FACIES	27	263-284	Pl. 52-57	7 Figs.	--	ERLANGEN 1992

Microfacies of Cambrian Limestones in Jordan

Rafie **Shinaq**, Irbid and Klaus **Bandel**, Hamburg

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SUMMARY

The limestones of the Wadi Nasb Formation of the uppermost Lower Cambrian of Jordan are under- and overlain by massive sandstones of a near-shore facies. Facies analysis is based on samples from an outcrop at the northeastern shore of the Dead Sea and two oil test wells in the Wadi Sirhan Depression in eastern Jordan. Limestones were deposited in the shallow sea and within the coastal tidal area. Cyanobacteria, algae, echinoderms, trilobites and hyoliths have contributed the bulk of the carbonate and phosphatic material composing the Wadi Nasb limestone. Fine-grained facies types are composed of peloidal carbonate muds with laminar and nodular algal and cyanobacterial mats. They formed within a quiet tidal-lagoonal environment. The coarse grained facies types consist of carbonate sands with layers of shell debris deposited in crossbeds in an environment with a rich endobenthic fauna. Here most particles were coated by cyanobacterial crusts. Ooids, oncoids and various coated grains are present. Consolidated sediments were commonly eroded within or near to this environment and their remains were integrated within the sands. Diagenesis is reconstructed step by step with deposition, first cementation, aragonite dissolution, compaction, pore filling, formation of pressure solution, growth of dolomite and anhydrite within the calcitic limestone and final fissure formation and filling.

1 THE GEOLOGICAL SETTING AND ITS HISTORY

Cambrian rocks are extensively exposed in southern Jordan and along the fault line which represents the eastern border of the Dead Sea/ Wadi Araba depression. The northernmost outcrops lie just to the north of the mouth of the Zarka Máin river, at the northeastern shore of the Dead Sea.

Over 100 years ago Cambrian limestones were first reported by Hull (1886) near the southern end of the Dead Sea (Wadi Nasb). Hull called them Wadi Nasb Limestones. The same locality was visited by BLANKENHORN (1912, 1931) who described the sequence of exposed rocks as consisting of about 30 m of reddish and greenish micaceous shales and marls overlain by about 30 m of limestones and dolomites. Some fossils collected in the Wadi Nasb were described by KING (1923) and RICHTER & RICHTER (1941).

According to Wetzel (1947), QUENELL (1951) and BURDON (1959) the Burj Limestone Formation represents the Wadi Nasb Limestone. This unit also crops out to the east of the Dead Sea near the town of Ghor Safi. The above mentioned authors along with PICARD (1942) attributed the sequence of the carbonates of the Wadi Nasb and of the Burj Limestone Formation to the Uppermost Cambrian and the lowermost Middle Cambrian.

BENDER (1968) subdivided the sequence of carbonates of the Burj Limestone Formation of Wadi Nasb into an upper and a lower part. The lower part consists of about 20 m of clay and sand-rich carbonates, while the upper part is composed of massive dolomites and dolomitic limestones with siliceous layers containing fossils in the upper beds.

From the northern Wadi Araba about 5 to 7 m of sandy dolomites can be traced southwards into the area of Bir Madhkur where they grade into fine-grained white sandstones. The thickness of this carbonate sequence increases slowly towards the north. BENDER (1968) preferred distinguishing a sequence of units according to their lithology and called it Burj Dolomite- Limestone and Shale Formation, while BANDEL (1986) called it the Wadi Nasb Limestone as originally proposed by HULL (1886).

Older Paleozoic sandstones unconformably overlying the Precambrian basement were named Ram Sandstone by QUENNEL (1951). This author and BURDON (1959) considered the age for the Ram Sandstones to be Ordovician to questionable Permian. BENDER (1968) suggested a Cambrian to Silurian age of the Ram Sandstones. LLOYD (1969) differentiated several formations within the Ram Sandstone: the basal Salib Formation, the Burj- Dolomite, Limestone, Shale unit (Wadi Nasb Limestone), the Um Ishrin, Disi and Um Sahm Formations.

Addresses: Dr. R. Shinaq, Department of Earth and Environmental Sciences, University of Yarmouk, Irbid, Jordan; Prof. Dr. K. Bandel, Geologisch-Paläontologisches Institut und Museum, Universität Hamburg, Bundesstraße 55, D-2000 Hamburg

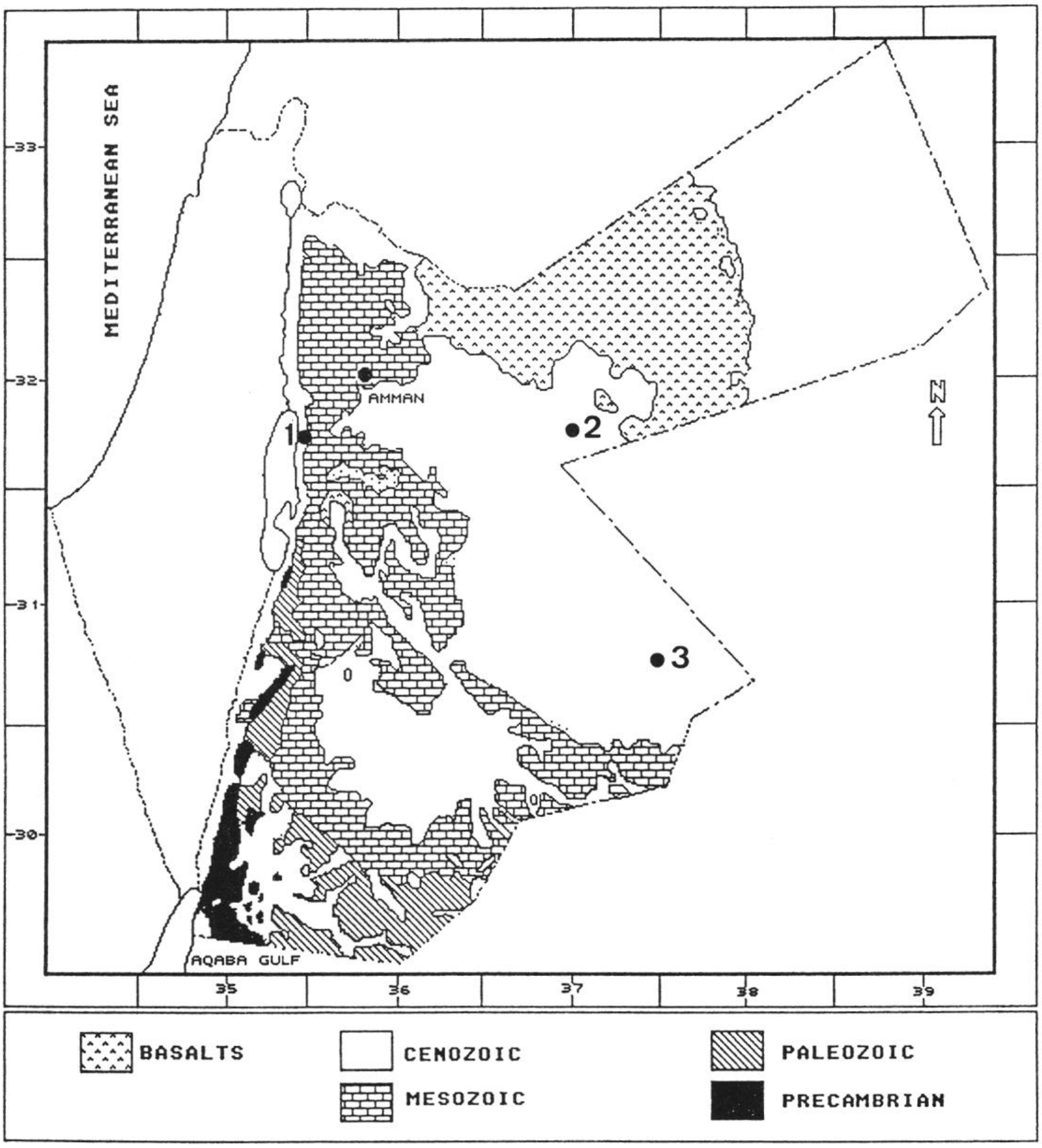


Fig. 1. Geological map of Jordan with the three localities indicated (1 outcrop at the Dead Sea, 2 test well of Wadi Al Ghadaf near Azraq, 3 test well of Wadi Sirhan).

POWELL (1988) distinguished three members within the Wadi Nasb Formation. The lower one was called the Tayan Member, named according to its occurrence in Wadi At Tayan and Jebal At Tayan (southeast of the Dead Sea) where it is well-exposed with a thickness of 18 to 20 m. The central unit was called the Numeyri Member after an outcrop to the east of the Dead Sea at Wadi Numayri exposed with a thickness of 40 to 60 m. The upper part of the Wadi Nasb Formation was called the Hanneh Member. Its type locality is the Jebal Tabaq Hanneh situated on the northern side of the Wadi Numayri.

The Wadi Nasb Formation is overlain by massive sandstones of the Um Ishrin Formation. It was named by LLOYD (1969) from its type locality of Jebel Um Ishrin in the southern desert of Jordan. This name was also used by SELLEY (1970, 1972). It is an equivalent to the upper Quweira Sandstone Formation of QUENNELL (1951) and BURDON (1959) and to the massive brown sandstones of BENDER (1975).

2 STUDY AREA

2.1 Cambrian exposure at the northeastern shore of the Dead Sea.

The northern most outcrop of Cambrian rocks in Jordan is exposed about 1 km to the north of the mouth of the Wadi Zerqa Máin at the northeast side of the Dead Sea. The lower part of this section has been described and measured by BANDEL (1986, Fig. 2) and was sampled and measured again in 1988 to encompass the upper carbonates (Fig. 3) (SHINAQ, 1990). The exposed carbonate sequence is 12.45 m thick and consists of limestones, dolomitic limestones and intercalated sand- and siltstones. The basal part of the sequence consists of finely laminated, crossbedded sandstones overlain by 4.35 m of limestone and dolomitic limestone. Following this is an approximately 45 m thick sandstone of the same composition and structure as that below the carbonates. It is overlain by 3.10 m of dolomitic

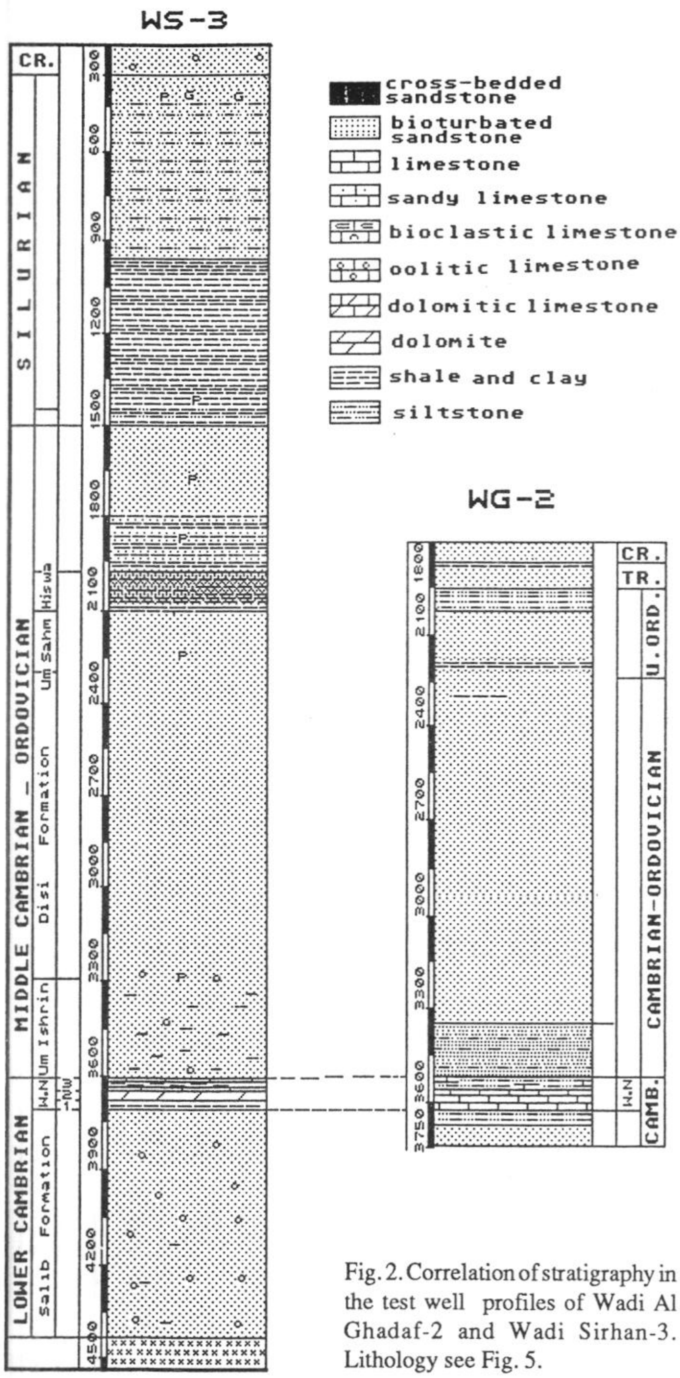


Fig. 2. Correlation of stratigraphy in the test well profiles of Wadi Al Ghadaf-2 and Wadi Sirhan-3. Lithology see Fig. 5.

limestone. The sequence is covered by massive sandstones of Cambrian age which are discordantly overlain by Triassic sediments (Bender, 1968) with a Permo-Triassic base from the Um Irna Formation of Bandel & Khoury (1981).

