

Correlation of the Lower Permian surface Saiwan Formation and subsurface Haushi limestone, Central Oman

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ABSTRACT

The palaeontology of the Saiwan Formation (Lower Permian) of the Al-Huqf outcrop area, Central Oman, has been the subject of significant study, but that of approximately equivalent beds in the subsurface (the Haushi limestone and 'basal sandstones' of the lower Gharif member) has been unknown until now. This has meant that the precise relationship between the surface and subsurface units has been poorly understood. A new subsurface brachiopod study has allowed a four-fold biozonation that correlates the surface Saiwan Formation with the subsurface Haushi limestone, implying that previous direct correlation of the Saiwan Formation with the lower Gharif member is not correct. Overall the brachiopod fauna of the subsurface is of lower diversity than that of the outcropping Saiwan Formation, suggesting deposition in quieter and deeper marine settings. The occurrence of a fusulinid assemblage with *Pseudofusulina* ex gr. *karapetovi* *karapetovi* Leven, the first such record in Gondwana, suggests a Sakmarian age for the Haushi limestone, and brachiopod data supports this determination. Subsurface Haushi limestone palynological assemblages, though diverse, are poorly preserved, and no palynomorphs have been recovered from equivalent surface outcrops. However, the distribution of autochthonous algal spores in three of the subsurface Haushi limestone sections suggest a local biozonation that is consistent with that indicated by brachiopods, while the terrestrially-sourced palynomorphs in the subsurface Haushi limestone sections indicate an OSPZ3c age. Surprisingly the sections contain no palynomorphs of unequivocal marine origin. Fusulinids indicate that a Sakmarian age for OSPZ3c is more likely than the Artinskian age suggested by previous palynological studies. The terrestrially sourced palynomorphs also suggest correlation of the carbonates of the Haushi limestone with the highest part of the clastic lower Gharif Member in South Oman, above the *Ulanisphaeridium omanensis* Biozone or Maximum Flooding Shale in that area. Using the new biozonation, the distribution of facies has been mapped for three time slices. This reveals an increase in carbonate deposition during the Sakmarian due to distancing and deepening of the terrigenous source, coupled with climatic warming, culminating with a regressive trend at the end of the cycle. A progressive increase in carbonate deposition is recorded westward into the basin.

INTRODUCTION

In central Interior Oman, Lower Permian strata are represented by the Al Khlata and Saiwan formations at outcrop (Figure 1) and by the Al Khlata Formation and the lower and middle Gharif members in the subsurface. Correlation of these units, particularly the Saiwan Formation and the lower Gharif member is not understood (see Angiolini et al., 2004; Osterloff et al., 2004). In addition, the lithostratigraphic nomenclature needs to be clarified because the same names have been used with different meanings in the surface and subsurface. For example the Gharif Formation [*sensu* Dubreuilh et al. (1992)] at outcrop does not correspond to the Gharif Formation in the subsurface [*sensu* Hughes Clarke (1988)] (Figure 2).

In the subsurface, the Gharif Formation *sensu* Hughes Clarke (1988) was informally subdivided into three members: the lower, middle and upper Gharif members, using subsurface sections (Hughes Clarke, 1988; Guit et al., 1995). In South Oman, the lower part of the lower Gharif member is a complex of fluvial and fluviodeltaic clastics succeeded by marginal marine clastics toward the top; while in Central and North Oman similar lower clastics, the 'basal sandstones' of Osterloff et al. (2004), give

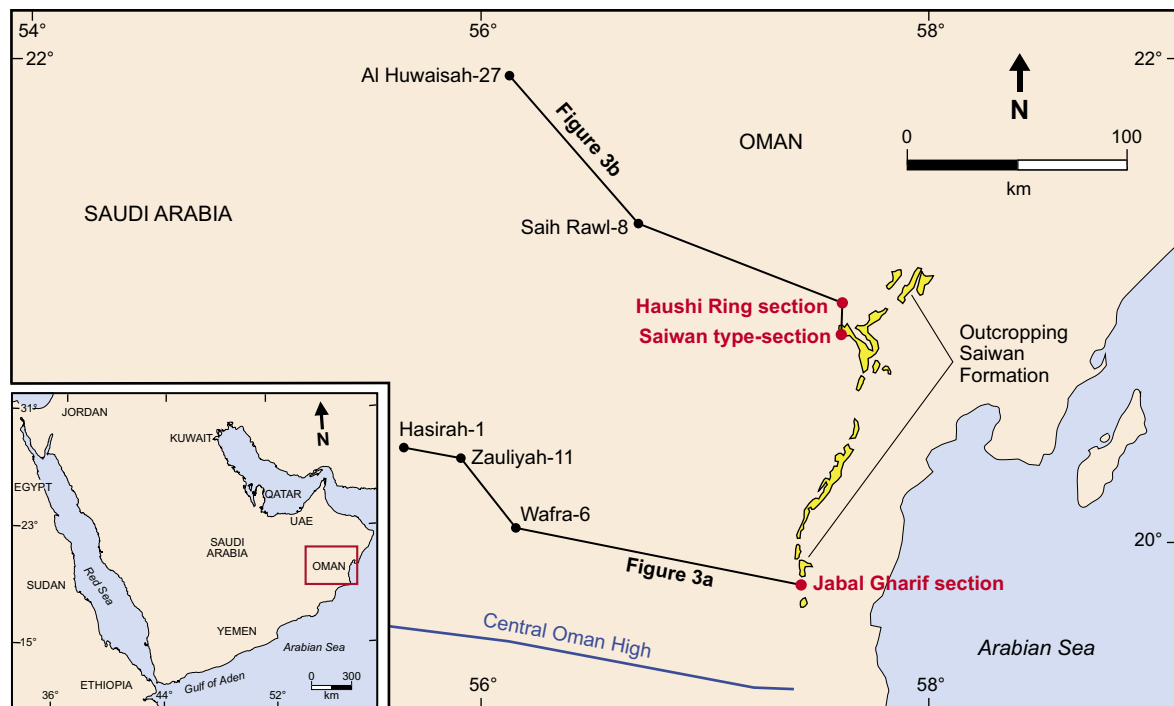


Figure 1: Locations of well and outcrop sections. The outcrop terminology used here is that used by Bureau de Recherche Géologiques et Minières (BRGM). The ‘Haushi Ring’ is also known as the ‘Haushi Anticline’, and ‘Jabal Gharif’ comprises sections lying between Wadi Gharif and Akaba Woolley.

way to bioclastic limestone, known to many PDO (Petroleum Development Oman) geologists as the Haushi limestone (Figure 2). The ‘basal sandstones’ are an irregular 0–30-m-thick blanket of shallow-marine shoreface and periglacial deposits that probably infill remnant topography of the Al Khlata Formation. The ‘basal sandstones’ in the subsurface consist of an unusual interbedding of bioturbated shoreface shaly sands, cross-bedded and massive sands, and black shales with fine laminae and starved ripples. The subsurface ‘basal sandstones’ lack macrofossils, but bioturbated intervals show a diverse marine trace fossil assemblage including *Skolithos*, *Planolites*, *Rhizocorallium* and *Ophiomorpha*. The Haushi limestone is a mixed clastic-carbonate unit that is recognised as a wireline log marker in the subsurface of Central Oman and a low but prominent ridge-former in the outcrops. It thickens westward into the Rub’ Al-Khali Basin. It consists of a stack of five or more 5–10-m-thick coarsening-upward parasequences. The carbonate content of each increases upwards also. A shale at the base of the Haushi limestone has the wireline log characteristics of a maximum flooding event (P10 of Sharland et al., 2001), though it does not contain open marine macrofossils.

The surface Saiwan Formation was introduced by Dubreuilh et al. (1992, p. 26) for the marine fossiliferous sandy limestones previously informally named Haushi limestone by Hudson and Sudbury (1959). Further on in the explanatory notes of the Khaluf map, Dubreuilh et al. (1992, p. 29) added that the lower Gharif member of Hughes Clarke (1988) corresponds to their newly defined Saiwan Formation. According to Angiolini et al. (2003), in the type section, the Saiwan Formation unconformably overlies red fine-grained sandstones and green siltstones ascribed to the Rahab shale by Roger et al. (1992, p. 13), or directly – as in the Haushi Ring - the diamictite of the Al Khlata Formation. In the southern Jabal Gharif area, the Saiwan Formation overlies cross-laminated sandstones or diamictites (Angiolini et al., 2003). At its top, the Saiwan Formation is believed to be bounded by an unconformity, separating it from the overlying continental Gharif Formation *sensu* Dubreuilh et al. (1992, p. 29). The latter authors restricted the name Gharif Formation to the middle and upper informal units of Hughes Clarke (1988) (Figure 2).

In this paper, following previous studies, we will use the term Saiwan Formation for the outcropping succession and ‘basal sandstones’ and Haushi limestone (which together constitute the lower Gharif member) for subsurface rocks.

Attempts at correlation between surface and subsurface have also been hampered by the lack of conjunct biostratigraphic studies. The primary tool of subsurface correlation is palynology and this has been studied in great detail in the lower Gharif member (Stephenson and Osterloff, 2002; Stephenson et al., 2003), but the lack of palynological yield in surface sections has meant that palaeontological correlation has not been possible between the surface and subsurface. Conversely, surface correlations are based chiefly on macropalaeontological data, the macropalaeontology of approximately equivalent beds in the subsurface having not been studied until now.

This paper focuses on a close comparison between the outcropping Saiwan Formation and subsurface lower Gharif member using biostratigraphic correlation. Data from analysis of palynology and macro- and micropalaeontology of five partly cored PDO wells (Hasirah-1, Zauliyah-11, Wafra-6, Saih Rawl-8 and Al Hawaisah-27) are compared with previous data collected from outcrop studies (Angiolini et al., 2003, 2004), with the objective of establishing an integrated palaeontological biozonation based on fusulinids, brachiopods and palynomorphs and a high-resolution correlation of subsurface and surface.

LITHOSTRATIGRAPHY OF THE SAIWAN FORMATION AND HAUSHI LIMESTONE

The Saiwan Formation was described by Angiolini et al. (2003, 2004) from surface sections at Jabal Gharif, Saiwan and the Haushi Ring (Figures 1 and 3). The detailed lithological sequence for the wells and outcrop sections is shown in Figure 3. At the type-section at Saiwan, it consists of coarse-grained, cross-laminated bioclastic sandstones, red and green mudrocks, and sandy calcarenites passing upward to coarse-grained and cross-laminated sandy calcarenites, bioclastic limestones, and marlstones. The P10 Maximum Flooding Surface (MFS) of Sharland et al. (2001, p. 169) is located in the shales immediately below bed OL15 (Figure 3b). At the Haushi Ring, the Saiwan Formation is dominated by bioclastic sandstones, and sandy bioclastic limestones with poorly exposed shales. The position of the MFS through this section is more difficult to assess; the most likely horizon is the interval OM35 to OM27bis, which records a significant increase in delicate branching bryozoans, thought to represent relatively deep water. In the Jabal Gharif area, the Saiwan Formation is thinner (5–15 m) and more calcareous, comprising a few metres of basal bioclastic arenites passing upward to bioclastic sandy limestones. In this section the P10 MFS is placed below bed OL108 and coincides with the base of the Saiwan Formation.

