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Sediments of the Precambrian Wadi Abu Barqa Formation influenced by life and their relation to the Cambrian sandstones in southern Jordan

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with 1 figure and 3 plates

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Abstract

Sediments exposed at Wadi Abu Barqa in southwestern Jordan have formed at the late Precambrian in the proximity of volcanoes. The tuffaceous sediments have been overprinted by cyanaobacterial mats which stabilized sediment surface under the cover of shallow water and within the wet zone of exposition. Wadi Abu Barqa Formation is characterized as a sedimentary sequence, covering the crystalline base and being covered by volcanic deposits. The deposition began with stromatolites encrusting the crystalline base. The relation to the underlying crystalline base and overlying Precambrian deposits as well as to the Saramuj Formation at Ghor Safi further to the north is discussed. A model for the location and time of formation of Wadi Abu Barqa Formation is presented. The Cambrian sandstones covered the Precambrian series after weak metamorphisation, deformation and the erosion of large portions (more than 100 m) of the series took place. The relation of Wadi Abu Barqa Formation to the Saramuj Formation is not resolved, but, in contrast to published models the latter may be younger than the former. Cambrian sandstones at the Wadi Abu Barqa region of Jordan covered a rugged landscape with aeolian sand at first, which afterwards (end of early Cambrian) was inundated by the sea. This marine pipe rock is correlated with the late lower Cambrian and early middle Cambrian deposits exposed near the Dead Sea.

Zusammenfassung

Im Südwesten Jordaniens sind im Bereich des Wadi Abu Barka spätproterozoische Sedimente aufgeschlossen, die in der Nähe eines aktiven Vulkans entstanden. Die von Tuffen beeinflussten Ablagerungen wurden von Cyanobakterienmatten verfestigt, die anfangs sogar stromatolitische Krusten auf dem kristallinen Untergrund bildeten. Die Abfolge der Wadi Abu Barqa Formation wird beschrieben und ihr Rahmen zwischen kristalliner Basis und vulkanoklastischer Überdeckung charakterisiert. Zudem wird die Beziehung zur Saramuj Formation Jordaniens bei Ghor Safi diskutiert und die aus der Literatur erhältlichen Altersbeziehungen werden in Frage

gestellt. Ein Modell des Ablagerungsraumes der Wadi Abu Barqa Formation wird vorgestellt. Die kambrischen Sandsteine überlagerten die proterozoische Serie, nachdem diese schwach metamorphisiert und nach Osten hin gekippt worden, und von ihr ein großer Teil (mehr als 100 Meter des ursprünglichen Schichtenstapels) abgetragen worden war. Die kambrischen Sandsteine überlagerten im Gebiet von Wadi Abu Barqa ein bergiges Gelände anfangs mit eingeblasenem Sand, später mit Flusssanden und schließlich mit Ablagerungen eines Meeresvorstoßes. Diese letzte Phase wird mit marinen Ablagerungen des höchsten Unterkambriums und tiefsten Mittelkambriums aus den Bereich des Toten Meeres in Verbindung gebracht.

1 Introduction

The basement, shaped by the Pan-African Orogeny more than 600 Ma ago, and the deep reaching truncation of the former mountain ranges is exposed in the southern area of Jordan. It represents the northern portion of the basement exposure that surrounds the Red Sea and belongs to the Arabo-Nubian shield that consists mainly of metamorphic rocks and of numerous, mainly granitic plutons. Plutonic rocks and highly metamorphosed gneisses are transected by numerous dykes of light and dark color with their composition described by Jarrar (1985) and Andrews (1991). The dykes created a zebra pattern noted to characterize the rock outcrops on both sides of the highway descending from the former Precambrian peneplain that has been excavated by erosion near the turnoff to Wadi Ram and near Quweira further to the south and to the coast of the Gulf of Aqaba.

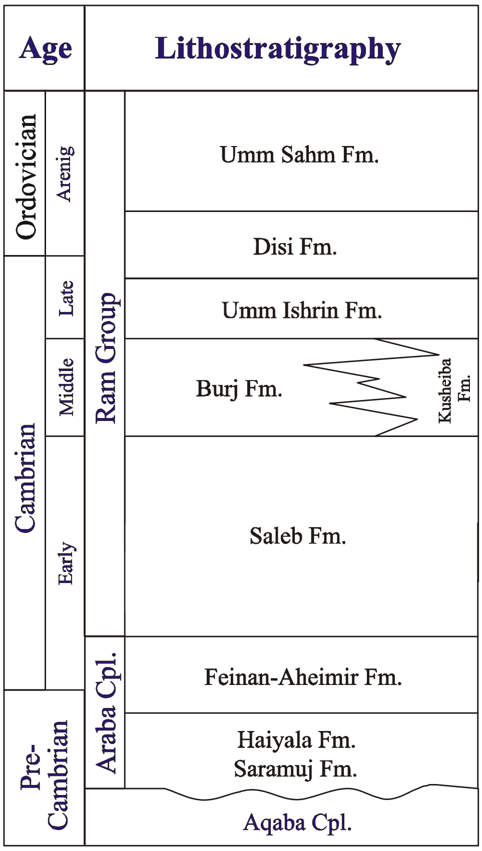

Fig. 1: Lithostratigraphic scheme of the late Precambrian and early Palaeozoic of Jordan (modified after Powell, 1989).

