranulatus*, MPA 57518, S17/1, MPK 13908, Tobra Formation; b) *Microbaculispora tentula*, MPA 57511, T26, MPK 13913, Tobra Formation; c) *Vallatisporites arcuatus*, R44/2, MPA 60511, MPK 14195, Kuhlan Formation; d) *Spelaeotriletes triangulus*, K61, MPA 60507, MPK 14199, Kuhlan Formation ; e) *Anapiculatisporites concinnus*, D40/1, MPA 58568, MPK 14205, Akbarah Formation; f) *Brevitriletes leptoacaina*, T11/4, MPA 57512, MPK 13916, Tobra Formation; g) *Horriditriletes ramosus*, H11, MPA 57520, MPK 13921, Tobra Formation; h) *Cannanoropollis janakii*, D40/2, MPA 60513, MPK 14192, Kuhlan Formation; i) *Cannanoropollis janakii*, G66, MPA 60511, MPK 14196, Kuhlan Formation.

Figure 5. Distribution of selected palynomorph groups and taxa from the Tobra Formation, Zaluch Nala, Pakistan. For details of section and lithology, see Jan and Stephenson (2011). Blue squares indicate barren samples.

Figure 6. Selected palynomorph groups and taxa from the Tobra Formation, Choa Road section, near Khewra, Pakistan.

Figure 7. Selected palynomorphs from the Tobra Formation, Choa Road section. Scale bar shown in (a). MPA and MPK numbers are British Geological Survey Collection codes. a) *Microbaculispora tentula*, B55, MPA 58401, MPK 14358; b) *Lophotriletes sparsus*, F58/3, MPA 58401, MPK 14359; c) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK 14360, proximal focus; d) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK 14360, distal focus; e) *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, proximal focus; f) *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, distal focus; g) *Converrucosisporites* cf. *confluens*, M64, MPA 58403, MPK 14362. h) *Alisporites indarraensis*, E44/2, MPA 58401, MPK 14363; i) *Alisporites indarraensis*, G42/4, MPA 58402, MPK 14364; j) *Hamiapollenites fusiformis*, C53/3, MPA 58401, MPK 14365; k) *Striatopodocarpites cancellatus*, Q60/2, MPA 58401, MPK 14366; l) *Protohaploxypinus limpidus*, U49, MPA 58401, MPK 14367; m) *Cycadopites cymbatus*, T58/2, MPA 58403, MPK 14368; n) *Cycadopites cymbatus*, C52/3, MPA 58401, MPK 14369.

Figure 8. Correlation of Oman, Yemen and Pakistan sections. ‘PDO production units’ are lithological subdivisions of the Al Khlata Formation similar to lithostratigraphic members (see Penney et al. 2008 for more detail).

Table 1. Main characteristics of the biozones of Penney et al. (2008).

Palynology and correlation of Carboniferous - Permian glacigene rocks in Oman, Yemen and Pakistan

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Abstract

Palynological assemblages from sections in Yemen and Pakistan are similar enough to allow the application of biozones based on the Pennsylvanian glacigene sediments of interior Oman. Thirty four samples from the upper 84 m of a 125 m thick section of the Tobra Formation at Zaluch Nala, western Salt Range, Pakistan yielded palynomorph taxa including *Microbaculispora tentula*, abundant monosaccate pollen including *Cannanoropollis janakii* and *Plicatipollenites malabarensis*, *Converrucosisporites grandegranulatus*, *Horriditriletes ramosus* and *Horriditriletes tereteangulatus* indicating the late Pennsylvanian Oman 2165B Biozone. Eleven samples from the Yemen Kuhlan Formation, and 22 samples from the underlying Akbarah Formation from approximately 300m of a section near Kuhlan in northwest Yemen, suggest a 2165A Biozone age (also late Pennsylvanian). This correlation

indicates the widespread nature of glacial sediments of a narrow biostratigraphic late Pennsylvanian age range (the Oman P5 unit) in basins across part of the north Gondwana margin. New data from three samples from the Tobra Formation at the Choa Road section near Khewra in the eastern Salt Range, Pakistan are assignable to the earliest Permian 2141B Biozone, indicating a possible correlation between the 'Tobra shale' and the Rahab Shale Member of Oman, which is considered to mark the final deglaciation sequence in Oman.

Keywords: palynology, Gondwana, Yemen, Oman, Pakistan

1. Introduction

The Pennsylvanian to Cisuralian non-marine, cold-climate sediments of the Gondwana continent are notoriously difficult to correlate both within the continent and with the standard stages (Stephenson et al., 2007; Stephenson 2008). This is because the rocks do not contain the key zonal fossils which are marine (e.g., foraminifera, corals and most importantly conodonts). Thus historically, correlation has relied mainly on palynology. However palynological correlation across Gondwana is difficult, due mainly to disparate stratigraphic and taxonomic methods and different standards of documentation of palynological data used in areas of Gondwana (Stephenson, 2008). Also cold climate palynological assemblages are difficult to compare with those of the palaeoequator which is where the standard stages are based.

Stephenson (2008) assessed palynostratigraphic schemes in the main Gondwana basins and focused on precise basin-to-basin or region-to-region correlations underpinned by careful taxonomy and stratigraphy, giving examples of Arabian to Australian correlation and Australian to South African correlation. He concluded that consolidation of basin-to-basin correlations will probably lead to the most reliable Gondwana–wide correlations. The objective of this study was to test the applicability of a newly-published Oman biozonation across basins in Yemen and Pakistan, to correlate using the biozonation, and thereby understand the age-distribution of glacigene rocks in the three areas (Fig. 1).

The palynology samples described in the paper were prepared by crushing, followed by hydrochloric and hydrofluoric acid treatments (Wood et al., 1996). The post-hydrofluoric acid organic residues were oxidized using Schulze's solution and dilute nitric acid. The slides from Yemen and Pakistan are held in the Collection of the British Geological Survey, Keyworth, Nottingham, UK, NG12 5GG. For details of locations of studied sections see Stephenson et al. (2005) for Oman, Jan and Stephenson (2011) for Pakistan, and Stephenson and Al-Mashaikie (2011) for Yemen. The Choa Road section near Khewra in the eastern Salt Range is at GPS N 32 39 57, E 72 59 08.8.

2. The Oman sequence and the Al Khlata Formation biozonation

Pennsylvanian to Cisuralian rocks of the Al Khlata Formation crop out at the Haushi-Huqf outcrop area in Oman but are present widely in the subsurface, where they form important hydrocarbon reservoirs (Hughes Clarke, 1988). The Al Khlata Formation ranges from conglomerates through diamictites, gravels, pebbly sandstones, siltstones to silty shales (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; 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 on the Precambrian Khufai Formation have been found (Fig. 2; Braakman et al., 1982; Al-Belushi et al., 1996). The type section of the Al Khlata Formation is located at Wadi Al Khlata near the Haushi-Huqf Uplift (57°25'46"E, 19°46'43"N) where it is about 100 m thick (Levell et al., 1988) and there is a subsurface reference section 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). 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). 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). During its deposition, the Cambrian Ara salt in the South Oman Salt Basin moved diapirically to form salt domes. As a result, thick Al Khlata Formation 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 (for details of locations see Penney et al., 2008; Heward, 1990; Osterloff et al., 2004). These long periods of subsidence have lead to the most complete record of Pennsylvanian to Cisuralian glaciations in Arabia and to the most complete palynological record, with the result that the palynological succession of Oman forms the standard with which other less complete successions are correlated. The assemblages have been described in great detail before (e.g. Besems and Schuurman, 1987; Love, 1994; Stephenson and Filatoff, 2000; Stephenson and Osterloff, 2002; Stephenson, 2004; Stephenson et al., 2003; 2005; 2007;) but in general the diversity and yield increases up 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 (Stephenson et al., 2005). The earliest assemblages (e.g. 2159) are characterised by common monosaccate pollen and *Punctatisporites*, while later assemblages are of greater diversity including cingulicamerate and cheilocardioid spores, and colpate and bisaccate pollen (e.g. 2141; see Penney et al., 2008). Biozones were defined in the Al Khlata Formation by Penney et al. (2008) on the basis of quantitative changes in defined palynomorph groups (Table 1) and on the ranges of certain distinctive taxa, for example *Anapiculatisporites concinnus*, *Cycadopites cymbatus*, and *Kingiacolpites subcircularis*. The details of the biozones and how they are applied are given by Penney et al. (2008), however for the reader's convenience a summary of the relevant biozones is given here.