Between 100–150 km to the west of Jabal Gharif, the Haushi limestone is penetrated in three of the cored wells examined: Hasirah-1 (between 2,654.8 m and 2,610 m), Zauliyah-11 (between 2,470 m and 2,442 m) and Wafra-6 (between 1,936 m and 1,907.8 m) (Figures 1 and 3). The lowest part of the Haushi limestone has been studied in the lower cores of Hasirah-1; here it consists of laminated calcareous siltstones passing to dark micaceous quartz-sandstones, to burrowed sandstones and to bioclastic calcareous sandstones. The upper 20–30 m of Hasirah-1, Zauliyah-11 and Wafra-6 contain four broadly defined units, a lower bioclastic limestone and shale unit, followed by a clastic shale and sandy unit and then by a thick oolitic limestone unit. The highest unit of the Haushi limestone in the three well sections is a thin laminated siltstone. The mostly non-marine shales and sandstones of the middle Gharif member *sensu* PDO [= Gharif Formation *sensu* Dubreuilh et al. (1992)] overlie the succession in the three wells. To the northwest of the Haushi Ring, the Haushi limestone is penetrated

HAUSHI-HUQF OUTCROP		SUBSURFACE	
Dubreuilh et al. (1992)	Roger et al. (1992) Angiolini et al. (2003)	Hughes Clarke (1988); PDO usage	
Gharif Formation	Gharif Formation	Gharif Formation	upper Gharif mbr
			middle Gharif mbr
Saiwan Formation	Saiwan Formation	lower Gharif mbr	Haushi limestone "basal sst"
Al Khlata Formation	Rahab shale Al Khlata Formation	Rahab mbr	Al Khlata Formation

Figure 2: Nomenclature of the Lower and Middle Permian formations in the surface and subsurface of Central Oman. No correlation is implied. The members and other constituent units of the Gharif Formation are informally named, hence these are referred to with a lower case first letter in the word 'member'.

between 3,875 m and 3,863.4 m in the partly cored Al Huwaisah-27 well, while the 'basal sandstones' are penetrated between 2,977.6 m and 2,944.6 m in Saih Rawl-8 (Figure 3b). The Haushi limestone in Al Huwaisah-27 consists of bioclastic limestones and thin, intercalated black shales. In Saih Rawl-8 the 'basal sandstones' are a monotonous succession of loosely cemented sandstones, quartz-sandstones, burrowed sandstones and intercalated black shales.

FOSSIL CONTENT OF THE SAIWAN FORMATION AND HAUSHI LIMESTONE

The very rich faunal content of the Saiwan Formation includes brachiopods, bivalves, gastropods, conularids, bryozoans, echinoderms, barnacles, ostracods, fishes, asterozoans, nautiloids and few ammonoids (Angiolini et al. 1997, 2003, 2004; Angiolini and Bucher, 1999). Sections of the Saiwan Formation have been sampled for palynology on numerous occasions (PDO, oral communication, 2004), but have been found to be almost exclusively barren, probably due to modern weathering in surface rocks.

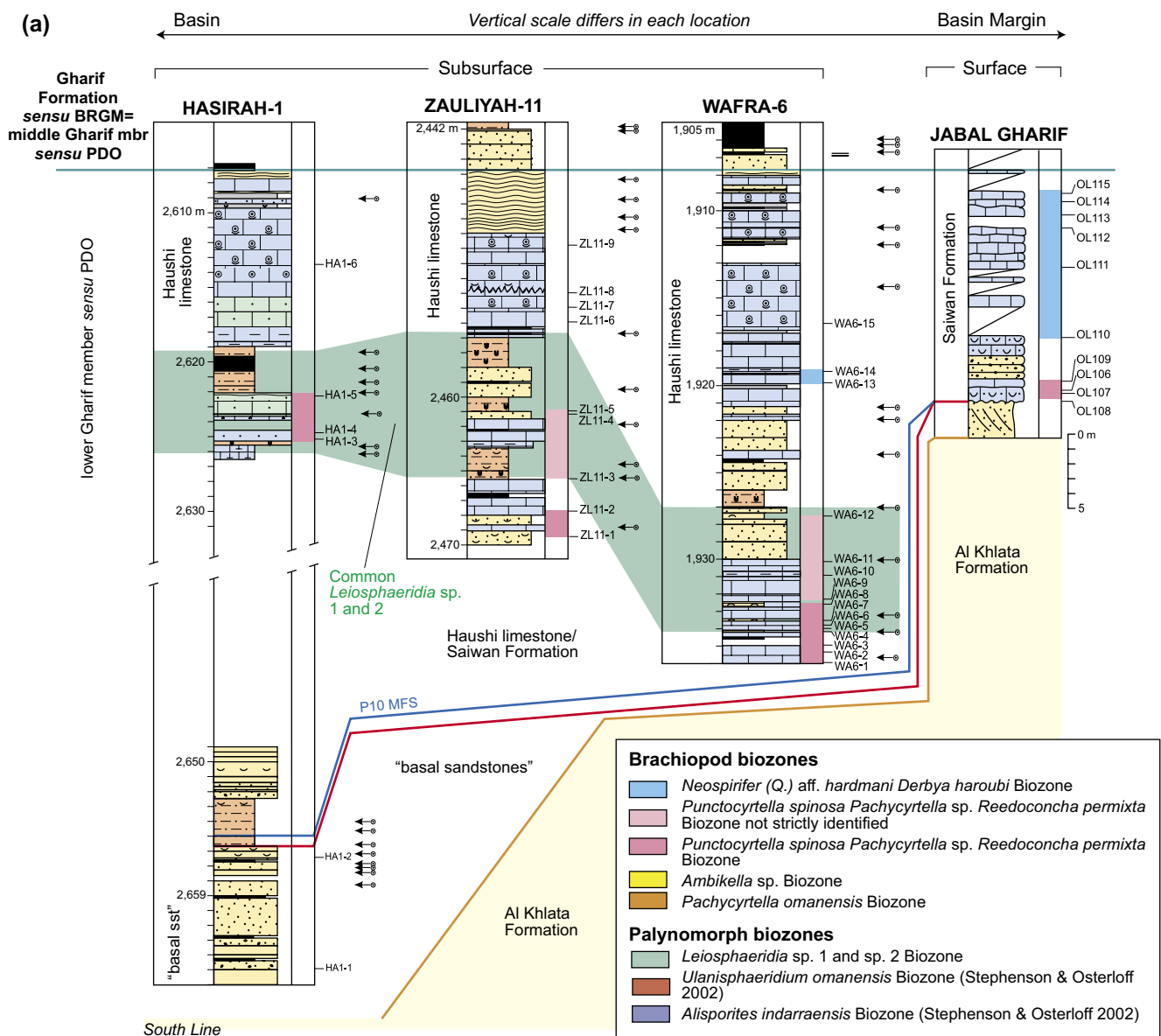
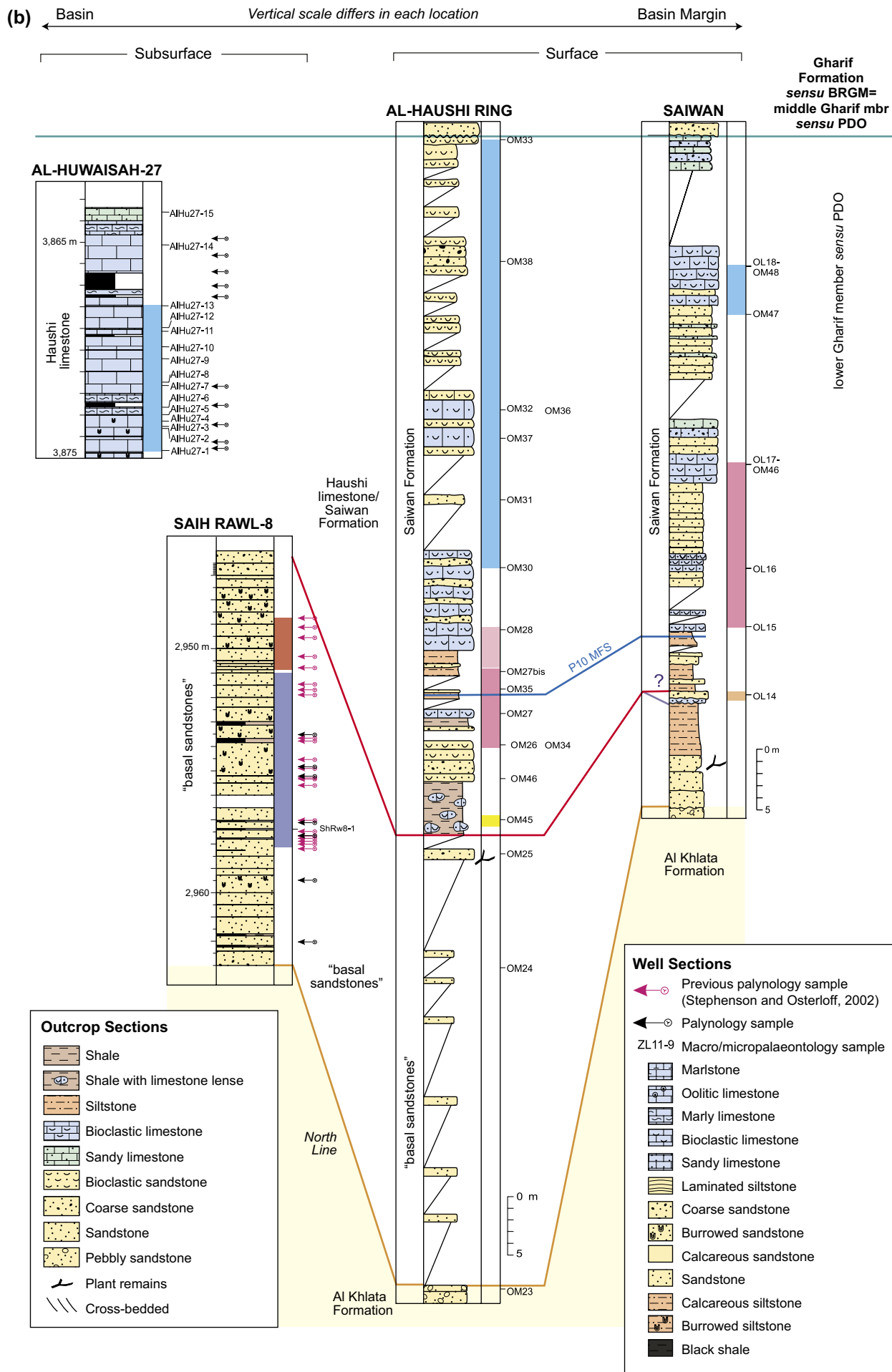


Figure 3a and b: Correlation chart of well sections of the Haushi limestone and three outcrop sections of the Saiwan Formation of Angiolini et al. (2003). The well and outcrop sections are arranged along two lines from E to WNW: (a) south line from Jabal Gharif to Wafra-6, to Zauliyah-11 and to Hasirah-1; and (b) north line from Saiwan, to Haushi Ring, to Saih Rawl-8 and to Al Huwaisah-27. Coloured lines separate the Gharif Formation (*sensu* BRGM) on top, the Haushi limestone/Saiwan Formation, the 'basal sandstones' and at the base, the Al Khlata Formation.