2.2 Subsurface data from the test wells of Wadi Al Ghadaf 2 (Figs. 2, 4)

The test well of Wadi Al Ghadaf 2 lies within the Wadi Sirhan depression that extends for about 300 km from the southern margin of the Jebel ed Drouz basalt shield in a southeasterly direction ranging from the Azraq oasis to Al Jauf in Saudi Arabia. The geographic position of the drill site of Wadi Al Ghadaf is shown in Fig. 1 and lies at the coordinates N= 114000, E = 319000 of the Palestine grid. The drilling operation was completed 1983 and the well reached a total depth of 3740 m; it did not completely penetrate the Cambrian sequence.

At Wadi Al Ghadaf-2 Cambrian sediments are more than 1200 m thick. They consist predominantly of sandstones. Subordinate limestones and siltstones are intercalated in the lower part of the section. The Wadi Nasb Limestone Formation is composed of a 157 m thick sequence of limestone and siltstone which was completely penetrated by the test well (Fig. 2).

Subordinate dolomitic, dark-brown limestones were intercalated within a 50 m thick silt unit (3620 - 3670 m). The pure limestones unit is 40 m thick (3580 - 3620 m). Limestones are white, light gray and brown, partly of oolitic composition, and locally dolomitized. This is followed by 63 m of intercalated limestones and sandy and silty sediments between a depth of 3517- 3580 m. The limestones of this sequence are hard, dark-gray to dark-brown, partly oolitic and partly dolomitized. The light-colored, siliceously cemented sandstones are composed of well rounded quartz grains with patches of pyrite.

2.3 Subsurface data from the test well Wadi Sirhan 3 (Figs. 2, 5)

The Wadi Sirhan test well No.3 lies within the Azraq-Wadi Sirhan depression and was completed in1987. A total depth of 4530 m was reached and the Cambrian sequence was fully penetrated.

The Precambrian sequence consists of dark-brown, brown to gray finely crystalline rocks containing feldspar, olivine, augite, mica and hematite along with some grains of quartz and carbonate cement (4460 to 4530 m). They may be considered as tuffaceous material derived from basaltic magma.

The Lower Cambrian Ram Sandstones were penetrated beween 3708 - 4460 m. The lower part of the Salib Formation is 305 m thick (4155 - 4460 m) and consists predominantly of hard, reddish, arkosic sandstones. These sandstones are moderately sorted, siliceously cemented and encompass angular to weakly rounded components. Their immature nature is indicated by the presence of feldspar grains. Some intercalations of clay beds rich in mica on bedding surfaces are present.

The upper Salib Formation (3708 - 4155 m) consists of 447 m of reddish to white sandstones with siliceous cement. Quartz grains are angular to subrounded and moderately sorted. Intercalations with lithoclasts of reworked clay- and silt beds containing hematite and mica and kaolinitic beds occur.

The Wadi Nasb Formation was penetrated for 99 m (3609 - 3708 m). The three members of the formation can be recognized. The Tayan Member measures 23 m and consists of fine clay beds and finely grained, crossbedded sandstones of reddish and greenish colours. Lenticular dolomitic intercalations occur in the central part of the unit and contain pyrite as well as mica and hematite. The central Numeyri Member is 45 m thick (3640 - 3685 m). Its upper part consists

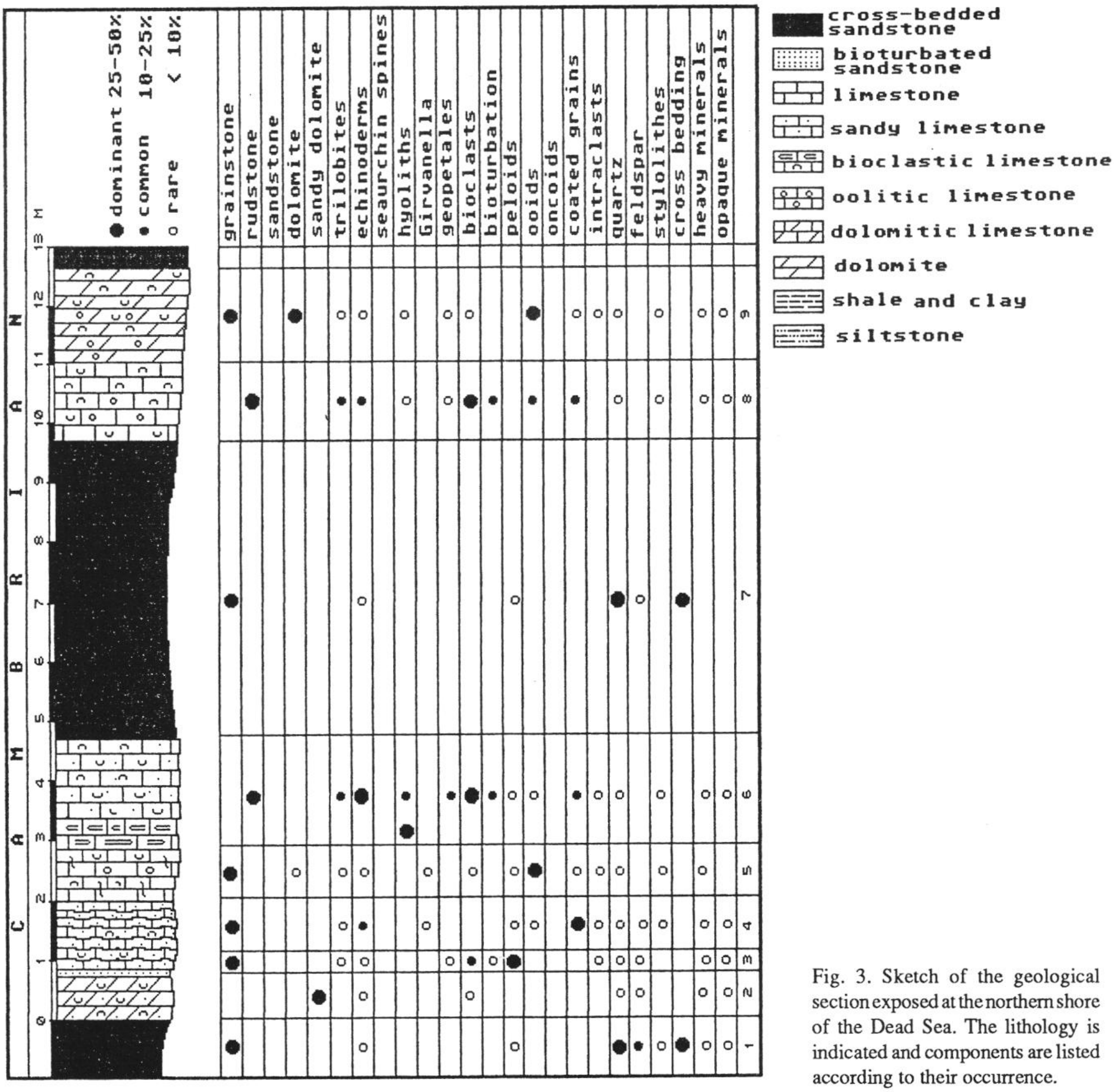


Fig. 3. Sketch of the geological section exposed at the northern shore of the Dead Sea. The lithology is indicated and components are listed according to their occurrence.

of gray to dark gray, well consolidated, clay- rich, fine-grained dolomites. Some of the carbonates have been replaced by anhydrite; in places fossils such as trilobites, brachiopods and hyoliths are common. Its lower section is formed by dolomitic claystone and dark gray recrystallized oolitic limestone. Cracks, fissures and cavities within the rock were filled by white dolomite. The Hanneh Member (3609-6640 m) is 31 m thick and consists of an intercalation of limestones and claystones. Oolites as well as fossil remains of brachiopods and trilobites are present. The claystones of reddish, brownish and grayish coloration are partly cemented by calcareous material and contain abundant mica on bedding planes.

The Wadi Nasb Formation is overlain by the sandstones of the Um Ishrin Formation (3325- 3609 m) and the Umm Sahm/Disi Formation (2100- 3325 m). The Um Ishrin Formation in Wadi Sirhan- 3 test well is 284 m thick and consists of multi-coloured, middle- to coarsely grained sandstones that are cemented partly by siliceous or calcareous matrix. In the upper sections of the sequence layers of fine-grained lithoclasts as well as claystone are intercalated within the sandstones. The Um Sahm/Disi Formation consist of white or light coloured fine to middle grained, rarely coarsely grained sandstones of up to 1225 m thickness. The sand is moderately lithified by siliceous cement and contains mica.

3 FACIES DESCRIPTION OF THE THREE CAMBRIAN CARBONATE SEQUENCES

3.1 Outcrop at the Dead Sea (Fig. 3)

Bed 1: Sandstone- grainstone

Fine-grained, cross-bedded sands mainly composed of quartz and feldspar dominate. The rock consists of 75% of angular to well rounded quartz grains (ø ranges between 0.19 and