The primary diagnostic criteria of the 2165A Biozone are (1) the Cingulicamerate Group (Table 1) 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. Distinctive accessory taxa include *Ahrensisporites cristatus* and *Wilsonites australiensis*. The 2165B Biozone is defined according to: (1) the *Horriditriletes* Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) the *Microbaculispora* Group constitutes usually around 3 to 5% of assemblages but can be absent. *Cycadopites cymbatus*, *Converrucosisporites confluens*, *C. grandegranulatus*, *Marsupipollenites* spp. and the *Vittatina* and Taeniate Bisaccate groups appear towards the top of this biozone. *Spelaeotriletes triangulus* is also present. The 2141A Biozone is defined according to: (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. Taxa or groups that occur rarely include *Kingiacolpites subcircularis* and the *Vittatina* Group, *Brevitriletes cornutus*, *Dibolisporites disfacies*, *Verrucosisporites* spp., *Botryococcus*, *Deusilites tentus*, *Tetraporina* spp. and *Tasmanites*. Other distinctive accessory taxa include *Converrucosisporites confluens* and *Vittatina* cf. *scutata*. In the 2141B Biozone, the *Microbaculispora* Group (mainly *M. tentula*) become very common (10-60% of assemblages), and *Cycadopites cymbatus* is also common (5-10% of assemblages). In addition, the Cingulicamerate Group is very rare or absent. Accessory taxa include *Converrucosisporites confluens* and *Vittatina* cf. *scutata*.

3. Yemen; Akbarah and Kuhlan formations

The Pennsylvanian glacigene sediments of Yemen are represented by the Akbarah and overlying Kuhlan formations (Stephenson and Al-Mashaikie, 2010; 2011). The type section of the Kuhlan Formation is close to the village of Kuhlan, northwest Yemen, about 70 km northwest of Sana'a city, and is there underlain by the Akbarah Formation (Fig. 2). The Kuhlan Formation consists of yellowish-brown, pinkish and red, massive, cross-bedded, medium to fine-grained sandstone units, which are interbedded with thick, fissile and stratified siltstone/shale beds of grey to red colour (Kruck and Thiele, 1983; Al-Mashaikie 2005). The Akbarah Formation at Kuhlan is in two parts (Stephenson and Al-Mashaikie, 2011). The lower part is composed of thick sandstone beds fining upwards to siltstone and thick fissile shale. These units are interbedded with massive and stratified diamictite beds. Dropstones are embedded within the sandstone and the shale beds, and their size decreases upward illustrating increasingly distal conditions. This part is broadly interpreted to be of glacial origin. The upper part is composed of several cycles beginning with beds of thin, fine-grained sandstone fining upwards to thick fissile shale beds, interpreted to be of marine origin (Stephenson and Al-Mashaikie, 2011). Eleven samples from the Yemen Kuhlan Formation, and 22 samples from the underlying Akbarah Formation from 180m of the Kuhlan section were analysed by Stephenson and Al-Mashaikie (2011). The Kuhlan Formation assemblages contain common indeterminate monosaccate pollen, *Cristatisporites* spp., *Cannanoropollis janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp. Other taxa include *Brevitriletes cornutus*, *B. parmatus*, *Dibolisporites disfacies*, *Horriditriletes uruguaiensis*, *H. ramosus*, *Lundbladispora braziliensis*, *Microbaculispora tentula*, *Spelaeotriletes triangulus*, *Vallatisporites arcuatus* and *Verrucosisporites andersonii*. Rarer taxa include *Ahrensisporites cristatus*, *Anapiculatisporites concinnus* and *Wilsonites australiensis.* The ranges and quantitative character of selected taxa are shown in Fig. 3 and selected taxa are illustrated in Fig. 4. The Akbarah Formation assemblages are broadly similar (Stephenson and Al-Mashaikie, 2011) in being dominated by indeterminate monosaccate pollen, *Cristatisporites* spp., *Cannanoropollis janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp.

though monosaccate pollen, *Microbaculispora tentula*, and *Critstatisporites* spp. are more common in the Kuhlan Formation.

4. Pakistan; Tobra Formation

The Pennsylvanian to Cisuralian succession of the Salt Range, Pakistan consists of the Tobra and Dandot formations (Jan and Stephenson, 2011). The Tobra Formation, consisting of boulder beds and conglomerates, was long known as the Talchir boulder beds (e.g. Noetling, 1901) because of its similarity to beds of that name in peninsular India. However the unit was designated the Tobra Formation by Kummel and Teichert in 1970 and correlated with the Talchir Stage of India. Its type locality is near Tobra Village in the eastern Salt Range, where its thickness is 20 m (Shah, 1977). The Tobra Formation was interpreted as glaciogenic by Wynne (1878, 1886) and Koken (1907). At the Zaluch Nala gorge (Fig. 2) in the western Salt Range, Teichert (1967) reported the thickness of the Tobra Formation to be 122 m and divided the formation into three members, A, B and C, all of diamictite facies type. In Zaluch Nala and in the Khisor Range to the west, the Tobra Formation is unconformably overlain by the Warchha Formation, a medium- to coarse-grained, purple, arkosic sandstone interpreted as an arid climate deposit (Ghazi and Mountney, 2009). In the eastern Salt Range, the Tobra Formation, for example at the Choa Road section near Khewra, is however conformably overlain by the Dandot Formation (Fig. 2; Shah, 1977). The Dandot Formation consists of pale grey to olive-green sandstone with scattered pebbles up to 10 cm in diameter, or pebbly beds with subordinate dark grey and greenish splintery shales (Shah, 1977), as well as *Eurydesma* and *Conularia* (Pascoe, 1959; Jan and Stephenson, 2011).

The palynomorph assemblages of the Tobra Formation at Zaluch Nala, studied by Jan and Stephenson (2011) can be divided into two. The lower assemblages between 84 and 73 m (5 samples), are dominated by the *Punctatisporites* Group of Penney et al. (2008; Table 1) constituting an average 20% of the assemblages. Cingulicamerate spores (Penney et al. 2008) represent 18% of the assemblages (*Cristatisporites crassilabratus, Cristatisporites* spp., *Lundbladispora braziliensis*, *Vallatisporites arcuatus* and *Vallatisporites* spp.). Indeterminate spores also make up 18% of the lower assemblages. The monosaccate pollen *Cannanoropollis janakii*, *Plicatipollenites malabarensis, Potonieisporites novicus* and *Potonieisporites* spp. make up 6% of these lower assemblages. The *Horriditriletes* Group (*Horriditriletes tereteangulatus*, *Horriditriletes ramosus* and *Horriditriletes uruguaiensis*) and the *Microbaculispora* Group (mostly *Microbaculispora tentula*) make up 1% each. The upper assemblages between 47 and 4 m (24 samples), are dominated by the *Punctatisporites* Group which makes up on average 17% of the assemblages, followed by the cingulicamerate spores, which represent 13% on average. The *Horriditriletes* Group makes up 11% of the upper assemblages and the *Microbaculispora* Group (*Microbaculispora tentula* and *Converrucosisporites grandegranulatus*) represents 4%. *Brevitriletes cornutus, Brevitriletes parmatus* and *Brevitriletes leptoacaina* are generally rare. Radially- and bilaterally-symmetrical monosaccate pollen are represented by poorly-preserved common *Barakarites* cf. *rotatus* and *Plicatipollenites malabarensis*. *Cannanoropollis janakii* is also present. Taeniate and non-taeniate bisaccate pollen are represented by *Hamiapollenites* spp., *Limitisporites rectus*, *Protohaploxypinus* cf. *hartii* and *Striatopodocarpites* spp. The ranges and quantitative character of selected taxa are shown in Fig. 5 and selected taxa are illustrated in Fig. 4.

