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Biogenic silica microfossils in sediments of the Permian – Carboniferous Unayzah Formation, Saudi Arabia

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ABSTRACT

Biogenic silica particles (BSPs) have been discovered in sediments of the Permian – Carboniferous Unayzah Formation of Saudi Arabia. The BSPs are extracted from sediments that are generally barren of macro- or microfossils. BSPs have been found in the Basal Khuff Clastics (BKC), and the Unayzah A, B, and C members, that were sampled in six different wells over a large geographic area. More than 3,500 BSPs have been identified in 83 samples examined and have been classified into 14 different BSP morphotypes. Furthermore, three outcrop samples of the Permian – Carboniferous Al Khlata and Gharif formations of Oman were analysed. Herein seven BSP morphotypes were identified. For comparison of the Paleozoic BSPs with modern analogues, recent plant material from the Rub' Al Khali Desert was studied. The presence of BSPs in Paleozoic deposits and their morphological difference is encouraging. Variations in morphotype abundance and occurrence may ultimately provide a means of subdividing and correlating the Unayzah Formation. Research presently underway is testing the distribution of morphotypes in terms of stratigraphic position, depositional facies, and paleoclimatic setting.

INTRODUCTION

The sequence of Late Carboniferous to Mid-Permian clastic sediments resting on the Middle Carboniferous 'Hercynian' unconformity and overlain by the Permian Khuff carbonates is known from Oman, the United Arab Emirates, Qatar and Saudi Arabia on the Arabian Plate. In Saudi Arabia this sequence comprises the Unayzah Formation and the Basal Khuff Clastics (BKC). In eastern Saudi Arabia this sequence contains large reserves of sweet gas, condensate and oil. The economic significance of these Permian – Carboniferous sandstones was first realized in 1979 when gas was discovered in the Qirdi field (McGillivray and Husseini, 1992; Konert et al., 2001). Subsequently, in 1989, super-light oil was discovered in the Hawtah field in central Saudi Arabia. Since that time, the discovery of deep gas in the South Haradh field at the southern end of the Ghawar structure and nearby satellite fields (e.g. Tinat, Waqr and Ghazal) has added significantly to Saudi Arabia's gas reserves.

The investigated strata in Saudi Arabia include, from the base upward, the informal Unayzah C, B and A members and the BKC (Figure 2). The sequence of rocks was deposited mostly in continental environments and likely under a variety of paleoclimatic conditions as the Arabian Plate moved from high southerly latitudes to near tropical latitudes (Beydoun, 1991; Konert et al., 2001). However, there is little or no published data documenting climatic changes in the Unayzah members and the BKC. Unpublished petrographic data and geochemical analyses, however, have been used to classify paleosols in the scheme of Mack et al. (1993) and to calculate climofunctions following the techniques of Sheldon et al. (2002). These techniques suggest that paleoclimates ranged from cold and dry during Unayzah C time, to cool and humid (Unayzah B), hot and dry (lower Unayzah A) to cool and dry (Upper Unayzah A), and finally warm and humid (BKC) (Franks, 2008; Franks, unpublished Saudi Aramco reports). Because of the continental nature of most of the sediments and the often harsh climatic conditions, preservation of fossils is very poor and biostratigraphic control, therefore, is sparse (Hooker and Filatoff, 2008). Rapid facies changes and numerous hiatuses and unconformities make stratigraphic correlation difficult at both the local and regional scale.

During a petrographic/diagenetic study of the Unayzah Formation, small orbicular objects (3–10 μm) interpreted to be of biological origin, were noted in some Unayzah sandstones. A search of the literature revealed that similar objects had been described in Permian sediments from Antarctica and were identified as phytoliths (Carter, 1999).

Phytoliths (literally meaning ‘plant stone’) are composed of hydrated silica (SiO_2 with 5–15% H_2O) and originate from the cells of higher land plants which store phytoliths in their leafs, stems, or roots (Piperno, 2006). Their size ranges from 5 to c. 250 μm. Phytoliths are important for structural shaping, nutrition, homeostasis and preservation or as mineral barriers for pathogens (Exley et al., 1993; Williams, 1984). After death and decay of the plant and depending on the diagenetic conditions, phytoliths may be preserved in the fossil record.

The possible presence of siliceous microfossils in the generally unfossiliferous Unayzah sandstones may provide a means of subdividing and correlating this succession of rocks. To test this hypothesis, a suite of samples was collected from the Unayzah in six wells over an area of about 65,000 sq km (Figure 1). The samples were examined to determine whether siliceous microfossils are present and if these exhibit sufficient variability to warrant further investigation as a biostratigraphic tool. Additionally, we compared the siliceous microfossils extracted from the Unayzah Formation with siliceous microfossils extracted from three outcrop samples of approximately time-equivalent units in Oman (Al Khlata and Gharif formations).

The Unayzah A was deposited in a desert setting (Franks, 2008; Franks, unpublished Saudi Aramco reports), perhaps similar to that of present-day Saudi Arabia. Recent plant material from the eastern Rub Al Khali desert has been sampled and processed for comparison.