Studies on the basement of the area to the east and west of the Wadi Araba (Bentor, 1961; Bender, 1968a & b; Weissbrod, 1969; Jarrar, 1985; Powell, 1988; Andrews, 1991; Jarrar et al., 1991) indicate that the Precambrian can be subdivided into two rock complexes. The first consists of the orogenic complex that includes the metamorphic and plutonic rocks that were shaped by tectonic and thermal events of the Pan-African Orogeny (Schandelmeier et al., 1997). The second has formed during a rifting phase with high level intrusions and almost non-metamorphosed sediments and volcanic rocks (Bentor, 1961, Bender, 1968a, Jarrar et al., 1991). At this late Proterozoic period the Arabian platform as found in Jordan today was situated approximately at latitude 30° S. After erosion of the mountains, formed during the Pan-African Orogeny, a volcano-conglomeratic series formed. It rests on the peneplained central mountain range that had been eroded down to its metamorphic roots. These late Proterozoic sediments have been described from SE Israel by Bentor (1961), from boreholes in the central and northern Negev by Weissbrod (1969), and in the subsurface of eastern Jordan by Andrews (1991) consisting of immature clastics associated with various igneous rocks. From Jordan some of these rocks as they are exposed in the central Wadi Araba at Wadi Abu Barqa have been described by Bender (1968) and termed slate-greywacke series.

At the time of the ending Precambrian an extended ice-age came to its end, which was just terminated as Gondwana became fully assembled. This was after the Pan-African collisional event that occurred about 600 Ma ago. The continent “Greater Gondwana” may have had a role in creating the ice-age conditions during the Late Precambrian. This period was followed by a global warming during the Cambrian. During the Vendian period (about 570 Ma) the Arabian platform has been reconstructed to have been situated in the area of tropical to subtropical climate on the southern hemisphere (Schandelmeier et al., 1997). The rock sequence described here, therefore, in its lower part may have been shaped under cold climate and in its upper part under warm conditions.

The oldest almost unaltered sediments in Jordan have been deposited at the late Precambrian (fig. 1). They are composed of a conglomerate (Saramuj Formation) exposed to the East of the southern end of the Dead Sea near Ghor Safi and a series of slates and tuffaceous beds (in part Wadi Abu Barka Formation) about 80 km to the south of the Dead Sea in the central Wadi Araba just north of Gharandal at Wadi Abu Barqa. In contrast to Cambrian and later sediments deposited on top of this sequence, these sediments have become affected by a weak metamorphosis and clay stones of the Wadi Abu Barqa Formation have been transformed due to diagenetic processes connected to pressure into slates.

From the western side of the Araba-Jordan Rift, WEISSBROD (1969) described rock columns encountered in several drill sites in the Negev. The Precambrian rocks here consist of arkoses, siltstones, conglomerates and some intrusive and extrusive volcanic rocks. The sequence is usually overlain by the Carboniferous to Permian Negev Group and only in the southern Negev by Cambrian sandstones as found in Jordan. The Precambrian consists of the more than 500 m thick Zenifim Formation named after Har Zenifim in the southern Negev where the drill site was positioned. It resembles the Saramuj Conglomerate of BLANCKENHORN (1912) that is exposed to the SE of the Dead Sea. PICARD (1941) analyzed the Saramuj Formation as consisting predominantly of conglomerates with pebbles of slightly metamorphosed sediments and volcanic rocks as well as pebbles of crystalline rocks such as found in the Precambrian basement, interlayered with arkosic sandstones. It is transected by numerous volcanic dykes and sills.

BENDER (1968a) suggested that the Saramuj Formation is overlain by the slate and greywacke series (here Wadi Abu Barqa Formation), which is not exposed near Ghor Safi, but quite some distance of about 80 km to the south near Gharandal. According to own observations the Saramuj Formation, as exposed at the ancient monastery of Lut (that has been excavated from these rocks) near the town of Ghor Safi, appears to be less altered by diagenesis in composition than the rocks of the Wadi Abu Barqa Formation described below. It appears to be composed of the debris of erosion of the mainly volcanic rocks and their crystalline base and surroundings before this area became covered by the Cambrian "sandsea".

JARRAR et al. (1991) have found in the Saramuj Conglomerate next to several types of pebbles derived from the crystalline basement also volcanic debris with a wide range of composition. LILLICH (1968) had noted that the Saramuj Conglomerate had been intruded by porphyry. JARRAR et al. (1991) also noted that into the conglomerate a dioritic magma had intruded which they dated as being 595 Million years old. The Saramuj Formation outside of the contact aureole of the intrusive diorite according to their analysis showed anchizone metamorphism. It is overlain by Cambrian sandstone with a clear unconformity developed between both units. Interpreting the Saramuj Conglomerate, JARRAR et al. (1991) noted that its depositional setting is that of a fault controlled intermontane basin quite similar to the recent Wadi Araba Rift valley. But, in contrast to this reasonable reconstruction, which resembles that offered by BENDER (1968a), they characterized the sediment as “Pan-African molasse sequence”. This assumption had been stated by JARRAR (1985) and repeated by POWELL (1988). If that were the case, the Pan-African Orogeny should have occurred not very distant in time from the deposition of the Saramuj Formation. But pebbles forming this conglomerate come from a crystalline basement as is exposed in SE Jordan and from volcanic rocks similar to those exposed at the eastern margin of the Wadi Araba just to the north of the Gharandal area at Wadi Abu Barqa and Wadi Abu Kushaybah (JARRAR, 1985). According to JARRAR et al. (1991) the Saramuj Conglomerate is older than the slate-greywacke series of BENDER (1968a) and the later “paraconformably” overlies the former. Since the later series of Wadi Abu Barqa has no contact to the Saramuj and lies more than 80 km further to the south this is an unproven assumption, in part based on rather doubtful age dating (BENDER, 1974; repeated by JARRAR 1985). In the contrary, it may be possible that pebbles of volcanic rocks contained within the Saramuj Formation have been eroded from a similar sequence as that holding the slate-greywacke series of BENDER (1968), that is here called the Wadi Abu Barqa Formation