The Tobra Formation is exposed beneath the Dandot Formation at the Choa Road section near Khewra in the eastern Salt Range (Fig. 2 (g); GPS N 32 39 57, E 72 59 08.8). At this locality, the Tobra Formation is approximately 9m thick and consists, at the base, of clast– and matrix–supported conglomerate; and towards the top of mudstones which contain occasional dropstones. Two palynological samples were collected from the matrix of the conglomerate and one from the upper mudstone. The palynomorph assemblages of three samples contain common *Alisporites indarraensis*, *Cycadopites cymbatus*, *Horriditriletes* spp., and *Microbaculispora tentula*, as well as rare *Brevitriletes cornutus*, *Converrucosisporites confluens*, *Microbaculispora grandegranulata*, *Verrucosisporites andersonii*, and *Vittatina* cf. *scutata* (Figs. 6, 7).

5. Correlation and conclusions

Palynological assemblages from sections in Yemen and Pakistan are similar enough to allow the application of biozones based in the Carboniferous-Permian glacigene sediments of interior Oman (Fig. 8). The commonness of the *Horriditriletes* Group (see text-figure 3 of Penney et al., 2008) suggests that the upper assemblages of Zaluch Nala (Pakistan) correspond to the 2165B Biozone of south Oman, probably below the stratigraphical level where *Converrucosisporites confluens* appears first; the lower assemblages are tentatively correlated with 2165A Biozone (for details see Jan and Stephenson, 2011). The 2165 A and B biozones correspond to the Al Khlata AK P5 Production Unit of Petroleum Development Oman (Penney et al., 2008).

In the Yemen Akbarah and Kuhlan formations, the presence of common cingulicamerate spores (e.g. *Cristatisporites* spp.) and monosaccate pollen, and the presence of *Brevitriletes cornutus*, *B. parmatus, Deusilites tentus, Dibolisporites disfacies*, *Microbaculispora tentula* and *Verrucosisporites andersonii*, as well as the presence of *Anapiculatisporites concinnus* and *Spelaeotriletes triangulus* suggest a range within the 2165A to 2141A biozones (Fig. 8). However the presence of *Ahrensisporites cristatus* and *Wilsonites australiensis* indicates that the section is most likely of 2165A age.

This correlation (Fig. 8) indicates the widespread nature of glacial sediments of a narrow biostratigraphic age range (the Oman AK P5 Production Unit) in basins across part of the north Gondwana margin. Unpublished work by Jan (2011) in other parts of the Salt and Khisor ranges in Pakistan, although not fully representing the full extent of Upper Carboniferous stratigraphy, do not show the presence of the oldest Oman AK P1 Production Unit of 2159 Biozone age. Similarly, the Akbarah Formation at Kuhlan in Yemen rests on metamorphosed basement. It is interesting to speculate on the apparent absence of the oldest Oman P1 Production Unit in these parts of Yemen and Pakistan. This may relate to the fact that salt withdrawal and dissolution was more common in south Oman (Heward, 1990), creating the accommodation space for these earliest of Arabian Carboniferous glacial sediments.

The Tobra Formation in Zaluch Nala, Pakistan lacks the deglaciation sequence of 2141 A and 2141B Biozone age that is common in Oman (see for example Stephenson et al., 2007). This is an indication of either non-deposition during the deglaciation period, or erosion associated with the unconformity between the Tobra Formation and the overlying red bed Warchha Formation (Jan and Stephenson, 2011). However the three samples from the Tobra Formation at the Choa Road section in the eastern Salt Range are assignable to the 2141B Biozone of Penney et al. (2008). In Oman, the 2141B Biozone is closely associated with the Rahab Shale Member, a widespread shale facies in South Oman which is considered to represent the final Permian deglaciation in the form of a large melt-out lake (Stephenson et al. 2005; Fig. 8). It is interesting to speculate whether the 'Tobra shale' correlates with the Rahab Shale Member.

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References

Al-Belushi, J.D., Glennie, K.W., Williams, B.P.J., 1996. Permo-Carboniferous Glaciogenic Al Khlata Formation, Oman: a new hypothesis for origin of its glaciation. GeoArabia 1, 389-404.

Al-Mashaikie, S.Z.A.K., 2005. Lithofacies and petrography of siliciclastic red bed sequences: a new lithostratigraphic concept of the early Mesozoic Kuhlan Formation (NW Yemen). Freiberger Forschungshefte, C507: Palaontologie, Stratigraphie, Fazies 13, 27-47.

Angiolini, L., Balini, M., Garzanti, E., Nicora, A., Tintori, A., 2003. Gondwanan deglaciation and opening of Neotethys: the Al Khlata and Saiwan formations of interior Oman. Palaeogeography, Palaeoclimatology, Palaeoecology 196, 99-123.

Angiolini, L., Gaetani, M., Muttoni, G., Stephenson, M. H., Zanchi, A., 2007. Tethyan oceanic currents and climate gradients 300 m.y. ago. Geology 35, 1071–1074.

Besems, R.E., 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., Van Vliet, A., 1982. Late Palaeozoic Gondwana glaciation in Oman. Nature 299, 48-50.

Ghazi, S., Mountney, N.P., 2009. Facies and architectural elements of a meandering fluvial succession: The Permian Warchha Sandstone, Salt Range, Pakistan. Sedimentary Geology, 221, 99-126.

Heward, A., 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.H., 1988. Stratigraphy and rock unit nomenclature in the oil-producing area of Interior Oman. Journal of Petroleum Geology 11, 5-60.

Jan, I.U., Stephenson, M.H., 2011. Palynology and correlation of the Upper Pennsylvanian Tobra Formation from Zaluch Nala, Salt Range, Pakistan. Palynology 35, 212–225

Jan, I.U. 2011. Unpublished PhD thesis, University of Leicester, UK.

Koken, E., 1907. Indisches Perm und permische Eiszeit. Neues Jahrbuch für Geologie und Paläontologie, Festband, 446-546.

Kruck, W., Thiele, J., 1983. Late Palaeozoic glacial deposits in the Yemen Arab Republic. Geologisches Jahrbuch, Reihe B 46, 3–29.

Kummel, B., Teichert, C., 1970. Stratigraphy and Paleontology of the Permian-Triassic Boundary Beds, Salt Range and Trans-Indus Ranges, West Pakistan. In: Kummel, B., Teichert, C., (Eds.), Stratigraphic Boundary Problems: Permian and Triassic of West Pakistan. University Press of Kansas, Department of Geology Special Publication 4, 2-110.

Levell, B.K., Braakman, J.H., Rutten, K.W., 1988. Oil-bearing sediments of Gondwana glaciation in Oman. AAPG Bulletin 72, 775-796.

Love, C.F., 1994. The palynostratigraphy of the Haushi Group (Westphalian-Artinskian) in Oman. In: Simmons M.D (Ed.), Micropalaeontology and Hydrocarbon Exploration in the Middle East. Chapman and Hall, 23-39.

