

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 grandegrnulatus*, *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

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

28 Keywords: palynology, Gondwana, Yemen, Oman, Pakistan

29 **1. Introduction**

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

40 Stephenson (2008) assessed palynostratigraphic schemes in the main Gondwana
41 basins and focused on precise basin-to-basin or region-to-region correlations underpinned by
42 careful taxonomy and stratigraphy, giving examples of Arabian to Australian correlation and
43 Australian to South African correlation. He concluded that consolidation of basin-to-basin
44 correlations will probably lead to the most reliable Gondwana-wide correlations. The
45 objective of this study was to test the applicability of a newly-published Oman biozonation

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46 across basins in Yemen and Pakistan, to correlate using the biozonation, and thereby
47 understand the age-distribution of glaciogene rocks in the three areas (Fig. 1).

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

56 **2. The Oman sequence and the Al Khlata Formation biozonation**

57 Pennsylvanian to Cisuralian rocks of the Al Khlata Formation crop out at the Haushi-
58 Huqf outcrop area in Oman but are present widely in the subsurface, where they form
59 important hydrocarbon reservoirs (Hughes Clarke, 1988). The Al Khlata Formation ranges
60 from conglomerates through diamictites, gravels, pebbly sandstones, siltstones to silty shales
61 (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; Al-Belushi et al., 1996;
62 Angiolini et al., 2003). The glaciogenic nature of the Al Khlata Formation was established
63 from studies of the outcrop area on the western flank of the Haushi-Huqf Uplift, where
64 striated pavements on the Precambrian Khufai Formation have been found (Fig. 2; Braakman
65 et al., 1982; Al-Belushi et al., 1996). The type section of the Al Khlata Formation is located
66 at Wadi Al Khlata near the Haushi-Huqf Uplift (57°25'46"E, 19°46'43"N) where it is about
67 100 m thick (Levell et al., 1988) and there is a subsurface reference section in Rahab-2 well,
68 south Oman (55°06'32"E, 18°01'09"N) where the formation is more than 246 m thick
69 (Hughes Clarke, 1988). In the subsurface of south Oman, the thickness of the Al Khlata
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70 Formation varies from about 100 to 800 m (Levell et al., 1988; Love, 1994). The variation of
71 thickness is largely the result of syn-depositional subsidence and erosional palaeorelief on the
72 pre-Al Khlata unconformity (Levell et al., 1988). During its deposition, the Cambrian Ara
73 salt in the South Oman Salt Basin moved diapirically to form salt domes. As a result, thick Al
74 Khlata Formation sediments are found in synclines formed by salt withdrawal. On the Eastern
75 Flank, thick Al Khlata Formation deposits are also found where salt was apparently
76 syndepositionally dissolved by groundwater (for details of locations see Penney et al., 2008;
77 Heward, 1990; Osterloff et al., 2004). These long periods of subsidence have lead to the most
78 complete record of Pennsylvanian to Cisuralian glaciations in Arabia and to the most
79 complete palynological record, with the result that the palynological succession of Oman
80 forms the standard with which other less complete successions are correlated. The
81 assemblages have been described in great detail before (e.g. Besems and Schuurman, 1987;
82 Love, 1994; Stephenson and Filatoff, 2000; Stephenson and Osterloff, 2002; Stephenson,
83 2004; Stephenson et al., 2003; 2005; 2007;) but in general the diversity and yield increases up
84 through the Al Khlata Formation, probably in response to climatic amelioration, related to
85 global post glacial warming and the northward movement of the Arabian Plate (Stephenson et
86 al., 2005). The earliest assemblages (e.g. 2159) are characterised by common monosaccate
87 pollen and *Punctatisporites*, while later assemblages are of greater diversity including
88 cingulicamerate and cheilocardioid spores, and colpate and bisaccate pollen (e.g. 2141; see
89 Penney et al., 2008). Biozones were defined in the Al Khlata Formation by Penney et al.
90 (2008) on the basis of quantitative changes in defined palynomorph groups (Table 1) and on
91 the ranges of certain distinctive taxa, for example *Anapiculatisporites concinnus*, *Cycadopites*
92 *cymbatus*, and *Kingiacolpites subcircularis*. The details of the biozones and how they are
93 applied are given by Penney et al. (2008), however for the reader's convenience a summary
94 of the relevant biozones is given here.

95 The primary diagnostic criteria of the 2165A Biozone are (1) the Cingulicamerata
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
96 Group (Table 1) constitutes up to approximately 30% of the assemblages (mainly
97 *Vallatisporites arcuatus*, *Lundbladispota braziliensis* and *Cristatisporites* spp.); and (2) the
98 *Microbaculispora* Group constitutes approximately 5% of assemblages, although it can be
99 rare or absent locally. Distinctive accessory taxa include *Ahrensisporites cristatus* and
100 *Wilsonites australiensis*. The 2165B Biozone is defined according to: (1) the *Horriditriletes*
101 Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) the
102 *Microbaculispora* Group constitutes usually around 3 to 5% of assemblages but can be
103 absent. *Cycadopites cymbatus*, *Converrucosisporites confluens*, *C. grandegrnulatus*,
104 *Marsupipollenites* spp. and the *Vittatina* and Taeniate Bisaccate groups appear towards the
105 top of this biozone. *Spelaeotriletes triangulus* is also present. The 2141A Biozone is defined
106 according to: (1) non-taeniate and taeniate bisaccate groups together represent more than 10%
107 of the assemblages; and (2) *Cycadopites cymbatus* is rare towards the base but increases to 5
108 to 10% of assemblages towards the top. Taxa or groups that occur rarely include
109 *Kingiocolpites subcircularis* and the *Vittatina* Group, *Brevitriletes cornutus*, *Dibolisporites*
110 *disfacies*, *Verrucosisporites* spp., *Botryococcus*, *Deusilites tentus*, *Tetraporina* spp. and
111 *Tasmanites*. Other distinctive accessory taxa include *Converrucosisporites confluens* and
112 *Vittatina* cf. *scutata*. In the 2141B Biozone, the *Microbaculispora* Group (mainly *M. tentula*)
113 become very common (10-60% of assemblages), and *Cycadopites cymbatus* is also common
114 (5-10% of assemblages). In addition, the Cingulicamerata Group is very rare or absent.
115 Accessory taxa include *Converrucosisporites confluens* and *Vittatina* cf. *scutata*.

51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 116 **3. Yemen; Akbarah and Kuhlan formations**

117 The Pennsylvanian glaciogene sediments of Yemen are represented by the Akbarah
118 and overlying Kuhlan formations (Stephenson and Al-Mashaikie, 2010; 2011). The type
119 section of the Kuhlan Formation is close to the village of Kuhlan, northwest Yemen, about 70

120 km northwest of Sana'a city, and is there underlain by the Akbarah Formation (Fig. 2). The
121 Kuhlan Formation consists of yellowish-brown, pinkish and red, massive, cross-bedded,
122 medium to fine-grained sandstone units, which are interbedded with thick, fissile and
123 stratified siltstone/shale beds of grey to red colour (Kruck and Thiele, 1983; Al-Mashaikie
124 2005). The Akbarah Formation at Kuhlan is in two parts (Stephenson and Al-Mashaikie,
125 2011). The lower part is composed of thick sandstone beds fining upwards to siltstone and
126 thick fissile shale. These units are interbedded with massive and stratified diamictite beds.
127 Dropstones are embedded within the sandstone and the shale beds, and their size decreases
128 upward illustrating increasingly distal conditions. This part is broadly interpreted to be of
129 glacial origin. The upper part is composed of several cycles beginning with beds of thin, fine-
130 grained sandstone fining upwards to thick fissile shale beds, interpreted to be of marine origin
131 (Stephenson and Al-Mashaikie, 2011). Eleven samples from the Yemen Kuhlan Formation,
132 and 22 samples from the underlying Akbarah Formation from 180m of the Kuhlan section
133 were analysed by Stephenson and Al-Mashaikie (2011). The Kuhlan Formation assemblages
134 contain common indeterminate monosaccate pollen, *Cristatisporites* spp., *Cannanoropollis*
135 *janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp. Other taxa include
136 *Brevitriletes cornutus*, *B. parmatus*, *Dibolisporites disfacies*, *Horriditriletes uruguiensis*, *H.*
137 *ramosus*, *Lundbladispora braziliensis*, *Microbaculispora tentula*, *Spelaeotriletes triangulus*,
138 *Vallatisporites arcuatus* and *Verrucosisporites andersonii*. Rarer taxa include *Ahrensisporites*
139 *cristatus*, *Anapiculatisporites concinnus* and *Wilsonites australiensis*. The ranges and
140 quantitative character of selected taxa are shown in Fig. 3 and selected taxa are illustrated in
141 Fig. 4. The Akbarah Formation assemblages are broadly similar (Stephenson and Al-
142 Mashaikie, 2011) in being dominated by indeterminate monosaccate pollen, *Cristatisporites*
143 spp., *Cannanoropollis janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp.