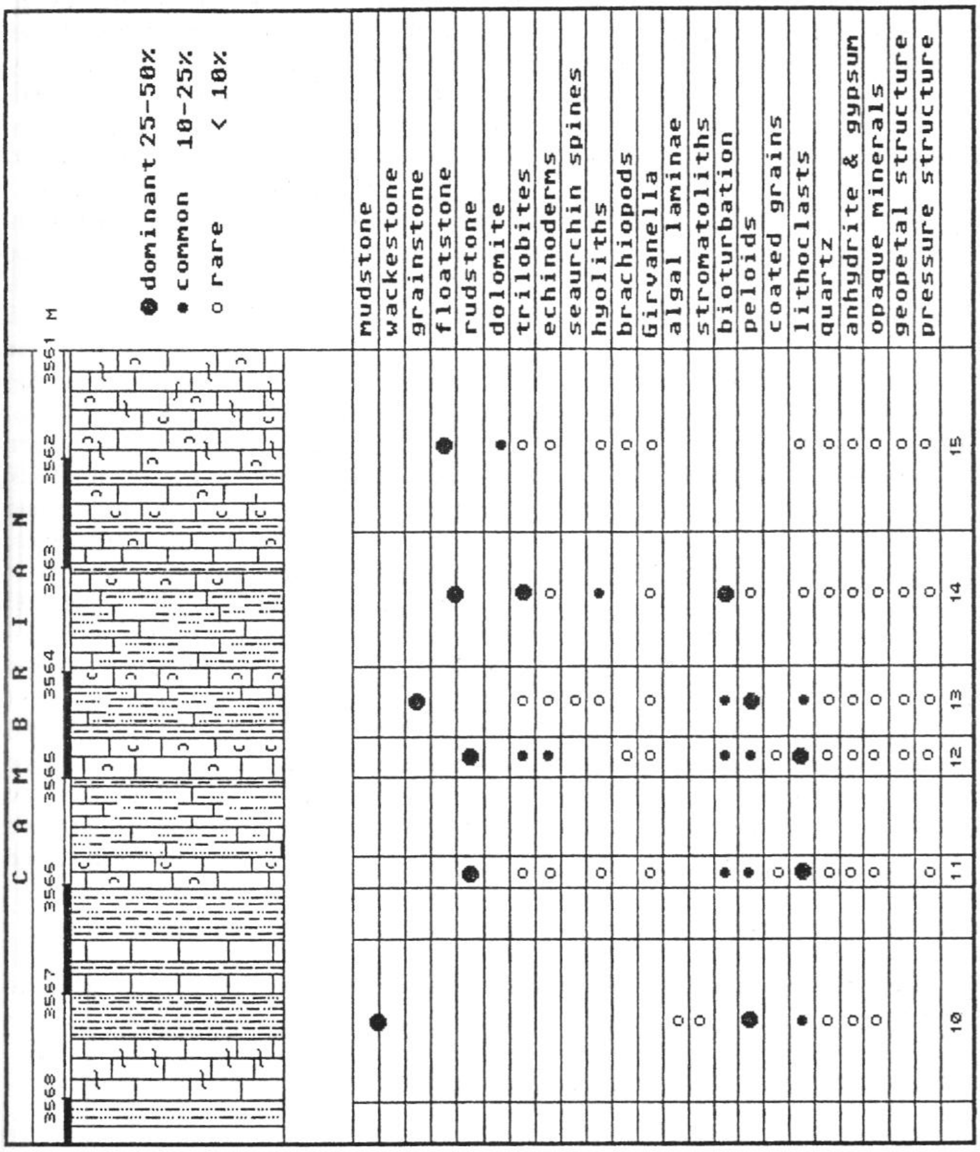


Fig. 4. Sketch of the geological section found within core 12 of the Wadi Al Ghadaf-2 test well site. The lithology is indicated and components are listed according to their occurrence.

0.24 mm) derived from a variety of crystalline rocks similar to those exposed in southern Jordan. Some grains have been fused to each other by siliceous cement. Grains of plagioclase feldspar with angular or subrounded shapes and the same size as the quartz compose about 5 % of the rocks. Contacts between feldspar and quartz are often sutured. Mica blades are concentrated along some bedding planes and heavy minerals (zircon, tourmaline, rutile, epidote) are of minor importance.

Peloids and echinoderm debris were deposited together with silicoclastic particles (Pl. 52/1). The carbonate cement between mineral grains and bioclasts contains opaque ferruginous oxides and subordinate silicous cement. Some etching of quartz grains prior to the formation of the pore filling carbonate cement is present.

Bed 2: Finely crystalline dolomite

The basal sandstones are overlain by 75 cm of cross-bedded dolomite (Fig. 5) that represents a secondarily dolomitized, fine, calcareous sand of similar sedimentological features as in bed 1. Angular to subrounded, 0.05 to 0.18 mm large quartz grains form around 2-3 % of the rock, plagioclase represent 1%.

Bed 3: Peloidal grainstone

Above the sandy dolomitic bed 2, 10 cm of fine sand follow, overlain by 25 cm of limestone of peloidal grainstone facies. Its matrix is homogeneous and composed of microsparite. Bioclasts (Ø < 0.1 mm) form nearly 5 % of the rock and consist mainly of echinoderms exhibiting microborings and micritic rims. Some remains of trilobites are present.

Peloids compose about 60 % of the rock. The shape of the larger ones is somewhat irregular, mostly long-oval (length width relation of 1:2) and somewhat subangular (Pl. 52/2), the smaller peloids (0.1 to 0.18 mm) are well rounded and sorted. Micritic peloids are darker than the white matrix and show irregular internal structures. Intraclasts (1 - 2% of the total rock, Ø 0.5 to 3.5 mm) are angular to subrounded, dark gray with no visible compaction. Non-carbonate, angular or subangular particles (about 5 % of the rock; Ø 0.05 to 0.18 mm) consist of quartz (90%) and feldspar (10%). Heavy minerals (rutile, zircon, tourmaline, opaque grains) are rare and present in a similar composition as in bed 1 and 2. The angular to rounded components of the rock are densely packed and have been mixed by strong bioturbation (cf. Pl. 52/2).

Bed 4: Bioclast-bearing coated grain- grainstone
The 25 cm thick limestone of bed 3 is overlain by 100 cm of nodular, hard limestone composed of bioclast-bearing grainstone limestone with coated grains and a matrix of homogeneous sparitic cement filling the pores (Pl. 52/3).

Skeletal grains such as algae and other bioclasts (85% echinoderm fragments, 15% trilobites) compose 20% of the rock (Pl. 52/3). Echinoderm fragments (0.5 to 2 mm) and trilobite remains (smaller than 2 mm) are usually bored and coated by a micritic rim. Internal cavities of the fragments have been closed by clear calcite. *Girvanella* sp. exhibit 0.005 to 0.01 mm wide, intertwined tubes.

Carbonate components compose 50% of the rock, consisting of coated grains (60%), peloids (20%) and ooids (20%) (Pl. 52/3) with a micrite envelope and bored surfaces to a depth of 0.01 to 0.05 mm. Homogenous micritic peloids (Ø < 0.18 mm) represent different fecal pellets and algal constructs. Ooids (Ø 0.2 to 0.3 mm) consist of one or several layers coating a sand grain. Several micitized layers may be present in multilayered ooids. The rare lithoclasts have commonly been dolomitized, are partly rounded and black. Non carbonate components (up to 5 % of the limestone) consist of quartz, feldspar and small clayey lithoclasts and have become concentrated in stylolites together with ferru-ginous oxides and sulfides. The rock structure is characterized by densely packed particles in contact with each other. Components are usually rounded, moderately to well sorted and affected by pressure solution.

Bed 5: Oolitic grainstone
The nodular bed 4 is overlain by an 80 cm thick oolitic limestone with a matrix consisting of pore filling sparitic cement (Pl. 52/4). Biogenes are *Girvanella* sp., fragments of trilobites (70%) and echinoderms (5%). Other carbonate components (60% of the rock) are ooides (65%), peloids (15%), intraclasts (10%) and coated grains (10%) (Pl. 52/4). The ooids (Ø 0.5 to 1 mm) are 'superficial ooids' with only one or a few layers around the core. Most ooids have a dark calcareous, cryptocrystalline core or rarely have formed around a quartz grain. Coated grains (Ø 0.5 mm) and elongate, dark intraclasts (Ø 0.5 to 3.4 mm) are well rounded. Non-carbonate particles (1 % of the rock) consist mainly of quartz and feldspar and minor amounts of zircone, tourmaline and other heavy minerals. The rock structure is dominated by larger, well sorted and non-graded particles in a grain-supported texture.

Bed 6: Echinoderm-trilobite-hyolith rudstone
The oolitic, limestone of bed 5 is overlain by 2 m of strongly bioturbated limestone which is very fossiliferous in the lower section and sandier higher up. The matrix consists of a pore filling sparite and microsparite (Pl. 52/5, Pl. 57/1-4).

The rock consists of 50% bioclasts (50% echinoderm fragments, 30% hyoliths, 20% trilobites). Complete, fractured and corroded shells of *Hyolithes kingi* (50% of the rock; up to 5 mm in diameter) are dominant in basal portions of this bed with shells commonly in a parallel orientaion caused by current action. Echinoderm remains (Ø 0.15 to 3 mm) are moderately sorted, bored and coated. Pores have usually been closed by calcitic cement (Pl. 52/5, 6), but the original porous structure of the echinoderm fragments are often filled with ferruginous material. Often several of the conical shells of hyoliths are nested within each other and are partially or totally filled with fine or coarse sediment (Pl. 53/3, 4, 5). Some are filled with micritic material that has been cemented by ferruginous cements (Pl. 53/3). Others still have their operculum near or in place within their tubes, indicating that they have lived in the area of deposition (Bandel, 1986). Trilobite remains with a homogeneous to prismatic structure of the calcitic- phosphatic shells are up to several mm thick (Pl. 53/1). The other carbonate components make up around 25% of the rock and are 60% coated grains, 20% peloids, 10% ooids and 10% dark, 1-2 mm large intraclasts.

The non-carbonate components, mostly quartz grains (Ø 0.07 to 0.1 mm), are more common in the upper portion of the unit (5-7%) than in the lower (1-2%). The grains are often angular to subrounded and commonly form the centres of ooids. Quartz is common within intraclasts and is concentrated along the numerous stylolites. Grains of zircon, tourmaline and rutile are present and ferruginous oxides and pyrite are locally common. The rock is characterized by grain-supported structure with geopetal fabrics (Pl. 53/5), bioturbations and well sorted particle (Pl. 53/1).

Bed 7: Sandstone
The massive and partly dolomitic limestones of bed 6 are overlain by 5 m of fine-grained and cross-bedded sandstones composed of 90% quartz and 5% plagioclase feldspar. Components are angular to subrounded, well-sorted and cemented by calcitic as well as silicate matrix as in bed 1.

Bed 8: Coated grain-ooidal rudstone with abundant biogenes
The sandstones of bed 7 are overlain by 1.1 m limestone with a homogeneous sparitic matrix of pore-filling cement (Pl. 53/7, 8). Bioclasts represent about 35% of the rock (55% trilobite fragments, 40% echinoderms, 5% hyoliths). Trilobite remains are up to 1 mm thick and 12 mm long and exhibit a two layered, fine-prismatic structure. Trilobites and echinoderms (0.3 - 2.2 mm) are often coated by a micritic rim with fine borings (Pl. 53/8). Ooids (Ø 0.4-0.8 mm) compose 20% of the rock. Their shape depends upon the morphology of their nuclei (quartz or bioclasts; Pl. 53/7) and they have few to many layers, may be abraded and fragmented due to synsedimentary erosion and pressure solution. Many of the bioclasts are spherical to ellipsoidal. Coated grains compose about 15% of the rock. The non-carbonate particles such as quartz (1-2%) usually represent cores of ooids. The texture is grain supported.

Bed 9: Ooid-grainstone
The massive limestone of bed 8 is overlain by 2.8 m of a dolomitized oolitic limestone with some intercalations of coarse shell debris. The matrix is a homogeneous sparite that

was totally transformed into dolomite (Pl. 53/6). Biogenes compose around 10% of the rock (echinoderms 50%, trilobites 40%, hyoliths 10%). Bioclasts usually bear micritic rims, are bored, badly sorted, dolomitized and concentrated in some layers. Coated grains have been largely dolomitized. Ooids (size: 0.3 - 1 mm mostly 0.6 mm) compose about 60% of the rock, their internal structure is destroyed by dolomitization (Pl. 53/6) and their nuclei are usually micritic pellets and rarely quartz and glauconite grains or bioclasts. The texture of the rock is grain-supported and bioturbated.

3.2 Wadi Al Ghadaf-2 test well (Figs. 2, 4)

From core no. 12 (3561- 3569 m) of the Wadi Al Ghadaf test drill 10 samples were selected from the following depths 3561m, 3562.60m, 3563.83m, 3564.10m, 3564.80m, 3565m, 3566.10m, 3566.40m, 3567.50m, and 3567.85m. All the samples represent hard, finely crystalline, dark gray to dark brown partly dolomitized and anhydritized limestones. Five beds (10 to 15) can be distinguished withinthese 6.85 m of rock section.

Bed 10: Algal- stromatolite- mudstone- wackestone
The matrix of the rock consists of a heterogenous mixture of micrite and microsparite. Algal laminites in mm-thin crusts of micritic and pelmicritic stromatolitic layers (Pl. 54/1,2) are the only biogenes. The fine layering is well developed and only here and there is it disrupted by burrows. The regular planilaminar pattern of finer and coarser material with some intercalated peloidal layers is characteristic of stromatolites.