2 Precambrian sediments of the Wadi Abu Barqa area

BENDER (1968a, 1974) noted that Precambrian plutonic and metamorphic rocks and local occurrences of Proterozoic conglomerates, greywacke and slate, as well as late Proterozoic to early Cambrian quartz porphyry are exposed along the eastern side of the Wadi Araba. About 5.5 km north of Wadi Gharandal at the mouth of the Wadi Abu Barqa a basal conglomerate that may have been related to the Saramuj Conglomerate by LILLICH (1968), is much thinner and laterally discontinous and overlain by the slate-graywacke series of BENDER (1965), here called Wadi Abu Barqa Formation (pl. 1, fig. 1 between arrow 2 and 3). The conglomeratic base of the Abu Barqa Formation belongs to this series and has been effected by the same diagenesis as the rest of it. It has, therefore, become more altered than the actual Saramuj Formation as found in its type locality near Ghor Safi.

In the mountains above Wadi Abu Barqa, about 90 km south of the Dead Sea and a few kilometers north of

Gharandal police station expose about 120 m of sediments, and additional more than 200 m of volcanic tuffs, intrusions and volcanic rocks of different types which overlie the metamorphic basement (pl. 1, fig. 2). A few kilometers to the southwest this volcano-sedimentary series intercalated between Precambrian basement and Cambrian sandstones is no longer present but Cambrian sandstones rest directly on the ancient crystalline basement.

Volcanism had stopped during the early Cambrian when the sea transgressed over the peneplain in the east. These deposits usually bear the sedimentary imprint of alluvial emplacement, while the rugged surface of the volcanic rocks and older sediments, present between the area of Gharandal in the south and Wadi Finan in the North, first sandstones covering them have been emplaced by eolian dunes (pl. 1, fig. 3).

The section described here can be encountered when tracing the route that is indicated on the aerial photograph in plate 1 (fig.1, arrow 1) showing the entrance to Wadi Abu Barqa from Wadi Araba and the mountain range to the south of this steep valley.

In Wadi Abu Barqa range the base of the sedimentary unit is well exposed in a less steep valley that enters the mountains to the south of the large dune at the end of Wadi Abu Barqa. The base is formed by crystalline rocks which consist of coarsely crystalline granite which is transected by dikes. A 0-6 m thick arkose or conglomerate composed of angular and little rounded pebbles of up to 30 cm in diameter may cover the crystalline base. These pebbles consist predominantly of granite and crystalline rock with porphyritic structure, more rarely of gneisses. The base on which this coarse sediment rests has irregular surface and consists of pinkish granite that is transected by many dikes. At other localities nearby the base of the sedimentary rocks of Wadi Abu Barqa Formation consists of granite without any conglomeratic cover.

The basal unit on granite or conglomerate consists of finer sediment with 4 m of alternating tuffaceous material and greenish shales and slates. At places where fine sediments occur right on the crystalline base, solid basement may be covered by a calcarous stromatolite (pl. 1, fig. 2, arrow). This stromatolite has the characteristic laminar and nodular structure and is found at its former place of growth (pl. 2, figs. 1 & 2). Some of the stromatolites have a digitate structure. The tuffaceous beds next to it and covering it have a porphyritic texture containing crystals of larger angular outline in a fine greenish matrix. The slates show a massive appearance and brake into angular large slabs. Their texture, commonly, is that of laminated beds, often somewhat wavy as found in stromatolites (pl. 3, fig. 6). Also fine cross bedding is preserved in layers as well as a few volcanic bombs.

28 m of finely laminated, predominantly greenish slate follow which brake forming sharp angular corners. In beds angular mud clasts may be preserved as they form when mud coated by cyanobacterial mats dries, brakes into sherds and is reworked by the returning water (pl. 3, fig. 5). 44 m of greenish, mostly thinly laminated slates follow above, sometimes finely interlaminated and with stromatolitic fabric. They break along their bedding planes as well as along vertical fractures. Many bedding planes show rippled surfaces with ripple crest having a distance of about 3.5 cm from each other and a rounded symmetrical shape with straight alignment to each other. Many marks of small impacts that have been produced by small volcanic bombs are found on these surfaces (pl. 2, fig. 6) as well as rain drop marks (pl. 2, fig. 7), some mud cracks (pl. 2, fig. 8), and straight elongate marks which may have formed when crystals of ice grew in the wet sediment (pl. 2, fig. 4).

18 m of dark gray slate with marks and trail-like features on their surface follow. These are overlain by 20 m of green and gray slate with marks and ripples usually about 5 cm distant from each other and of slightly sinuous orientation. 24 m reddish and more rarely green slates follow which also have marks on the thinner beds. They represent a deposition of graded silts and muds.

In this sedimentary series in Wadi Abu Barqa Formation fine grained rocks have been strongly affected by the presence of cyanobacterial crusts. Bubbles of oxygen that formed during their photosynthetic activity are commonly preserved on bedding surfaces (pl. 2, fig. 3). They can be distinguished from the marks that have been formed by rain drops on some layers (pl. 2, fig. 7). Their presence also had influence on the shape of mud cracks that formed. Slippery but continuous surfaces produced by them also served as gliding plane for pieces of pumice that had fallen onto the still wet sediment (pl. 2, fig. 1). These, sometimes, have been propelled by the wind, sometimes changing their direction within this movement, and left a trail that resembles trace fossils or the shape of tadpole- frog larvae (pl. 3, fig. 2).

The Wadi Abu Barqa Formation is largely the product of rhyodacitic volcanism with ignimbritic and pumice products. The greywackes are actually reddish grey-violett, strongly lithified dense rocks rich with inclusions of quartz and quartz-porphyry fragments typical of a rhyodacitic volcanism of middle acidic type. The pumice is a very porous, white rock with sanidine and biotite inclusions.