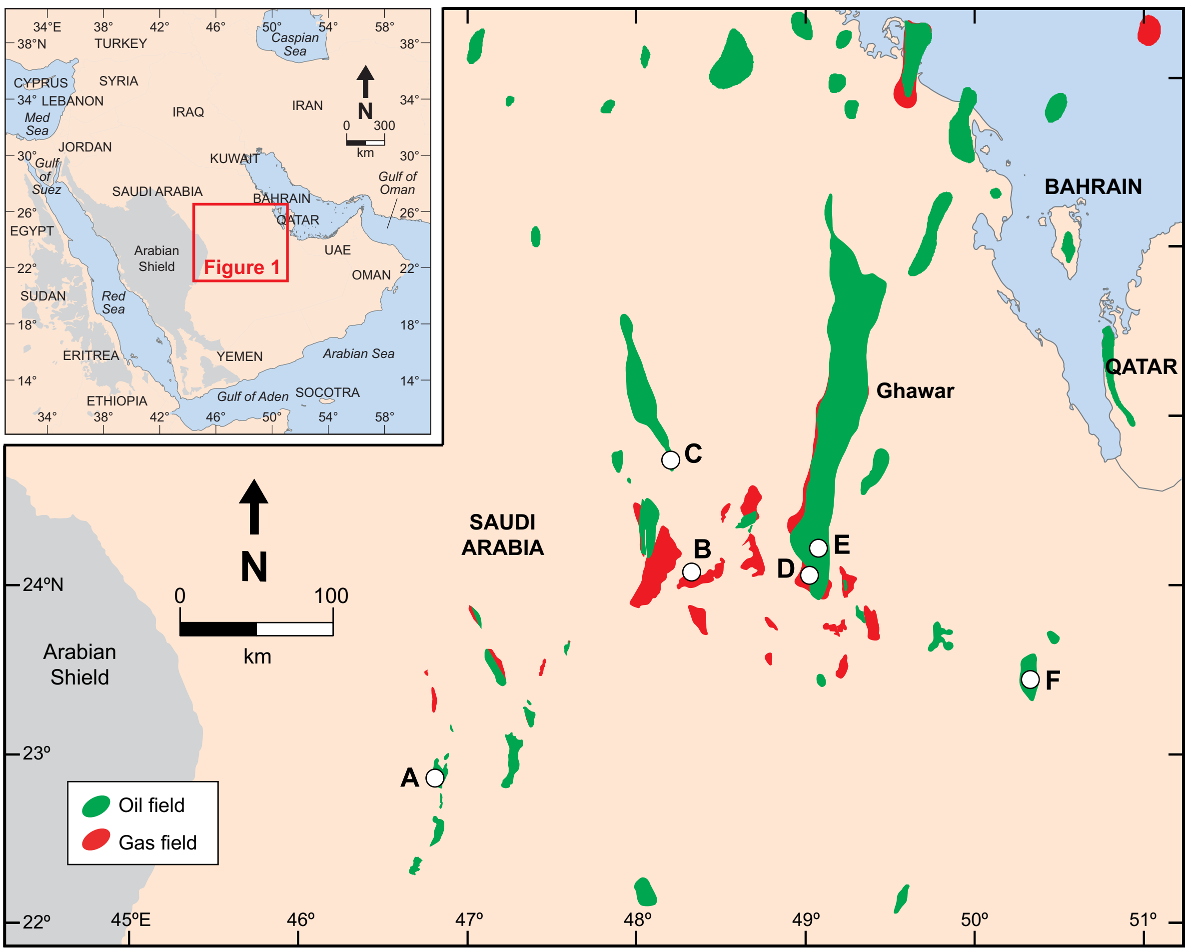

Figure 1: Locations of the studied wells (A-F) and oil and gas fields in central eastern Saudi Arabia.

STRATIGRAPHY

The stratigraphic interval investigated includes the Unayzah A, B and C members of McGillivray and Husseini (1992), the overlying BKC (Al-Laboun, 1987, 1988; Ferguson and Chambers, 1991; Senalp and Duaiji, 1995, 2001), as well as the Al Khlata Formation and the younger Gharif Formation in Oman. The Al Khlata is generally considered to be coeval with the Unayzah C and B (Stephenson et al., 2003). The Gharif is generally correlated with the Unayzah A of Saudi Arabia.

Saudi Arabian Stratigraphy

The Unayzah Formation rests with angular unconformity on pre-Hercynian sediments and is unconformably overlain by the BKC which is sometimes included as part of the informally-designated "Unayzah reservoir" interval (Figure 2). The BKC is conformably overlain by the Permian Khuff Formation carbonates (Al-Husseini, 2004).

The Unayzah C member is composed mostly of quartz-cemented quartz arenites that typically give a monotonously low gamma log response. Senalp and Duaiji (2001) interpreted the Unayzah C (their Haradh Formation) as braided streams and sandurs originating as glacial outwash. Melvin and Sprague (2006) put forward a similar interpretation. Additionally, the latter authors attribute slumps, folds, and shear zones within the Unayzah C to glacial deformation. The age of the Unayzah C is unknown, but it can be bracketed by the age of the youngest pre-Hercynian sediments beneath it and a (reworked) palynological assemblage (Cm in Saudi Aramco terminology), which is sometimes found above and below it (Hooker and Filatoff, 2008).

The youngest pre-Hercynian sediments in eastern Saudi Arabia are Late Visean to Early Namurian, based on palynological data (Clayton, 1995; Clayton et al., 2000). The youngest component of the mixed Cm assemblage is no older than Late Serpukhovian (Nigel Hooker, personal communication). Stephenson et al. (2003) correlate the Unayzah C with the lower Al Khlata of Oman, a sequence

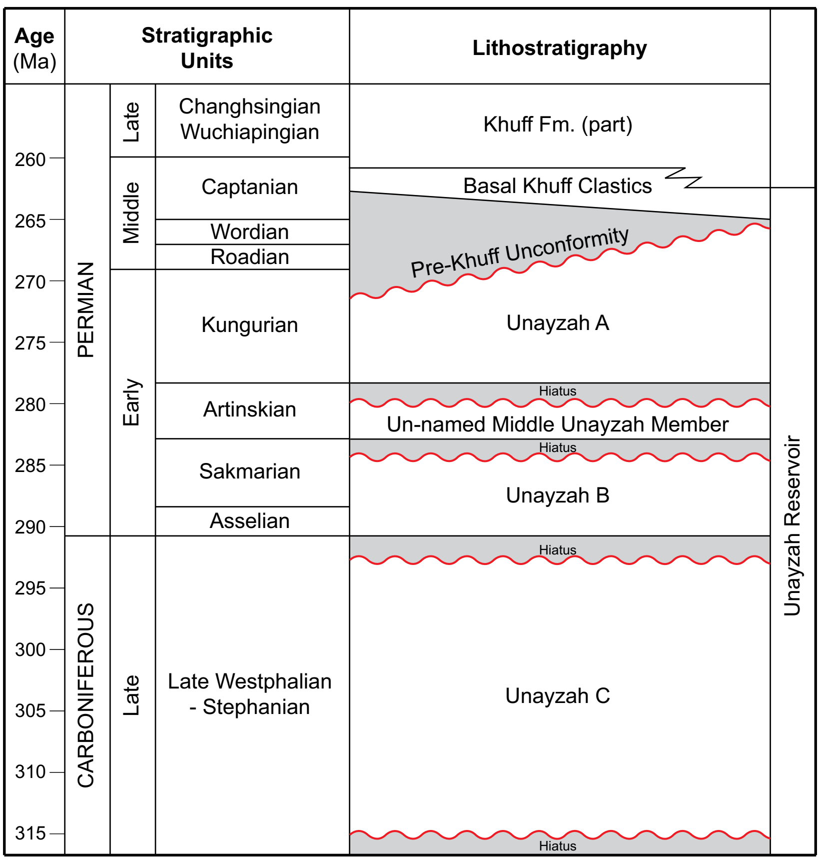

Figure 2: Stratigraphy of the Unayzah Formation adapted from Melvin and Sprague (2006). The number of BSP samples in each stratigraphic unit is as follows: Basal Khuff Clastics = 7, Unayzah A = 26, Un-named Middle Unayzah Member (UMUM) = 13, Unayzah B = 24, and Unayzah C = 13. Note that not all stratigraphic units are present or sampled in each well.