Carbonate components (40% of the rock) consist of peloids (80%) and intraclasts (20%). The peloids (Ø 0.05 - 0.2 mm) are fecal pellets, algal peloids, pseudopeloids and pelletoids. Pelletoid formation was preceded by micritization of particles resulting in angular micritic grains. Intraclasts (0.3 -3 mm) are either reworked algal crusts or mud-chips (pseudointraclasts).

Non-carbonate components (1% of the rock) are represented by angular to subrounded quartz grains (Ø 0.02- 0.1 mm), clay flakes enriched within distinct layers, some phosphatic grains and some crystals of gypsum and anhydrite. The texture of the rock is mud-grain supported and laminar, with oriented, largely rounded, moderately sorted and ungraded particles.

Bed 11: Algal-intraclast- peloid- rudstone
The matrix of the limestone consists of homogeneous sparite (Pl. 54/3). Bioclasts (5% of the rock) consisting largely of trilobite (90%) and echinoderm fragments (10%) are strongly abraded, bored, often coated by a micritic rim and badly sorted (Pl. 54/3).

The remaining carbonate components (70 % of the rock) consist of lithoclasts (60%), pelletoids (35 %) and coated grains (5%) (Pl. 54/3). Most lithoclasts (0.5 to 1.2 cm size) are fragments of cyanobacterial crusts, and similar crusts coat the intraclasts, many of which contain quartz grains. Dark extraclasts (pseudopeloids) are usually the result of erosion and abrasion of indurated carbonate mud; they are small, well rounded and arranged in layers parallel to the bedding plane. Fecal pellets, algal pellets and pseudopeloids are well-rounded, spherical to elongate-elliptical with a micritic fabric; only algal peloids are irregular and of different sizes. Anhydrite within the cement formed during diagenesis. The texture of the rock is characterized by densely packed components and strong bioturbation. Accumulation of clay minerals on stylolites is common.

Bed 12: Trilobite- brachiopod- intraclast- rudstone
The matrix of micritic and microsparitic material is heavily bioturbated. Sparite fills the remaining original voids within the sediment. Biogenes (30% of the rock) consist of remains of trilobites (35%), echinoderms (25%), brachiopods (25%) and some hyoliths and sponges (Pl. 54/4). The remaining carbonate components (35% of the rock) consist of intraclasts (70%) and peloids (30%). Intraclasts represent reworked cyanobacterial mats (0.3 - 12 mm size) of irregularly nodular outline and rounded appearance. Spherical and egg-shaped peloids (< 0.2 mm in diameter) are often micritized.

Non-carbonate particles consist of small quartz grains in intraclasts (< 0.05 mm), some pyrite and anhydritized parts of the cement. The texture of the rock is grain supported, particles are usually densely packed and stylolites are present with non-carbonate particles accumulated on their sutures.

Bed 13: Peloidal grainstone with biogenes
The matrix of the limestone consists of micrite and microsparite - former voids are filled by sparite. Bioclasts (10% of the rock) consist of echinoderms (45%), trilobites (45%) and hyoliths. Biogenes are weakly rounded, badly sorted and commonly show abraded, bored and encrusted surfaces. *Girvanella* sp.occurs with short unbranched tubes that may be fused into aggregates and mats. Peloids (50% of the rock; Pl. 54/5) are moderately sorted, well-rounded with a spherical to ovoidal shape (0.1 - 0.3 mm in size). Algal intraclasts made of well rounded peloids form about 20% of the rock.

Non-carbonate particles predominantly quartz (3% of the rock; Ø 0.05 mm) are concentrated within the intraclasts. Some feruginous oxides, pyrite and anhydrite are present. The texture consists of densely packed components affected by bioturbation. Pressure solution is common.

Bed 14: Trilobite- hyolithe- floatstone- rudstone.
The matrix is heterogeneous and consists of bioturbated micritic to microsparitic material. Pores formed by burrowing organisms were filled with sparitic cement. Biogenes (40% of the rock) consist of up to 3 cm long carapax fragments of trilobites (60%), hyolith tubes (35%) and some echinoderm remains (5%; < 0.5 mm) and calcareous sponge spicules. Bioclasts have been partly bored by microorganisms, and are coated with micritic rims and crusts. Two different types of hyolith- tubes occur. *Hyolithes kingi* has a round cross-section, another species reveals triangular cross-section. The tubes are filled with micritic material or sparitic cement (Pl. 55/1) and the operculum is often preserved within them or near them (Pl. 54/6). Some of the tubes (up to 1.1 cm long and 2.8 mm wide) are broken and bored, micritized and strongly recrystallized. *Girvanella* sp. coats surround the

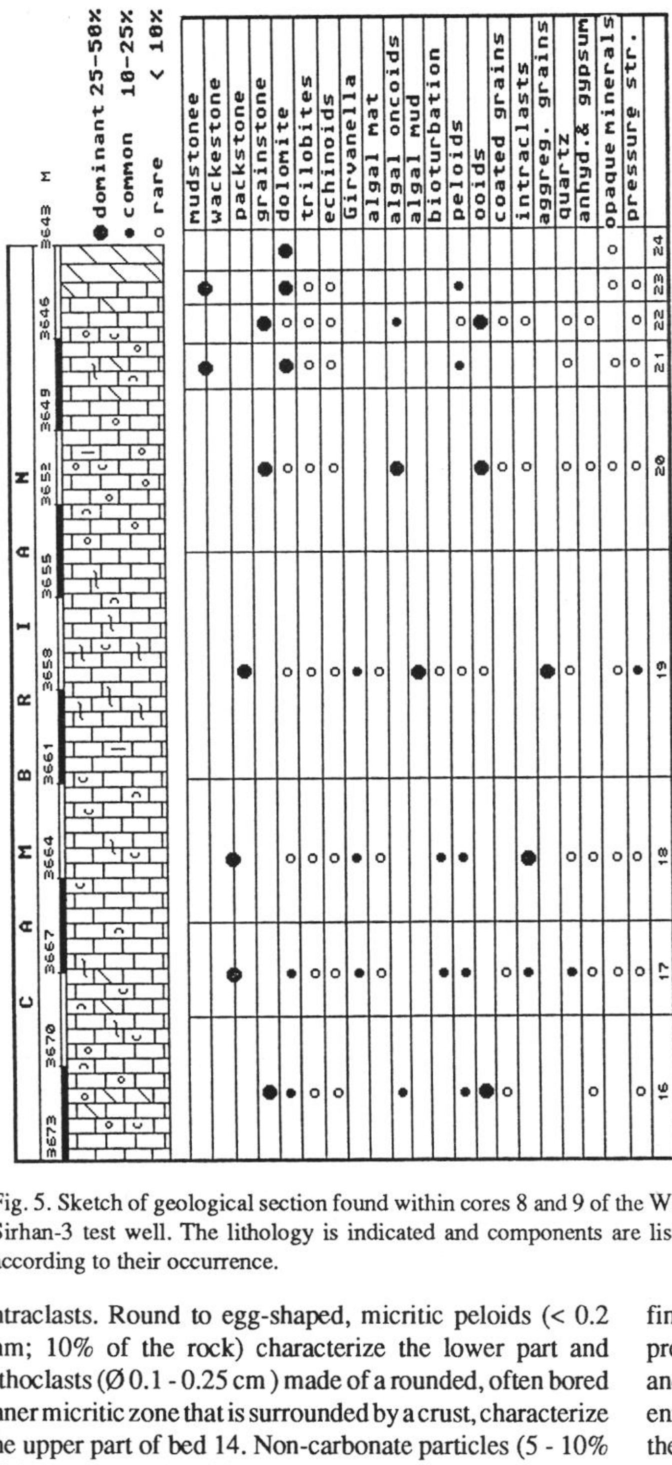


Fig. 5. Sketch of geological section found within cores 8 and 9 of the Wadi Sirhan-3 test well. The lithology is indicated and components are listed according to their occurrence.

intraclasts. Round to egg-shaped, micritic peloids (< 0.2 mm; 10% of the rock) characterize the lower part and lithoclasts (Ø 0.1 - 0.25 cm) made of a rounded, often bored inner micritic zone that is surrounded by a crust, characterize the upper part of bed 14. Non-carbonate particles (5 - 10% of the rock) consist of 0.01 to 0.1 mm large, angular quartz grains and clay flakes. Some pyrite and anhydrite is locally present. The texture of the rock is mud-supported with loosely distributed components. Geopetal structures and stylolites with clay concentrated on their sutures are present.

Bed 15: Floatstone with biogenes.
The matrix of the rock is micritic and microsparitc, exhibiting bioturbation. Sparry calcite fills only limited area. Biogenes (15% of the rock) consist of up to 1.2 cm long trilobite remains (55%), up to 1.5 cm wide brachiopod shells (20%) (Pl. 55/2), hyolith tubes (20%) and echinoderm fragments (5%; Ø 0.3-4 mm). Biogenes may be coated by algae, micritized and bored (Pl. 55/2). Some of the hyloliths still hold their opercula within their conical tubes, others show abraded and eroded shells. The tube wall has usually been totally replaced by sparite cement and tubes are partly filled by micrite and partly by sparite.

Well-rounded lithoclasts make up 5% and non-carbonate particles (quartz, feldspar and clay-flakes) 5-10% of the rock. The grains are 0.02 to 0.1 mm large and angular to subrounded. Clay, pyrite and anhydrite are accumulated along the common sutures of stylolites. Microcrystalline dolomite occurs scattered throughout the rock. The texture is mud-supported with geopetal structures.

3.3 **Wadi Sirhan-3 test well** (Figs. 2, 5)

13 samples were taken and analysed from cores 8 (3643 to 3652m) and 9 (6654 to 3672m) from the penetrated section of the Numayri Member (Fig.5). They come from the following depth: 3643.30m, 3644.43m, 3645.20m, 4645.75m, 3647.75m, 3652m, 3654.70m, 3661.30m, 3662.23m, 3663.20m, 3666.25m, 3669.16m, and 3671.76m. The brown and grey limestones are finely crystalline and partly dolomitized. Fissures are predominantly filled with calcite, in places with dolomite and pyrite. Stylolites are common and often show clay-enriched sutures. 9 beds (16 - 24) were distinguished from the approximately 28 m thick sequence.

Plate 52 Microfacies of Cambrian limestones from the outcrop at the northeastern shore of the Dead Sea.