In the subsurface, fusulinids, algae, brachiopods, bryozoans, gastropods, echinoderms and small foraminifers are common. Wafra-6 contains the highest biodiversity of the four well sections, as brachiopods and the associated biota occur continuously over about 19 metres, from the base of the studied section to the base of the oolitic limestones that occur at the top of the section.

The occurrence of fusulinids in Hasirah-1 and Wafra-6 is significant because this is their first published record in the Haushi limestone, and also one of the first records of fusulinids in the Lower Permian succession of Gondwana, including Australia, India, Antarctica, southern Africa and South America. Their discovery now allows direct correlation of the Lower Permian succession of Gondwana with the Uralian stratotypes; this correlation was previously hampered by lack of fusulinids (Archbold, 2001 a). Besides resolving correlation, their occurrence may suggest that the Haushi environment was characterise by relatively warm water since these foraminifers usually avoid cold water. Fusulinids are found in two samples WA6-11 and HA1-4. WA6-11 contains (Plate 1, Table 1): *Pseudofusulina inobservabilis* Leven, 1993, *Pseudofusulina* ex gr. *karapetovi karapetovi* Leven, 1993, *Pseudofusulina* aff. *karapetovi tezakensis* Leven, 1993, *Pseudofusulina licis* Leven, 1993, *Pseudofusulina incompta* Leven, 1993 and *Pseudofusulina* (?) sp. HA1-4 contains *Pseudofusulina incompta* Leven, 1993, *Pseudofusulina* cf. *insignis* Leven, 1993, *Pseudofusulina* aff. *karapetovi tezakensis* Leven, 1993 and *Pseudofusulina* cf. *inobservabilis* Leven, 1993.

Among the brachiopods (Plates 2 and 3, Table 1), worthy of note is the occurrence of *Coledium* sp. in Wafra-6 and *Neochonetes* (*Sommeriella*) sp. in Wafra-6 and Hasirah-1, since these are the first records of these taxa in the Lower Permian succession of Oman. The records are also significant because

Table 1
Range chart for brachiopods and fusulinids.

BRACHIOPODS		FUSULINIDS														
		<i>Neochonetes</i> (<i>Sommeriella</i>) sp.	<i>Derbya heroubi</i>	<i>Reedocorcha permixta</i>	<i>Coledium</i> sp.	<i>Punctocytella spinosa</i>	<i>Neospirifer</i> (<i>Quadrospira</i>) aff. <i>hardmani</i>	<i>Gilledia</i> sp.	<i>Pseudofusulina incompta</i>	<i>Pseudofusulina</i> cf. <i>insignis</i>	<i>Pseudofusulina</i> aff. <i>karapetovi tezakensis</i>	<i>Pseudofusulina</i> cf. <i>inobservabilis</i>	<i>Pseudofusulina inobservabilis</i>	<i>Pseudofusulina</i> ex gr. <i>karapetovi karapetovi</i> aff.	<i>Pseudofusulina licis</i>	<i>Pseudofusulina</i> (?) sp.
Zauliyah-11	ZL11-5	0	6	0	0	0	0	0								
	ZL11-4	0	5	0	0	0	0	0								
	ZL11-3	0	6	0	0	0	0	0								
	ZL11-2	0	1	1	0	0	12	2								
	ZL11-1	0	0	0	0	1	1	0								
Hasirah-1	HA1-5	3	3	0	0	0	3	0	x	x	x	x				
	HA1-4															
	HA1-3	0	0	0	0	0	10	1								
Wafra-6	WA6-14	0	0	0	3	0	0	0								
	WA6-13	0	1	0	0	0	3	0								
	WA6-12	0	3	0	0	0	0	0								
	WA6-11								x		x		x	x	x	x
	WA6-9	0	1	0	0	0	0	0								
	WA6-8	3	12	4	0	0	2	0								
	WA6-7	2	4	2	0	0	0	0								
	WA6-5	2	4	7	0	0	5	1								
	WA6-4	0	4	6	0	0	0	0								
	WA6-3	0	0	3	0	0	0	0								
AI Huwaisah-27	AIHu27-11	0	0	0	0	0	3	0								
	AIHu27-10	0	0	0	0	0	3	0								
	AIHu27-9	0	0	0	0	0	2	0								
	AIHu27-8	0	0	0	0	0	5	0								
	AIHu27-7	0	3	0	0	0	1	0								
	AIHu27-6	0	2	0	0	0	4	0								
	AIHu27-5	0	1	0	0	0	3	0								
	AIHu27-4	0	3	0	0	0	0	0								
	AIHu27-3	0	6	0	0	0	0	0								
	AIHu27-2	0	0	0	0	0	10	0								
AIHu27-1	0	0	0	0	0	1	0									

X's Indicate presence

they increase brachiopod biodiversity in the Early Permian of Oman by one suborder (Chonetidina) and one order (Rhynchonellida). Both genera occur elsewhere in the Lower Permian succession of Gondwana and Peri-Gondwana. Their presence in the subsurface Haushi limestone rather than in the surface Saiwan Formation may indicate slightly deeper, quieter waters than the more proximal environment postulated for the Saiwan Formation. The newly recorded *Coledium* sp. in Wafra-6 is similar to *Coledium elvinia* Waterhouse, 1986 from the Sakmarian Elvinia Formation of the Bowen Basin (Eastern Australia), in its shape and strength of the lateral costae. It differs from *C. elvinia* in bearing 3 ribs instead of 2 in the ventral sulcus. Except for the occurrence of the two newly reported taxa, the brachiopod fauna of the subsurface Haushi limestone is of lower diversity than that of the outcropping Saiwan Formation, being dominated by *Derbyia haroubi* Angiolini, 1997, *Reedoconcha permixta* (Reed, 1932), *Neospirifer (Quadrospira) aff. hardmani* (Foord, 1890), and lacking the large and thick shelled Syringothyridid, which are abundant in the Saiwan Formation. This is again consistent with deposition in slightly deeper marine settings far from the source of terrigenous input.

Overall, pollen and spores are common in subsurface samples (Plate 4), but their preservation is poor, showing fragmentation and signs of pyrite damage. The most common taxa in Hasirah-1, Zauliyah-11, Wafra-6 and Al Huwaisah-27 are indeterminate bisaccate pollen (probably mainly poorly preserved specimens of *Alisporites indarraensis* Segroves, 1969), *Vesicaspora* spp., *Kingiacolpites subcircularis* Tiwari and Moiz, 1971, *Corisaccites alutas* Venkatachala and Kar, 1966 (or cf. *C. alutas*) and *Florinites flaccidus* Menéndez and Azcuy, 1973. Within these well sections there are no significant trends in terrestrially-derived palynomorphs, but a group of autochthonous algal palynomorphs shows some changes through the Hasirah-1, Zauliyah-11 and Wafra-6 sequences. In Hasirah-1, for example, between 2,619.48 m and 2,626.31 m, the algal palynomorphs *Leiosphaeridia* sp. 1 and 2 are common or abundant. In Zauliyah-11 the same taxa are common between 2,455.7 m and 2,465.5 m, and in Wafra-6 they are common between 1,927.04 m and 1,934.24 m. In addition, in Wafra-6, between 1,906.2 m and 1,906.73 m the probable autochthonous algal palynomorphs 'Large *Leiosphaeridia* sp. 1' and *Peroaletes* sp. B are common. The origin of these autochthonous algal palynomorphs is uncertain, but their lack of acanthomorphic sculpture suggests that they are unlikely to indicate fully marine conditions.

The palynological assemblages of Saih Rawl-8 are more diverse than those of Hasirah-1, Zauliyah-11, Wafra-6 and Al Huwaisah-27. The most common taxa are *A. indarraensis* Segroves, 1969, indeterminate monosaccate and bisaccate pollen, *K. subcircularis* Tiwari and Moiz 1971, *Microbaculispora tentula* Tiwari, 1965, *M. grandegrnulata* Anderson, 1977, *Protohaploxyypinus amplus* (Balme and Hennelly) Hart, 1964, *P. limpidus* (Balme and Hennelly) Balme and Playford, 1967 and *Horriditriteles ramosus* (Balme and Hennelly) Bharadwaj & Salujah, 1964. *Microbaculispora tentula* Tiwari, 1965, *M. grandegrnulata* Anderson, 1977 and *H. ramosus* (Balme and Hennelly) Bharadwaj and Salujah, 1964 are common between 3,001 m and 2,983.75 m, while the upper part of the core section contains more common *A. indarraensis* Segroves, 1969, *K. subcircularis* Tiwari and Moiz, 1971 and *Protohaploxyypinus* spp. The stratigraphically significant taxon *Ulanisphaeridium omanensis* Stephenson and Osterloff, 2002 occurs between 2,954.58 m and 2,948.98 m.

BIOZONATION AND CORRELATION

Brachiopods

Based on the brachiopod content of the Jabal Gharif, Saiwan and Haushi sections two biozones were established by Angiolini et al. (1997, 2003, 2004) in the outcropping Saiwan Formation: the *Pachycyrtella omanensis* Biozone in the basal bed of the formation and the *Reedoconcha permixta-Punctocyrtella spinosa* Biozone starting a few metres above and reaching the top of the formation. As the brachiopod composition is rather uniform through both the outcropping sections and the well sections, application of deterministic stratigraphic methods, such as the Unitary Associations method of Guex (1991), cannot improve the biostratigraphic zonation of Angiolini et al. (1997, 2003) hampering a detailed correlation. Superposition of statistical methods (cluster analyses based on Jaccard, Dice and Correlation coefficients) as well as taxonomic and biodiversity criteria (Margalef index, Shannon-Wiener index), can slightly improve the biozonation, identifying 4 biozones. These are in descending stratigraphic order:

- (4) *Neospirifer* (Q.) aff. *hardmani-Derbya haroubi* low diversity Assemblage Biozone;
- (3) *Punctocyrtella spinosa-Pachycyrtella* sp.-*Reedoconcha permixta* Assemblage Biozone;
- (2) *Ambikella* sp. Range Biozone; and
- (1) *Pachycyrtella omanensis* Range Biozone.