Noetling, F., 1901. Beiträge zur Geologie der Salt Range, insbesondere der permischen und triassischen Ablagerungen. Neues Jahrbuch für Mineralogie, Geologie und Paläontologie 14, 369-471.

Osterloff, P., Al-Harthy, A., Penney, R., Spaak, P., Williams, G., Al-Zadjali, F., Jones, N., Knox, R., Stephenson, M.H., Oliver, G., Al-Husseini, M.I., 2004. Depositional sequence of the Gharif and Khuff formations, subsurface Interior Oman. In: Al-Husseini M.I. (Ed.), Carboniferous, Permian and Early Triassic Arabian Stratigraphy. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, 83-147.

Pascoe, E.H., 1959. A manual of the geology of India and Burma. India Government Press Calcutta. II 484-1338.

Penney, R.A., Al Barram, I., Stephenson, M.H., 2008. A high resolution palynozonation for the Al Khlata Formation (Pennsylvanian to Lower Permian), South Oman. Palynology 32, 213-231.

Shah, S.M.I., 1977. Stratigraphy of Pakistan. *Geological Survey of Pakistan Memoir* 12, 26.

Stephenson, M.H., Filatoff, J., 2000. Correlation of Carboniferous-Permian palynological assemblages from Oman and Saudi Arabia. In: Al-Hajri, S. & Owens, B. (eds.) Stratigraphic palynology of the Palaeozoic of Saudi Arabia, Gulf Petrolink, Bahrain GeoArabia Special Publication No. 1, 168-191.

Stephenson, M.H., 2004. Early Permian Spores from Oman and Saudi Arabia. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 185-215.

Stephenson, M.H., 2008. A review of the palynostratigraphy of Gondwanan Late Carboniferous to Early Permian glacigene successions. In: C.R. Fielding, T.D. Frank and J.L. Isbell (Eds.), Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper 441, 317-330.

Stephenson, M.H., 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 no. 40, p. 1-41.

Stephenson, M.H., Al-Mashaikie, S.Z.A.K., 2010. New age for the lower part of the Kuhlan Formation, northwest Yemen. GeoArabia 15, 161-170.

Stephenson, M.H., Al-Mashaikie, S.Z.A.K., 2011. Stratigraphic Note: Update on the palynology of the Akbarah and Kuhlan formations, northwest Yemen. GeoArabia 16, 17-24.

Stephenson, M.H., Al Rawahi, A., Casey, B. 2008. Correlation of the Al Khlata Formation in the Mukhaizna field, Oman, based on a new downhole, cuttings-based palynostratigraphic biozonation. GeoArabia 13, 15-34.

Stephenson, M.H., Angiolini, L., Leng, M.J., 2007. The Early Permian fossil record of Gondwana and its relationship to deglaciation: a review. In: Williams, M., Heywood, A.M., Gregory, F.J., Schmidt, D.N., (Eds.). Deep-Time perspective on Climate Change: Marrying the signal from Computer Models and Biological Proxies. The Micropalaeontological Society, Special Publications. The Geological Society, London, 169-189.

Stephenson, M.H., Leng, M.J., Vane, C.H., Osterloff, P.L., Arrowsmith, C., 2005. Investigating the record of Permian climate change from argillaceous sediments, Oman. Journal of the Geological Society, London 162, 641–651.

Stephenson, M.H., Osterloff, P.L., Filatoff, J., 2003. Palynological biozonation of the Permian of Oman and Saudi Arabia: Progress and challenges. GeoArabia 8, 467-496.

Teichert, C., 1967. Nature of the Permian glacial record, Salt Range and Khisor Range, West Pakistan. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 129, 167-184.

Torsvik, T.H., Van der Voo, R., 2002. Refining Gondwana and Pangea palaeogeography: estimates of Phanerozoic non-dipole (octupole) fields. Geophysical Journal International 151, 771–794.

Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Chapter 3. Palynological techniques - Processing and microscopy. In: J. Jansonius and D.C McGregor (Eds.), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists Foundation 1, p. 29-50.

Wynne, A.B., 1878. On the geology of the Salt Range in Punjab. Geological Survey of India Memoir 14, 1-313.

Wynne, A.B., 1886. On a facetted and striated pebbles from the Olive group conglomerate of Cliel Hill in the Salt Range of the Punjab, India. Geological Magazine 3, 492-494.

Figure Captions

Figure 1. Locations of studied sections on reconstruction of Gondwana after Angiolini et al. (2007). 1, Yemen; 2, Interior Oman; 3, Salt Range, Pakistan. For details of locations of studied sections on modern maps see Stephenson et al. (2005) for Oman, Jan and Stephenson (2011) for Pakistan, and Stephenson and Al-Mashaikie (2011) for Yemen. The Choa Road section near Khewra in the eastern Salt Range is at GPS N 32 39 57, E 72 59 08.8.

Figure 2. a) The Al Khlata Formation in Wadi Al Khlata, Oman showing diamictite overlying the striated surface of the Khufai Formation; b) Al Khlata Formation diamictite in Wadi Al Khlata; c) view of the Kuhlan and Akbarah formations at the type section of the Kuhlan Formation, Yemen; d) contact between Akbarah (lower) and Kuhlan (upper) formations; e) contact between the Tobra and Warchha formations, Khisor Range, Pakistan; f) view of the Tobra and Wargal formations, Zaluch Nala, western Salt Range, Pakistan; g) the Choa Road section near Khewra, eastern Salt Range, Pakistan; h) diamictite facies in the Tobra Formation of the Choa Road section.

Figure 3. Distribution of selected palynomorph groups and taxa from the Yemen Kuhlan and Akbarah formations, Kuhlan, northwest Yemen. For details of section and lithology, see Stephenson and Al-Mashaikie (2011). Blue squares indicate barren samples.

Figure 4. Selected palynomorphs from the Kuhlan and Akbarah formations, and the Tobra Formation, Zaluch Nala. Scale bars for each specimen. MPA and MPK numbers are British Geological Survey Collection codes. a) *Converrucosisporites grandegranulatus*, MPA 57518, S17/1, MPK 13908, Tobra Formation; b) *Microbaculispora tentula*, MPA 57511, T26, MPK 13913, Tobra Formation; c) *Vallatisporites arcuatus*, R44/2, MPA 60511, MPK 14195, Kuhlan Formation; d) *Spelaeotriletes triangulus*, K61, MPA 60507, MPK 14199, Kuhlan Formation ; e) *Anapiculatisporites concinnus*, D40/1, MPA 58568, MPK 14205, Akbarah Formation; f) *Brevitriletes leptoacaina*, T11/4, MPA 57512, MPK 13916, Tobra Formation; g) *Horriditriletes ramosus*, H11, MPA 57520, MPK 13921, Tobra Formation; h) *Cannanoropollis janakii*, D40/2, MPA 60513, MPK 14192, Kuhlan Formation; i) *Cannanoropollis janakii*, G66, MPA 60511, MPK 14196, Kuhlan Formation.

Figure 5. Distribution of selected palynomorph groups and taxa from the Tobra Formation, Zaluch Nala, Pakistan. For details of section and lithology, see Jan and Stephenson (2011). Blue squares indicate barren samples.

Figure 6. Selected palynomorph groups and taxa from the Tobra Formation, Choa Road section, near Khewra, Pakistan.