The sedimentary series of almost 120 m in thickness is here defined to compose the Wadi Abu Barqa Formation, beginning on top of the granite and its debris and ending with the deposits of tuff and ignimbrites. It was deposited in a subsiding basin and always near the surface of the water that periodically filled this basin. Signs of very shallow water and desiccation and exposure of the sediment surface are present throughout. The wavy surface (pl. 3, fig. 3) indicates cyanobacterial influence as may be observed in tidal flats nowadays. In the

exposed sequence current marks are common (pl. 2, fig. 5, pl. 3, fig. 4), but there is no indication of tidal currents that formed channels of any kind. Mud cracks are rare in this lower series, while they become more common in the upper portion of this series and in the sediment beds included in the mainly tuffitic and volcanic flow beds following above the Wadi Abu Barqa Formation.
Tuffaceous layers are included in the sedimentary series and they can be traced for long distances without changes in their thickness, which is from a few cm to almost one meter. This indicates, that the volcanic eruptions during sedimentation were common and represent a rather uniform rain of volcano-clastics onto the surface of the basin deposits. Single volcanic bombs are also present, usually small with a size of only a few centimeters in maximum (pl. 2, fig. 6). They did not form deep impact craters, so that the original material was probably rich in gas inclusions (pumice) and thus light in weight. This also explains, why these volcanic bombs have subsequently become compacted and flattened during diagenesis (pl. 3, fig. 1).
This series and the Wadi Abu Barqa Formation is overlain by 35 m of bedded tuffs (indicated in the aerial photograph, pl. 1, fig. 1 between arrows 3 and 4). This series also holds some sedimentary layers which usually are finely laminated, may show stromatolitic lamination and cross beds. Mud cracks are more commonly observed here than in the layers of the Wadi Abu Barqa Formation below. These sediments also show signs of slumping and folding due to sliding on a slope. This is especially so in a sedimentary series of more sandy composition than observed below, that is found just below the first Cambrian sandstones here and forming a small hill in its outcrop on the base of these sandstones.
In this upper series of the measured sequence, especially that forming a package of sediments of about 15 m thickness in the upper portion of it right below the base of the Cambrian sandstones, the sediment is more sandy and has been effected by synsedimentary sliding. The whole segment has been deformed into sliding folds indicating that this unit was moving on a slope. When this movement occurred, the sediment had been semi-consolidated since movement did not only deform these beds into folds of larger and smaller dimension but also movement occurred along the bedding planes leaving striations there. This later feature indicated that the sediment was partly dehydrated when it moved down the slope.
A very well pronounced angular unconformity is present here, with the Precambrian rocks inclined towards the south and southeast in the eastern area of their exposure while the Cambrian deposits are almost horizontally oriented and are still quite as they had been at the time of their deposition (pl. 1, figs. 2 & 5). The surface of the Precambrian series was eroded, forming a rugged hilly landscape with the Cambrian sandstones covering it up.
The second bed of slate and greywacke mentioned by BENDER (1968b) to occur in the Wadi Abu Barqa area can be examined behind (to the east) the isolated mountains range formed by the Cambrian sandstones. It here actually is not a sediment but rather composed of volcanic material partly of a sill of andesite with large crystals in fine-grained matrix all arranged in one direction and still documenting its direction of flow during emplacement. It is exposed further up in the Precambrian succession in a dry valley that has been eroded into the Cambrian sandstones exposing their base behind the first outliers of this formation. Here the original surface of deposition is clearly a hilly landscape with rock strewn slopes covered by the Cambrian sands and also with former valleys present in which rocks have become rounded by the action of water.
Above the sill there are many more layers mainly composed of tuffaceous material, with layer of fused material as is found in ignimbritic fused tuffs. These beds are representing an extended series of predominantly volcanic material a few hundred meters in thickness exposed above the described section and to the east of it before being covered by Cambrian sandstone. A similar series of rocks has been described from the subsurface of eastern Jordan and was named Haiyala Volcanoclastic Formation (cited by JARRAR et al., 1991).

Interpretation:
This depositional environment could represent a lake in a caldera with partly inundating sediment surface and partly having its bottom falling dry periodically. This would explain the flat beds as well as slumps and impacts. The caldera may have formed as collaps structure in a crystalline environment representing the crystalline basement rocks composed of granitic material riddled by many dikes of differing dark or light coloration depending on its predominantly acidic to basic mineral composition.
It is not clear whether the depositional environment was that of fresh water or of marine water. Water was not very salty since no trace of salt crystals or gypsum crystals are preserved, while other traces are preserved quite well. The presence of bubbles produced by cyanobacterial mats, rain drops, drag and tool marks, current stripes, erosive marks formed by currents, ripples of the size as formed by wind in shallow water or even in puddles of water, are all in accordance with deposition under the influence of a periodical cover with shallow water. The rarity of desiccation cracks on the surfaces which otherwise indicate that they have been exposed to the air, may be interpreted as sign of relatively cold and humid climate. What can be interpreted as traces formed by ice growing in the muddy surface is not common though. The volcano was not far away and almost constantly active. Volcanic material usually came from above and there are no dikes that cut through the series of the Wadi