comprised mostly of glacial diamictites. They place both the Unayzah C and the Al Khlata in their OSPZ1 palynozone for which they suggest a Stephanian age.

The Unayzah B is composed of sandstone, siltstone, shale, and pebbly mudstones. Senalp and Duaiji (2001) referred to this interval as the Jawb Formation and interpreted the pebbly mudstones as glacial diamictites, suggesting deposition during glacial retreat, an interpretation generally followed by Melvin and Sprague (2006). A palynomorph assemblage (Upper P4 in Saudi Aramco usage) in some places recovered from diamictites in the Unayzah B indicates an Early Permian (Asselian to Sakmarian) age (Stephenson et al., 2003). Melvin and Sprague (2006) report a paleosol within the Unayzah B, which led them to suggest an "un-named middle Unayzah member" (herein abbreviated as UMUM) between the Unayzah B and the overlying Unayzah A. They interpret the UMUM as a drying-out phase, following the glacial retreat of Unayzah B time. According to Melvin and Sprague (2006) the UMUM is Artinskian in age and equivalent to the Lower Gharif Member of Oman. Work by Angiolini et al. (2006), however, suggests that the Lower Gharif Member is no younger than Late Sakmarian.

The Unayzah A consists of mostly sandstones and siltstones deposited in a variety of desert settings including aeolian dunes, sandsheets, playas, sabkhas and fluvial settings. Melvin and Sprague (2006) identified a paleosol separating the UMUM from the Unayzah A in some wells, indicating a hiatus of unknown duration. Senalp and Duaiji (2001) interpret the Unayzah A as having been deposited under hot, arid conditions. The Unayzah A is usually barren of palynomorphs and has never been directly dated. Its age is bracketed by the age of the underlying UMUM and the overlying BKC. Based on these constraints, it probably lies mostly within the OSPZ4 zone of Stephenson et al. (2003) indicating a late Early Permian (Artinksian – Kungurian) age.

The BKC rests unconformably on the underlying members of the Unayzah. At the so-called pre-Khuff unconformity (PKU), at the base of the BKC, varying amounts of the older Unayzah Formation have been eroded. In places the entire Unayzah Formation is missing, and the PKU merges with the Hercynian unconformity. The BKC is composed of granule-to-pebble conglomerate, sandstone, siltstone, and shale with some local carbonates. Significant bioturbation is present in some of the finer sediments. Senalp and Duaiji (2001) refer to the BKC as the Ash-Shiqqah Formation and interpret the depositional environment as fluvio-estuarine to shallow marine.

The unit grades upward into shale, carbonate, and anhydrite of the Permian – Triassic Khuff Formation. The BKC is characterized by a palynological assemblage (Saudi Aramco Upper P2 Palynozone) of late Wordian or younger age (Stephenson and Filatoff, 2000). It is considered to be slightly younger than the Upper Gharif of Oman, which is early Wordian – Roadian (Stephenson, 2006; Stephenson et al. 2003).

Oman Stratigraphy

The Haushi Group of Oman is approximately the time equivalent of the Unayzah/BKC interval in Saudi Arabia (Stephenson, et al., 2003). The Haushi Group is composed of two formations, the Al Khlata and the overlying Gharif (Levell et al., 1988; Hughes Clarke, 1988; Osterloff et al., 2004a, b). Stephenson et al. (2003) correlate the Al Khlata with the Unayzah C and B of Saudi Arabia and the Lower and Middle Gharif members with the Unayzah A. They suggest that the Upper Gharif Member is somewhat older than the BKC (see figure 2 in Stephenson et al., 2003).

The Al Khlata Formation rests on the Hercynian unconformity on rocks of lower Carboniferous to Proterozoic age. It consists of a facies assemblage of non-marine diamictites, conglomerates, sandstones, and siltstones and mudstones deposited during the Late Moscovian to Sakmarian glacial episode (Martin et al., 2008; Al-Belushi et al., 1996; Osterloff et al., 2004a). It is characterized by rapid lateral and vertical facies changes and by large variations in thickness. Martin et al. (2008) provide an excellent recent review of the stratigraphy and sedimentology of the Al Khlata.

The contact of the Al Khlata with the overlying postglacial Gharif Formation is broadly conformable (Penney et al., 2008). Hughes Clarke (1988) divided the Gharif into the Lower, Middle, and Upper members. Overall, depositional environments range from marginal marine to coastal alluvial plain (Osterloff et al., 2004b). The Lower Gharif is composed of mostly marine sediments in northern Oman but environments become more continental to the south. In northern Oman the Lower Gharif is capped by the marine bioclastic Haushi Limestone. The Middle Gharif overlies the Haushi Limestone and is dominantly fluvial except in western Oman where marginal marine clastics directly overlie the Haushi. Paleosols are abundant within the Upper Gharif Member, which consists largely of continental sandstones and red-brown mudstones of fluvial and lacustrine origin.