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

146 4. Pakistan; Tobra Formation

147 The Pennsylvanian to Cisuralian succession of the Salt Range, Pakistan consists of the
148 Tobra and Dandot formations (Jan and Stephenson, 2011). The Tobra Formation, consisting
149 of boulder beds and conglomerates, was long known as the Talchir boulder beds (e.g.
150 Noetling, 1901) because of its similarity to beds of that name in peninsular India. However
151 the unit was designated the Tobra Formation by Kummel and Teichert in 1970 and correlated
152 with the Talchir Stage of India. Its type locality is near Tobra Village in the eastern Salt
153 Range, where its thickness is 20 m (Shah, 1977). The Tobra Formation was interpreted as
154 glaciogenic by Wynne (1878, 1886) and Koken (1907). At the Zaluch Nala gorge (Fig. 2) in
155 the western Salt Range, Teichert (1967) reported the thickness of the Tobra Formation to be
156 122 m and divided the formation into three members, A, B and C, all of diamictite facies
157 type. In Zaluch Nala and in the Khisor Range to the west, the Tobra Formation is
158 unconformably overlain by the Warchha Formation, a medium- to coarse-grained, purple,
159 arkosic sandstone interpreted as an arid climate deposit (Ghazi and Mountney, 2009). In the
160 eastern Salt Range, the Tobra Formation, for example at the Choa Road section near Khewra,
161 is however conformably overlain by the Dandot Formation (Fig. 2; Shah, 1977). The Dandot
162 Formation consists of pale grey to olive-green sandstone with scattered pebbles up to 10 cm
163 in diameter, or pebbly beds with subordinate dark grey and greenish splintery shales (Shah,
164 1977), as well as *Eurydesma* and *Conularia* (Pascoe, 1959; Jan and Stephenson, 2011).

165 The palynomorph assemblages of the Tobra Formation at Zaluch Nala, studied by Jan
166 and Stephenson (2011) can be divided into two. The lower assemblages between 84 and 73 m
167 (5 samples), are dominated by the *Punctatisporites* Group of Penney et al. (2008; Table 1)

168 constituting an average 20% of the assemblages. Cingulicamerate spores (Penney et al. 2008)
169 represent 18% of the assemblages (*Cristatisporites crassilabratus*, *Cristatisporites* spp.,
170 *Lundbladispota braziliensis*, *Vallatisporites arcuatus* and *Vallatisporites* spp.). Indeterminate
171 spores also make up 18% of the lower assemblages. The monosaccate pollen
172 *Cannanoropollis janakii*, *Plicatipollenites malabarensis*, *Potonieisporites novicus* and
173 *Potonieisporites* spp. make up 6% of these lower assemblages. The *Horriditriletes* Group
174 (*Horriditriletes tereteangulatus*, *Horriditriletes ramosus* and *Horriditriletes uruguiensis*)
175 and the *Microbaculispora* Group (mostly *Microbaculispora tentula*) make up 1% each. The
176 upper assemblages between 47 and 4 m (24 samples), are dominated by the *Punctatisporites*
177 Group which makes up on average 17% of the assemblages, followed by the cingulicamerate
178 spores, which represent 13% on average. The *Horriditriletes* Group makes up 11% of the
179 upper assemblages and the *Microbaculispora* Group (*Microbaculispora tentula* and
180 *Converrucosisporites grandegrnulatus*) represents 4%. *Brevitriletes cornutus*, *Brevitriletes*
181 *parmatum* and *Brevitriletes leptocaina* are generally rare. Radially- and bilaterally-
182 symmetrical monosaccate pollen are represented by poorly-preserved common *Barakarites*
183 cf. *rotatus* and *Plicatipollenites malabarensis*. *Cannanoropollis janakii* is also present.
184 Taeniate and non-taeniate bisaccate pollen are represented by *Hamiapollenites* spp.,
185 *Limitisporites rectus*, *Protohaploxylinus* cf. *hartii* and *Striatopodocarpites* spp. The ranges
186 and quantitative character of selected taxa are shown in Fig. 5 and selected taxa are illustrated
187 in Fig. 4.

188 The Tobra Formation is exposed beneath the Dandot Formation at the Choa Road
189 section near Khewra in the eastern Salt Range (Fig. 2 (g); GPS N 32 39 57, E 72 59 08.8). At
190 this locality, the Tobra Formation is approximately 9m thick and consists, at the base, of
191 clast- and matrix-supported conglomerate; and towards the top of mudstones which contain
192 occasional dropstones. Two palynological samples were collected from the matrix of the

193 conglomerate and one from the upper mudstone. The palynomorph assemblages of three
194 samples contain common *Alisporites indarraensis*, *Cycadopites cymbatus*, *Horriditriletes*
195 spp., and *Microbaculispora tentula*, as well as rare *Brevitriletes cornutus*,
196 *Converrucosisporites confluens*, *Microbaculispora grandegranulata*, *Verrucosisporites*
197 *andersonii*, and *Vittatina cf. scutata* (Figs. 6, 7).

5. Correlation and conclusions

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

208 In the Yemen Akbarah and Kuhlan formations, the presence of common
209 cingulicamerate spores (e.g. *Cristatisporites* spp.) and monosaccate pollen, and the presence
210 of *Brevitriletes cornutus*, *B. parmatus*, *Deusilites tentus*, *Dibolisporites disfacies*,
211 *Microbaculispora tentula* and *Verrucosisporites andersonii*, as well as the presence of
212 *Anapiculatisporites concinnus* and *Spelaeotriletes triangulus* suggest a range within the
213 2165A to 2141A biozones (Fig. 8). However the presence of *Ahrensiporites cristatus* and
214 *Wilsonites australiensis* indicates that the section is most likely of 2165A age.

215 This correlation (Fig. 8) indicates the widespread nature of glacial sediments of a
216 narrow biostratigraphic age range (the Oman AK P5 Production Unit) in basins across part of

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217 the north Gondwana margin. Unpublished work by Jan (2011) in other parts of the Salt and
218 Khisor ranges in Pakistan, although not fully representing the full extent of Upper
219 Carboniferous stratigraphy, do not show the presence of the oldest Oman AK P1 Production
220 Unit of 2159 Biozone age. Similarly, the Akbarah Formation at Kuhlan in Yemen rests on
221 metamorphosed basement. It is interesting to speculate on the apparent absence of the oldest
222 Oman P1 Production Unit in these parts of Yemen and Pakistan. This may relate to the fact
223 that salt withdrawal and dissolution was more common in south Oman (Heward, 1990),
224 creating the accommodation space for these earliest of Arabian Carboniferous glacial
225 sediments.

226 The Tobra Formation in Zaluch Nala, Pakistan lacks the deglaciation sequence of
227 2141 A and 2141B Biozone age that is common in Oman (see for example Stephenson et al.,
228 2007). This is an indication of either non-deposition during the deglaciation period, or
229 erosion associated with the unconformity between the Tobra Formation and the overlying red
230 bed Warchha Formation (Jan and Stephenson, 2011). However the three samples from the
231 Tobra Formation at the Choa Road section in the eastern Salt Range are assignable to the
232 2141B Biozone of Penney et al. (2008). In Oman, the 2141B Biozone is closely associated
233 with the Rahab Shale Member, a widespread shale facies in South Oman which is considered
234 to represent the final Permian deglaciation in the form of a large melt-out lake (Stephenson et
235 al. 2005; Fig. 8). It is interesting to speculate whether the ‘Tobra shale’ correlates with the
236 Rahab Shale Member.