Biozones (3) and (4) can be traced from surface to subsurface, whereas biozones (1) and (2) are identifiable only locally in surface rocks (Figure 3). The *Pachycyrtella omanensis* Biozone is characterised by the dominance of *P. omanensis* Angiolini, 2001, alongside *Strophalosia* sp. and rare specimens of *Arctitreta* cf. *A. bioni* (Reed, 1932), *Trigonotreta* sp., *Callispirina* sp. and *Punctospirifer* sp. This biozone occurs only in the basal 60 cm of the Saiwan Formation at Saiwan. The *Ambikella* sp. Biozone contains the eponymous taxon and also rare specimens of *Reedoconcha permixta* (Reed, 1932) and *Gilledia* sp. This zone is restricted to the basal shales of the Saiwan Formation at Haushi. More interesting for their lateral reproducibility are the following two biozones which can be identified in the surface sections and most of the well sections. The *Punctocyrtella spinosa-Pachycyrtella* sp.-*Reedoconcha permixta* Assemblage Biozone shows the highest biodiversity (Shannon-Wiener index up to 2.2; Margalef index up to 2.8) and comprises, besides the index species, species of the genera *Neochonetes* (*Sommeriella*), *Derbyia*, *Arctitreta*, *Coleidium*, *Neospirifer*, *Trigonotreta*, *Subansiria*, *Cyrtella*, *Punctospirifer*, *Callispirina*, *Fletcherithyris* and *Gilledia*. This biozone has been identified in the Hasirah-1, Zauliyah-11 and Wafra-6 well sections as well as in the three outcropping sections. However, its occurrence in samples ZL11-3 to ZL11-5 in Zauliyah-11, as well as in sample OM28 at the Haushi Ring section, is still questioned, due to conflicting results in the statistical methods. The highest biozone is the *Neospirifer* (Q.) aff. *hardmani-Derbya haroubi* low diversity Assemblage Biozone, which is characterised by the numerical dominance and almost exclusive occurrence of the two index species. Shannon-Wiener and Margalef indices for the biozone are usually low, around 0.9–1.5 and 0.8–2.4. In fact, the two species also occur in the *Punctocyrtella spinosa-Pachycyrtella* sp.-*Reedoconcha permixta* Assemblage Biozone where, however, they are associated with a greater number of other taxa. The definition of this biozone may thus be questionable as it is chiefly based on a sharp decrease of biodiversity.

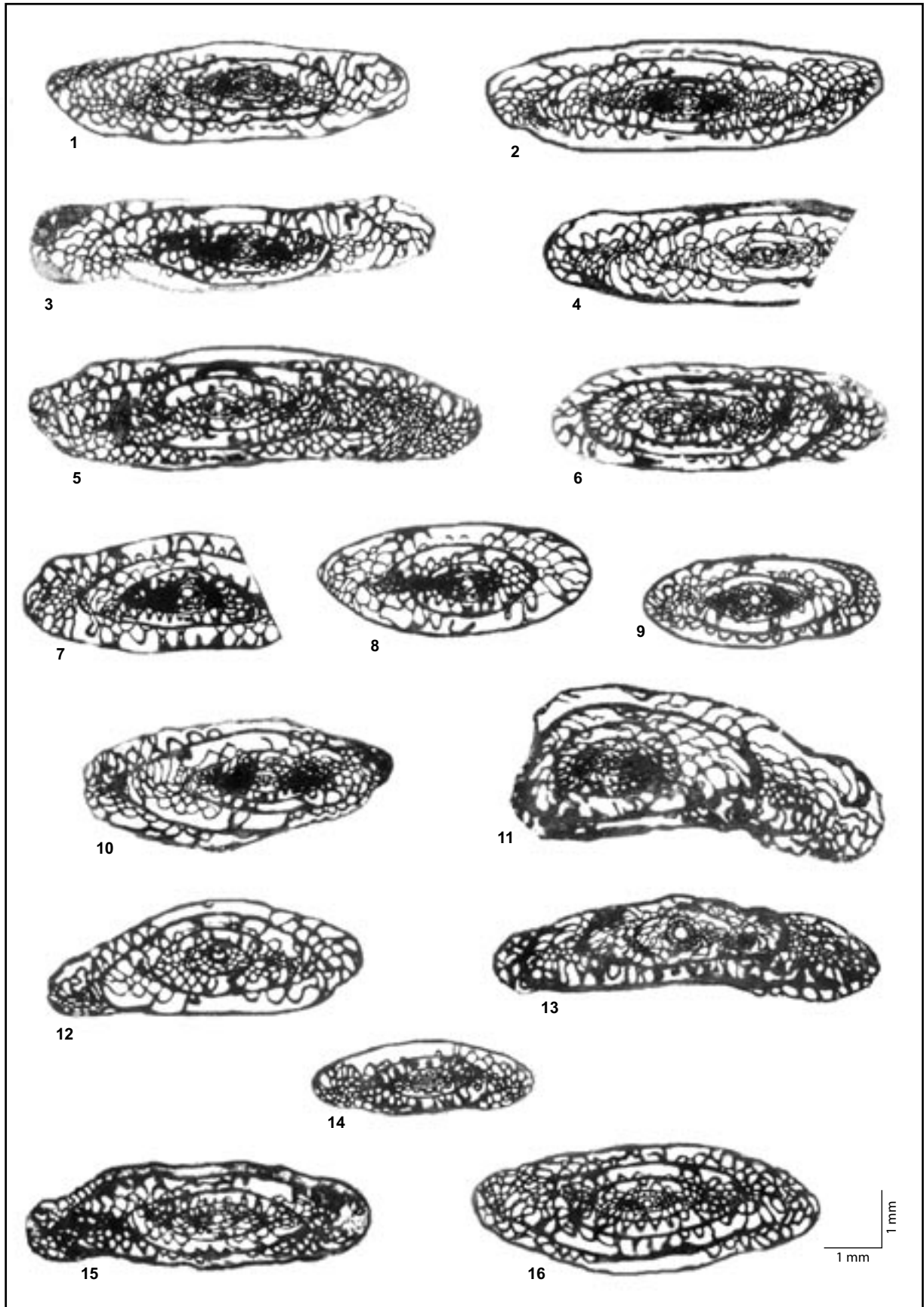
Palynology

Terrestrially sourced spores and pollen are closely similar in the Haushi limestone sections (Hasirah-1, Zauliyah-11, Wafra-6 and Al Huwaisah-27), and there is little doubt that, on palynological evidence, these sections are of the same age (Figure 4). Correlation of intervals within these sections using terrestrially sourced spores and pollen is difficult because there is little variation in these palynomorphs. However, there is variation in the autochthonous algal spores (spores produced by algae growing in the aquatic sedimentary environment), and the pattern of their occurrence can be used to characterise parts of the sections in the southern wells, Hasirah-1, Zauliyah-11 and

Plate 1 (opposite page): Fusulinids from the Haushi limestone. All thin sections are held at the Institute of Geology, Russian Academy of Sciences, Moscow, Russia. Magnification x 10.

- (1–3) *Pseudofusulina inobservabilis* Leven, 1993. Axial sections. Wafra-6 well section, sample WA6-11.
- (4) *Pseudofusulina* ex gr. *inobservabilis* Leven, 1993. Axial section. Wafra-6 well section, sample WA6-11.
- (5–6) *Pseudofusulina* ex gr. *karapetovi karapetovi* Leven, 1993. 5: axial section; 6: oblique section; Wafra-6 well section; sample WA6-11.
- (7–10) *Pseudofusulina* aff. *karapetovi tezakensis* Leven, 1993. 7, 9: axial sections; 8, 10: subaxial sections. Wafra-6 well section, sample WA6-11.
- (11) *Pseudofusulina* cf. *insignis* Leven, 1993. Subaxial section. Hasirah-1 well section, sample HA1-4.
- (12) *Pseudofusulina licis* Leven, 1993. Axial section. Wafra-6 well section, sample WA6-11.
- (13) *Pseudofusulina kalaktashensis* Leven, 1993. Axial section. Hasirah-1 well section, sample HA1-4.
- (14) *Pseudofusulina* (?) sp. Axial section. Wafra-6 well section, sample WA6-11.
- (15–16) *Pseudofusulina incompta* Leven, 1993. Axial sections. 15: Hasirah-1 well section, sample HA1-4; 16: Wafra-6 well section, sample WA6-11.