Figure 7. Selected palynomorphs from the Tobra Formation, Choa Road section. Scale bar shown in (a). MPA and MPK numbers are British Geological Survey Collection codes. a) *Microbaculispora tentula*, B55, MPA 58401, MPK 14358; b) *Lophotriletes sparsus*, F58/3, MPA 58401, MPK 14359; c) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK 14360, proximal focus; d) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK 14360, distal focus; e) *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, proximal focus; f) *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, distal focus; g) *Converrucosisporites* cf. *confluens*, M64, MPA 58403, MPK 14362. h) *Alisporites indarraensis*, E44/2, MPA 58401, MPK 14363; i) *Alisporites indarraensis*, G42/4, MPA 58402, MPK 14364; j) *Hamiapollenites fusiformis*, C53/3, MPA 58401, MPK 14365; k) *Striatopodocarpites cancellatus*, Q60/2, MPA 58401, MPK 14366; l) *Protohaploxypinus limpidus*, U49, MPA 58401, MPK 14367; m) *Cycadopites cymbatus*, T58/2, MPA 58403, MPK 14368; n) *Cycadopites cymbatus*, C52/3, MPA 58401, MPK 14369.

Figure 8. Correlation of Oman, Yemen and Pakistan sections. ‘PDO production units’ are lithological subdivisions of the Al Khlata Formation similar to lithostratigraphic members (see Penney et al. 2008 for more detail).

Table 1. Main characteristics of the biozones of Penney et al. (2008).