Abu Barqa Formation as it is exposed in the studied mountainous region just to the south of the deep valley of Wadi Abu Barqa.
The sequence of the Wadi Abu Barqa Formation formed in a subsiding shallow basin, perhaps a lake with commonly exposed bottom and no steeper slopes present in the area of the studied section. Later, more volcanic material covered the sediments, sometimes with ashes so hot that particles still fused with each other on the ground to form ignimbritic layers. Later these beds were again covered by water. Again sediments fell dry and dried out forming desiccation cracks. Later on, this sedimentary series with the volcano-clastics became inclined and began sliding down a slope. The whole series became intruded by at least one thick sill. Much more volcano-clastic materials were deposited on top of this measured section and are exposed further to the east. The whole thick series was deformed, slightly metamophosed and inclined dipping to the east (pl. 1, figs. 4 & 5). It was than eroded to form a hilly landscape with oldest beds now near the edge of the Araba Rift. No indication of schistosity is found in the Cambrian sediments above, while in the Precambrian series clay rich beds were transformed into slate. This indicates, that an orogenic cycle distinguishes this series from the overlying rocks.
A continuous sedimentation into the Cambrian as had been suggested by BENDER (1968a & b, 1974) and also by JARRAR (1985) is, thus, not possible. JARRAR et al. (1991, fig.3) suggested that the slate bearing series comprising the Wadi Abu Barqa Formation became tilted before it was covered by ignimbritic layers and rhyolithic lava flows. This interpretation is also not supported.
According to the interpretation of BENDER (1974), the magmatic activity of quartz porphyry took place towards the end of the Proterozoic and at the beginning of the Cambrian. But in contrast, according to our observations, already mentioned by BANDEL (1981), this volcanism did not extend into the Cambrian rocks. The Precambrian metamorphic basement that consists of crystalline rocks formed between 800 and 750 million years ago (JARRAR, 1985) was already eroded to a peneplain when a rift formed and volcanism erupted (BENDER, 1974). JARRAR (1985) recognized a second metamorphosis to have occurred between 625 and 610 million years ago. JARRAR et al. (1991) changed these dates to 625-600 which indicates that some caution may be useful in regarding the value of the age interpretation that have been assembled from these rocks. This somewhat doubtful time interval may actually be related to the late Proterozoic orogeny that metamorphosed and inclined the Wadi Abu Barqa Formation as well as the volcano-clastic series above it. Perhaps rifting and associated volcanism stood in some kind of relation to the Cadomian deformation which happened around 545 Ma.
Precambrian basement just east and southeast of Gharandal and thus only a few kilometers (about 5) to the south of Wadi Abu Barqa consists of metamorphic rocks and plutonic rocks that have been transected by numerous light and dark dikes and were evenly truncated into a peneplain onto which the Cambrian sandstones were deposited. According to BENDER (1974) the slate series of the Wadi Abu Barqa Formation was intruded by numerous dike rocks, such as diabase, porphyrite, quartz porphyry, the later according to BENDER's interpretation even penetrated and invaded the Cambrian clastic rocks. Neither the first nor the second statement can be confirmed in the field at the area of Wadi Abu Barqa. Cambrian sandstones were always noted to overlie the volcanic rocks and were never intruded by them. Slabs of volcanic material found in the basal layers of the Cambrian sandstones in the outcrops of these on the top of the slope to the north and south of the steep Wadi Abu Barqa are due to the rugged morphology of the region when it became covered and inundated by the sand. Coarse debris on the steep slopes is thus preserved, but when viewed from close up can not be mistaken with intrusions. The erroneous interpretations are also due to not concise age determinations. According to BENDER (1974) the age of the ignimbrite in the Wadi Abu Barqa series was determined by potassium-argon whole rock analysis as 471 +/- 7 Ma. Regarding the geological arguments mentioned above, this suggested age is much too young.
According to PARKER (1970) the Saramuj Formation was also found in the subsurface of the Azraq trough and here the total thickness of sediments covering the crystalline base in SE Jordan in the Jaffr Basin exceeds 4000 m. Such a thickness can be comprehended when the full sequence exposed at Wadi Abu Barqa is taken into consideration.
BENDER (1965, 1968a & b, 1974) noticed that a zone of structural weakness along the modern Araba-Jordan Rift was already present at late Precambrian time. But these directions are not the same as those noted by WEISSBROD (1968) and also JARRAR et al. (1991). From the area on the other side of the modern Wadi Araba Rift, WEISSBROD (1968) described from the subsurface of the southern Negev about 500 m of conglomerates like those of the Saramuj near Makhtesh Qatan, and more than 2000 m of sediments near Makhtesh Ramon. Here, conglomerates alternate with arkose and mudstones and igneous rocks are present on top of the section. At the Hameishar I well a thick conglomerate forms the base and igneous rocks follow with basalts, andesites, trachyte and some acidic volcanic breccia and tuff. The basin or rift filled with these sediments is transversal to the Araba-Jordan Rift and has SW to NE direction instead of N-S direction.

3 The drowning of the Precambrian surface of Jordan by a Cambrian "sand-sea"

The transition from the Precambrian to the Cambrian is commonly considered as one of the major global changes in the lithosphere, hydrosphere and atmosphere. A revolution from very cold climate to warmer climate has been assumed. A combination of tectonic and climatic changes has been interpreted to have resulted in a major global transgression at the beginning of the Cambrian. Quartz rich sandstone sequences may represent a body of material that was deposited on extended and collapsed Pan-African continental crust between 550 and 450 Ma, and eroded from Pan-African mountains and plateaus further south (present co-ordinates) (BURKE & KRAUS, 1998).

In Jordan the Precambrian volcano-clastic and sedimentary slate series were found to have been eroded to a rugged surface onto which the Cambrian sandstones were deposited, clearly with aeolic dune sands at first. In the mountains above Wadi Abu Barqa the Cambrian sediments were found undisturbed by dikes of any kind. Certainly, there is no quartz porphyry intruding into Cambrian sandstones above the Precambrian series as was "documented" by BENDER (1974, figs. 5a-c), but also no lava flow on tilted layers formed in a lake and connected to ignimbritic beds as indicated by JARRAR et al. (1991, fig. 3 right). Sandstones overlie a rugged surface of a mountain range composed predominantly of volcanic rocks which may be misinterpreted as intrusions when seen from the distance, but only if one is not close to these surfaces.