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45 343 **Figure Captions**

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48 344 Figure 1. Locations of studied sections on reconstruction of Gondwana after Angiolini et al.
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50 345 (2007). 1, Yemen; 2, Interior Oman; 3, Salt Range, Pakistan. For details of locations of
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52 346 studied sections on modern maps see Stephenson et al. (2005) for Oman, Jan and Stephenson
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54 347 (2011) for Pakistan, and Stephenson and Al-Mashaikie (2011) for Yemen. The Choa Road
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56 348 section near Khewra in the eastern Salt Range is at GPS N 32 39 57, E 72 59 08.8.
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349 Figure 2. a) The Al Khlata Formation in Wadi Al Khlata, Oman showing diamictite overlying
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2 350 the striated surface of the Khufai Formation; b) Al Khlata Formation diamictite in Wadi Al
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4 351 Khlata; c) view of the Kuhlan and Akbarah formations at the type section of the Kuhlan
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6 352 Formation, Yemen; d) contact between Akbarah (lower) and Kuhlan (upper) formations; e)
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8 353 contact between the Tobra and Warchha formations, Khisor Range, Pakistan; f) view of the
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10 354 Tobra and Wargal formations, Zaluch Nala, western Salt Range, Pakistan; g) the Choa Road
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12 355 section near Khewra, eastern Salt Range, Pakistan; h) diamictite facies in the Tobra
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14 356 Formation of the Choa Road section.
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20 357 Figure 3. Distribution of selected palynomorph groups and taxa from the Yemen Kuhlan and
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22 358 Akbarah formations, Kuhlan, northwest Yemen. For details of section and lithology, see
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24 359 Stephenson and Al-Mashaikie (2011). Blue squares indicate barren samples.
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29 360 Figure 4. Selected palynomorphs from the Kuhlan and Akbarah formations, and the Tobra
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31 361 Formation, Zaluch Nala. Scale bars for each specimen. MPA and MPK numbers are British
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33 362 Geological Survey Collection codes. a) *Converrucosisporites grandegrnulatus*, MPA
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35 363 57518, S17/1, MPK 13908, Tobra Formation; b) *Microbaculispora tentula*, MPA 57511,
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37 364 T26, MPK 13913, Tobra Formation; c) *Vallatisporites arcuatus*, R44/2, MPA 60511, MPK
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39 365 14195, Kuhlan Formation; d) *Spelaeotriletes triangulus*, K61, MPA 60507, MPK 14199,
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41 366 Kuhlan Formation ; e) *Anapiculatisporites concinnus*, D40/1, MPA 58568, MPK 14205,
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43 367 Akbarah Formation; f) *Brevitriletes leptocaina*, T11/4, MPA 57512, MPK 13916, Tobra
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45 368 Formation; g) *Horriditriletes ramosus*, H11, MPA 57520, MPK 13921, Tobra Formation; h)
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47 369 *Cannanoropollis janakii*, D40/2, MPA 60513, MPK 14192, Kuhlan Formation; i)
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49 370 *Cannanoropollis janakii*, G66, MPA 60511, MPK 14196, Kuhlan Formation.
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371 Figure 5. Distribution of selected palynomorph groups and taxa from the Tobra Formation,
372 Zaluch Nala, Pakistan. For details of section and lithology, see Jan and Stephenson (2011).

373 Blue squares indicate barren samples.

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

376 Figure 7. Selected palynomorphs from the Tobra Formation, Choa Road section. Scale bar
377 shown in (a). MPA and MPK numbers are British Geological Survey Collection codes. a)

378 *Microbaculispora tentula*, B55, MPA 58401, MPK 14358; b) *Lophotriletes sparsus*, F58/3,

379 MPA 58401, MPK 14359; c) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK

380 14360, proximal focus; d) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK 14360,

381 distal focus; e) *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, proximal focus; f)

382 *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, distal focus; g)

383 *Converrucosisporites cf. confluens*, M64, MPA 58403, MPK 14362. h) *Alisporites*

384 *indarraensis*, E44/2, MPA 58401, MPK 14363; i) *Alisporites indarraensis*, G42/4, MPA

385 58402, MPK 14364; j) *Hamiapollenites fusiformis*, C53/3, MPA 58401, MPK 14365; k)

386 *Striatopodocarpites cancellatus*, Q60/2, MPA 58401, MPK 14366; l) *Protohaploxylinus*

387 *limpidus*, U49, MPA 58401, MPK 14367; m) *Cycadopites cymbatus*, T58/2, MPA 58403,

388 MPK 14368; n) *Cycadopites cymbatus*, C52/3, MPA 58401, MPK 14369.

389 Figure 8. Correlation of Oman, Yemen and Pakistan sections. ‘PDO production units’ are

390 lithological subdivisions of the Al Khlata Formation similar to lithostratigraphic members

391 (see Penney et al. 2008 for more detail).

392 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 grandegrnulatus*, *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

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

28 Keywords: palynology, Gondwana, Yemen, Oman, Pakistan

29 **1. Introduction**

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

40 Stephenson (2008) assessed palynostratigraphic schemes in the main Gondwana
41 basins and focused on precise basin-to-basin or region-to-region correlations underpinned by
42 careful taxonomy and stratigraphy, giving examples of Arabian to Australian correlation and
43 Australian to South African correlation. He concluded that consolidation of basin-to-basin
44 correlations will probably lead to the most reliable Gondwana-wide correlations. The
45 objective of this study was to test the applicability of a newly-published Oman biozonation

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46 across basins in Yemen and Pakistan, to correlate using the biozonation, and thereby
47 understand the age-distribution of glaciogene rocks in the three areas (Fig. 1).

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

56 2. The Oman sequence and the Al Khlata Formation biozonation

57 Pennsylvanian to Cisuralian rocks of the Al Khlata Formation crop out at the Haushi-
58 Huqf outcrop area in Oman but are present widely in the subsurface, where they form
59 important hydrocarbon reservoirs (Hughes Clarke, 1988). The Al Khlata Formation ranges
60 from conglomerates through diamictites, gravels, pebbly sandstones, siltstones to silty shales
61 (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; Al-Belushi et al., 1996;
62 Angiolini et al., 2003). The glaciogenic nature of the Al Khlata Formation was established
63 from studies of the outcrop area on the western flank of the Haushi-Huqf Uplift, where
64 striated pavements on the Precambrian Khufai Formation have been found (Fig. 2; Braakman
65 et al., 1982; Al-Belushi et al., 1996). The type section of the Al Khlata Formation is located
66 at Wadi Al Khlata near the Haushi-Huqf Uplift (57°25'46"E, 19°46'43"N) where it is about
67 100 m thick (Levell et al., 1988) and there is a subsurface reference section in Rahab-2 well,
68 south Oman (55°06'32"E, 18°01'09"N) where the formation is more than 246 m thick
69 (Hughes Clarke, 1988). In the subsurface of south Oman, the thickness of the Al Khlata
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70 Formation varies from about 100 to 800 m (Levell et al., 1988; Love, 1994). The variation of
71 thickness is largely the result of syn-depositional subsidence and erosional palaeorelief on the
72 pre-Al Khlata unconformity (Levell et al., 1988). During its deposition, the Cambrian Ara
73 salt in the South Oman Salt Basin moved diapirically to form salt domes. As a result, thick Al
74 Khlata Formation sediments are found in synclines formed by salt withdrawal. On the Eastern
75 Flank, thick Al Khlata Formation deposits are also found where salt was apparently
76 syndepositionally dissolved by groundwater (for details of locations see Penney et al., 2008;
77 Heward, 1990; Osterloff et al., 2004). These long periods of subsidence have lead to the most
78 complete record of Pennsylvanian to Cisuralian glaciations in Arabia and to the most
79 complete palynological record, with the result that the palynological succession of Oman
80 forms the standard with which other less complete successions are correlated. The
81 assemblages have been described in great detail before (e.g. Besems and Schuurman, 1987;
82 Love, 1994; Stephenson and Filatoff, 2000; Stephenson and Osterloff, 2002; Stephenson,
83 2004; Stephenson et al., 2003; 2005; 2007;) but in general the diversity and yield increases up
84 through the Al Khlata Formation, probably in response to climatic amelioration, related to
85 global post glacial warming and the northward movement of the Arabian Plate (Stephenson et
86 al., 2005). The earliest assemblages (e.g. 2159) are characterised by common monosaccate
87 pollen and *Punctatisporites*, while later assemblages are of greater diversity including
88 cingulicamerate and cheilocardioid spores, and colpate and bisaccate pollen (e.g. 2141; see
89 Penney et al., 2008). Biozones were defined in the Al Khlata Formation by Penney et al.
90 (2008) on the basis of quantitative changes in defined palynomorph groups (Table 1) and on
91 the ranges of certain distinctive taxa, for example *Anapiculatisporites concinnus*, *Cycadopites*
92 *cymbatus*, and *Kingiacolpites subcircularis*. The details of the biozones and how they are
93 applied are given by Penney et al. (2008), however for the reader's convenience a summary
94 of the relevant biozones is given here.