BIOGENIC SILICA MICROFOSSILS IN PERMIAN – CARBONIFEROUS DEPOSITS

BSPs are frequently described in Quaternary deposits as so-called phytoliths (Clarke, 2003), but the record of phytolith-bearing Paleozoic and Mesozoic rocks is sparse. The single report of phytoliths in Late Devonian, Permian and Triassic rocks from Antarctica was published by Carter (1999). The presence of gymnosperms, lycopods and ferns in the fossil record at the end of the Devonian (Briggs and Crowther, 2001) supports the assumption that BSPs were already formed by Paleozoic land plants and hence, should be preserved in Paleozoic rocks. The analysis of fresh material from various living plant fossils, among them horsetail, ginkgo, and club moss, reveal a number of BSPs that strongly resemble those found in Permian deposits (Garming et al., unpublished data). However, the possibility that the BSPs identified in the Unayzah Formation are of a different origin, for example skeletons of siliceous aquatic algae, cannot be entirely excluded at the moment.

As noted by Boyd et al. (1998) problems exist in categorizing BSPs even in modern sediments because individual plants can produce many different morphological types according to cell structure. This is referred to as multiplicity. A second issue is that different plants can produce similar phytoliths making it difficult to differentiate the plant types. This is referred to as redundancy. As a result BSP assemblages can be very large even where the number of species is limited, unlike pollen assemblages, where each plant species produces only one pollen type. The problem is compounded in ancient sediments where even the origin of the BSPs, is not yet entirely clear.

MATERIAL AND METHODS

Eighty-three, sand to siltstone, samples from six wells (Figure 1) representing the BKC and Unayzah A, B and C members of central eastern Saudi Arabia were analyzed for BSP content, as well as three Oman outcrop samples. Two Omani samples were taken from outcrops of Al Khlata diamictites. The first was taken at Wadi Al Khlata South (19º45.940′N; 57º26.390′E) from the matrix of a massive diamictite containing granitic boulders and cobbles which overlies a striated surface on Proterozoic limestone, the Khufai Formation. A second sample of Al Khlata diamictite matrix was taken about 2.25 km to the southwest (19º45.266′N; 57º25.299′E) approximately 30 meters higher in the section (John Aitken, personal communication). The third Omani sample (19º54.895′N; 57º22.354′E) is from an Upper Gharif sandstone about 17 km NNW of the Al Khlata diamictite samples.

All samples were processed according to a laboratory protocol developed at TNO Built Environment and Geosciences. The procedure involves three general steps: (1) removal of organic material, carbonate, and clay particles; (2) repeated heavy liquid flotation for the extraction and concentration of BSPs; and (3) slide preparation. A step-by-step description of the procedure is provided in Table 1. The use of sedimentation trays for the slide preparation (Battarbee, 1973) results in a homogenous distribution of the extracted particles on the cover slips.

Light microscopic analysis was carried out with a Leitz Diaplan microscope, equipped with differential interference contrast (DIC), at a magnification of ×600. Micrographs for the documentation of the morphological variability of the identified BSPs were produced with a Leica DFC 320 digital camera.

Table 1:
Detailed, 21 step, laboratory protocol developed at TNO Built Environment and Geosciences

	PRE-FLOTATION STEPS
Step 1	Wet or moist samples: Dry overnight at 65 ºC, crush sample with mortar and pestle. Rock samples: Clean sample with metal brush and water. Shred samples in a crusher to a particle size of 500 µm.
Step 2	Weigh-in approximately 10 grams of dried/crushed material in a 50 ml centrifuge tube.
Step 3	Add 5% of Calgon® solution. Shake the samples for 12 hrs.
Step 4	Centrifuge samples twice with demineralized water (2 min at 3,000 rpm).
Step 5	a) Transfer sample into a 400 ml beaker and place on a hot plate. Add 10 ml of 30% HCl for the removal of carbonates. After 10 min. add another 10 ml of 30% HCl after a light shake. Proceed to Step 5b when reaction ceases. b) Add 20 ml of 35% H_2O_2 in 5 ml steps for the removal of organic material. Gently shake beaker every 10 minutes until reaction ceases (after approximately 1-2 hrs). c) Fill beaker with demineralized water and allow the slurry to settle for at least 24 hrs. Decant excess water with a water pump.
Step 6	Transfer the sample back into 50 ml centrifuge tubes and centrifuge twice with demineralized water (3 min at 2000 rpm). Use a pH-indicator to ensure that the sample is acid free.
Step 7	Wash the sample through a 250 µm sieve (nylon mesh) with a 5% Calgon® solution into 400 ml beakers. Discard the material on the sieve. Continue with Step 8 when the sample contains a large clay fraction, otherwise continue with Step 9.
Step 8	Sieve the < 250 µm fraction through a 5 µm sieve (nylon mesh) with a 5% Calgon® solution. Use an ultrasonic bath. Wash the material on the sieve into a 400 ml beaker.
Step 9	Allow the slurry to settle for 24 hrs. Decant water with a water pump and transfer the sample back into a 50 ml centrifuge tube. Centrifuge twice with demineralized water (3 min at 2,000 rpm).
	HEAVY LIQUID FLOTATION
Step 10	a) Prepare a heavy liquid solution with a specific gravity of 2.4 using ZnI_2. b) Check the specific gravity using a densitometer
Step 11	Add 10 – 15 ml (depends on sample size) of the heavy liquid solution into the 50 ml centrifuge tube. Centrifuge for 5 min at 3,000 rpm.
Step 12	Decant the supernatant (containing the BSPs) into another 50 ml centrifuge tube. Set the residue sample aside.
Step 13	Fill the centrifuge tube with demineralized water and centrifuge for 10 min at 3,000 rpm. Decant heavy liquid.
Step 14	Repeat steps 11-13 with the residue sample, that was set aside in step 12.
Step 15	Pour both tubes containing the BSPs together. Centrifuge twice (10 min at 3,000 rpm).
Step 16	Wash the residue sample by centrifuging twice (2 min at 2,000 rpm) and preserve for further analysis
	PREPARATION OF SLIDES
Step 17	Use sedimentation trays to make permanent slides. Fill the sedimentation tray with water and place 1-4 cover slips into the stamped pits. Distribute an aliquot of the BSP solution over the sedimentation tray. Settle for 2 hrs, and then remove water by paper strips.
Step 18	Place cover slips on a hot plate (80 ºC) using a razor blade. Add a drop of the mounting medium Naphrax™ (Brunel Microscopes Ltd, Wiltshire, UK).
Step 19	Pick up the cover slip with a clean and inscribed slide. Turn the slide and place it on the hot plate.
Step 20	Increase the temperature of the hot plate to 140 ºC and allow the toluene to evaporate for 90 min.
Step 21	Take slides from the hot plate and allow them to cool down on a cold surface.