Plate 1



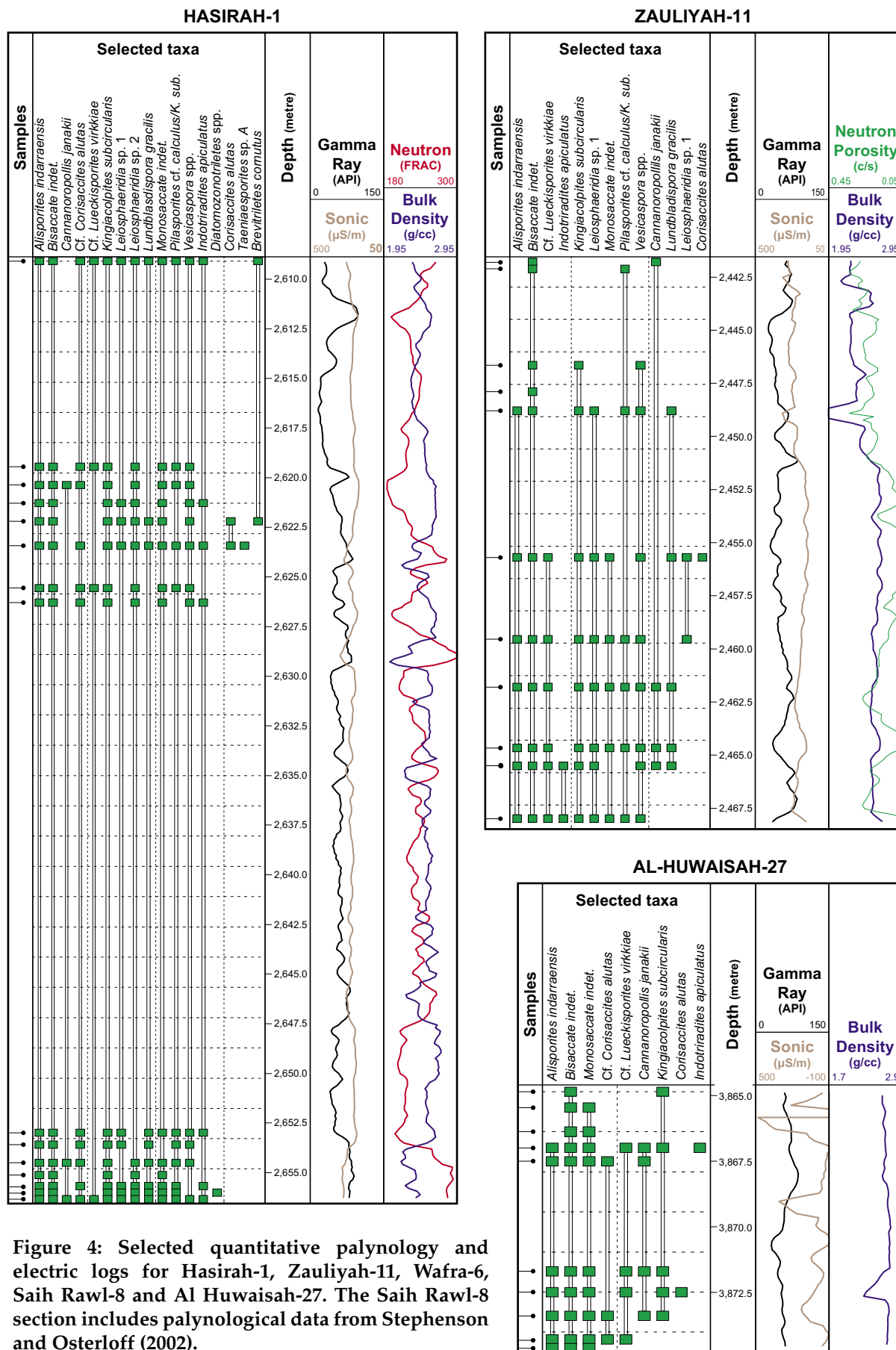
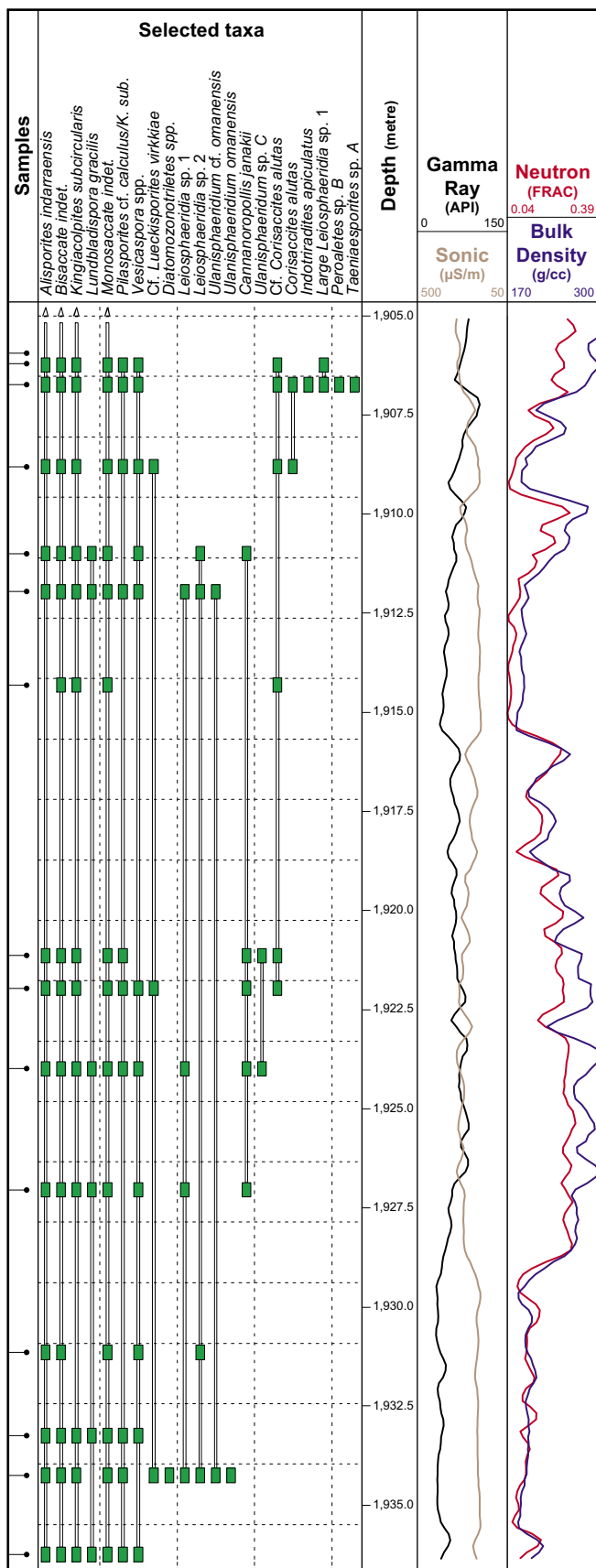
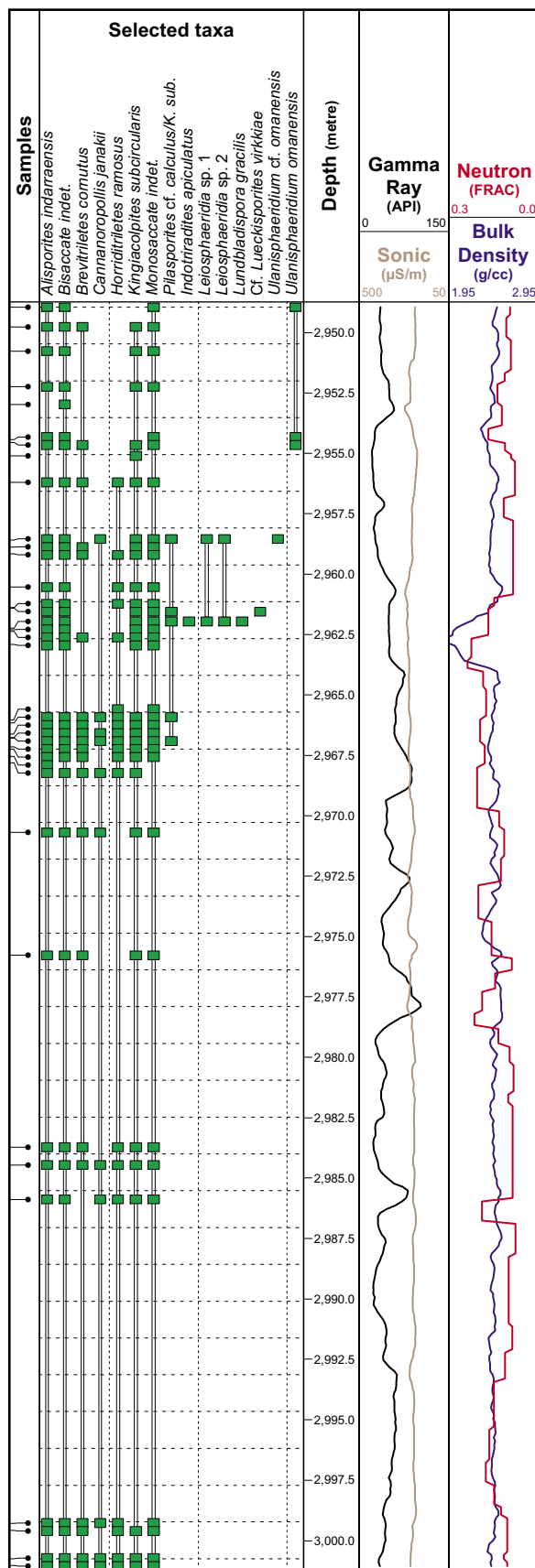


Figure 4: Selected quantitative palynology and electric logs for Hasirah-1, Zauliyah-11, Wafra-6, Saih Rawl-8 and Al Huwaisah-27. The Saih Rawl-8 section includes palynological data from Stephenson and Osterloff (2002).

WAFRA-6



SAIH RAWL-8



Wafra-6 (Figure 4). A correlation using the occurrence of common *Leiosphaeridia* sp. 1 and 2 is shown in Figure 3a, along with suggested correlations based on brachiopods. The correlation suggested by palynology in Hasirah-1, Zauliyah-11 and Wafra-6 is consistent with that indicated by brachiopods, and the new palynological biozone appears to correlate broadly with the brachiopod *Punctocyrtella spinosa*-*Pachycyrtella* sp.-*Reedoconcha permixta* Assemblage Biozone. This suggests that the 'pre-oolitic limestone' sections (Figure 3a) of the three wells are of similar age.

Leiosphaeridia sp. 1, a small, smooth, thick-walled palynomorph, occurs elsewhere in the Gharif Formation, but does not reach the high levels of abundance seen in the argillaceous sections of the Haushi limestone (for example in Zauliyah-11). *Leiosphaeridia* sp. 2, which differs from *Leiosphaeridia* sp. 1 in being microgranulate rather than smooth, seems not to have been recorded outside these beds. Hence the combination of the taxa, when they are common, could be used to identify at least part of the Haushi limestone.

The absence of *Ulanisphaeridium omanensis* Stephenson and Osterloff, 2002 in Hasirah-1, Zauliyah-11 and Al Huwaisah-27, but its presence in Saih Rawl-8, as well as the presence in Saih Rawl-8 of common *Microbaculispora grandegrnulata* Anderson, 1977 and *M. tentula* Tiwari, 1965 indicates that this section is older than the Haushi limestone sections. Two of the biozones established earlier by Stephenson and Osterloff (2002) are shown in Saih Rawl-8 in Figure 3b.

The palynological characteristics of the lower Gharif member in South Oman were discussed in detail by Stephenson and Osterloff (2002). The presence of abundant bisaccate pollen (particularly *A. indarraensis* Segroves, 1969), common *Vesicaspora* spp., *Corisaccites alutas* Venkatachala and Kar, 1966 (or cf. *C. alutas*) and *Florinites flaccidus* Menéndez and Azcuy, 1973, as well as small numbers of taxa such as *Diatomozonotriletes* spp. indicate strong similarities between the Haushi limestone sections (Hasirah-1, Zauliyah-11, Wafra-6 and Al Huwaisah-27) and sections of the highest clastic lower Gharif member (above the *Ulanisphaeridium omanensis* Biozone) in South Oman, for example Marmul-151 (3,038.5 ft–3,012.5 ft), Qaharir-2 (4,354 ft–4,318 ft), Thuleilat-16 (908.84 m–890.25 m) and Thuleilat-42 (907.26 m–885.9 m). A detailed comparison of the occurrence of key taxa is shown in Table 2. These similarities indicate a close correlation, suggesting that the carbonates of the Haushi limestone are the lateral equivalents of the highest part of the clastic lower Gharif Member in South Oman, but not of the *Ulanisphaeridium omanensis* Biozone or Maximum Flooding Shale of South Oman.

SURFACE-SUBSURFACE CORRELATION IN CENTRAL AND SOUTH OMAN

The redefinition of the lower Gharif member as the Saiwan Formation (Dubreuilh et al., 1992) at the surface in Central Oman caused several problems including: (1) the definition of its lower boundary and relationships with the underlying formations; (2) its detailed correlation with the two units of the subsurface lower Gharif member (i.e. 'basal sandstones' and Haushi limestone); and (3) the identification of a local, significant unconformity at the top of the Saiwan Formation [supra-Saiwan or supra-lower Gharif member unconformity (Blendinger et al., 1990; Dubreuilh et al., 1992)]. As the third point is out of the scope of the present paper, we will focus on discussion of the former two.

Plate 2 (opposite page): Brachiopods from the Haushi limestone. All specimens are held at the Department of Earth Sciences "A. Desio", University of Milano, Italy.