95 The primary diagnostic criteria of the 2165A Biozone are (1) the Cingulicamerata
96 Group (Table 1) constitutes up to approximately 30% of the assemblages (mainly
97 *Vallatisporites arcuatus*, *Lundbladispora braziliensis* and *Cristatisporites* spp.); and (2) the
98 *Microbaculispora* Group constitutes approximately 5% of assemblages, although it can be
99 rare or absent locally. Distinctive accessory taxa include *Ahrensisporites cristatus* and
100 *Wilsonites australiensis*. The 2165B Biozone is defined according to: (1) the *Horriditriletes*
101 Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) the
102 *Microbaculispora* Group constitutes usually around 3 to 5% of assemblages but can be
103 absent. *Cycadopites cymbatus*, *Converrucosisporites confluens*, *C. grandegrnulatus*,
104 *Marsupipollenites* spp. and the *Vittatina* and Taeniate Bisaccate groups appear towards the
105 top of this biozone. *Spelaeotriletes triangulus* is also present. The 2141A Biozone is defined
106 according to: (1) non-taeniate and taeniate bisaccate groups together represent more than 10%
107 of the assemblages; and (2) *Cycadopites cymbatus* is rare towards the base but increases to 5
108 to 10% of assemblages towards the top. Taxa or groups that occur rarely include
109 *Kingiocolpites subcircularis* and the *Vittatina* Group, *Brevitriletes cornutus*, *Dibolisporites*
110 *disfacies*, *Verrucosisporites* spp., *Botryococcus*, *Deusilites tentus*, *Tetraporina* spp. and
111 *Tasmanites*. Other distinctive accessory taxa include *Converrucosisporites confluens* and
112 *Vittatina* cf. *scutata*. In the 2141B Biozone, the *Microbaculispora* Group (mainly *M. tentula*)
113 become very common (10-60% of assemblages), and *Cycadopites cymbatus* is also common
114 (5-10% of assemblages). In addition, the Cingulicamerata Group is very rare or absent.
115 Accessory taxa include *Converrucosisporites confluens* and *Vittatina* cf. *scutata*.

3. Yemen; Akbarah and Kuhlan formations

117 The Pennsylvanian glaciogene sediments of Yemen are represented by the Akbarah
118 and overlying Kuhlan formations (Stephenson and Al-Mashaikie, 2010; 2011). The type
119 section of the Kuhlan Formation is close to the village of Kuhlan, northwest Yemen, about 70

120 km northwest of Sana'a city, and is there underlain by the Akbarah Formation (Fig. 2). The
121 Kuhlan Formation consists of yellowish-brown, pinkish and red, massive, cross-bedded,
122 medium to fine-grained sandstone units, which are interbedded with thick, fissile and
123 stratified siltstone/shale beds of grey to red colour (Kruck and Thiele, 1983; Al-Mashaikie
124 2005). The Akbarah Formation at Kuhlan is in two parts (Stephenson and Al-Mashaikie,
125 2011). The lower part is composed of thick sandstone beds fining upwards to siltstone and
126 thick fissile shale. These units are interbedded with massive and stratified diamictite beds.
127 Dropstones are embedded within the sandstone and the shale beds, and their size decreases
128 upward illustrating increasingly distal conditions. This part is broadly interpreted to be of
129 glacial origin. The upper part is composed of several cycles beginning with beds of thin, fine-
130 grained sandstone fining upwards to thick fissile shale beds, interpreted to be of marine origin
131 (Stephenson and Al-Mashaikie, 2011). Eleven samples from the Yemen Kuhlan Formation,
132 and 22 samples from the underlying Akbarah Formation from 180m of the Kuhlan section
133 were analysed by Stephenson and Al-Mashaikie (2011). The Kuhlan Formation assemblages
134 contain common indeterminate monosaccate pollen, *Cristatisporites* spp., *Cannanoropollis*
135 *janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp. Other taxa include
136 *Brevitriletes cornutus*, *B. parmatus*, *Dibolisporites disfacies*, *Horriditriletes uruguiensis*, *H.*
137 *ramosus*, *Lundbladispora braziliensis*, *Microbaculispora tentula*, *Spelaeotriletes triangulus*,
138 *Vallatisporites arcuatus* and *Verrucosisporites andersonii*. Rarer taxa include *Ahrensisporites*
139 *cristatus*, *Anapiculatisporites concinnus* and *Wilsonites australiensis*. The ranges and
140 quantitative character of selected taxa are shown in Fig. 3 and selected taxa are illustrated in
141 Fig. 4. The Akbarah Formation assemblages are broadly similar (Stephenson and Al-
142 Mashaikie, 2011) in being dominated by indeterminate monosaccate pollen, *Cristatisporites*
143 spp., *Cannanoropollis janakii*, *Deusilites tentus*, *Leiosphaeridia* sp. and *Punctatisporites* spp.

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

146 4. Pakistan; Tobra Formation

147 The Pennsylvanian to Cisuralian succession of the Salt Range, Pakistan consists of the
148 Tobra and Dandot formations (Jan and Stephenson, 2011). The Tobra Formation, consisting
149 of boulder beds and conglomerates, was long known as the Talchir boulder beds (e.g.
150 Noetling, 1901) because of its similarity to beds of that name in peninsular India. However
151 the unit was designated the Tobra Formation by Kummel and Teichert in 1970 and correlated
152 with the Talchir Stage of India. Its type locality is near Tobra Village in the eastern Salt
153 Range, where its thickness is 20 m (Shah, 1977). The Tobra Formation was interpreted as
154 glaciogenic by Wynne (1878, 1886) and Koken (1907). At the Zaluch Nala gorge (Fig. 2) in
155 the western Salt Range, Teichert (1967) reported the thickness of the Tobra Formation to be
156 122 m and divided the formation into three members, A, B and C, all of diamictite facies
157 type. In Zaluch Nala and in the Khisor Range to the west, the Tobra Formation is
158 unconformably overlain by the Warchha Formation, a medium- to coarse-grained, purple,
159 arkosic sandstone interpreted as an arid climate deposit (Ghazi and Mountney, 2009). In the
160 eastern Salt Range, the Tobra Formation, for example at the Choa Road section near Khewra,
161 is however conformably overlain by the Dandot Formation (Fig. 2; Shah, 1977). The Dandot
162 Formation consists of pale grey to olive-green sandstone with scattered pebbles up to 10 cm
163 in diameter, or pebbly beds with subordinate dark grey and greenish splintery shales (Shah,
164 1977), as well as *Eurydesma* and *Conularia* (Pascoe, 1959; Jan and Stephenson, 2011).

165 The palynomorph assemblages of the Tobra Formation at Zaluch Nala, studied by Jan
166 and Stephenson (2011) can be divided into two. The lower assemblages between 84 and 73 m
167 (5 samples), are dominated by the *Punctatisporites* Group of Penney et al. (2008; Table 1)

168 constituting an average 20% of the assemblages. Cingulicamerate spores (Penney et al. 2008)
169 represent 18% of the assemblages (*Cristatisporites crassilabratus*, *Cristatisporites* spp.,
170 *Lundbladispota braziliensis*, *Vallatisporites arcuatus* and *Vallatisporites* spp.). Indeterminate
171 spores also make up 18% of the lower assemblages. The monosaccate pollen
172 *Cannanoropollis janakii*, *Plicatipollenites malabarensis*, *Potonieisporites novicus* and
173 *Potonieisporites* spp. make up 6% of these lower assemblages. The *Horriditriletes* Group
174 (*Horriditriletes tereteangulatus*, *Horriditriletes ramosus* and *Horriditriletes uruguiensis*)
175 and the *Microbaculispora* Group (mostly *Microbaculispora tentula*) make up 1% each. The
176 upper assemblages between 47 and 4 m (24 samples), are dominated by the *Punctatisporites*
177 Group which makes up on average 17% of the assemblages, followed by the cingulicamerate
178 spores, which represent 13% on average. The *Horriditriletes* Group makes up 11% of the
179 upper assemblages and the *Microbaculispora* Group (*Microbaculispora tentula* and
180 *Converrucosisporites grandegrnulatus*) represents 4%. *Brevitriletes cornutus*, *Brevitriletes*
181 *parmatum* and *Brevitriletes leptocaina* are generally rare. Radially- and bilaterally-
182 symmetrical monosaccate pollen are represented by poorly-preserved common *Barakarites*
183 cf. *rotatus* and *Plicatipollenites malabarensis*. *Cannanoropollis janakii* is also present.
184 Taeniate and non-taeniate bisaccate pollen are represented by *Hamiapollenites* spp.,
185 *Limitisporites rectus*, *Protohaploxypinus* cf. *hartii* and *Striatopodocarpites* spp. The ranges
186 and quantitative character of selected taxa are shown in Fig. 5 and selected taxa are illustrated
187 in Fig. 4.

188 The Tobra Formation is exposed beneath the Dandot Formation at the Choa Road
189 section near Khewra in the eastern Salt Range (Fig. 2 (g); GPS N 32 39 57, E 72 59 08.8). At
190 this locality, the Tobra Formation is approximately 9m thick and consists, at the base, of
191 clast- and matrix-supported conglomerate; and towards the top of mudstones which contain
192 occasional dropstones. Two palynological samples were collected from the matrix of the

193 conglomerate and one from the upper mudstone. The palynomorph assemblages of three
194 samples contain common *Alisporites indarraensis*, *Cycadopites cymbatus*, *Horriditriletes*
195 spp., and *Microbaculispora tentula*, as well as rare *Brevitriletes cornutus*,
196 *Converrucosisporites confluens*, *Microbaculispora grandegrnulata*, *Verrucosisporites*
197 *andersonii*, and *Vittatina cf. scutata* (Figs. 6, 7).