Scanning Electron Microscope (SEM) analysis (JSM-6450, JEOL, Japan) was performed on one sample from well F (Figure 1) to study the microstructure of the BSPs and to compare them with quartz and clay particles of similar size. The SEM is equipped with an Energy Dispersive X-ray (EDX) probe (Bruker AXS, U.S.A.) that was used to characterize the elemental composition of selected particles. Gold (Au) was used as a conductivity coating.

The recent plant material analyzed was collected along the base of large barchanoid dunes near Shaybah Field. The area lies in the eastern Rub Al Khali desert some 600 km southeast of the study area. It was processed using the dry ashing technique (8 hours by 450 °C), as this produces clean, *in-situ* phytolith assemblages (Parr et al., 2001, and references therein).

BSP MORPHOLOGY

Light and SEM microscopic analyses of the 'barren' rocks of the Unayzah Formation, the Oman outcrop samples and the study of recent plant material, revealed a rich assemblage of biogenic silica microfossils. The in this study identified Paleozoic specimens will be referred to as BSPs, as their biogenic source (i.e. plants, algae, etc.) is not (yet) clear.

Unayzah Formation and BKC Samples

On average 43 BSPs are identified per slide, with a minimum of nine and a maximum of 114 BSPs. In total, more than 3,500 BSPs were identified and classified based on recognizable morphological features (size, shape, ornamentation). This resulted in the discrimination of 14 different BSP morphotypes that are described in Table 2. For the description, where possible, the shape, texture and ornamentation descriptions suggested by Madella et al. (2005) were used. Micrographs of the BSP morphotypes are shown on Plate 1.

The abundance of the BSP morphs within the sample-set and for the individual wells is given in Table 3. The BSPs 004 and 006 are very frequent observed within the studied sample set, whereas the BSPs 002 and 012 are commonly present. The remaining BSPs all are rarely observed. Note that abundance variations between the total sample-set and the individual wells may be influenced by the limited sample set.

Table 2:
Description of BSPs identified in this study

BSP	Width [μm]	Length [μm]	General shape	Surface texture	Remarks	Micrograph no. [Plate 1]
001	0.5 – 1.5	3.5 – 12.5	Elongate	Smooth	Particles are very slender (tenuis) with rounded (obtuse) ends	1 - 4
002	2.0 – 11.5	6.0 – 75.0	Elongate	Striate to smooth	Fragments of larger particles. Central vein running through the long axis	5 - 12
003	4.5 – 18.0		Round to ovall	Irregular	Ring covered with irregular protuberances, not orbicular	13 - 16
004	3.0 – 9.5		Round to oval	Smooth	Easily confused with rounded detrital material	17 - 21
005	1.5 – 5.0	7.0 – 19.5	Elongate	Smooth to irregular	Particles have a circular cross section	22 - 26
006	4.5 – 9.0		Round to oval	Irregular wart like processes	The number of processes varies form very high to little	27 – 33
007	2.0 – 5.0	6.0 – 18.0	Elongate	Smooth	Particles have a circular cross section with sinuate, or ruminate features on generally one side	34 – 37
008	1.5 – 4.5	7.0 – 9.0	Elongate, slightly curved	Smooth	Internal segmentation	38 – 44
009	9.0 – 20.0	8.0 – 38.5	Elongate	Smooth, woven, scrobiculated (pitted)	Fragments of larger particles. Clearly identifiable thickened rims with a smooth to striate texture	45 – 49
010	5.0 – 11.0		Round to oval	Smooth	Raised smooth margin/rim with occasional ornamentation	50 - 55
011	2.0 – 7.0	5.0 – 11.0	Square to rectangle	Smooth	Slightly convex (pillow like)	56 - 61
012	3.0 – 6.5		Round to oval	Small pointed protuberances	The number of processes is variable.	62 - 66
013	5.5 – 16.5		Round to oval	Uneven (sugar-coated)	Fine irregular surface texture, neither wart like or pointed protuberances	67 - 72
014	7.0 – 19.0		Round to oval	Granulate to irregular	Finely granulate, with granules < 1 μm.	73 - 75

Table 3:
BSP abundance within the total sample set . Rare 0-2%, Occasional 2-4%, Comon 4-14%, Frequent 14-25%, Very Frequent 25-50%, Dominant > 50%

BSP	Total BSP abundance	Well A 9*	Well B 34*	Well C 5*	Well D 14*	Well E 12*	Well F 9*
001	Rare	Common	Rare	Common	Rare	Common	Common
002	Common	Common	Common	Common	Common	Frequent	Common
003	Rare	Rare	Rare	Rare	Rare	Rare	Rare
004	Very Frequent	Very Frequent	Very Frequent	Very Frequent	Very Frequent	Very Frequent	Very Frequent
005	Rare	Rare	Rare	Rare	Rare	Rare	Rare
006	Very Frequent	Very Frequent	Frequent	Very Frequent	Very Frequent	Common Frequent	Very Frequent
007	Rare	Rare	Rare	Rare	Rare	Rare	Rare
008	Rare	Rare	Rare	Rare	Rare	Rare	Rare
009	Rare	Rare	Rare	Rare	Rare	Rare	Rare
010	Rare	Rare	Rare	Rare	Rare	Rare	Rare
011	Rare	Rare	Rare	Rare	Rare	Common	Common
012	Common	Common	Common	Common	Common	Common	Common
013	Rare	Rare	Rare	Rare	Rare	Rare	Rare
014	Rare	Rare	Rare	Rare	Rare	Rare	Rare

(= no. of samples)*

Oman Outcrop Samples

The two Al Khlata diamictite samples yielded the most BSPs, 35 and 38 specimens from the youngest and oldest, respectively. The Upper Gharif sandstone yielded only five BSPs. Seven morphotypes were identified among the 78 Oman specimens (Plate 2), analogous to the morphotypes found in the Unayzah Formation. Five of the morphotypes were present in all samples (BSP 002, 004, 006, 009, and 011), but morphotypes BSP 005 and 008 were present only in the oldest diamictite. The data are too few to speculate about potential for stratigraphic correlation at this point, but the presence of BSPs in both the Omani and the Saudi Permian – Carboniferous sections is encouraging.