- (1) *Neochonetes (Sommeriella)* sp., ventral valve, Wafra-6 well section, sample WA6-8, x 3.
- (2) Strophomenid species, ventral valve, Wafra-6 well section, sample WA6-7, x 3.5.
- (3) *Neochonetes (Sommeriella)* sp., ventral valve, Hasirah-1 well section, sample HA1-5, x 5.
- (4) *Reedoconcha permixta* (Reed, 1932), dorsal valve, Wafra-6 well section, sample WA6-7, x 2.5.
- (5) *Derbyia haroubi* Angiolini, 1997, dorsal valve, Zauliyah-11 well section, sample ZL11-5, x 1.5.
- (6) *Derbyia haroubi* Angiolini, 1997, ventral valve, Wafra-6 well section, sample WA6-5, x 2.
- (7) *Coledium* sp., ventral valve, Wafra-6 well section, sample WA6-14, x 4.

Plate 2

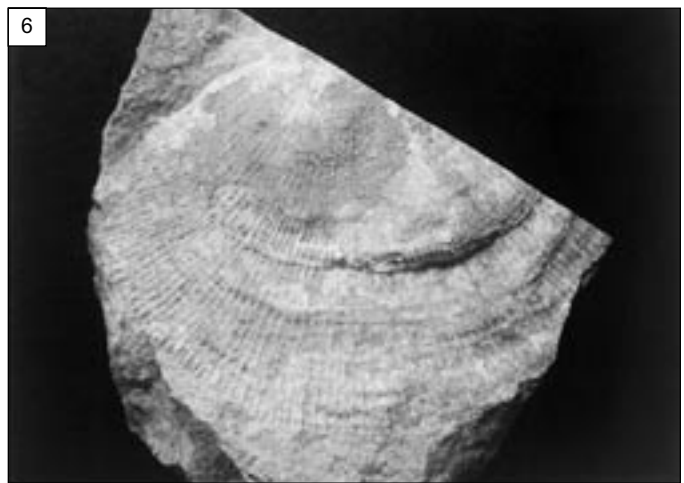
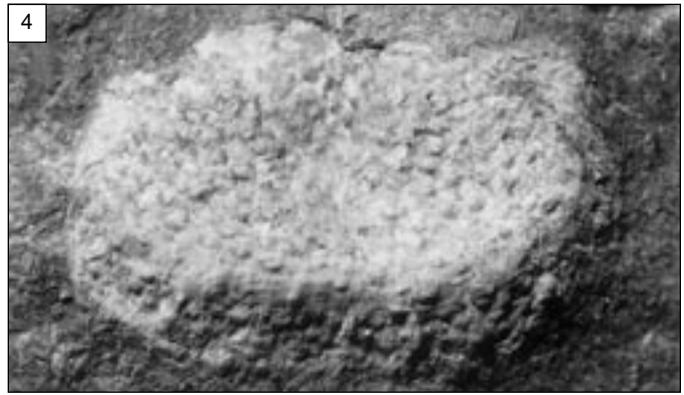
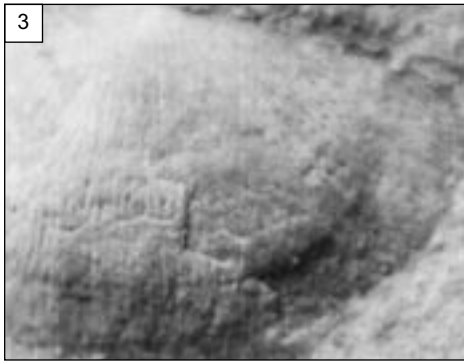


Table 2
Comparison of key taxa in beds above the *Ulanisphaeridium omanensis*
Biozone in South Oman, and in the Haushi limestone sections.

Taxon (x = present)	Marmul-151	Qaharir-2	Thuleilat-16	TL-42	Hasirah-1	Zauliyah-11	Wafra-6	Al-Huwaisah-27
Common <i>Vesicaspora</i> spp.		x	x	x	x	x	x	x
Common <i>Corisaccites alutas</i> or <i>C. cf. alutas</i>	x	x	x	x	x	x	x	x
<i>Diatomozonotriletes</i> spp.	x	x					x	
<i>Lundbladispора gracilis</i>	x	x	x	x	x	x	x	
<i>Indotriradites apiculatus</i>						x	x	x
<i>Florinites flaccidus</i>		x		x	x	x	x	x
Common <i>Kingiacolpites subcircularis</i>	x	x	x	x	x	x	x	

According to Dubreuilh et al. (1992, p. 26), the Saiwan Formation conformably overlies the diamictite and silty shale of the Al Khlata Formation. This definition was also adopted by Angiolini et al. (2003, 2004), who described in greater detail the basal boundary showing its unconformable nature, and pointed out the occurrence of marine shales and cross-laminated sandstones which lie with variable thickness between the diamictite and the base of the Saiwan Formation. Our detailed comparison with the subsurface succession suggests that these shales and sandstones, which were included in the Al Khlata Formation by Dubreuilh et al. (1992), Roger et al. (1992), Angiolini et al. (2003, 2004), correlate with the 'basal sandstones' of the lower Gharif member (Figures 3 and 5). In fact, the petrographic character of the sandstone, approximately 6 m below the base of the Saiwan Formation at the type section, is identical to that of sample HA1-1 toward the top of the 'basal sandstones' in Hasirah-1 (E. Garzanti, written communication, 2004). This suggests that the Saiwan Formation approximately correlates to the Haushi limestone and not to the lower Gharif member, a conclusion which is strongly supported by the brachiopod biozonation as well as by simple thickness criteria (Figure 3). Still problematic, however, is the nature of the basal Saiwan Formation boundary in the type section, where the formation starts with coarse, cross-laminated bioclastic sandstones (*Pachycyrtella* bed of Angiolini, 2001; Angiolini et al., 2003) followed by marlstones. The *Pachycyrtella* bed is more similar to the 'basal sandstones' than to the basal marlstones of the Haushi limestone (Figure 3), as also suggested by Angiolini et al. (2003, figure 5).

The correlation chart (Figure 3a, b) shows the great variation of thickness in the 'basal sandstones', Haushi limestone and Saiwan Formation. This may be due to infilling of the irregular topography of the top of the Al Khlata Formation or deposition on previous structural highs and lows. Thickness tends to decrease southward and eastward in the outcrops, indicating that the depocentre of the basin should be located to the northwest.

THIS STUDY	
OUTCROP	SUBSURFACE
Gharif Formation	upper Gharif member
	middle Gharif member
Saiwan Formation <i>Pachycyrtella</i> bed	Haushi limestone
Hiatus "basal sandstones"	"basal sandstones"
Al Khlata Formation	Al Khlata Formation

Figure 5: Surface subsurface correlation, based on macro and micro biostratigraphic correlation. No change of lithostratigraphic nomenclature is implied.

Plate 3

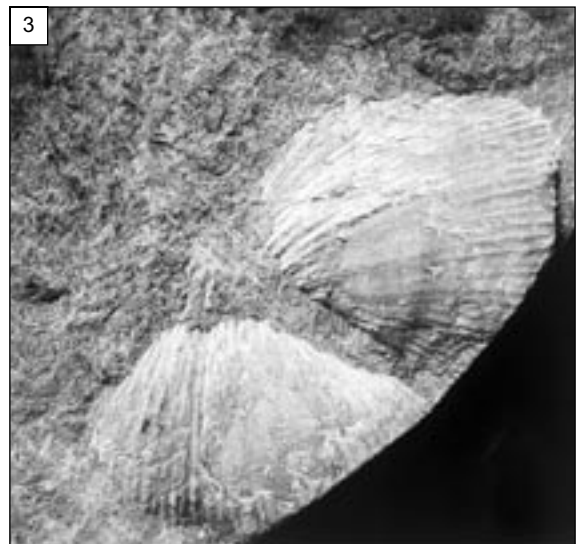
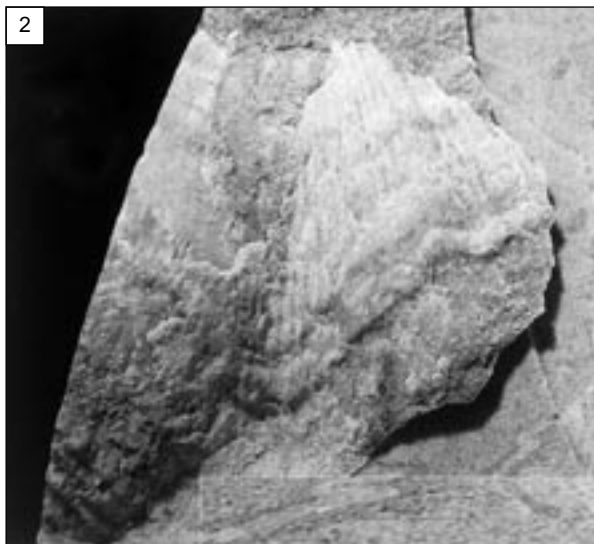
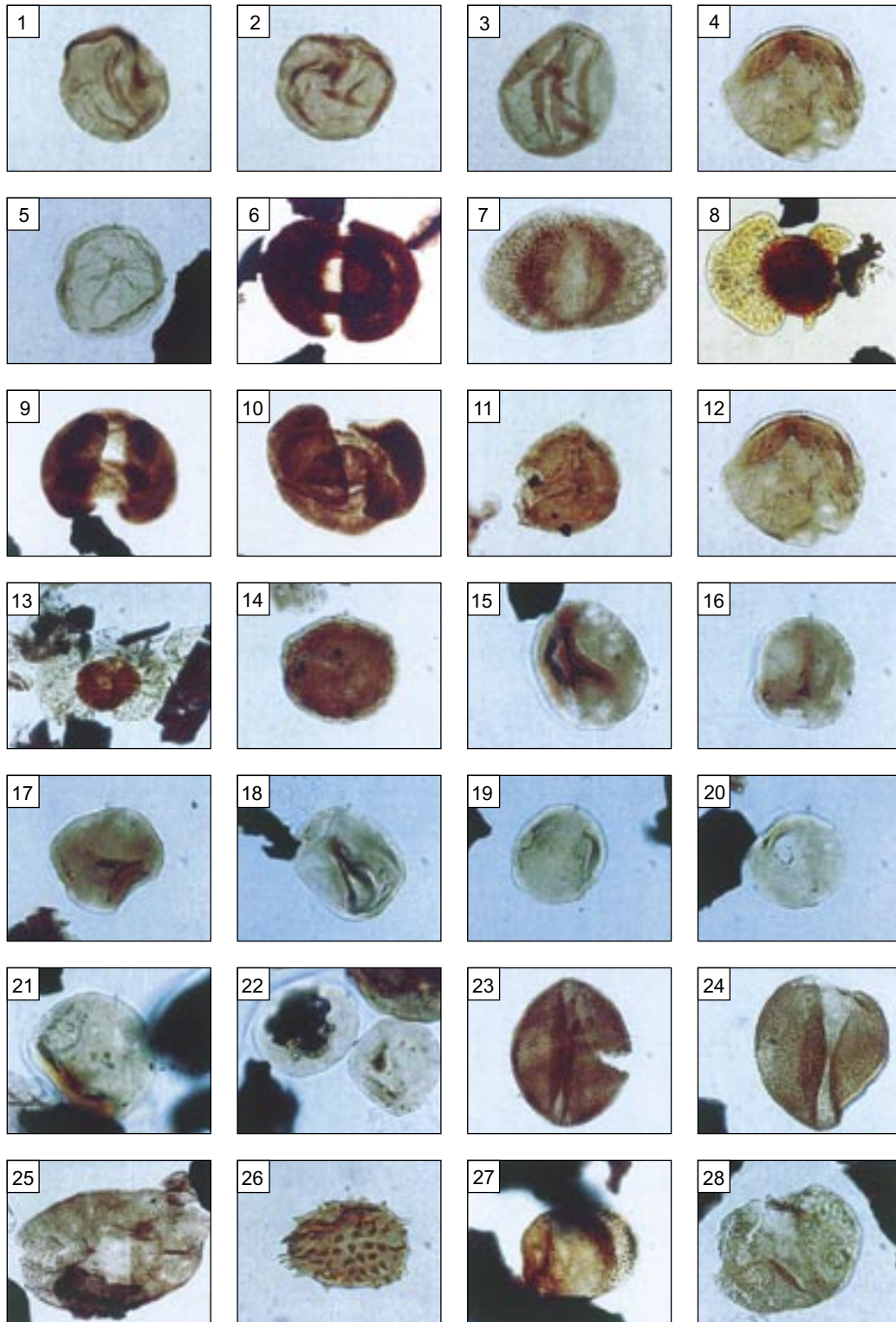