Figure 1

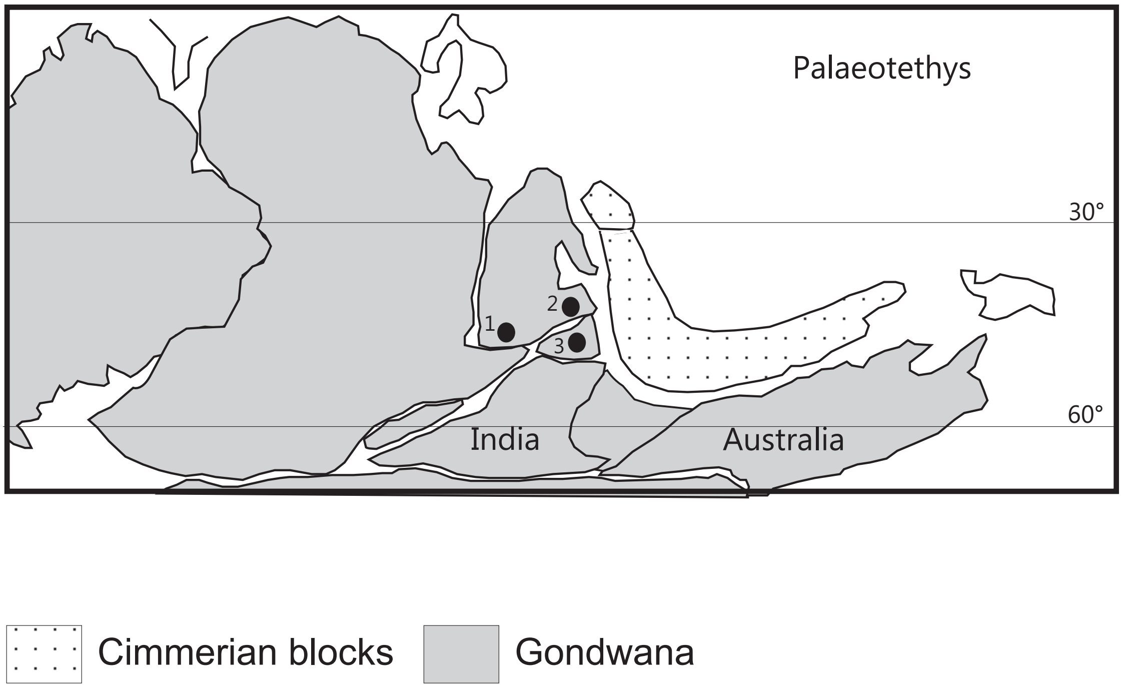

Fig 1

Figure 2

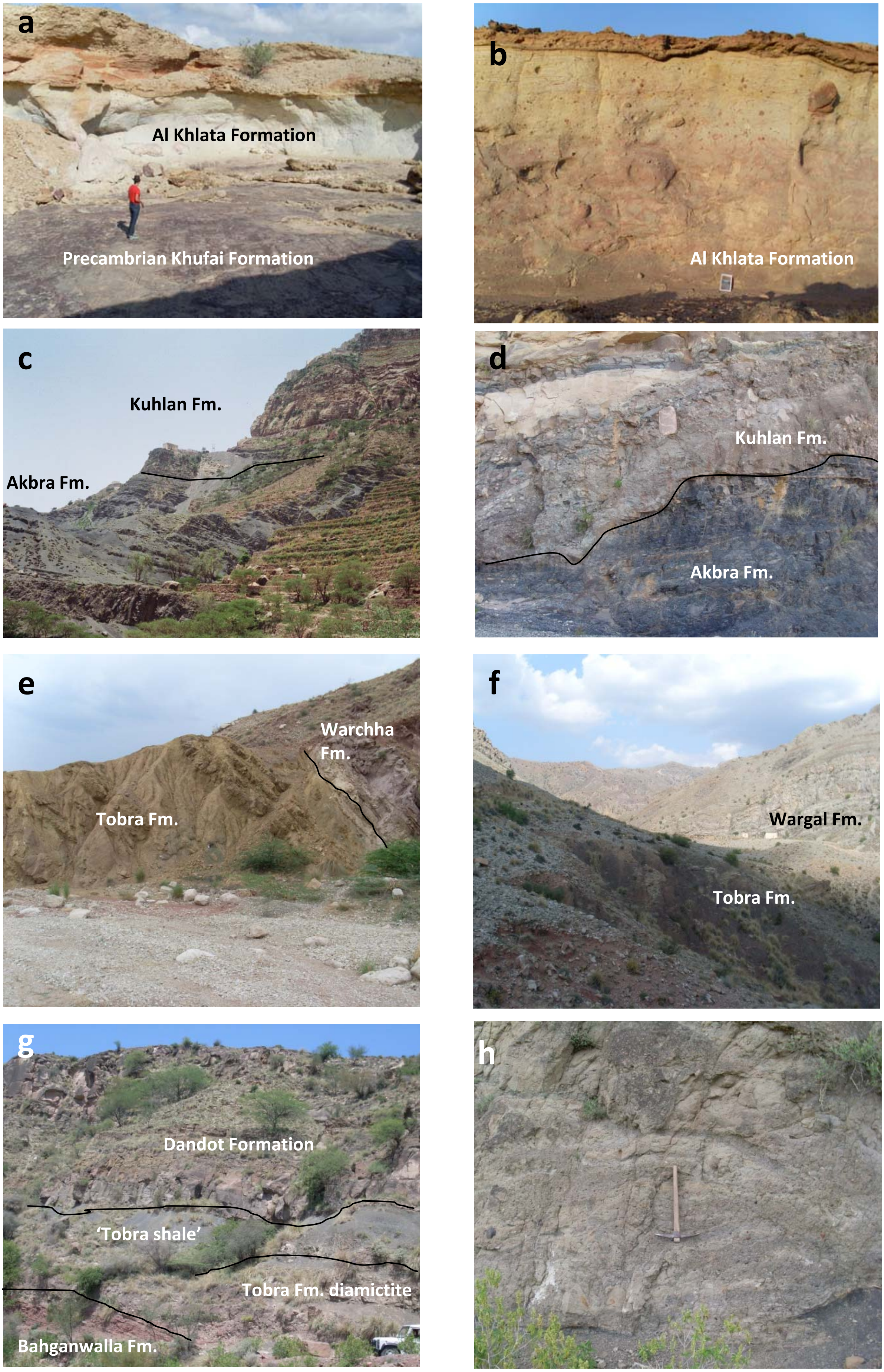

Fig 2

Figure 3

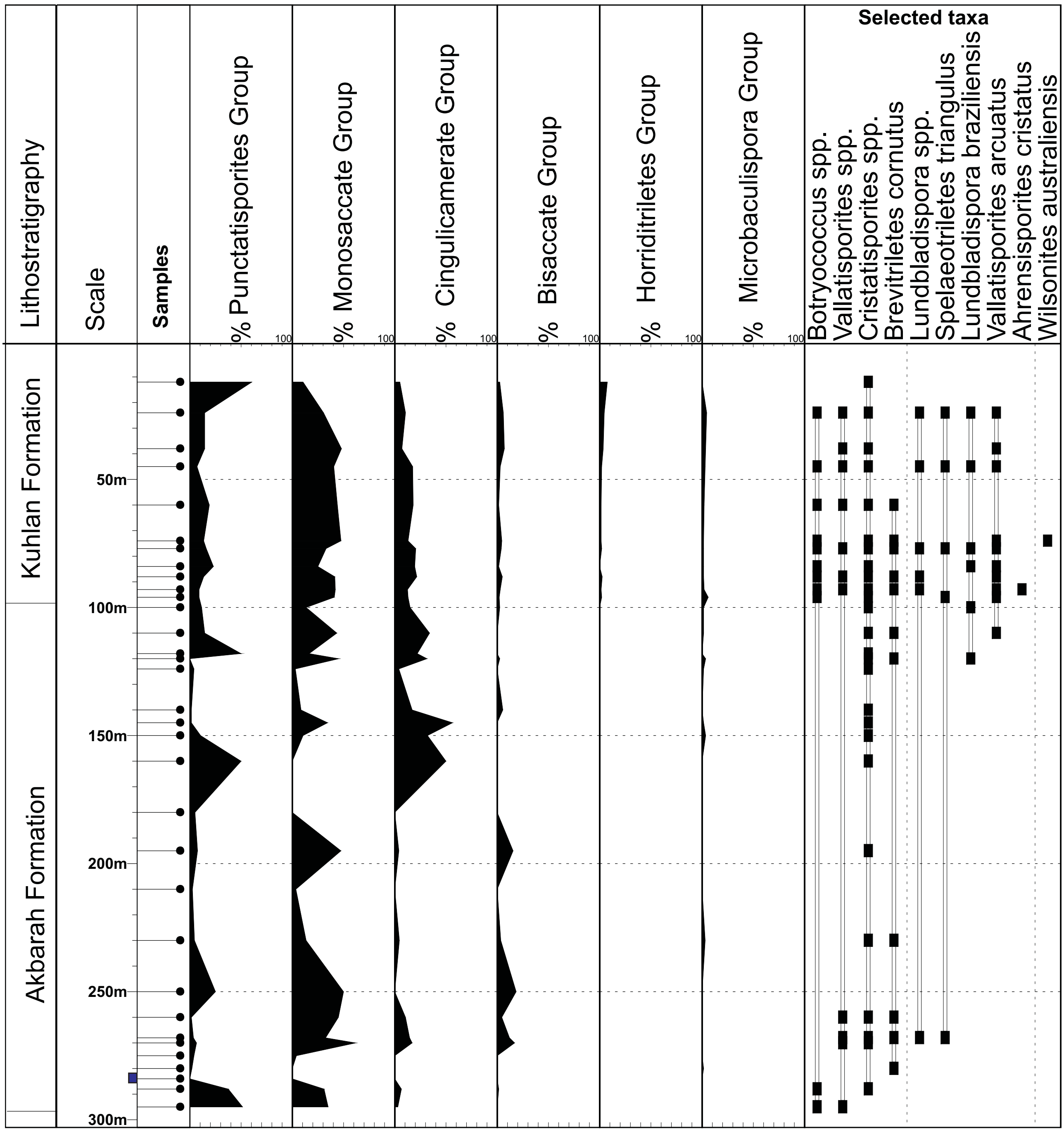

Fig 3