Scanning Electron Microscopy

Figure 3 shows a typical Energy Dispersive X-Ray Spectroscopy (EDS) spectrum of a BSP together with two SEM micrographs of the morphotypes BSP 002 and 005. The spectra of the numerous BSPs analyzed all contain these four element peaks, C (carbon), O (oxygen), Si (silicium) and Au (gold). The carbon peak originates from the filter used for the filtration of the biogenic silica extract prior to SEM analysis. The gold peak originates from the coating used for the enhancement of the electrical conductivity. Both peaks are therefore regarded as "background noise". The analyzed particles are therefore composed of Si and O, i.e. silica.

Recent Plant Material

Plate 3 shows BSPs separated from the plant material. Phytoliths similar to the Paleozoic BSP morphotypes 001, 004, 005 and 006 are identified as well as several other types. The phytoliths

Plate 1 (facing page): Biogenic silica microfossils (BSPs) from the Permian – Carboniferous Unayzah Formation. 1–4, BSP 001; 5–12, BSP 002; 13–16, BSP 003; 17–21, BSP 004; 22–26, BSP 005; 27–33, BSP 006; 34–37, BSP 007; 38–44, BSP 008; 45–49, BSP 009; 50–55, BSP 010; 56–61, BSP 011; 62–66, BSP 012; 67–72, BSP 013; 73–75, BSP 014. Micrograph sources: 1–3, 14, 18, 21, 24, 27, 29–30, 52, 55, 57–58, 67, Well D; 4, 8–13, 15–17, 19, 26, 28, 35, 38–41, 45–48, 50, 56, 59–60, 62, 68–70, 75, Well B; 5, 73, Well C; 6–7, 23, 25, 34, 43, 51, 64, 71, 74, Well E; 20, 22, 31–32, 36–37, 42, 44, 54, 63, 65–66, Well F; 33, 49, 53, 61, 71, Well A.

PLATE 1

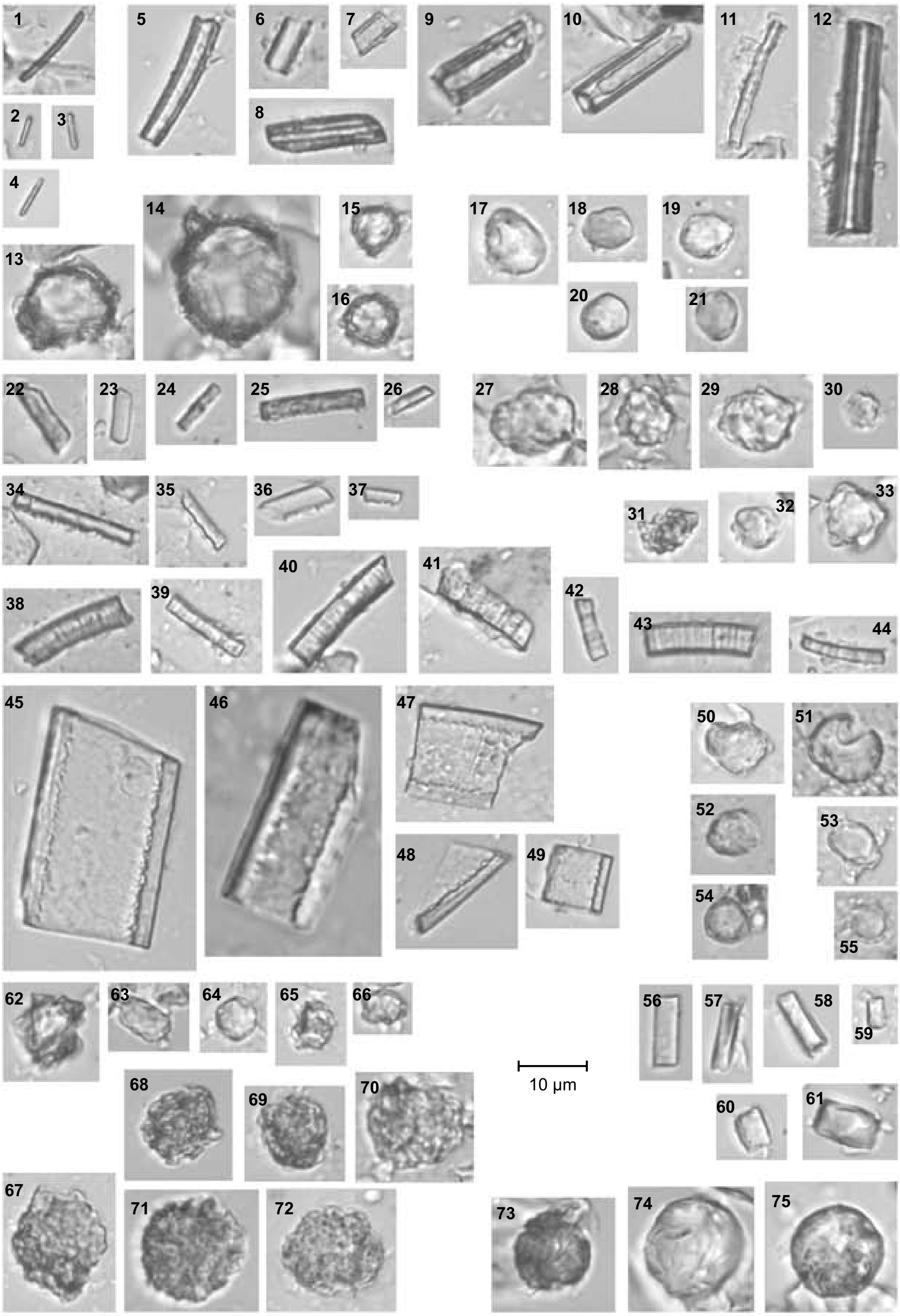
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PLATE 2