Plate 3: Brachiopods from the Haushi limestone. All specimens are held at the Department of Earth Sciences "A. Desio", University of Milano, Italy.

- (1) *Neospirifer (Quadrospira) aff. hardmani* (Foord, 1890), ventral valve, Hasirah-1 well section, sample HA1-5, x 2.
- (2) *Neospirifer (Quadrospira) aff. hardmani* (Foord, 1890), ventral valve, Zauliyah-11 well section, sample ZL11-1, x 1.5.
- (3) *Neospirifer (Quadrospira) aff. hardmani* (Foord, 1890), two ventral valves, Al Huwaisah-27 well section, sample AlHu27-11, x 1.5.

Plate 4



AGE

A Sakmarian age is suggested for the subsurface Haushi limestone by the newly recorded occurrence of the fusulinid assemblage from samples WA6-11 (Wafra-6) and HA1-4 (Hasirah-1), described from the Sakmarian 'Kalaktash complex' of Afghanistan, Central Pamir and Karakorum (Leven, 1993, 1997; Gaetani et al., 1995). The Sakmarian age for the Kalaktash fusulinid assemblage is based on close comparison with the standard Lower Permian Russian stages, with which it shares common species (Leven, 1993). The Haushi fusulinids expand the area of distribution of the Kalaktash assemblage. In the Early Permian this can be considered as a separate South-Tethyan or peri-Gondwanan palaeobiogeographic province (Leven, 1993).

Brachiopod assemblages in the Saiwan Formation and Haushi limestone support the age suggested by fusulinids. A late Sakmarian age was already suggested for the Saiwan Formation by Angiolini et al. (1997, 2003), by correlation with the Permian biostratigraphic zonation of Western Australia and in particular with the *Strophalosia irwinensis* Zone of the Perth and Carnarvon basins (Archbold, 1998). A late Sakmarian age is similarly indicated by the genus *Pachycyrtella*, which only occurs elsewhere in the Sakmarian of Central Afghanistan and by *Strophalosia* sp., which is close to the Sakmarian species of the genus, in particular *Strophalosia irwinensis* Coleman, 1957. Many brachiopod taxa of the Saiwan Formation and Haushi limestone [i.e. *Reedoconcha permixta* (Reed, 1932), *Neospirifer (Quadrospira) hardmani* (Foord, 1890), *Punctocyrtella spinosa* Plodowski, 1968] also occur in the Sakmarian succession of Central Afghanistan (Plodowski 1970, Termier et al., 1974) and the genus *Subansiria* only occurs elsewhere in the late Sakmarian of Himalaya (Singh and Archbold, 1993). The newly recorded *Coledium* sp. from Wafra-6 well section is similar to *Coledium elvinia* Waterhouse, 1986 from the Sakmarian Elvinia Formation of the Bowen Basin (eastern Australia).

Plate 4 (opposite page): Palynomorphs from the Haushi limestone and 'basal sandstones'. The locations of specimens are given first by England Finder reference and then by slide code. All slides are held in the Micropalaeontology Collection of Petroleum Development Oman.

- (1) 'Large *Leiosphaeridia* sp. 1', x 300, J44/1, 1906,2, Wafra-6.
- (2) 'Large *Leiosphaeridia* sp. 1', x 300, M45, 1906,2, Wafra-6.
- (3) 'Large *Leiosphaeridia* sp. 1', x 300, V50/2, 1906,2, Wafra-6.
- (4) *Peroaletes* sp. B, x 500, C55/1, 1906,73, Wafra-6.
- (5) *Peroaletes* sp. B, x 500, H47, 1906,73, Wafra-6.
- (6) Cf *Corisaccites alutas* Venkatachala and Kar, 1966, x 300, E55, 1906,73, Wafra-6.
- (7) *Vesicaspora* sp. x 500, P45/3, 1906,73, Wafra-6.
- (8) *Striatopodocarpites fusus* (Balme and Hennelly) Potonié, 1958, x 250, E54, 8715, Hasirah-1.
- (9) *Corisaccites alutas* Venkatachala and Kar, 1966, x 300, V54/1, 1906,73, Wafra-6.
- (10) *Corisaccites alutas* Venkatachala and Kar, 1966, x 300, N60, 1906,73, Wafra-6.
- (11) *Lundbladispota gracilis* Stephenson and Osterloff, 2002, x 300, J53, 1911, Wafra-6.
- (12) *Cyclogranisporites pox* Stephenson and Osterloff, 2002, x 700, E42/2, 8715, Hasirah-1.
- (13) *Striatopodocarpites fusus* (Balme and Hennelly) Potonié, 1958, x 250, U44, 8715, Hasirah-1.
- (14) *Lundbladispota gracilis* Stephenson and Osterloff, 2002, x 300, L46, 8704, Hasirah-1.
- (15) *Leiosphaeridia* sp. 2, x 500, M45, 8603, Hasirah-1.
- (16) *Leiosphaeridia* sp. 2, x 500, K42/1, 8603, Hasirah-1.
- (17) *Leiosphaeridia* sp. 2, x 500, W59/2, 8603, Hasirah-1.
- (18) *Leiosphaeridia* sp. 1, x 500, H5, 2465,5, Zauliyah-11.
- (19) *Leiosphaeridia* sp. 1, x 500, G34/3, 2465,5, Zauliyah-11.
- (20) *Leiosphaeridia* sp. 1, x 500, F51/3, 2465,5, Zauliyah-11.
- (21) *Leiosphaeridia* sp. 1, x 500, G11/3, 2465,5, Zauliyah-11.
- (22) *Leiosphaeridia* sp. 1, x 500, J11/3, 2465,5, Zauliyah-11.
- (23) *Kingiacolpites subcircularis* Tiwari and Moiz, 1971, x 500, Q49, 1906,2, Wafra-6.
- (24) *Kingiacolpites subcircularis* Tiwari and Moiz, 1971, x 500, J55/4, 1906,2, Wafra-6.
- (25) *Florinites flaccidus* Menéndez and Azcuy, 1973, x 200, H51/2, 1906,73, Wafra-6.
- (26) *Brevitriteles cornutus* (Balme and Hennelly) Backhouse, 1991, x 600, H5, 9733,5, Saih Rawl-8.
- (27) *Alisporites indarraensis* Segroves, 1969, x 500, W59/2, 9733,5, Saih Rawl-8.
- (28) *Alisporites indarraensis* Segroves, 1969, x 500, J53, 9733,5, Saih Rawl-8.

Ammonoids present in the surface Saiwan Formation include *Metalegoceras hudsoni*. In Western Australia the genus *Metalegoceras* is Sterlitamakian (late Sakmarian; Archbold, 2000). However, in the Urals the genus is Sakmarian-early Artinskian (Leonova, 1998). Similarly, according to G. Webster (oral communication, 2002), crinoids of the Saiwan Formation include the genus *Texacrinus* which is known from the Late Carboniferous to Sakmarian sedimentary successions of Texas.

Palynomorphs in the Haushi limestone include abundant *A. indarraensis* Segroves, 1969, and common *Vesicaspora* spp. and *Corisaccites alutas* Venkatachala and Kar, 1966 (or *C. cf. alutas*), indicating a correlation with the standard Arabian Permian OSPZ3c Biozone (Stephenson et al., 2003). Previously the age of the subsurface 'basal sandstones' of the lower Gharif member was suggested to be Artinskian (Love, 1994; Stephenson and Osterloff, 2002; Stephenson et al., 2003) on the basis of palynology, with the implication that the overlying Haushi limestone is therefore at least Artinskian in age. The basis for this date was the presence in the 'basal sandstones' of the *Striatopodocarpites fusus/cancellatus* complex, which generally appears close to the base of the unit. This allows correlation with the Western Australian *Striatopodocarpites fusus* Biozone of Backhouse (1991), which was calibrated using the macropalaeontological biozonation of Archbold (1999, 2001a, b), as Artinskian. However, there seems to be some uncertainty over the age of the base of the *S. fusus* Biozone, because Mory and Backhouse (1997) and Backhouse (1998) illustrate the biozone with a late Sakmarian base. The presence of the Kalaktash fusulinid assemblage confirms a Sakmarian age for the Haushi limestone and therefore a slightly older age for the underlying 'basal sandstones', and suggests a recalibration of the base of the *S. fusus* Biozone as Sakmarian.

PALAEOENVIRONMENTAL EVOLUTION

Palaeoenvironmental reconstruction in three time slices, from the *Pachycyrtella omanensis* Biozone to the *Neospirifer (Q.) aff. hardmani-Derbya haroubi* Biozone, is shown in Figure 6. As the geographic distribution of *Pachycyrtella omanensis* Angiolini, 2001 is restricted to the Saiwan area, Figure 6a also shows the distribution of the correlative topmost marine sandstones and shales of the 'basal sandstones'. At the time of the *Pachycyrtella omanensis* Biozone, which probably corresponds to the beginning of the 'greenhouse' climate after the Gondwanan deglaciation, marine clastic rocks were chiefly deposited, and palaeoenvironments were locally colonised by pioneer palaeocommunities, such as the *Pachycyrtella* palaeocommunity (Angiolini et al., 2003). The sedimentological character of the 'basal sandstones' does not allow determination of whether common cross bedding is due to fluvial or shallow-marine current activity. Hummocky cross-stratification seems absent. Mercadier and Livera (1993) interpreted possible herringbone cross-stratification (formed by reversing tidal currents) in borehole image logs in the Hasirah field. Little other evidence of tides seems present though. It is possible that massive and cross-bedded sands represent periglacial sandy deltas and rivers, while the laminated shales represent restricted lakes on a braidplain. Alternatively the cross-bedded sands could be unusual shoreface or shallow-marine deposits, but then the (rather restricted) laminated shales are difficult to explain. The bioturbated sands may represent low-energy shorefaces formed during forced regressions or brackish to marine transgressive/abandonment deposits.