Fig. 1. Sandstone of bed 1 with angular and subrounded quartz grains as well as peloids and skeletal remains of echinoderms. x 45

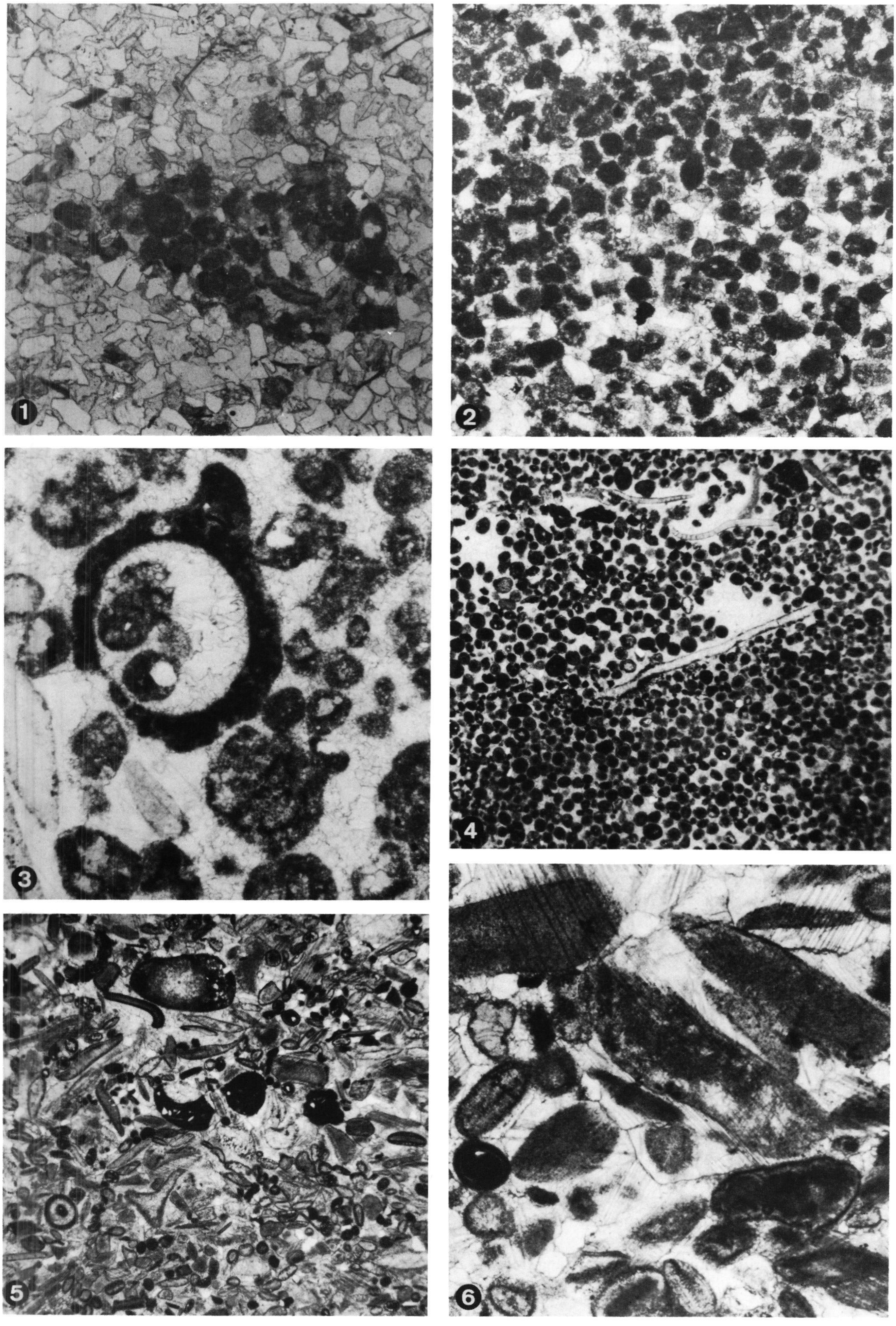
Fig. 2. Peloidal grainstone of bed 3 with fragments of trilobite and echinoderm sckletal parts. x 45

Fig. 3. Coated grain-grainstone of bed 4 with trilobite remains and echinoderm fragments which have partly been coated by Girvanella. x 50

Fig. 4. Ooidal grainstone with trilobite fragments of bed 5. x 6

Fig. 5. Rudstone composed of echinoderm, trilobite and hyolith biogenes of bed 6 with a sparitic matrix and micritic rims on some biogenes. x 6

Fig. 6. Rudstone of bed 6 with syntaxial cement on echinoderm fragments. x 45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Bed 16: Algal, oolitic, oncolitic grainstone.
The matrix consists of a homogeneous sparite as a pore-filling cement. Bioclasts such as echinoderms and trilobites compose only 2-3 % of the whole rock. The biogenes have often been abraded, bored and enveloped by crusts. Remaining carbonate particles (60% of the rock) consist of ooids (70%) oncoids (20%) and dark peloids (10%; Ø 0.1-0.18 mm) (Pl. 55/5, 6).

Simple ooids (Ø 0.3-0.6 mm) with tangential structures and micritic layers and composite polyooides with two or three complete or fractured ooids forming the core of one ooid are present. Fractured and abraded ooids were also formed by early diagenesis and reworked by late diagenesis along stylolite sutures (Pl. 55/4). Large oncoids (Ø 0.5 - 2 mm) formed by concentric growth of *Girvanella* sp. tubules around a biogene nucleus (Pl. 55/6).

About 10% of the whole rock is made up by rhombohedral dolomite crystals scattered throughout the fabric (Pl. 55/5). Some anhydrite crystals are present as well as a few quartz grains. The texture is grain-supported with well-rounded and sorted components. Pressure sutures and spar-filled fissures are common (Pl. 55/4).

Bed 17: *Girvanella*-wackestone-packstone.
The limestone is bioturbated and has an inhomogeneous micritic and microsparitic matrix. Sparry calcite cement is developed only in patches. Biogenes (30% of the rock) consist of nodular lumps of *Girvanella* sp. (Pl. 55/8), many other algal and/or cyanobacterial products, echinoderm and trilobite remains. *Girvanella* sp. (0.005 - 0.01 mm tubule width) are also interbedded with laminar micritic layers (Pl. 56/2). Bioclasts (Ø 2 mm) are usually bored, encrusted and may be recrystallized. Remaining carbonate components (25% of the rock) consist of peloids (60%) formed by algal activity and as fecal pellets and algal intraclasts (40%; Ø 2-5 mm) representing fragments of algal crusts and pelletoidal mud shreds encrusted by cyanobacteria (Pl. 55/8).

Finely crystalline dolomite (< 0.1 mm) may be present throughout the limestone, composing up to 20% of it (Pl. 56/2) and anhydrite has replaced some of the matrix. Quartz (< 0.04 mm) of angular or subangular shape and clay- flakes composes about 1% of the rock and is accumulated on the common stylolites. Ferruginous oxide as well as pyrite are present locally. The texture is mud-grain supported.

Bed 18: Algal- intraclast- wackestone- packstone
The matrix of the rock is heterogeneous and consists of micrite and microsparite mixed by bioturbation. Only cavities and open burrows are filled by sparry calcite cement. As in bed 17 *Girvanella* sp. lumps and clasts are present together with echinoderm and trilobite remains, but make up only about 20 % of the rock. The remaining 50% of carbonate particles consist of intraclasts of stromatolitic mats (75%) and peloids (25%). Intraclast are quite large (up to several cm) and consist of muddy substrate with ooids, peloids and coated grains. Ooids within the clasts have tangential and radial structures, may be fractured, abraded and recrystallized. The texture is mud-grain supported. Dolomitization and stylolites are apparent.

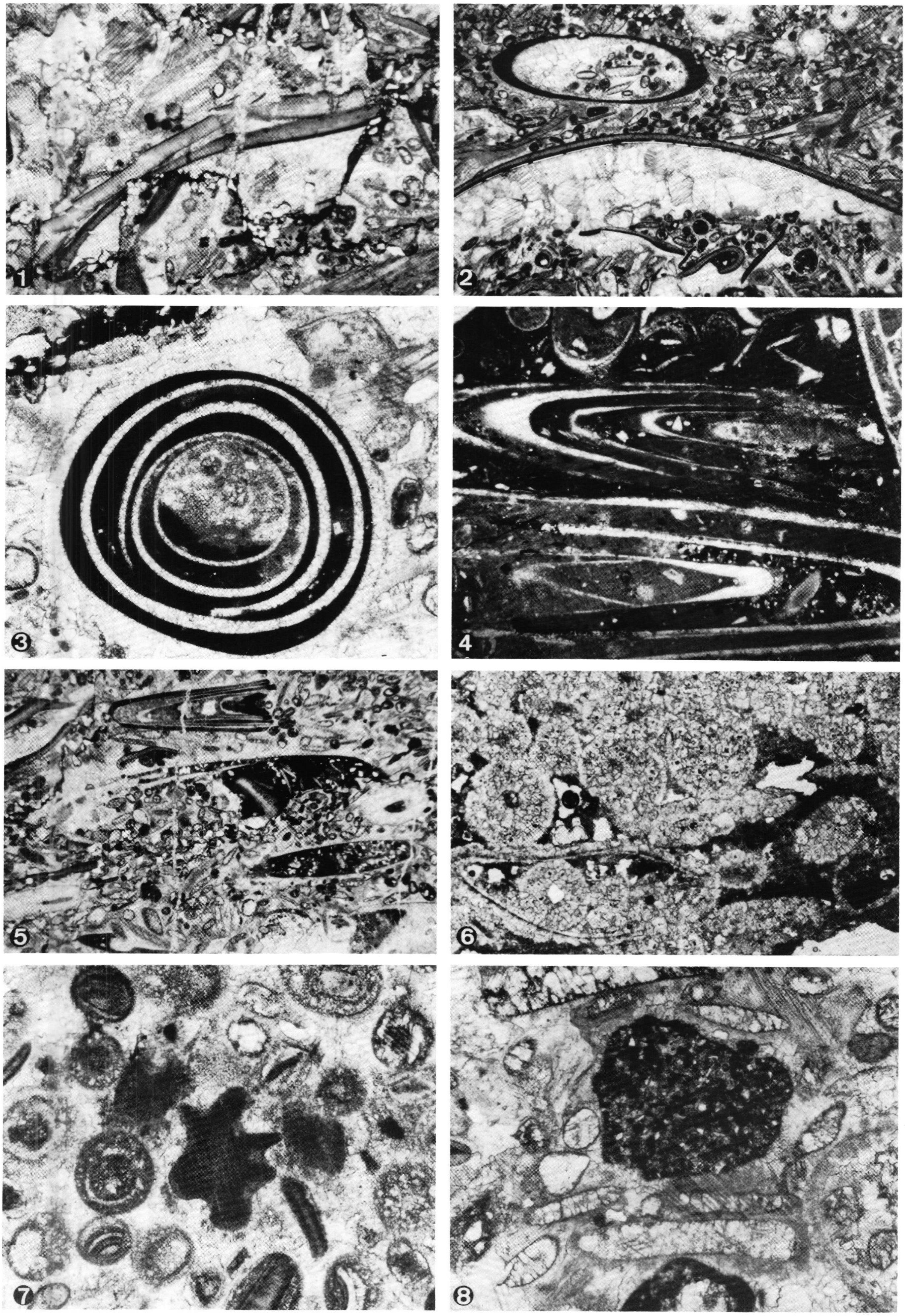
Bed 19: *Girvanella*-lumps-grapestone pelsparite
The rock has an inhomogeneous matrix consisting of micrite and microsparite. Biogenes (20% of the rock) are dominated by *Girvanella* sp. lumps, nodules and crusts. Echinoderm and trilobite fragments are bored and micritized. The remaining carbonate components (60% of the rock) consist of aggregate-grains, fecal pellets, algal peloids, lumps and a few ooids (Ø 0.5 mm; Pl. 56/1) with tangential and radial structures. The grapestones consist of rounded, somewhat irregular micritic lumps as a product of in situ agglutination of carbonate particles. Several ooids are deformed due to partial solution of internal layer and solution along the many stylolite sutures (Pl. 56/1).

During a late phase of diagenesis fine- to medium-sized dolomite crystals grew within the carbonate components. Some quartz, clay particles zircon, tourmaline, ferruginous oxide and pyrite are concentrated along the stylolites. The texture is grain-supported.

Bed 20: *Girvanella*-oncoidal, oolitic grainstone
The matrix consists of homogeneous sparite as a pore-filling cement (Pl. 56/4; Pl. 57/2, 5, 6). Bioclasts (Ø 0.2 - 2 mm) compose about 5% of the rock and consist of well-rounded, bored and encrusted trilobite and echinoderm remains. The remaining carbonate particles (65% of the rock) consist of algal oncoids (40%), ooids (40%) and algal intraclasts (10%). The oncoids with *Girvanella* sp. are like those of bed 16. Ooids (Ø 0.2- 0.6 mm) are tangentially structured (Pl. 56/4; Pl. 57/5), have one or several crusts, may be deformed (Pl.

Plate 53 Microfacies of Cambrian limestones from the northeastern shore of the Dead Sea.