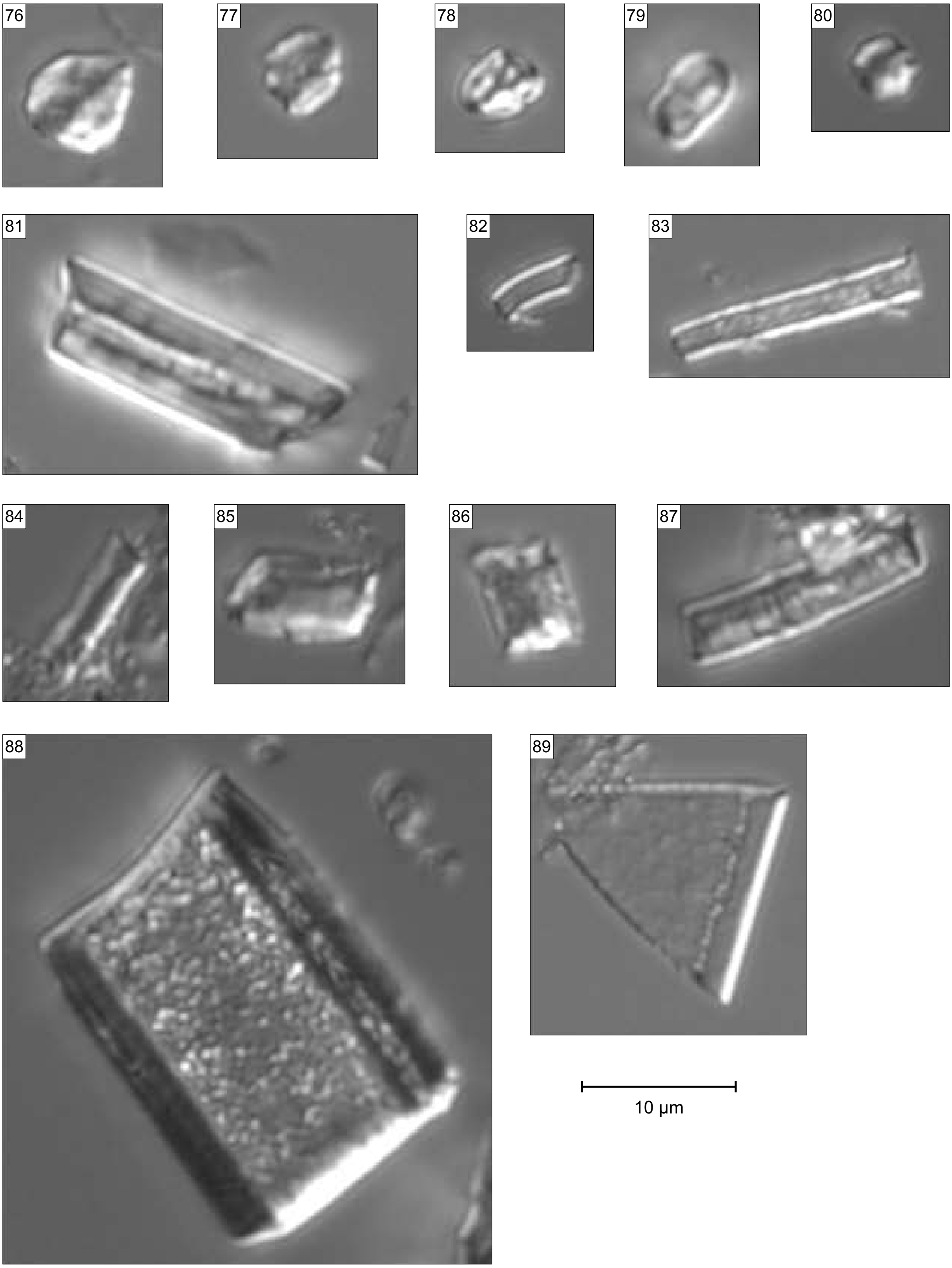

Plate 2: Biogenic silica microfossils (BSPs) from the Permian – Carboniferous Al Khlata and Gharif formations of Oman. 76–78, BSP 006; 79–80, BSP 004; 81–83, BSP 002; 84, BSP 005; 85–86, BSP 011; 87, BSP 008; 88–89, BSP 009. Micrograph sources: 76–77, 79, 81, 83, 86, 89, Youngest diamictite; 78, Upper Gharif sandstone; 80, 82, 84–85, 87–88, Oldest diamictite.

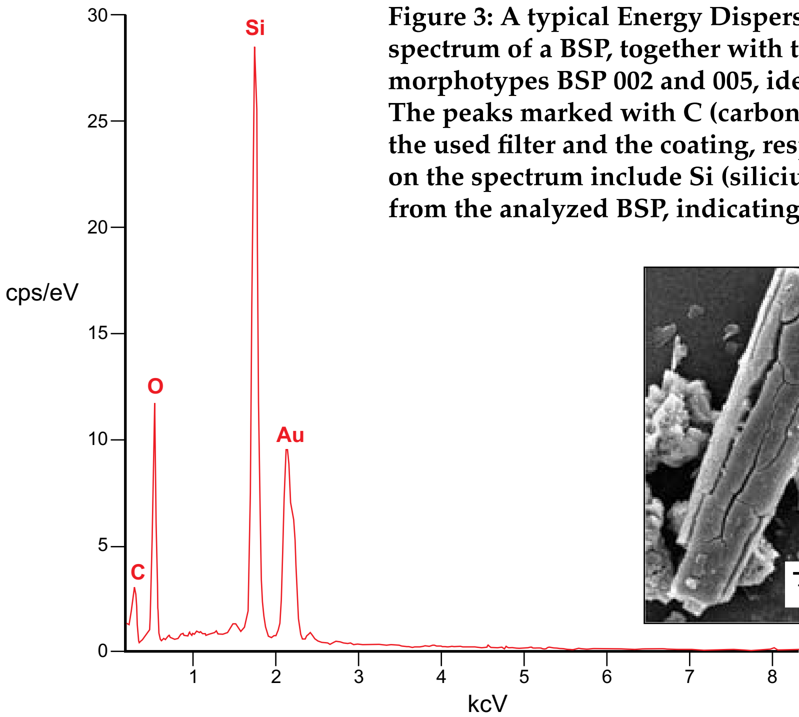

Figure 3: A typical Energy Dispersive X-Ray Spectroscopy (EDS) spectrum of a BSP, together with two SEM micrographs of the morphotypes BSP 002 and 005, identified in a sample from well F. The peaks marked with C (carbon) and Au (gold) are caused, by the used filter and the coating, respectively. The remaining peaks on the spectrum include Si (silicium) and O (oxygen), originating from the analyzed BSP, indicating its pure silica composition.