Figure 4

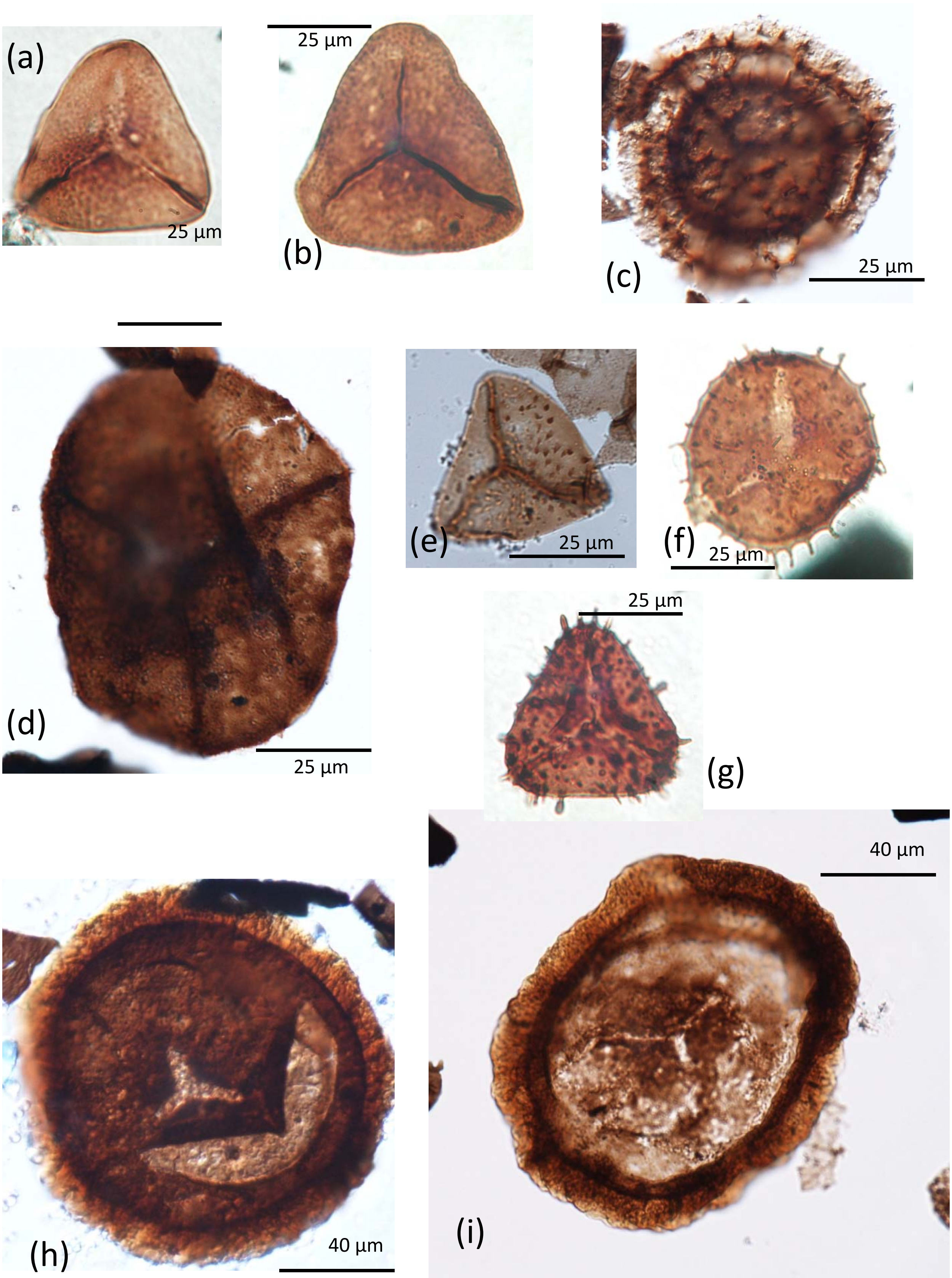

Fig 4

Figure 5

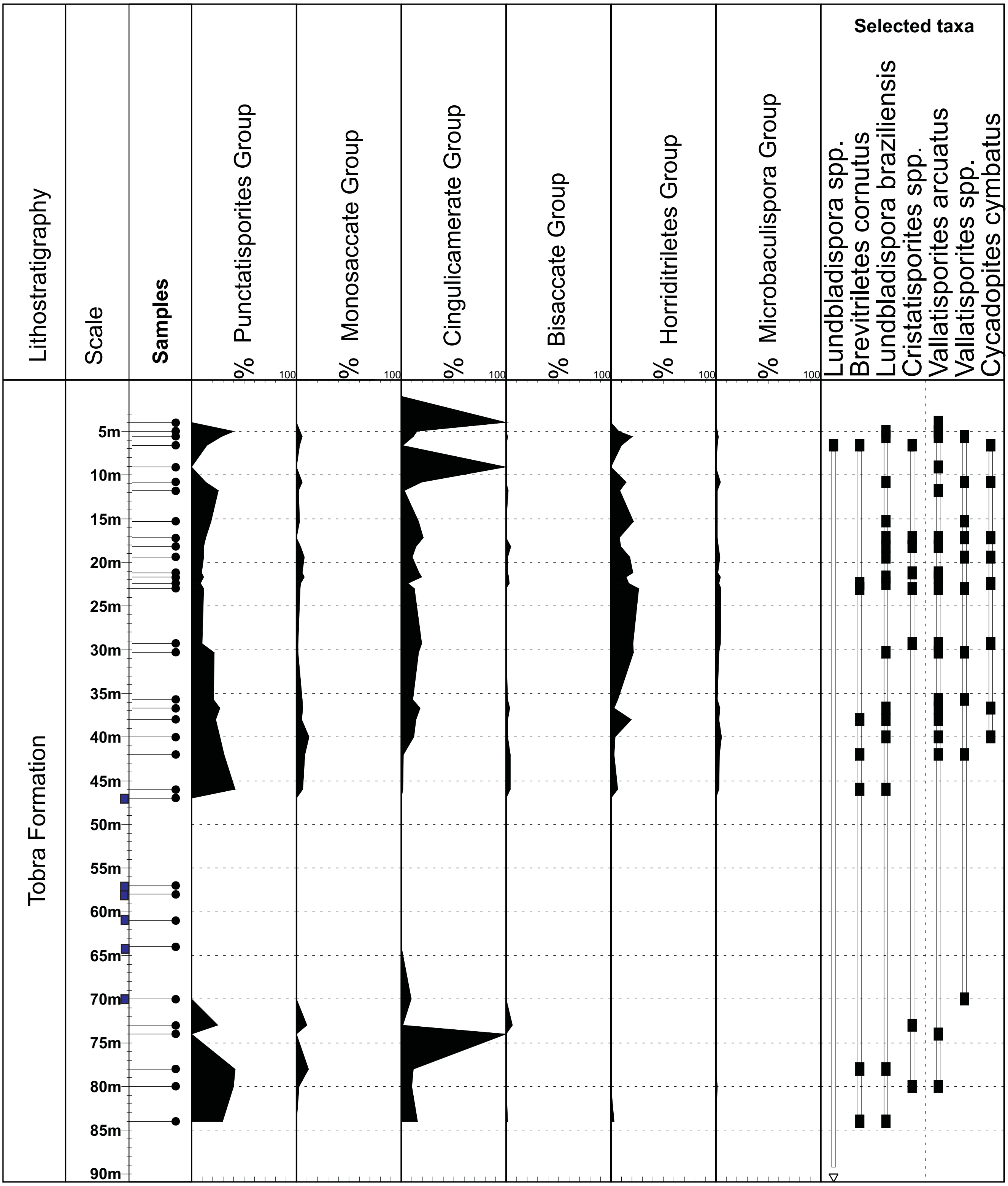

Fig 5

Figure 6

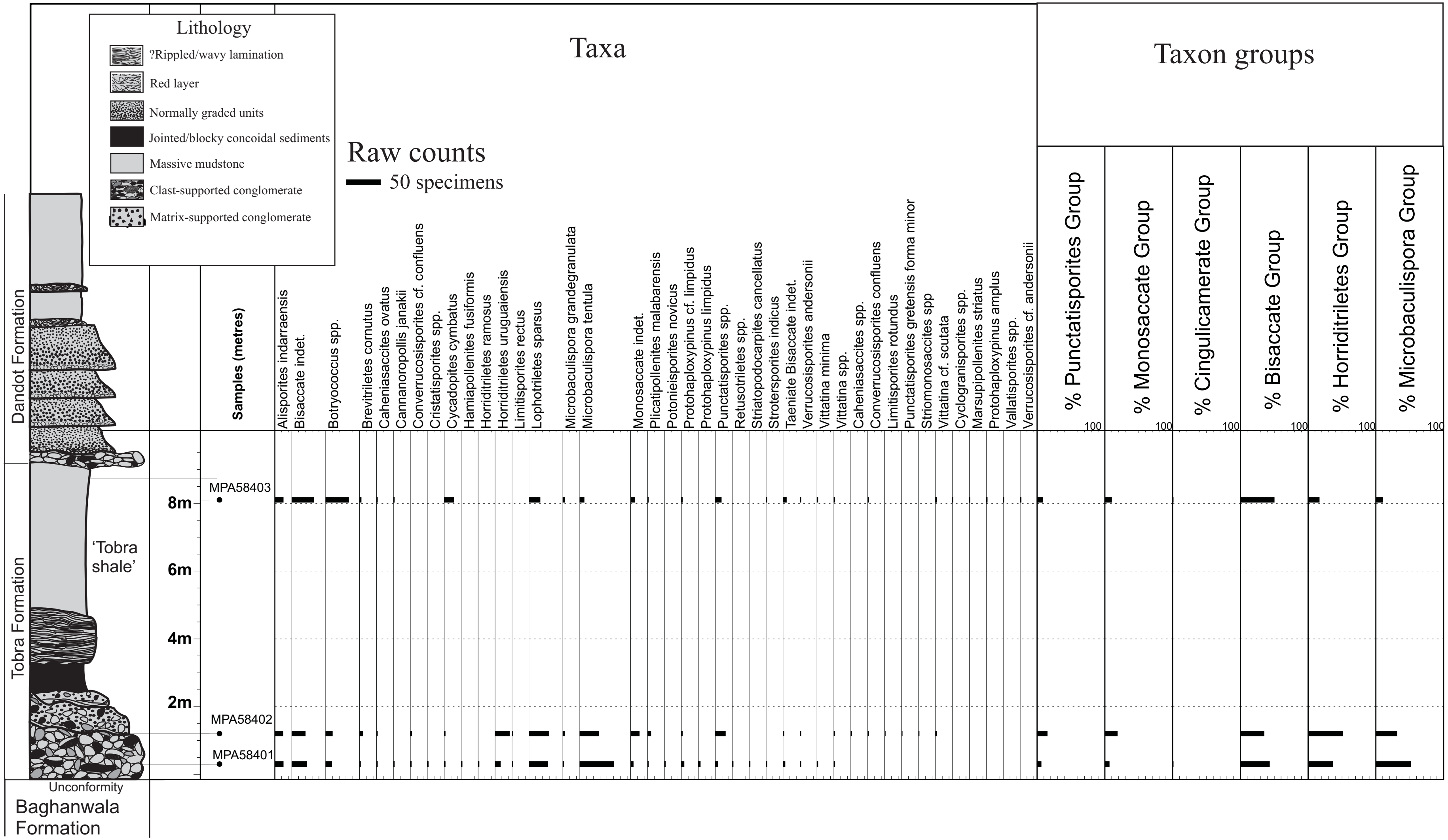

Fig 6