The rugged surface of the hilly landscape formed by the Precambrian rocks in the Wadi Abu Barqa area has been partly exhumed due to the erosion of the Cambrian sandstones. The former valleys had steep slopes and in their base gravel can be discovered with pebbles rounded by streams that flowed here. Slopes formed by rock exposures with hard ignimbritic or other volcanic material where covered by big slabs of rock debris, when the sand came. The first sand usually came with the wind and shows a large size cross bedded structure with relatively steep former slopes of the dunes. Later on and further up in the sandstone cross bedding indicates more alluvial sedimentation. In the small mountains of Cambrian sandstone found above and to the east of the exposure of Wadi Abu Barqa Formation, a layer with the vertical burrows of *Skolithos* is present (pl. 1, fig. 3). This pipe rock can be found in the same position also in sections nearby and indicates that the area had been inundated by the shallow sea when it formed. The pipe rock layer is found sometimes high up in the sandstone section, sometimes not far from its base. This gives evidence of the relief that was covered and equalized by the sands. In the studied area it appears as if all the former hills of the rugged Precambrian landscape had been covered by sand when the sea invaded the area.

The depositional environment of *Skolithos* lay probably near the shore in a high energy environment. The pipe rock layer, therefore, has progressed towards the former land, that is towards the SE, and was not deposited at the same time, but represents a time transgressive horizon. Here worm-like animals formed the vertical burrows as single-entrance burrow representing a dwelling burrow used for suspension feeding. For example burrows of lophophorate phoronids of tentacular crowned polychaetes are a possible explanation. Similar “pipe rocks” in Jordan also occur in the Jurassic near Deir Alla (BANDEL, 1981), also indicating deposition in shallow water and not quite normal marine environment.

The *Skolithos* layer of “pipe rock” may be time equivalent to the marine deposits found in the Cambrian of Jordan north of the Wadi Feinan area. Cambrian limestone was first discovered by HULL (1886) and called Wadi Nasb Limestone. From it KING (1923) discovered fossils such as hyolith shells. BLANKENHORN (1912) collected from these limestones fossils which RICHTER & RICHTER (1941) described. QUENNEL (1951) changed the name of the Cambrian limestone unit to “Burj Limestone” according to one of its outcrops at El-Burj near Ghor Safi. According to these authors and to PICARD (1941), the limestone unit of the Wadi Nasb (Burj) Limestone is of late early Cambrian age. The trilobite fauna from these beds was described by RUSHTON & POWELL (1998) who placed the fauna in the very early middle Cambrian. These authors also created some new formation names when describing again the section exposed at the shore of the Dead Sea just north of the mouth of Zarqa Main River, that has already been described by BANDEL (1986) and SHINAQ & BANDEL (1992). BANDEL (1986) had from here reconstructed "*Hyolithes kingi*" as annelid worm and included a section of the exposure. SHINAQ & BANDEL (1992) discussed the microfacies of these Cambrian limestones and the analysis of the carbonate facies was carried on to the area near the southern Dead Sea by ELICKI & SHINAQ (2000), and ELICKI et al. (2002). Accordingly the microfacies indicates that the influence of the open sea in the area of the northern Dead Sea was still strong, while further to the south lagoonal conditions prevailed.

Cambrian rocks are extensively exposed in southern Jordan. LILLICH (1969) described these Cambrian rocks which where deposited on the crystalline basement and interpreted the sandstone as deposited by rivers on a peneplained landscape with conditions of dry climate so that feldspar was not destroyed. Near Wadi Ram the base of the sandstones holds milk quartz pebbles, some of which are wind facetted (own observations). This indicates that a wind blown plain was the base of deposition to the sandstones. A well preserved *Cruziana* trail formed by a trilobite was found about 30 to 40 m above the Precambrian base (own observation). This position is equivalent to the basal portion of the brownish sandstone of the lower Quweira Sandstone of BENDER (1968a). According to this author the Cambrian Sandstone of the Quweira area (at the Desert Highway and near Wadi Ram) can be distinguished into the 20-60 m thick “Lower Quweira Sandstone” composed of a basal conglomerate and banked arcosic sandstone, a central "Upper Quweira Sandstone" ranging into the Middle Cambrian and composed of brown weathered sandstones up to 350 m thickness. Above follows the up to 250 m thick Ram Sandstone of early Ordovician age (BENDER 1965, 1968a). The Quweira Sandstone had been named first by QUENNELL (1951) who expressed the idea that lower and upper Quweira Sandstones are of terrestrial origin and the transgression depositing the Burj Limestone only reached as far south as the Feinan area. LILLICH (1969) interpreted brownish sandstones as fluvial depositions on arid plain lands with the brown crusts representing dried playas. But such crusts could also represent former water tables and have formed within the sand. A sandy fluvial lowland with the sea going across now and than is the interpretation of AMIREH (1990) and AMIREH et al. (1993). SELLEY (1970, 1972) found the Precambrian igneous basement overlain by 700 m of coarse cross bedded pebbly sandstone attributed to a braided alluvial environment. According to this author it is divisible in three formations which he supplied with new names. The planar unconformity in the Wadi Rum area is overlain by the Saleb Formation which thickens from 30 m at Wadi Rum to about 60 m in the north of it. This base of the overlying Ishrin Formation (about 300 m thick) is marked by huge channel complexes and its top is incised by channels over 5 m deep. They mark the base of the Disi Formation, which is again about 300 m thick. At the top of the Disi Formation marine shelf sands of the Um Sahm Formation appear. As a conclusion SELLEY (1972) reconstructed the depositional environment that the Arabian Shield was uplifted three times at Saleb, Ishrin and Disi to form alluvial deposits in southern Jordan.