Fig. 1. In the rudstone of bed 6 remains of trilobites have been affected by stylolites as well as by fissures. x 6
Fig. 2. Geopetal structure within larger biogenes of bed 6, former cavities have been filled with blocky cement. x 5
Fig. 3. Cross-section of several hyoliths nested within each other in bed 6. The originally aragonitic shell of the hyoliths was dissolved and filled with fibrous and blocky cement. x 20
Fig. 4. Hyoliths cut along their longest axis demonstrate the nesting within each other in bed 6. x 5
Fig. 5. Rudstone of bed 6 with hyoliths partly micritized and fractured by fissures. x 5
Fig. 6. Ooidal grainstone of bed 9 with totally dolomitized ooids and bioclasts. x 20
Fig. 7. Coated grain-ooidal rudstone of bed 8 with fractured and regenerated ooids and echinoderm remains within a sparitic matrix. x 30
Fig. 8. Sparitic matrix surrounding coated grains, intraclasts of peloidal limestone and grains of quartz in bed 8. x 30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56/3) and may represent polyooids (Pl. 56/6, Pl. 57/5). Coated grains show external dissolution and have locally been transformed into dolomite and anhydrite (Pl. 56/5). Well-rounded intraclasts (Ø < 5 mm) are composed of peloidal or oncoidal limestone. Non-carbonate particles (quartz grains) are concentrated on the stylolites. The fabric of the rock is grain-supported with well rounded, well-sorted components.

Bed 21: Mudstone- wackestone
The inhomogeneous matrix is composed of micrite, microsparite and local sparry patches. The bioclasts consist of a few bored and coated remains of trilobites and echinoderms. Especially echinoderms are still recognizable in the totally dolomitized part of the limestone. Peloids (Ø 0.5 mm) represent about 10% of the rock. The texture is mud-supported. Much of the micritic matrix may be transformed into dolomite and dolomite is concentrated along stylolites.

Bed 22: Oolitic, oncoidal grainstone
The matrix of the limestone consists heterogeneously of micrite and microspar with large voids filled with sparry cement. Biogenes (5% of the rock) are echinoderms and trilobites. Carbonate components (60% of the rock) consist of ooids (55%), oncoids (20%), peloids (15%), intraclasts (5%) and coated grains (5%). Most ooids are tangentially structured or multilayered, spherical to ovoidal (Ø 0.4-0.8 mm), some are fractured. Deformed polyooids consist of several simple or broken ooids in a thin sack-like cover (Pl. 56/3). Ooids are commonly bored and their core consists of a quartz grain or a bioclast that is often recrystallized or micritized. *Girvanella* sp. forms ovoid to slightly compacted oncoids (Ø up to 0.8 mm) most frequently with tubules arranged concentrically around a core or it may coat gray, rounded intraclasts (up to 1 cm long) containing ooids and peloids (Pl. 55/7). Well rounded, coated grains (< 0.5 mm) represent bioclasts with a micritic rim.

Crystals of dolomite and anhydrite have formed predominantly within ooids and oncoids. Angular quartz grains (Ø 0.05 - 0.15 mm) compose about 1 % of the rock. Quartz and clay were enriched on the common stylolites. The texture is grain-supported and particles show sorting and orientation but no gradation.

Bed 23: Mudstone- Wackestone
The dolomitized limestone resembles that of bed 21.

Bed 24: Finely crystalline dolomite
The homogeneous matrix of the rock consists of fine dolomite crystals. Some pyrite is present. The texture shows a mosaic pattern of xenomorph dolomite crystals.

4 INTERPRETATION OF THE FACIES AND RECONSTRUCTION OF THE ECOLOGICAL FACTORS ACTING DURING THE CARBONATE PRODUCTION IN THE CAMBRIAN SEA OF JORDAN

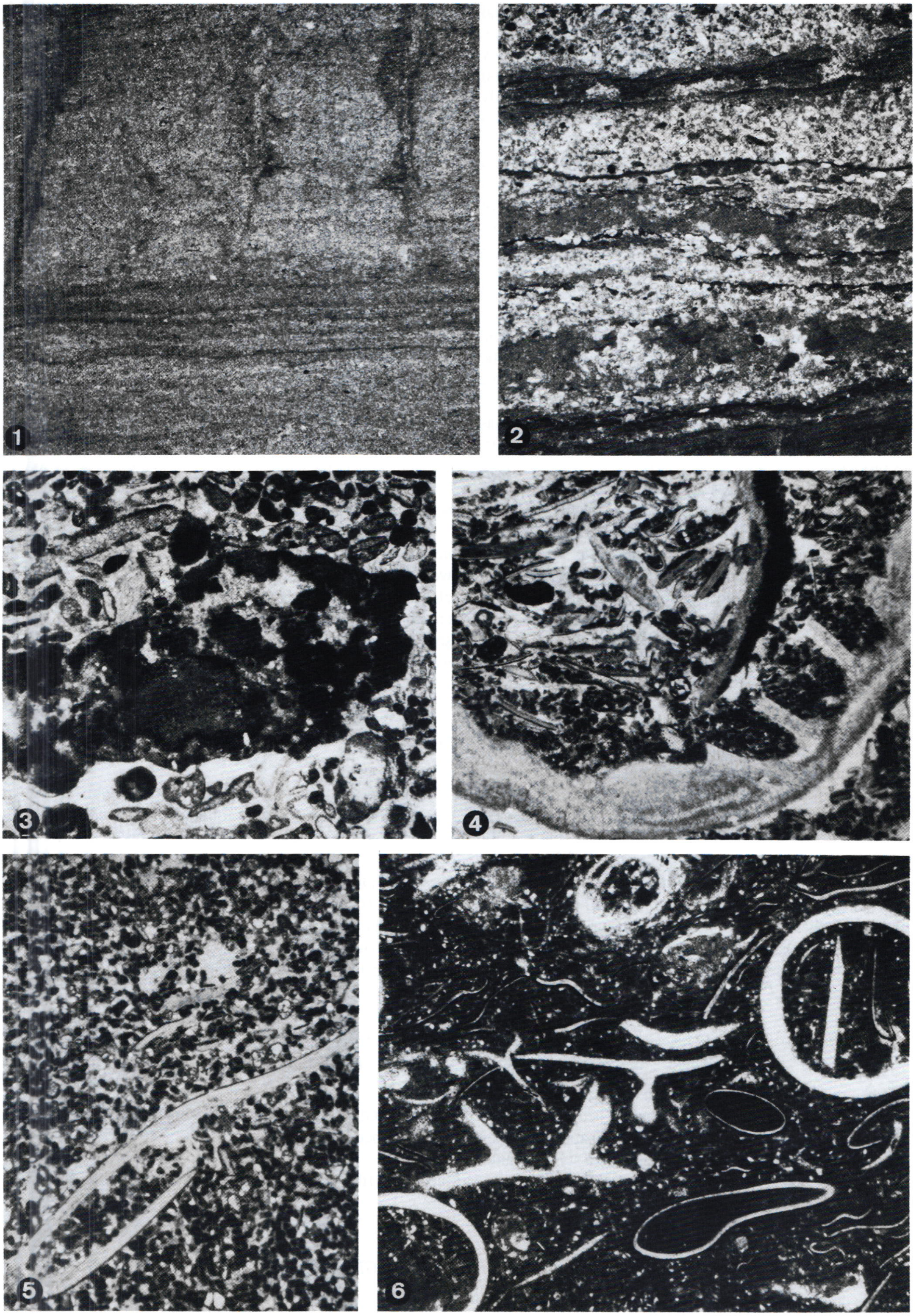
Mudstones, wackestones, packstones, grainstones, floatstones and rudstones are present in the 24 beds of the carbonate deposits from outcrop and subsurface occurrences of Cambrian rocks in Jordan. Floatstones and rudstones dominate and all the microfacies types are connected to each other by transitions.

Biogenes in all facies types consist of trilobite and echinoderm remains, hyolith tubes, brachiopod shells, sponge spicules and cyanobacterial crusts and tube structures of *Girvanella* sp. These are accompanied by ooids, oncoids, peloids, coated grains and lithoclasts. Peloids represent a number of different grains with micritic structure. Some represent fecal pellets probably belonging to different endobenthic and epibenthic organisms. Others are parts of primary and reworked algal and bacterial crusts. A third type was formed by micritized carbonate particles of different origin, including biogenes and reworked indurated sediment. All these particles demonstrate the influence of intense life activities on the depositional environment. The non-carbonate particles (quartz, feldspar and heavy minerals) were either washed or blown in from the nearby land. Pyrite, ferruginous oxides, dolomite and anhydrite were formed within the sediment during diagenesis.

The mudstone and wackestone facies are characterized by algal lamination consisting of mm-scale alternations of micritic and pelmicritic layers (stromatolites). Mudcracks are present as well as individual burrows which were not destroyed by further bioturbation. Deposition of these limestones occurred in coastal protected areas within shallow

Plate 54 Microfacies of Cambrian limestones in Jordan from the Wadi- Al Ghadaf-2 test site.

Fig. 1. Algal-stromatolithic mudstone- wackestone of bed 10 with plane lamination disrupted by only a few burrow structures. x 5
Fig. 2. Algal laminites of bed 10 consist of intercalation of micritic and pelmicritic layers in mm dimension. x 10
Fig. 3. Algal, peloidal rudstone of bed 11 with sparitic matrix and different components often forming aggregate grains and grapestone. x 7
Fig. 4. Brachiopod within the trilobite- echinoderm- intraclast- grainstone of bed 12 has been filled with peloids and bioclasts. x 6
Fig. 5. Peloidal grainstone of bed 13 with peloids, remains of a trilobite and quartz grains in a sparitic matrix. x 6
Fig. 6. Trilobite- hyolith- biosparite of bed 14 with dissected hyolith tubes and opercula as well as trilobites within a peloidal basic substrate. x 10.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lagoons possibly with raised salinity or within the intertidal and supratidal zone, where endobenthic life was scarce. Here mats of cyanobacteria flourished, broke up when they dried out and were transformed into mudchips (intraclasts) when the sea returned. Cemented portions of the muddy calcarous deposits were eroded and formed more solid intraclasts.

Grainstones with coated bioclasts, ooids and *Girvanella* sp. oncoids are composed of well rounded particles which are often well-sorted and oriented due to the action of currents (present in beds 13, 14, 16, 20, 22). The pore space that remained was later filled by cements. The particles especially ooids and oncoids composing these limestones were periodically coated on all sides when washed around within the well-lit probably very shallow intertidal environments. Here sand, skeletal fragments or chips of dried mud and beach rock were encrusted by *Girvanella* sp. and micritic crusts and exhibit bored surfaces. Microorganisms have altered the surface of the ooids and calcareous shells to a depth of 0.01 to 0.05 mm. Narrow and branched borings, as produced by fungi, and wide unbranched bundles of borings, as produced by cyanobacteria (Bromley 1965) are present. Oolitic sand bars formed as dune-like bodies in this current-swept shallow marine environment. In thicker beds the original coarse cross-bedding was not destroyed by bioturbation. Areas exposed to terrestrial conditions were rapidly cemented forming beach rock. Intraclasts and fragments of oolites formed which were repeatedly coated when the rocks at the beach were eroded (beds 7, 16, 20, 22).

The bioclastic grainstones, floatstones and rudstones are characteristic of a deposition within fully marine shallow water conditions. Here trilobites thrived, echinoids were broken up after death, sponges with calcareous spicules lived and disintegrated, some brachiopods occurred and hyoliths were very abundant. Bioclasts here were usually altered and bored by algae and cyanobacteria. The abundant coated grains and ooids indicate bioactivity and currents. The sediment was heavily bioturbated by a rich infauna.

Bandel (1986) came to a similar reconstruction of the depositional environment by analysing *Hyolithes kingi*. Limestones of the bed 6 contain hyoliths in a coquina in which their tubes are oriented in mainly one direction. While the larger tubes of the hyoliths reflect the original pattern of deposition, the smaller particles between them have been moved about and displaced by the activities of the vagile endobenthos in a shallow subtidal to lower tidal environment. The tubes of *Hyolithes kingi* are found in different stages of preservation, reflecting variations in their predepositional history. Many tubes are well preserved, some still have the operculum near its original position within the tube. These animals died where they were deposited. Other tubes are preserved as nested individuals (Pl. 53/3, 5; Pl. 55/1). Here the empty tubes were washed together. The wash of the waves moved them from one ripple depression to the next, causing them to become nested and concentrated. Other tubes were eroded and fractured and some are partly or locally filled with sediment particles cemented by a ferruginous matrix. Internal moulds are also present. Sediments with hyoliths were eroded and hyoliths redeposited. A reducing condition within the sediment resulted in the deposition of originally pyritic ferruginous cements within the tubes. These pyritic cements were oxidized during redeposition of the hyoliths or during later diagenesis.