Figure 7

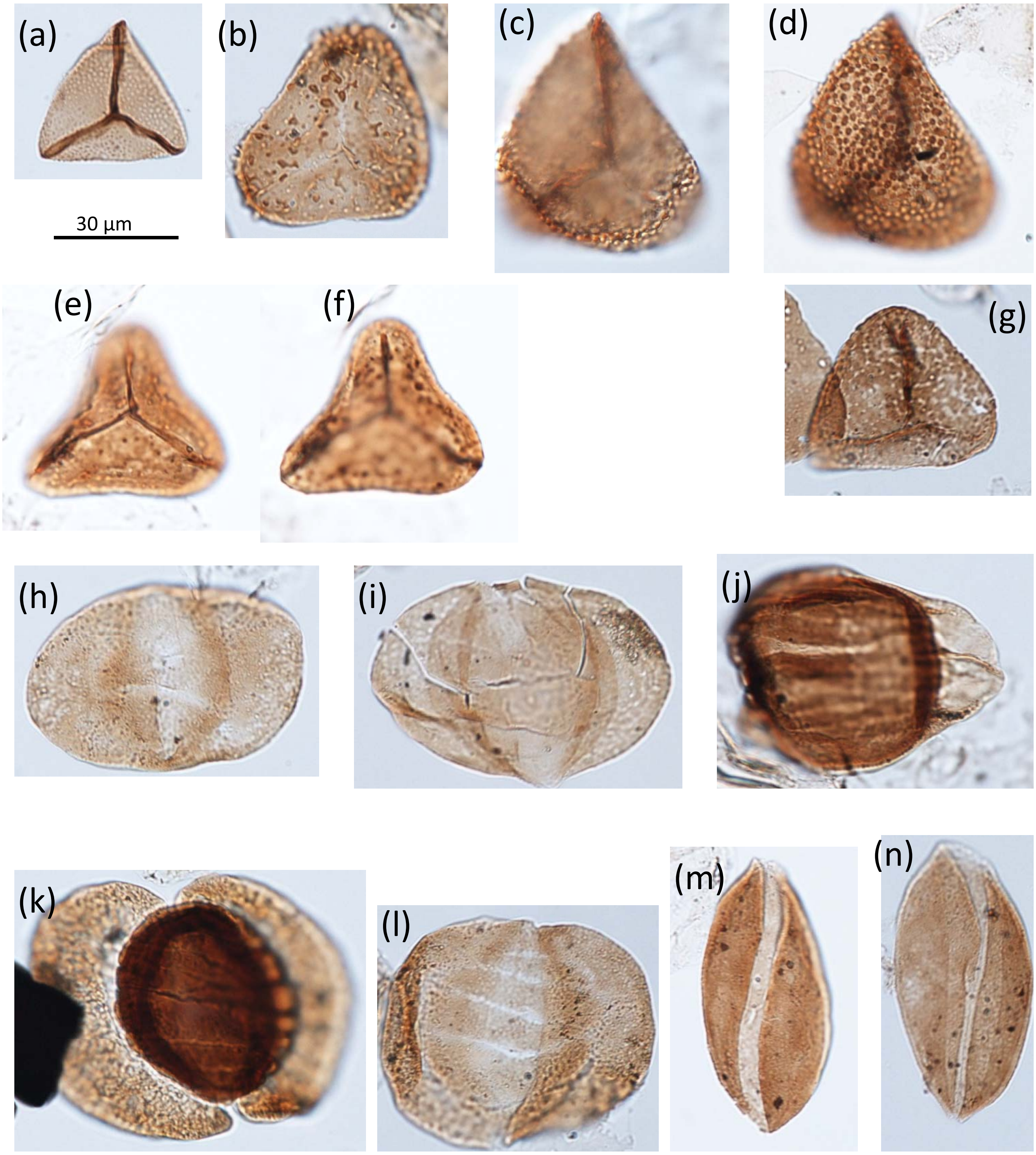

Fig 7

Figure 8

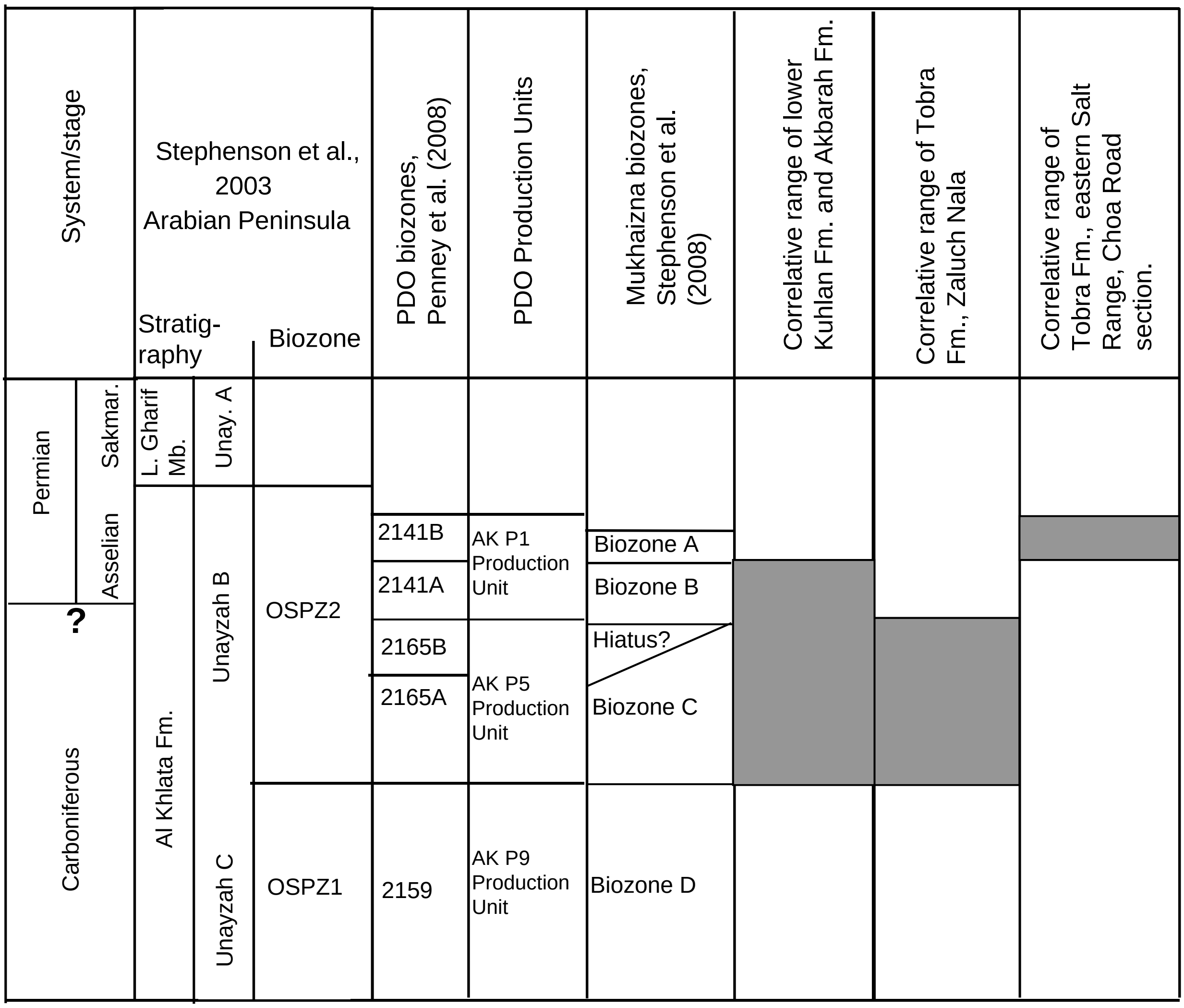

Fig 8

Table 1

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.