During *Punctocyrtella spinosa-Pachycyrtella sp.-Reedoconcha permixta* Biozone times, limestone deposition began probably due to deepening and distancing of the terrigenous source coupled with climatic warming (Angiolini et al., 2003). This biozone contains the P10 MFS of Sharland et al (2001) which is located at the base, or 5–15 metres above the base, of the Saiwan Formation at the outcrop, and in the shales below the Haushi limestone in the Hasirah-1 well section.

In the east, in the surface outcrops, coarse sandy limestones are dominant whereas to the west around Hasirah-1, Zauliya-11 and Wafra-6, finer sandy limestones with intercalated shales are most common, with Hasirah-1 more terrigenous than Wafra-6. This may reflect more distal basinal conditions toward the west.

The dark coloured argillaceous sediments of Hasirah-1, Zauliya-11 and Wafra-6, assigned to the *Punctocyrtella spinosa-Pachycyrtella sp.-Reedoconcha permixta* Biozone, contain a diverse suite of marine trace fossils indicating a probable marine environment. These sediments also contain abundant autochthonous algal spores (mainly *Leiosphaeridia* sp. 1 and 2). Such high numbers of non-terrestrial

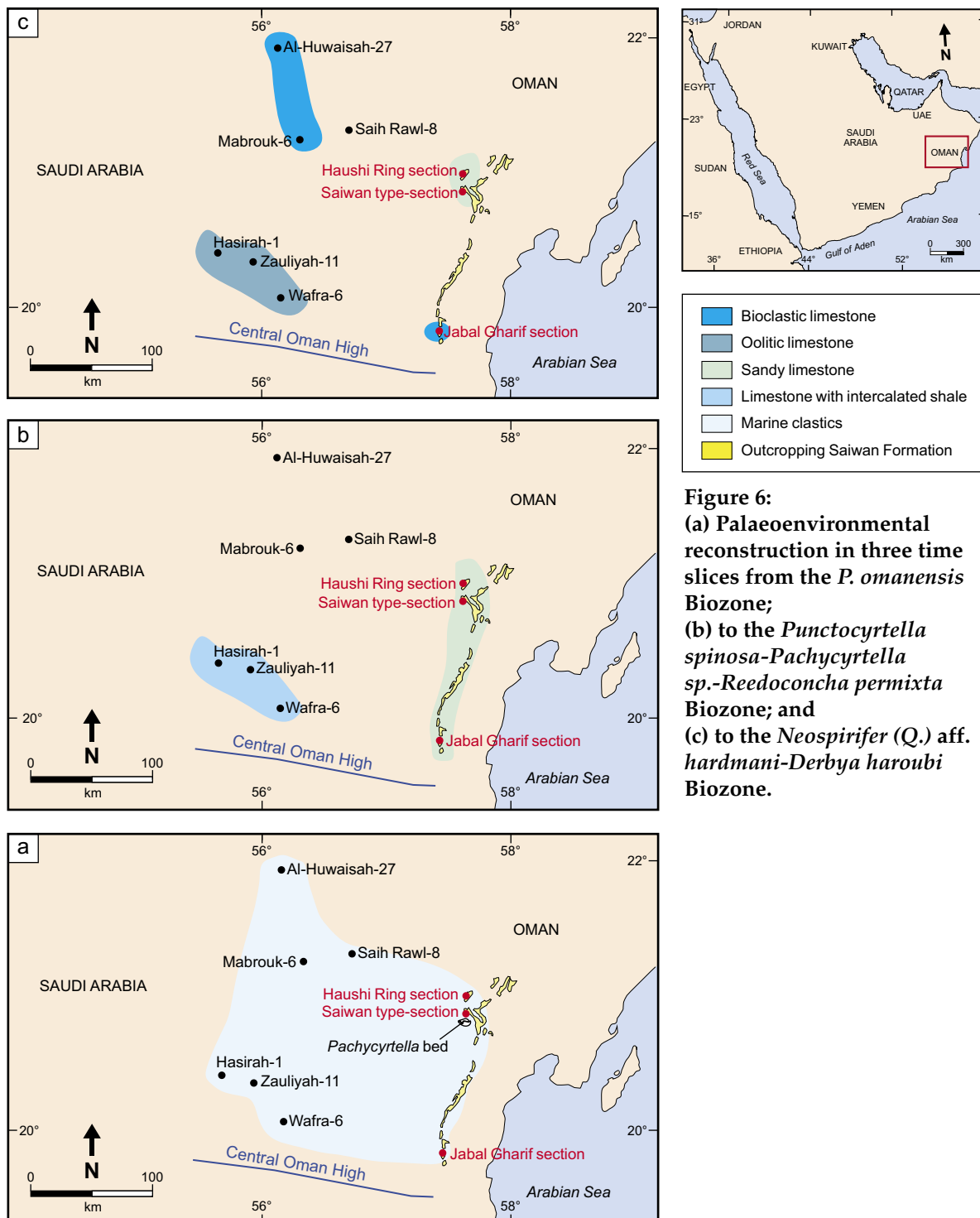


Figure 6:
(a) Palaeoenvironmental reconstruction in three time slices from the *P. omanensis* Biozone;
(b) to the *Punctocyrtella spinosa*-*Pachycyrtella sp.*-*Reedoconcha permixta* Biozone;
(c) to the *Neospirifer (Q.) aff. hardmani*-*Derbya haroubi* Biozone.

palynomorphs are rare in the assemblages of the Gharif Formation, and may indicate an unusual palaeoenvironment, though there is no direct evidence of its nature from the palynomorphs since their exact parentage is not known. However it is significant that there are no palynomorphs in these assemblages that indicate marine conditions, for example acanthomorph acritarchs, scolecodonts or microforaminiferal test linings. Thus palynological evidence does not concur with sedimentological evidence of 'marineness'. The combination of high autochthonous algal spore numbers, their low diversity and the absence of unequivocal marine indicators may, however, indicate a restricted non-marine or brackish water palaeoenvironment, perhaps of a coastal lagoon. In the lower 4 metres of Wafra-6 well section, at least six upward-thickening cycles occur, each cycle comprising coarse

grained bioclastic limestones passing to dark shales with convex-up brachiopod shells and common *Leiosphaeridia* sp. 1 and 2. The cycles suggest small-scale periodic variation in sea level and carbonate supply, suggesting that a high energy coastal palaeoenvironment alternated with a restricted lower energy lagoonal palaeoenvironment populated by algae, into which shelly fauna was occasionally washed.

During *N. (Q.)* aff. *hardmani*-*D. haroubi* Biozone times, the distribution of facies was more complex (Figure 6c). To the southwest, around Hasirah-1, Zauliyah-11 and Wafra-6, were oolitic limestones with small oolites; to the east, in the surface outcrops, coarse sandy limestones continued to be deposited. In the north, around Al Huwaisah-27, bioclastic limestones are present. This distribution indicates high-energy shoal or shelf-margin conditions toward the southwest of the study area, precluding a shelly fauna. To the north and east the bioclastic and sandy limestones indicate more terrigenous input. In Hasirah-1, Zauliyah-11 and Wafra-6, oolitic limestones give way to a thin capping of laminated siltstone which indicates a progressive shallowing of the environment.

Throughout the period of deposition of the 'basal sandstones' and the Haushi limestone, spores and pollen of terrestrial, mainly vascular plants, were present in abundance. The plants that produced these grew in various palaeoecological groupings in the terrestrial hinterland and were transported by streams or wind to the depositional basin. These spores and pollen represent a typical lower Gharif flora present in other Central and South Oman well sections (Stephenson and Osterloff, 2002). The 'basal sandstones' contain common fern and lycopsid spores, while the Haushi limestone assemblages are dominated by gymnosperm bisaccate and colpate pollen. This change from plants with a water dependent reproduction mechanism to those independent of water suggests a progressive drying of climate thorough the sequence. This trend is supported by petrographic evidence from samples of the 'basal sandstones' in Hasirah-1 (HA1-1) and of the top of the Haushi limestone in Al Huwaisah-27 (AlHu27-14), which suggests a shift from periglacial to semi-arid conditions (E. Garzanti, written communication, 2004).

CONCLUSIONS

- (1) The presence of abundant micro and macrofauna in the subsurface Haushi limestone of Central Oman has allowed the succession to be subdivided and compared to the surface Saiwan Formation in the Huqf outcrop area. Brachiopod biozones show that the surface Saiwan Formation correlates with the subsurface Haushi limestone, implying that previous direct correlation of the Saiwan Formation with the lower Gharif member is not correct.
- (2) The fusulinid assemblage from sample Wafra-6 (WA6-11) and Hasirah-1 (HA1-4) suggests a Sakmarian age for the Haushi limestone (and therefore the Saiwan Formation), and brachiopod data supports this determination.
- (3) Overall the brachiopod fauna of the subsurface Haushi limestone is of lower diversity than that of the outcropping Saiwan Formation, being dominated by *Derbyia haroubi* Angiolini, 1997, *Reedoconcha permixta* (Reed, 1932), *Neospirifer (Quadrospira)* aff. *hardmani* (Foord, 1890), and lacking the large and thick shelled Syringothyridid. This fauna is consistent with deposition in slightly deeper and distal marine settings than those envisaged for the surface Saiwan Formation, which is closer to the source of terrigenous input.
- (4) The autochthonous algal spores in three of the Haushi limestone sections suggest a local biozonation that is consistent with that indicated by brachiopods. The assemblages of terrestrially sourced palynomorphs are closely similar in the Hasirah-1, Zauliyah-11, Wafra-6 and Al Huwaisah-27 Haushi limestone sections and indicate an OSPZ3c age (Stephenson et al., 2003). The Sakmarian age from fusulinids indicates that the same age for OSPZ3c is more likely than the Artinskian age suggested by previous palynological studies. The terrestrially sourced palynomorphs also suggest correlation of the carbonates of the Haushi limestone with the highest part of the clastic lower Gharif Member in South Oman, above the *Ulanisphaeridium omanensis* Biozone or Maximum Flooding Shale in that area. Within the argillaceous intervals of the Haushi limestone no unequivocal marine palynomorphs occur.
- (5) Palaeoenvironmental reconstruction in three time slices shows a major transgressive-regressive cycle beginning with the deposition of marine clastic sediments and ending with the local development in the west of laminated siltstone at the top of the Haushi limestone.

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In accordance with conventional practice, references cited do not include authors associated exclusively with taxon names.

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