A recent model for the deposition of *Hyolithes kingi* coquinas in the Lower Cambrian sea was provided by Bandel (1986) from the intertidal and subtidal zone of the Belgian shore of the Channel, where similar tubes produced by the annelid *Pectinaria* form a comparable assemblage before their final burial.

Carbonates of the Cambrian deposits in Jordan were deposited in coastal areas. Mudstones and wackestones were laid down in current and wave protected zones of closed-in lagoons and coastal ponds in an intertidal mud flat environment. The other facies types represent deposits in a shallow to intertidal regime with strong currents; redeposition was common and bottoms well-lit.

5 INTERPRETATION OF THE DIAGENETIC HISTORY OF THE CAMBRIAN CARBONATES OF JORDAN

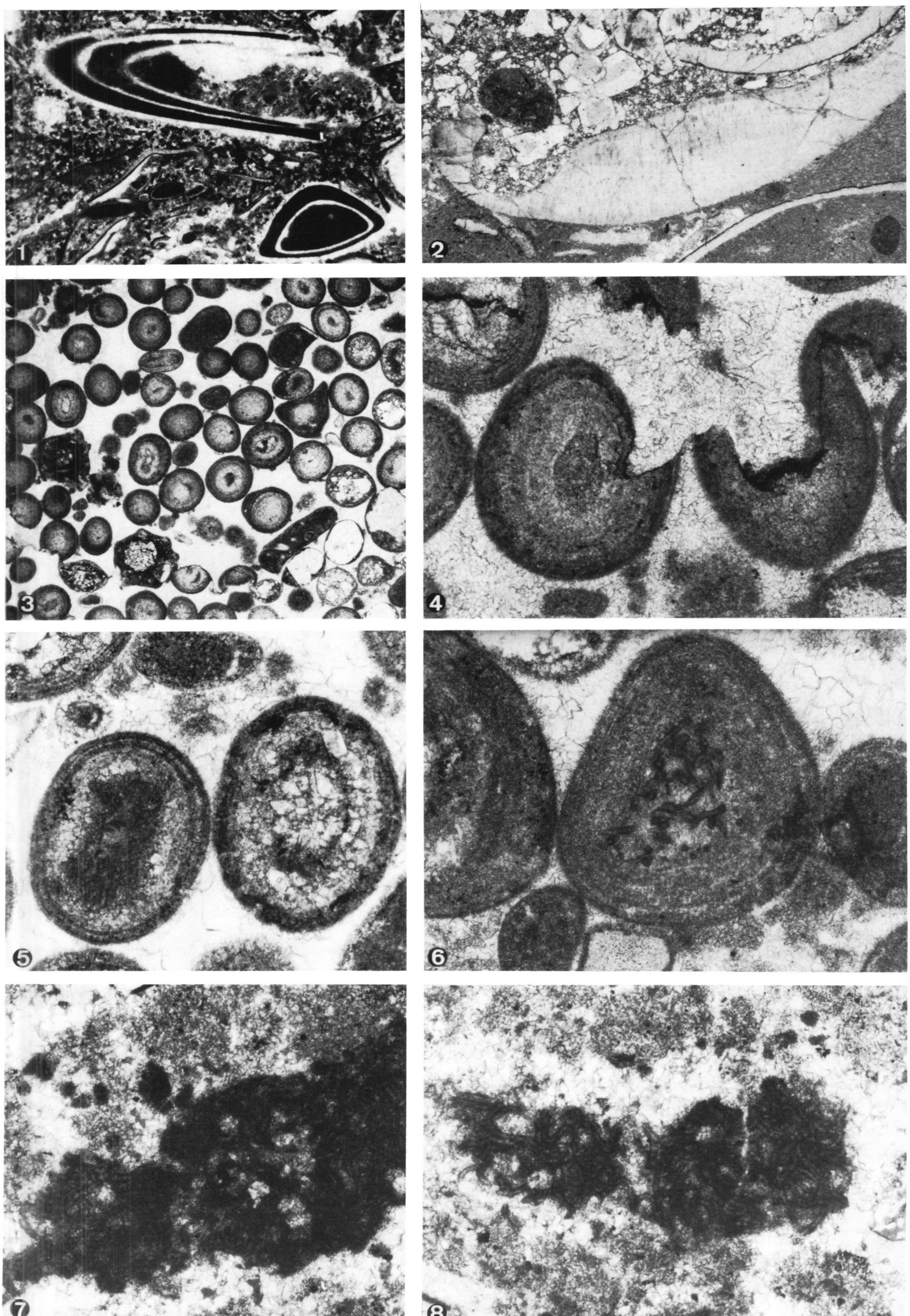
Diagenesis of the carbonates deposited during the Cambrian in the shallow sea of Jordan is interpreted with two samples and schematically illustrated in Figs. 6 and 7.

First example: Echinoderm-trilobite-hyolith-rudstone (bed 6, 14; Fig. 6)

After the deposition of all the components in a nearshore environment with strong current action, good illumination and strong bioturbation, particles became partially bored

Plate 55 Microfacies of Cambrian limestones in Jordan from the subsurface. Figures 1 and 2 from Wadi Al Ghadaf-2 and figures 3 to 8 from Wadi Sirhan-3 test wells.

Fig. 1. Two different hyoliths in the biosparite of bed 14. x 6
Fig. 2. Biogene-rich floatstone of bed 15 with large brachiopod and some components preserved as anhydrite. x 6
Fig. 3. Algal, oncoidal, ooidal grainstone with sparitic matrix of bed 20. x 12
Fig. 4. Ooids of bed 16 distorted at a stylolite suture. x 30
Fig. 5. Partly dolomitized Gir*vanella* ooids of bed 16 are coated by fibrous cement, while remaining pores have been filled with blocky cement. x 30
Fig. 6. *Girvanella*-ooid of bed 16. x 30
Fig. 7. G*irvanella*-coated intraclast of bed 22. x 75
Fig. 8. Intraclast coated by *Girvanella* from bed 17 consisting of *Girvanella* wackestone-packstone. x 75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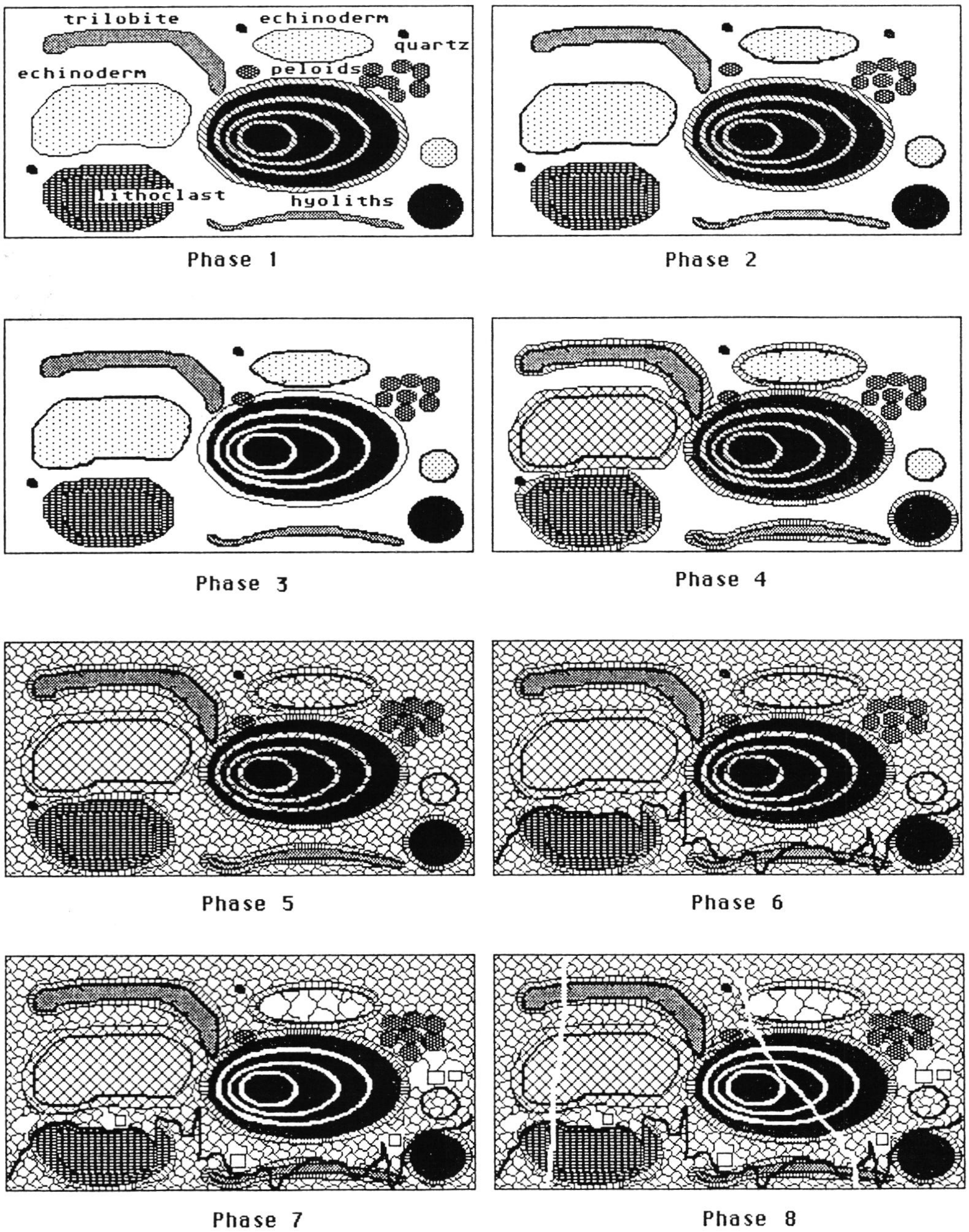


Fig. 6. Graphic interpretation of the course along which diagenesis proceeded within the echinoderm- trilobite- hyolith- rudstone of bed 6 from the outcrop at the northern end of the Dead Sea.
Particles were deposited during phase 1; in phase 2 carbonate was modified by organisms, finally implaced and fused by first cement coatings; in phase 3 aragonite dissolved; during phase 4 syntaxial cements and fibrous cements grew; in phase 5 all of the remaining pore spaces were filled by calcitic cement; in phase 6 pressure sutures formed; during phase 7 dolomite and anhydrite grew; in the final phase 8 fractures formed and fissures were closed with calcite.

Plate 56 Microfacies of Cambrian limestones in Jordan from the Wadi Sirhan-3 test well.