5. Correlation and conclusions

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

208 In the Yemen Akbarah and Kuhlan formations, the presence of common
209 cingulicamerate spores (e.g. *Cristatisporites* spp.) and monosaccate pollen, and the presence
210 of *Brevitriletes cornutus*, *B. parmatus*, *Deusilites tentus*, *Dibolisporites disfacies*,
211 *Microbaculispora tentula* and *Verrucosisporites andersonii*, as well as the presence of
212 *Anapiculatisporites concinnus* and *Spelaeotriletes triangulus* suggest a range within the
213 2165A to 2141A biozones (Fig. 8). However the presence of *Ahrensiporites cristatus* and
214 *Wilsonites australiensis* indicates that the section is most likely of 2165A age.

215 This correlation (Fig. 8) indicates the widespread nature of glacial sediments of a
216 narrow biostratigraphic age range (the Oman AK P5 Production Unit) in basins across part of

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217 the north Gondwana margin. Unpublished work by Jan (2011) in other parts of the Salt and
218 Khisor ranges in Pakistan, although not fully representing the full extent of Upper
219 Carboniferous stratigraphy, do not show the presence of the oldest Oman AK P1 Production
220 Unit of 2159 Biozone age. Similarly, the Akbarah Formation at Kuhlan in Yemen rests on
221 metamorphosed basement. It is interesting to speculate on the apparent absence of the oldest
222 Oman P1 Production Unit in these parts of Yemen and Pakistan. This may relate to the fact
223 that salt withdrawal and dissolution was more common in south Oman (Heward, 1990),
224 creating the accommodation space for these earliest of Arabian Carboniferous glacial
225 sediments.

226 The Tobra Formation in Zaluch Nala, Pakistan lacks the deglaciation sequence of
227 2141 A and 2141B Biozone age that is common in Oman (see for example Stephenson et al.,
228 2007). This is an indication of either non-deposition during the deglaciation period, or
229 erosion associated with the unconformity between the Tobra Formation and the overlying red
230 bed Warchha Formation (Jan and Stephenson, 2011). However the three samples from the
231 Tobra Formation at the Choa Road section in the eastern Salt Range are assignable to the
232 2141B Biozone of Penney et al. (2008). In Oman, the 2141B Biozone is closely associated
233 with the Rahab Shale Member, a widespread shale facies in South Oman which is considered
234 to represent the final Permian deglaciation in the form of a large melt-out lake (Stephenson et
235 al. 2005; Fig. 8). It is interesting to speculate whether the ‘Tobra shale’ correlates with the
236 Rahab Shale Member.

237 **Acknowledgments**

238 Mike Stephenson publishes with the permission of the Director, British Geological
239 Survey.

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343 **Figure Captions**

344 Figure 1. Locations of studied sections on reconstruction of Gondwana after Angiolini et al.
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49 345 (2007). 1, Yemen; 2, Interior Oman; 3, Salt Range, Pakistan. For details of locations of
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51 346 studied sections on modern maps see Stephenson et al. (2005) for Oman, Jan and Stephenson
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53 347 (2011) for Pakistan, and Stephenson and Al-Mashaikie (2011) for Yemen. The Choa Road
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55 348 section near Khewra in the eastern Salt Range is at GPS N 32 39 57, E 72 59 08.8.
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349 Figure 2. a) The Al Khlata Formation in Wadi Al Khlata, Oman showing diamictite overlying
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2 350 the striated surface of the Khufai Formation; b) Al Khlata Formation diamictite in Wadi Al
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4 351 Khlata; c) view of the Kuhlan and Akbarah formations at the type section of the Kuhlan
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6 352 Formation, Yemen; d) contact between Akbarah (lower) and Kuhlan (upper) formations; e)
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8 353 contact between the Tobra and Warchha formations, Khisor Range, Pakistan; f) view of the
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10 354 Tobra and Wargal formations, Zaluch Nala, western Salt Range, Pakistan; g) the Choa Road
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12 355 section near Khewra, eastern Salt Range, Pakistan; h) diamictite facies in the Tobra
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14 356 Formation of the Choa Road section.
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20 357 Figure 3. **Distribution of selected** palynomorph groups and taxa from the Yemen Kuhlan and
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22 358 Akbarah formations, Kuhlan, northwest Yemen. For details of section and lithology, see
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24 359 Stephenson and Al-Mashaikie (2011). **Blue squares indicate barren samples.**
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28 360 Figure 4. **Selected** palynomorphs from the Kuhlan and Akbarah formations, and the Tobra
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30 361 Formation, Zaluch Nala. Scale bars for each specimen. MPA and MPK numbers are British
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32 362 Geological Survey Collection codes. a) *Converrucosisporites grandegrnulatus*, MPA
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34 363 57518, S17/1, MPK 13908, Tobra Formation; b) *Microbaculispora tentula*, MPA 57511,
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36 364 T26, MPK 13913, Tobra Formation; c) *Vallatisporites arcuatus*, R44/2, MPA 60511, MPK
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38 365 14195, Kuhlan Formation; d) *Spelaeotriletes triangulus*, K61, MPA 60507, MPK 14199,
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40 366 Kuhlan Formation ; e) *Anapiculatisporites concinnus*, D40/1, MPA 58568, MPK 14205,
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42 367 Akbarah Formation; f) *Brevitriletes leptocaina*, T11/4, MPA 57512, MPK 13916, Tobra
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44 368 Formation; g) *Horriditriletes ramosus*, H11, MPA 57520, MPK 13921, Tobra Formation; h)
45
46 369 *Cannanoropollis janakii*, D40/2, MPA 60513, MPK 14192, Kuhlan Formation; i)
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48 370 *Cannanoropollis janakii*, G66, MPA 60511, MPK 14196, Kuhlan Formation.
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371 Figure 5. **Distribution of selected** palynomorph groups and taxa from the Tobra Formation,
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2 372 Zaluch Nala, Pakistan. For details of section and lithology, see Jan and Stephenson (2011).

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5 373 **Blue squares indicate barren samples.**

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7
8 374 Figure 6. Selected palynomorph groups and taxa from the Tobra Formation, Choa Road
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10 375 section, near Khewra, Pakistan.

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14 376 Figure 7. **Selected** palynomorphs from the Tobra Formation, Choa Road section. Scale bar
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16 377 shown in (a). MPA and MPK numbers are British Geological Survey Collection codes. a)

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18 378 *Microbaculispora tentula*, B55, MPA 58401, MPK 14358; b) *Lophotriletes sparsus*, F58/3,

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20 379 MPA 58401, MPK 14359; c) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK

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22 380 14360, proximal focus; d) *Converrucosisporites confluens*, L61/2, MPA 58402, MPK 14360,

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24 381 distal focus; e) *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, proximal focus; f)

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26 382 *Lophotriletes sparsus*, M66/4, MPA 58402, MPK 14361, distal focus; g)

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28 383 *Converrucosisporites cf. confluens*, M64, MPA 58403, MPK 14362. h) *Alisporites*

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30 384 *indarraensis*, E44/2, MPA 58401, MPK 14363; i) *Alisporites indarraensis*, G42/4, MPA

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32 385 58402, MPK 14364; j) *Hamiapollenites fusiformis*, C53/3, MPA 58401, MPK 14365; k)

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34 386 *Striatopodocarpites cancellatus*, Q60/2, MPA 58401, MPK 14366; l) *Protohaploxypinus*

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36 387 *limpidus*, U49, MPA 58401, MPK 14367; m) *Cycadopites cymbatus*, T58/2, MPA 58403,

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38 388 MPK 14368; n) *Cycadopites cymbatus*, C52/3, MPA 58401, MPK 14369.

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40
41 389 Figure 8. Correlation of Oman, Yemen and Pakistan sections. **'PDO production units' are**

42
43 390 **lithological subdivisions of the Al Khlata Formation similar to lithostratigraphic members**

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45 391 **(see Penney et al. 2008 for more detail).**

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52 392 Table 1. Main characteristics of the biozones of Penney et al. (2008).