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Plate 1

Fig. 1: Aerial photograph of the area in which the Wadi Abu Barqa Formation is exposed. Arrow 1 points at the dune which marks the begin of Wadi Abu Barqa from the eastern margin of the Wadi Araba. The arrow 2 indicates the base of Wadi Abu Barqa Formation, about at the same spot as indicated by the arrow in fig. 2. Arrow 3 points at the top of Wadi Abu Barqa Formation, and between 3 and 4 the predominantly tuffaceous layers are present, with 4 indicating the base of the Cambrian sandstone.

Fig. 2: View with the crystalline base and the overlying sediments of the Wadi Abu Barqa Formation with the arrow pointing at its stromatolitic base. The view is towards the east, and the rugged mountains in the back are composed of Cambrian sandstones.

Fig. 3: The location of arrow 4 in the aerial photograph of fig 1 with the Cambrian sands covering a rugged Precambrian base, at first by dune deposits.

Fig. 4: Standing between arrow 2 and 3 as shown in the aerial photo (see fig. 1) and looking in northerly direction. The Wadi Abu Barqa Formation forming the gentle slopes is overlain by predominantly volcanic deposits forming the rugged slope on the right.

Fig. 5: From a similar position as in fig.4 looking to the south the rugged crystalline base of the Wadi Abu Barqa Formation at the right, the central band of that formation in the middle and the easterly dipping beds above it are truncated and overlain by the almost horizontal Cambrian sandstones.


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2
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Plate 2

Fig. 1: The thin section exhibits alternating calcareous stromatolite crusts and sandy tuffaceous material between them.

Fig. 2: As in fig. 1 but with less irregular calcareous stromatolites, both samples are from the base of Wadi Abu Barqa Formation, location close to the arrow in pl. 1, fig. 2.

Fig. 3: Wrinkled bedding surface formed by a cyanobacterial crust. The coin measures 25 mm in diameter.

Fig. 4: Needle-like impressions on the bedding surface may have formed by ice crystals. Coin 25 mm in diameter.

Fig. 5: A bedding surface with marks produced by tools carried by the water that flowed in two different directions, and some impacts formed by pumice. Coin with 25 mm in diameter.

Fig. 6: Bedding surface with many volcanic bombs of different size on its surface. They were pumice-like and have been flattened by compaction. Coin with 25 mm across.

Fig. 7: A bedding plane with fine groove and ridge pattern formed by cyanobacterial crust and impacts of rain drops (diameter up to 10 mm) preserved as cast.

Fig. 8: Cast of mud cracks preserved on a bedding plane.

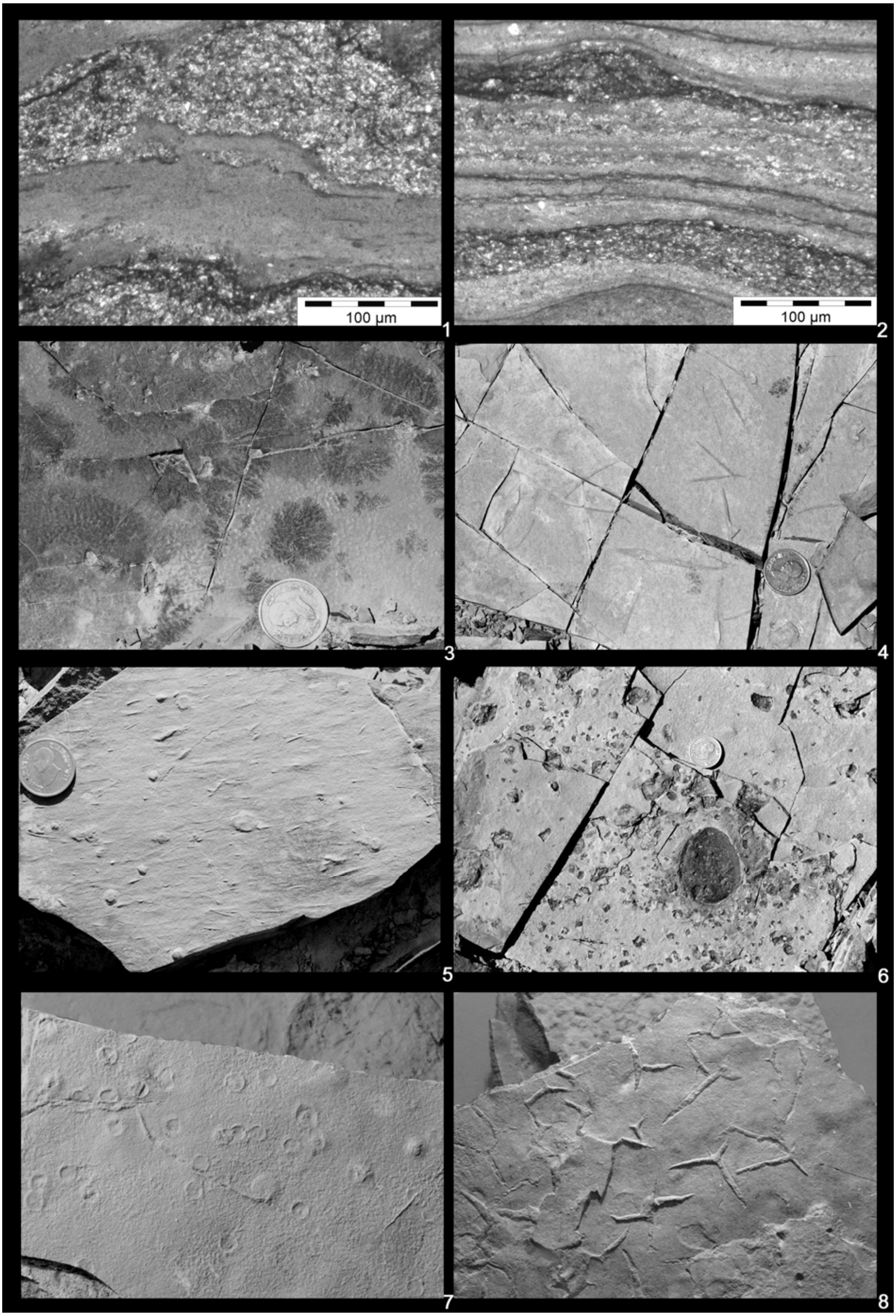
100 µm
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Plate 3