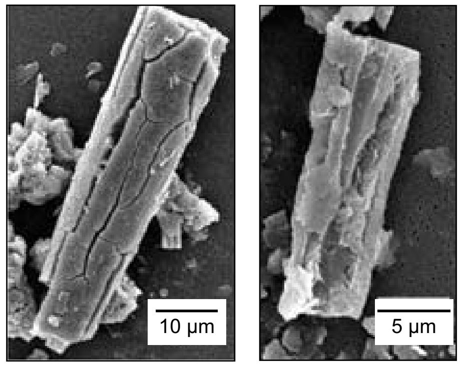

PLATE 3

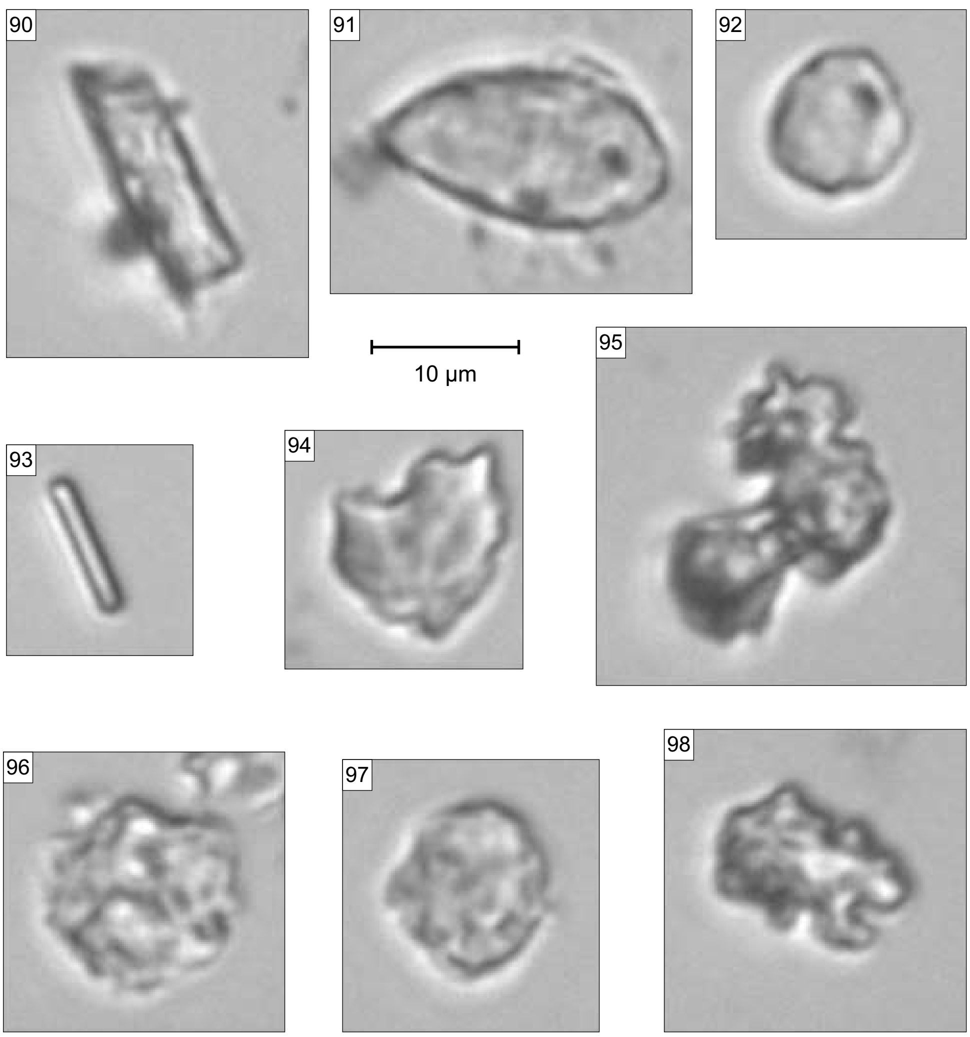

Plate 3: Phytoliths extracted from modern desert plants. Micrograph 90, similar to BSP 005; 91–92, similar to BSP 004; 93, similar to BSP 001; 96–97, similar to BSP 006; 95, 98, similar to BSP 006 and BSP 012. No analogue for the phytolith shown on micrograph 94 has been found in Paleozoic samples.

shown in the micrographs 95 and 98, are highly decorated and resemble superficially the Paleozoic morphs BSP 006 and 012. The phytolith in micrograph 94 has a facetate surface with irregular rims. No analogue of this morph has been identified in the Paleozoic sediments. The results confirm that similar biogenic microfossils were formed in modern and Paleozoic plants. Fossilized plant beds, living plant fossils, and Paleozoic deposits need to be studied, before drawing any conclusions on the origin of the BSPs identified in this study.

CONCLUSIONS

A suite of samples was collected from sediments of the Unayzah Formation and Oman outcrop samples to test whether BSPs are present and, if so, whether there are significant morphological differences in the BSPs. On both accounts the results were positive. The presence of BSPs in the subsurface Unayzah Formation of Saudi Arabia and in the outcrop samples of equivalent age strata in Oman are encouraging.

The presence of comparable siliceous microfossils in modern desert plants from Saudi Arabia and Permian – Carboniferous rocks supports the idea of a BSP fossil record. However, more study is needed in which (living plant) fossils and Paleozoic BSPs are compared.

No conclusions are drawn regarding the distribution of the BSP morphotypes in relation to stratigraphy, depositional facies, and paleoclimatic setting, due to the limited sample set. Additional samples were recently collected from the subsurface Unayzah to fill in gaps in the present sample collection and to add additional stratigraphic and areal coverage. If successful, this new microfossil assemblage may provide a breakthrough for subdividing this difficult-to-correlate sequence of strata that is mostly barren of palynomorphs or any other types of fossils.

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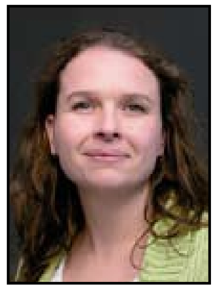

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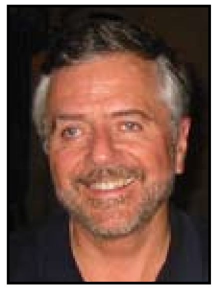

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