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Figure 1

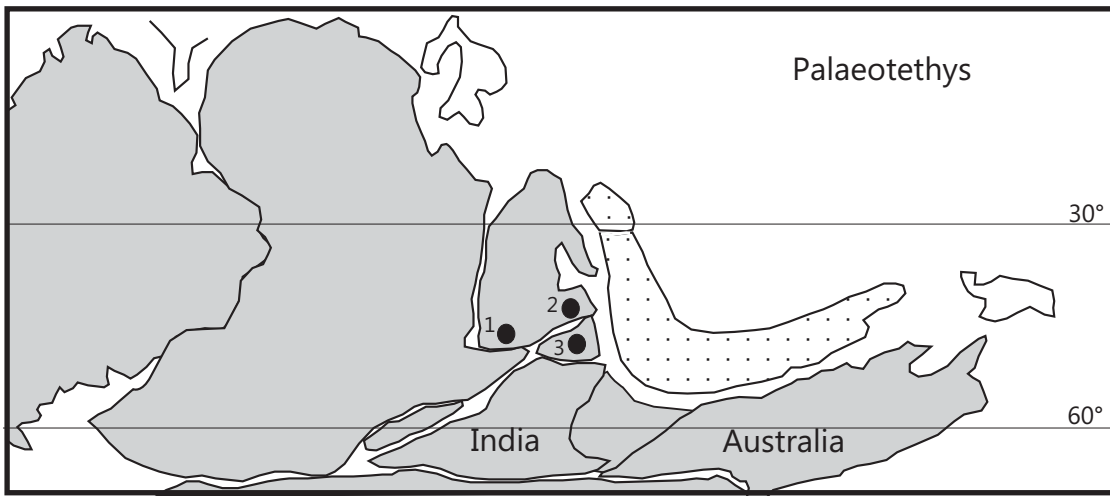


Fig 1

Figure 2

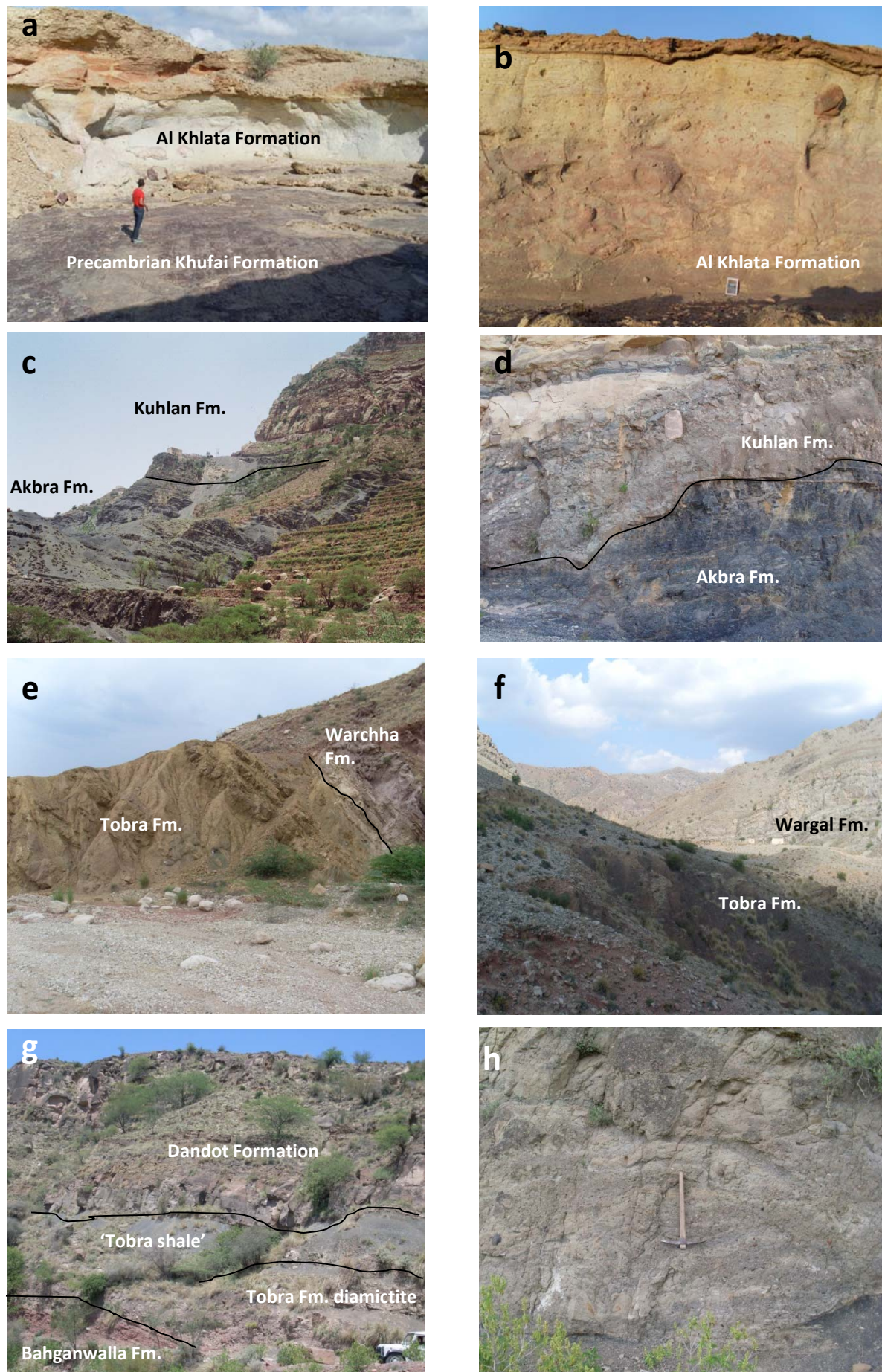


Fig 2

Figure 3

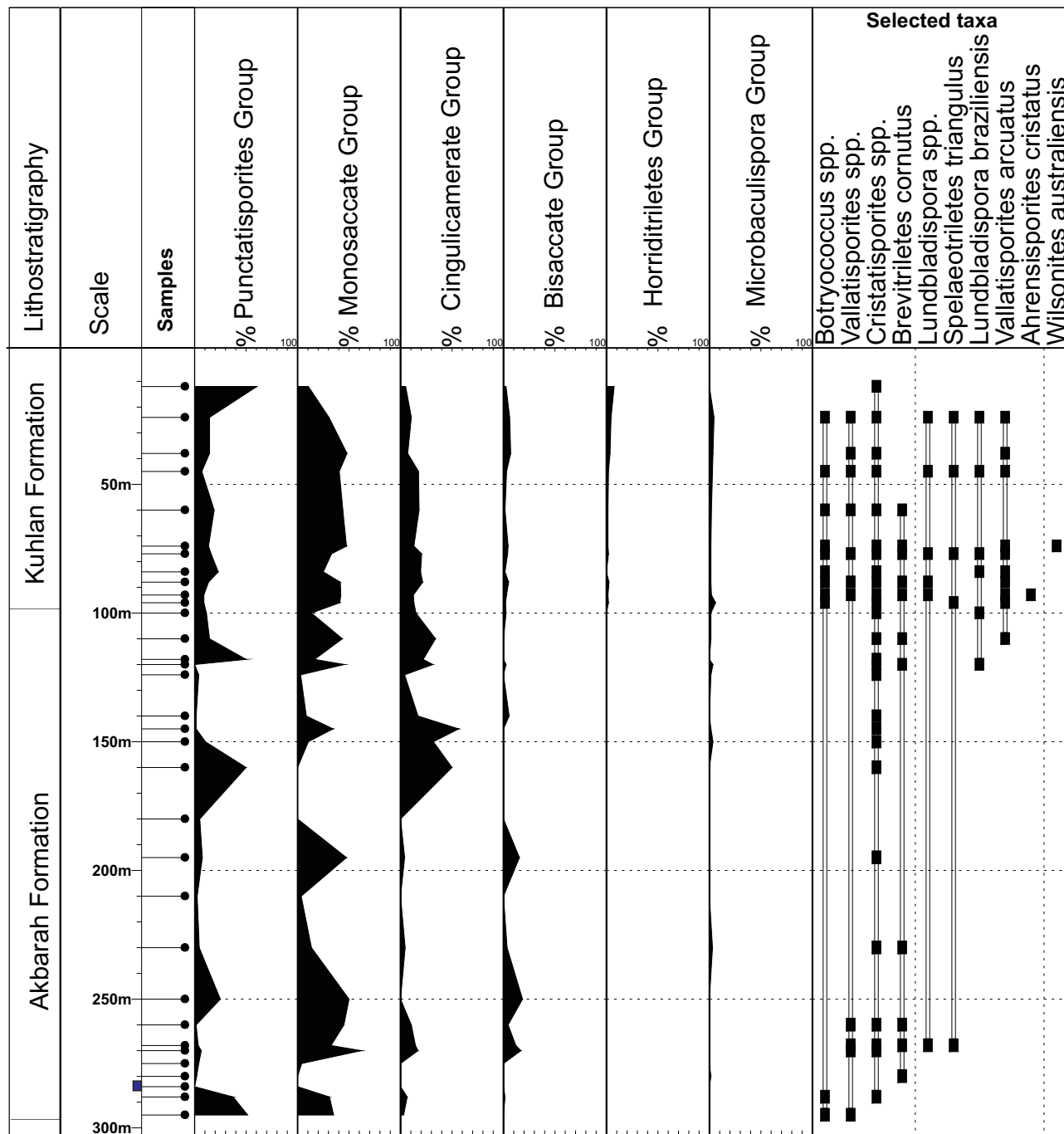


Fig 3

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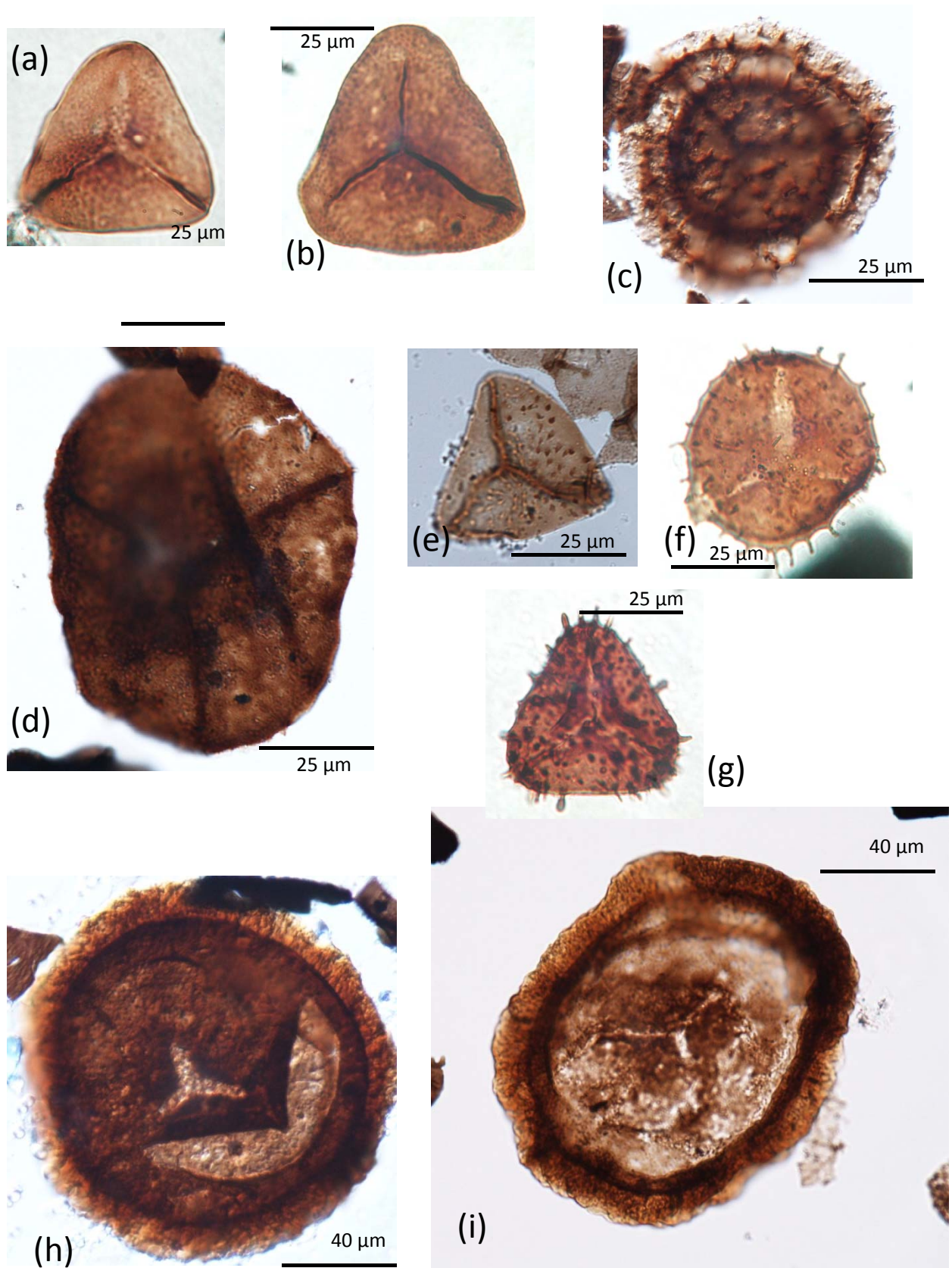