Fig. 1: Bedding plane with the cast of a pumice bomb that had been moved over the surface leaving a mark (about 15 mm wide) and later become flattened by compaction.

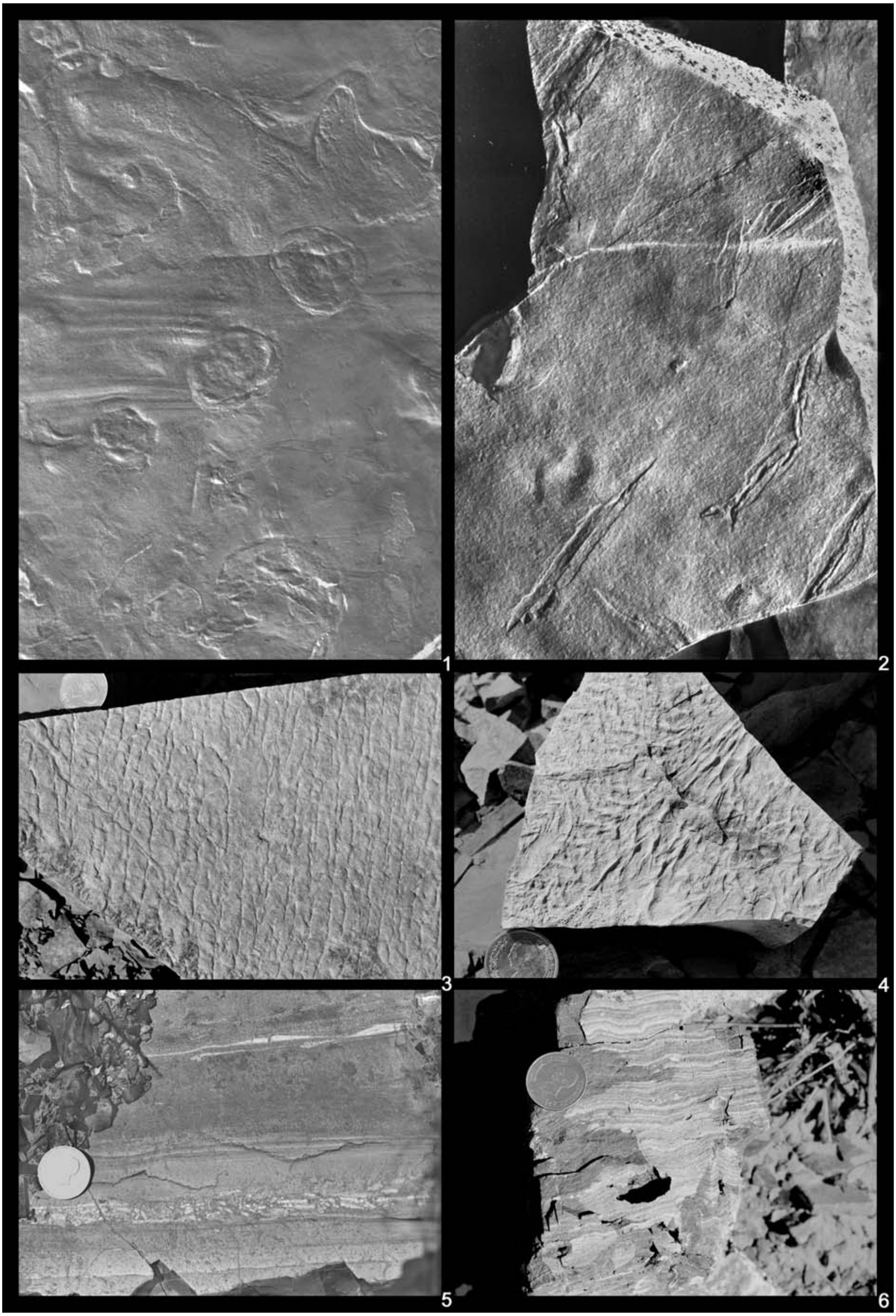
Fig. 2: Marks of tadpole-frog larvae shape (about 40 mm long) that formed when pumice was pushed over the wet sediment surface by wind. The bedding plane is a cast of the cyanobacteria coated sediment surface, as documented by the fine groove and mound surface.

Fig. 3: Bedding plane with wrinkled cyanobacterial mat that formed on a fine wind ripple surface.

Fig. 4: Tool mark resembling an arthropod trail well preserved due to cyanobacterial sealing of the sediment surface. Coin 25 mm across.

Fig. 5: A bed vertically broken shows lamination as well as mud sherd layer. Coin 25 mm across.

Fig. 6: Lamination is wavy in this bed fractured vertically, due to the growth of cyanobacterial crusts during deposition. Coin 25 mm across.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Paläontologie, Stratigraphie, Fazies

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