Fig 4

Figure 5

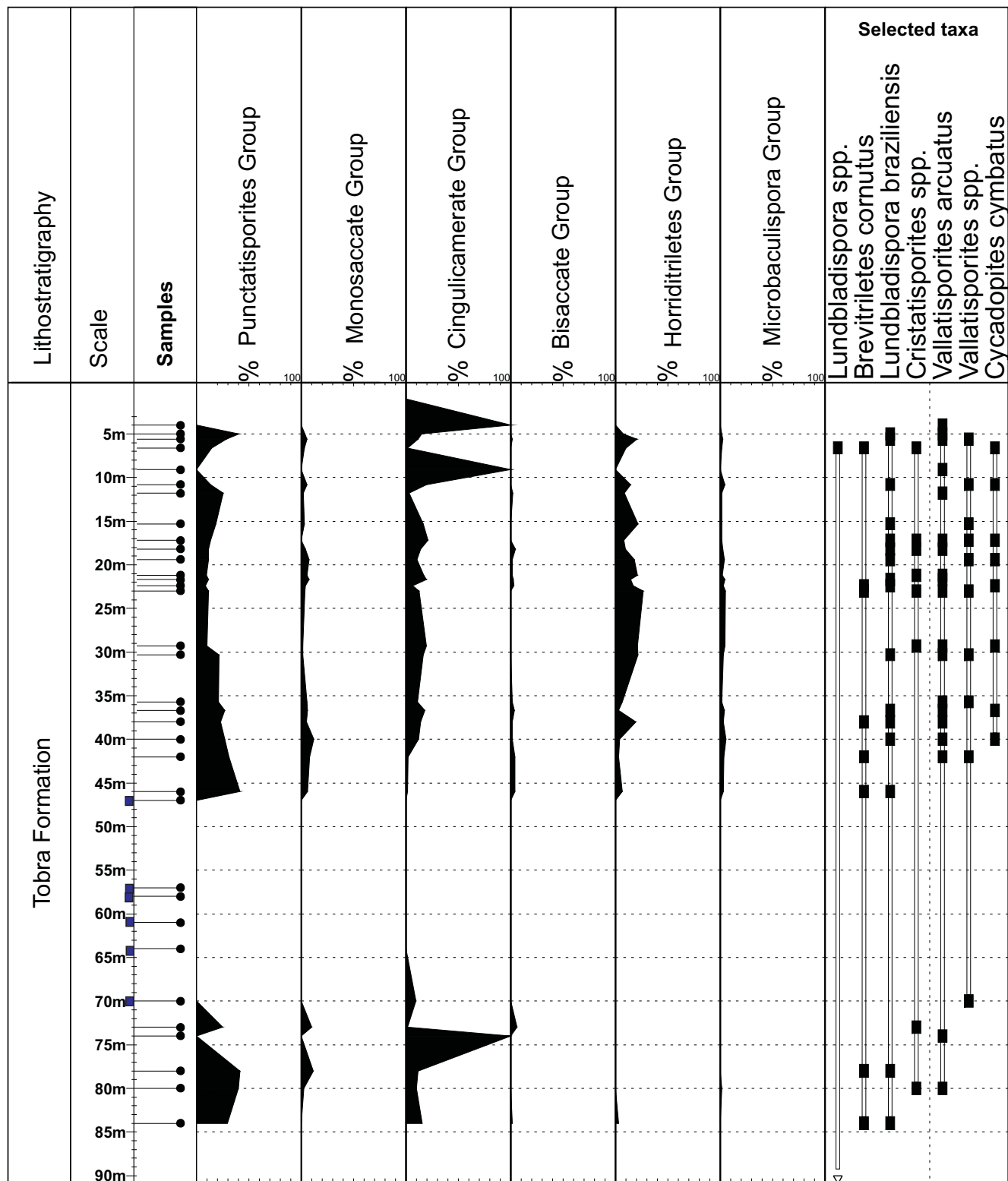


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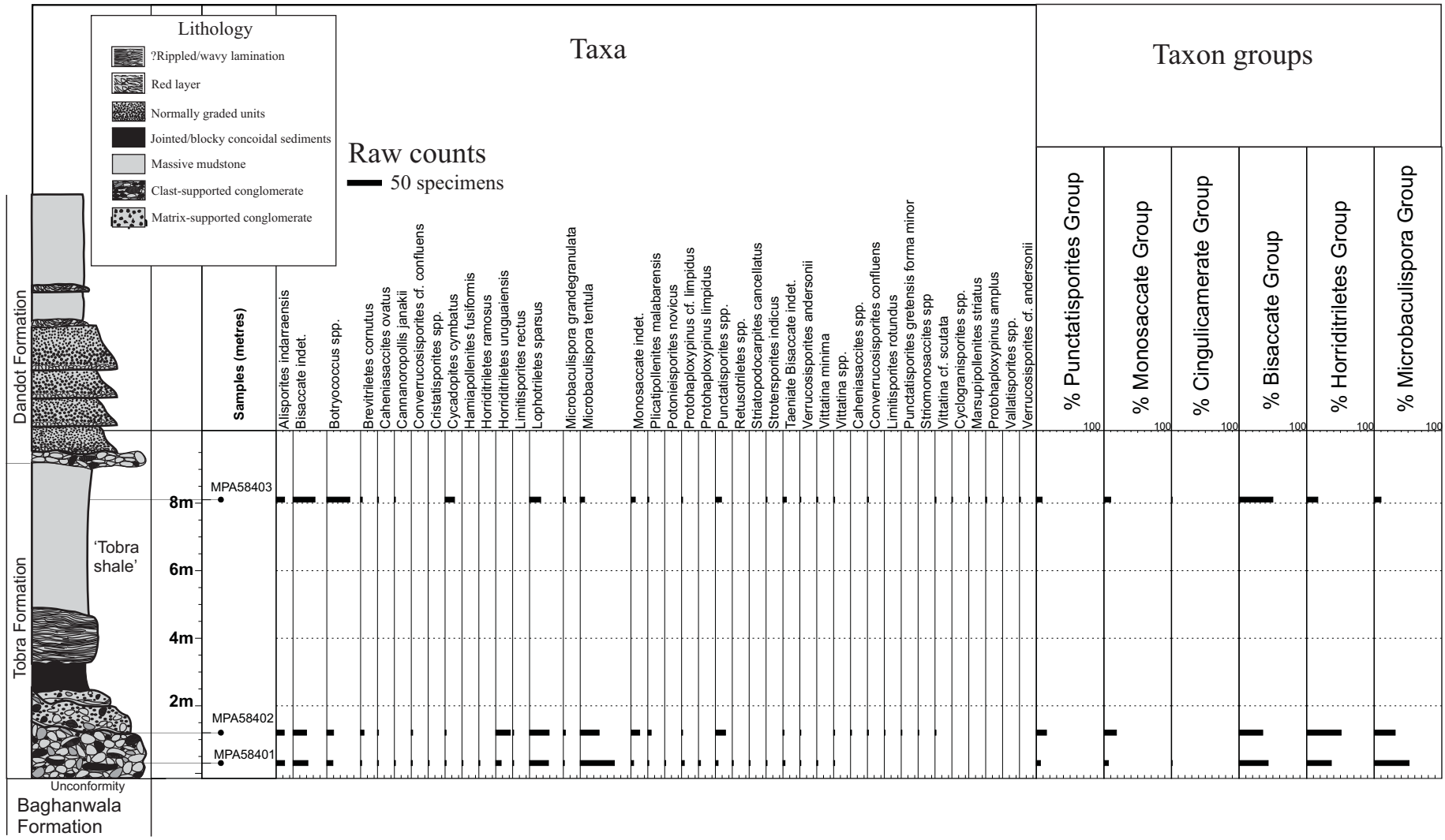


Fig 6

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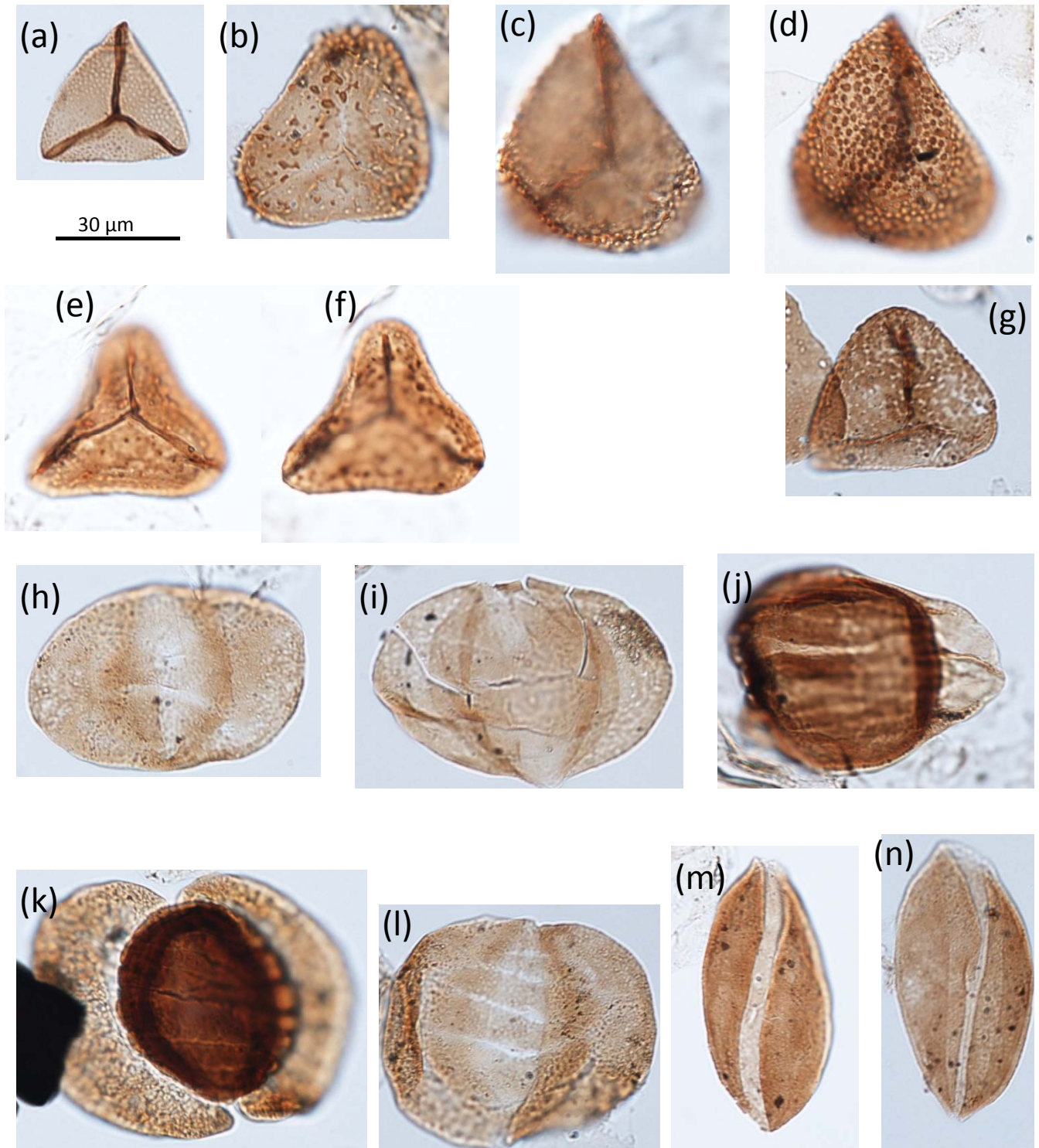


Fig 7

Figure 8

System/stage		Permian		Carboniferous		Stratigraphy		Biozone		PDO Production Units		Correlative range of lower Kuhlan Fm. and Akbarah Fm.		Correlative range of Tobra Fm., Zaluch Nala		Correlative range of Tobra Fm., eastern Salt Range, Choa Road section.																																																																																																																																																		
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Carboniferous	Al Khilata Fm.	Unayzah B	L. Gharif Mb.	Unayzah A	OSPZ2	2141B	AK P1 Production Unit	Biozone A	2141A	2165B	AK P5 Production Unit	Biozone B	Hiatus?	Biozone C																																																																																																																																																				
																			Unayzah C	OSPZ1	2159	AK P9 Production Unit	Biozone D																																																																																																																																											

Fig 8

Table 1

Biozone	Main characteristics
2159A	Abundance of <i>Punctatisporites</i> 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 <i>Punctatisporites</i> spp. does not exceed 90% of assemblages.
2165A	(1) the Cingulicamerate Group constitutes up to approximately 30% of the assemblages; and (2) the <i>Microbaculispora</i> Group constitutes approximately 5% of assemblages.
2165B	(1) <i>Horriditriletes</i> Group constitutes between 5 and 10%, or up to 20% of assemblages; and (2) <i>Microbaculispora</i> 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) <i>Cycadopytes cymbatus</i> is rare towards the base but increases to 5 to 10% of assemblages towards the top of the biozone.
2141B	(1) The <i>Microbaculispora</i> Group represents greater than 10% and can constitute up to 60% of assemblages, in addition the <i>Microbaculispora</i> Group is more abundant than the <i>Horriditriletes</i> Group; (2) <i>Cycadopytes cymbatus</i> makes up 5 to 10% of assemblages; and (3) the Cingulicamerate Group are extremely rare or absent.
2141C	The <i>Microbaculispora</i> Group represents more than 10% of assemblages, but the <i>Horriditriletes</i> Group exceeds it in numbers, reaching 30% or more.