Fig. 1. *Girvanella*-lump-grapestone-pelsparite of bed 19 with algal oncoids and a stylolite suture cutting through all the particles. x 20

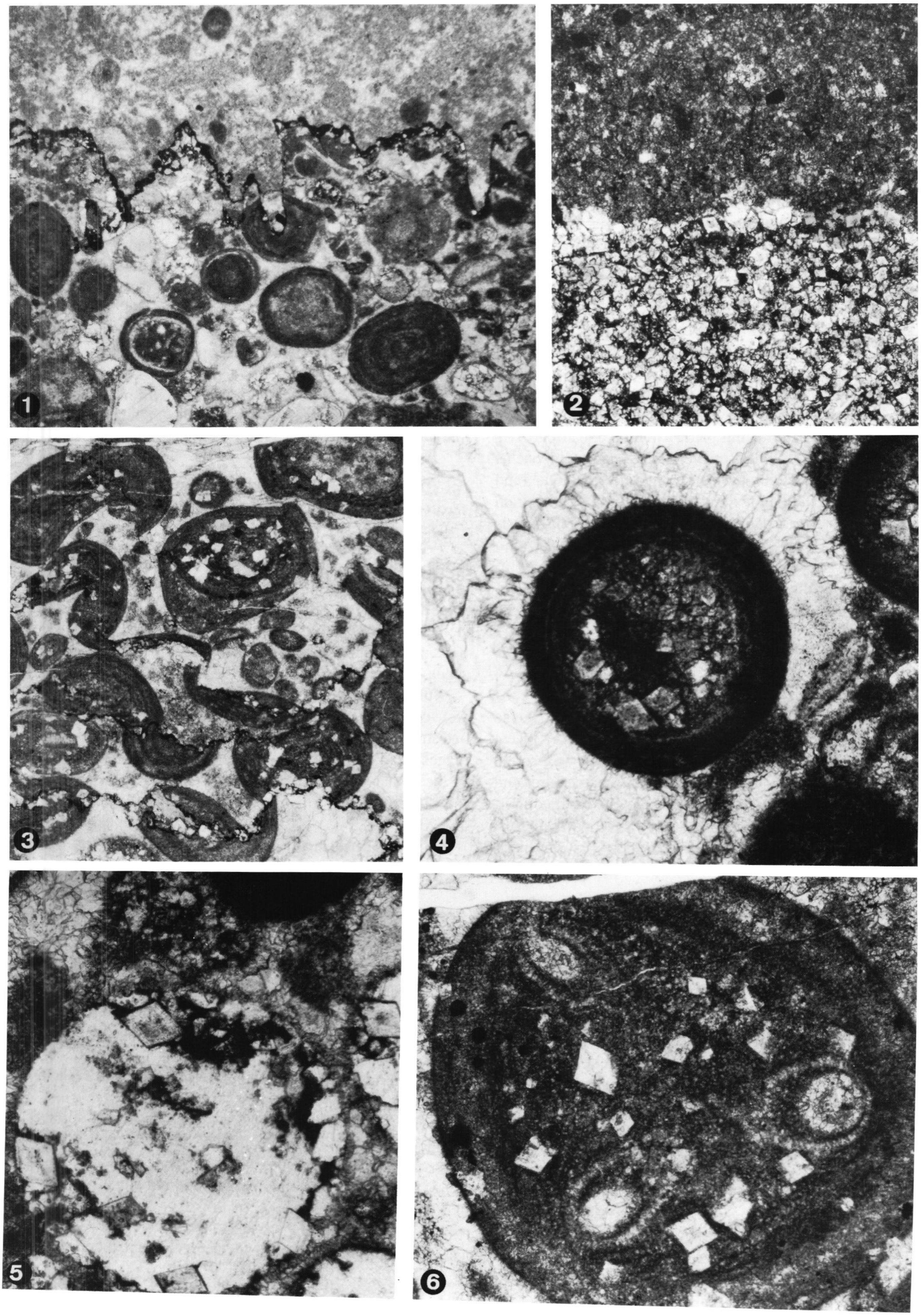
Fig. 2. Algal mat composed of *Girvanella* from bed 17 partly destroyed by dolomitization. x 30

Fig. 3. Sutures of stylolites have dissected and deformed ooids and oncoids of bed 20 and have, in addition, been altered by dolomite crystals growing within them. x 35

Fig. 4. Ooids with tangential structure and partial transformation into dolomite of bed 20 have been coated by fibrous cement and remaining voids have been filled by blocky cement. x 75

Fig. 5. Recrystallized coated grain of bed 20. Here the micritic envelope has been partly destroyed by the growth of dolomite crystals. x 75

Fig. 6. Polyooid of bed 20 with several complete ooids forming the core of one larger ooid. x 75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and micritized. During this phase 1 bioclasts received their final shape. In phase 2 carbonate particles became bored by organisms, coated by epiphytes and altered by micritization of their surface. Only afterward were components placed in their final position and compacted to such a degree that they formed a frame of particles touching each other and fusing with each other through the first cement crusts. During phase 3 aragonitic shells such as hyoliths were dissolved. Particles not affected by solution and loose particles neighbouring the new cavity are infilled into cavities formed by dissolution (Pl.53/2, 3). Aragonite of other particles was dissolved as well, but it is less easy to trace as it is in the large tubes of hyoliths. During the phase 4 which followed, cementation began with syntaxial growth of calcite on echinoderm fragments and prismatic growth of cements on other particles (Pl. 57/1, 3, 4). The remaining cavities were closed during phase 5 with blocky coarse calcitic cement that contained more iron than the former cements. The overburden produced continuous dehydration of the sediment and a compaction which resulted in pressure solution and the formation of stylolitic seams. During this phase 6 non-carbonate particles were concentrated along pressure sutures. Many components were dissolved, fractured and deformed along stylolites and these formed the paths along which sulfatic and Mg-rich pore water penetrated the rock at a later stages of diagenesis (phase 7). It replaced the calcite within biogenes or within cement by anhydrite or dolomite. A final eighth phase of diagenesis resulted in the fracturing of the rock and filling of the fractures with calcite or anhydrite.

Second example: Ooid- oncoid grainstone (beds 16, 20, 22; Fig. 7)

After transport and accumulation of the components (mainly ooids, oncoids and fragments of echinoderms) were deposited (phase 1). Here the particles of the well-sorted carbonate sand and intercalated coquinas became bored and microorganisms changed the structure of the outermost layers (phase 2). Afterwards particles reached their final location and became fused to each other during first diagenesis by prismatic cements that grew on the surface of the components (phase 3) (Pl. 57/2, 6). Only uncoated echinoderm fragments increased in size by syntaxial growth filling the internal pore space. Aragonitic shells, ooid layers and oncoids were then dissolved (phase 4). Compaction resulted in a deformation of particles especially those with secondary cavities formed due to aragonite dissolution (Pl. 56/3). Loose particles dropped into the cavities. In phase 5 all the free pores were filled with an iron-rich blocky calcite (Pl. 57/2, 6). Further load pressure and compaction resulted in dehydration and the formation of pressure sutures (phase 6) (Pl. 56/1, 3). Stylolitic sutures formed, dissecting and displacing carbonate particles and enriching non-carbonate particles like quartz grains and clay along their seams. During further diagenetic alterations the stylolites were the preferred pathway along which pore water migrated, bringing in Mg-rich material to form dolomite crystals (Pl. 57/5, 6) and sulfate waters to form anhydrite. These grew in place of earlier calcitic material in the cements as well as in biogenes or ooids (phase 7). Finally the limestone was fractured and the minute or larger fissures were filled with calcite (phase 8).

6 GENERAL SUMMARY OF THE DIAGENETIC ALTERATIONS

A more complex diagenetic history including two separate stages of diagnesis was described by Bandel (1986) for hylolith-rich layers (base of bed 6). Here muddy sediments were altered during early diagenesis (formation of pyritic steinkerns in hyolith tubes), were reworked and indurated parts were integrated into the final deposition of carbonate sands.

Stromatolites with alternating micritic and sparitic layers were consolidated synsedimentarily, so that their composition and structure remained generally unchanged during further diagenesis. Very fine-grained cements fixed mudstone facies in their final shape after stronger or weaker compaction, indicated by the deformation of burrow structures (beds 21 and 23).

Syntaxial rim cements usually grew around echinoderm

Plate 57 — Microfacies of Cambrian limestones in Jordan. Figures 1,3, and 4 are from bed 6 of the outcrop at the shore of the Dead Sea, while figures 2, 5 and 6 represent bed 20 from the subsurface of the Wadi Sirhan-3 test well.

Fig. 1. Trilobite remains and other polycrystalline bioclasts have been coated with fibrous cement that is especially well-developed in former cavites (geopetal structures). Syntaxial growth of calcite formes on echinoderm fragments during early diagenesis. x 90

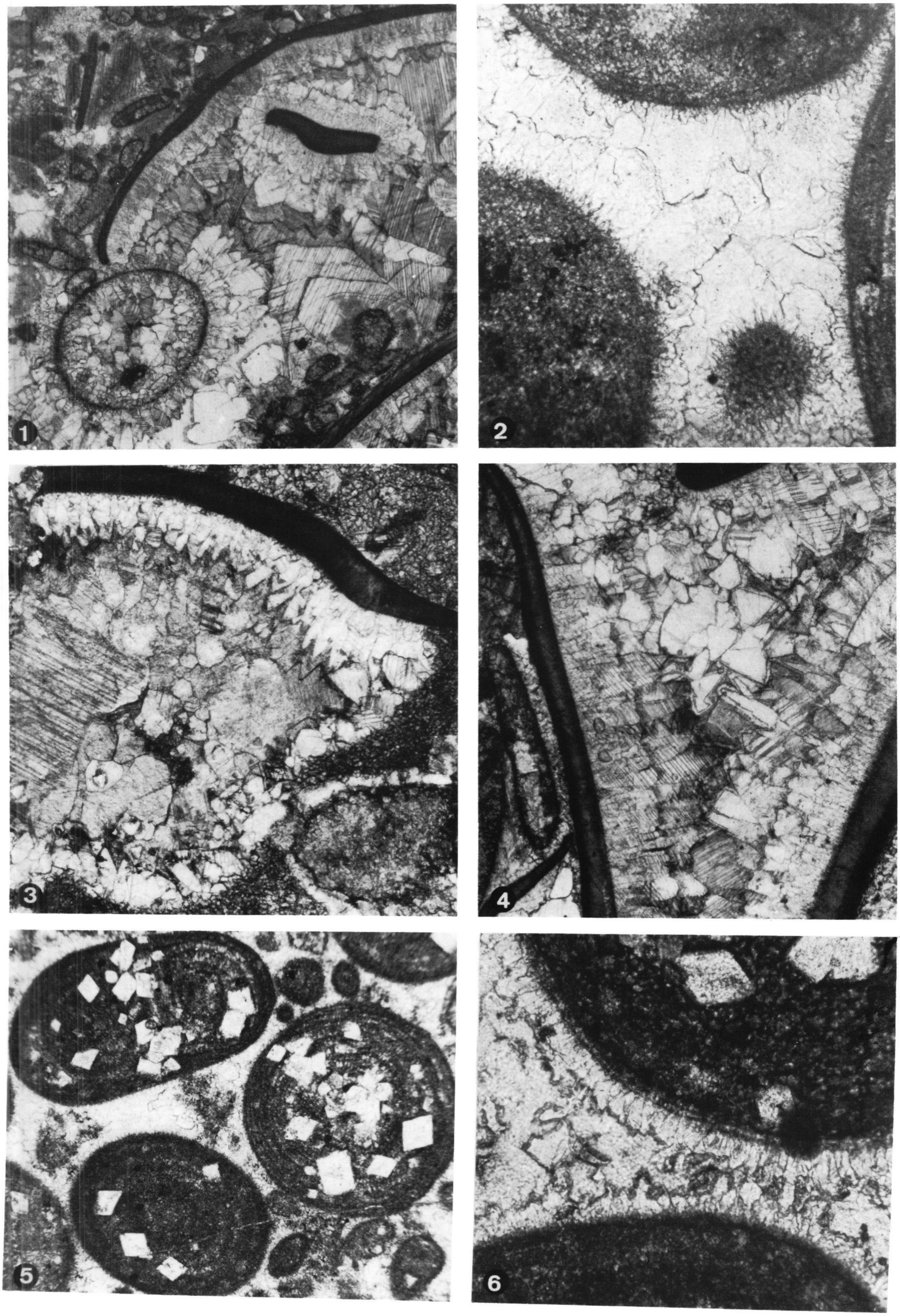
Fig. 2. Fibrous cement formed around coated grains and peloids during early diagenesis and remaining cavities have been filled by blocky calcite. x 100

Fig. 3. The geopetal structure formed under the shelter of a broken shell has been filled by a regular coating of fibrous cement hanging from the roof of the cavity. Irregular crystals grew from the base of the cavity and blocky cement filled the remaining space during a later phase of diagenesis. x 90

Fig. 4. Voids between larger biogenes show the succession of cements with several fibrous layers coating the surface of biogenes; blocky calcite fills remaining voids. x 90

Fig. 5. Crystals of dolomite formed within ooids and polyooids during late diagenesis. x 40

Fig. 6. Ooids fused with each other during early diagenesis due to the growth of a fibrous cement around them. x 100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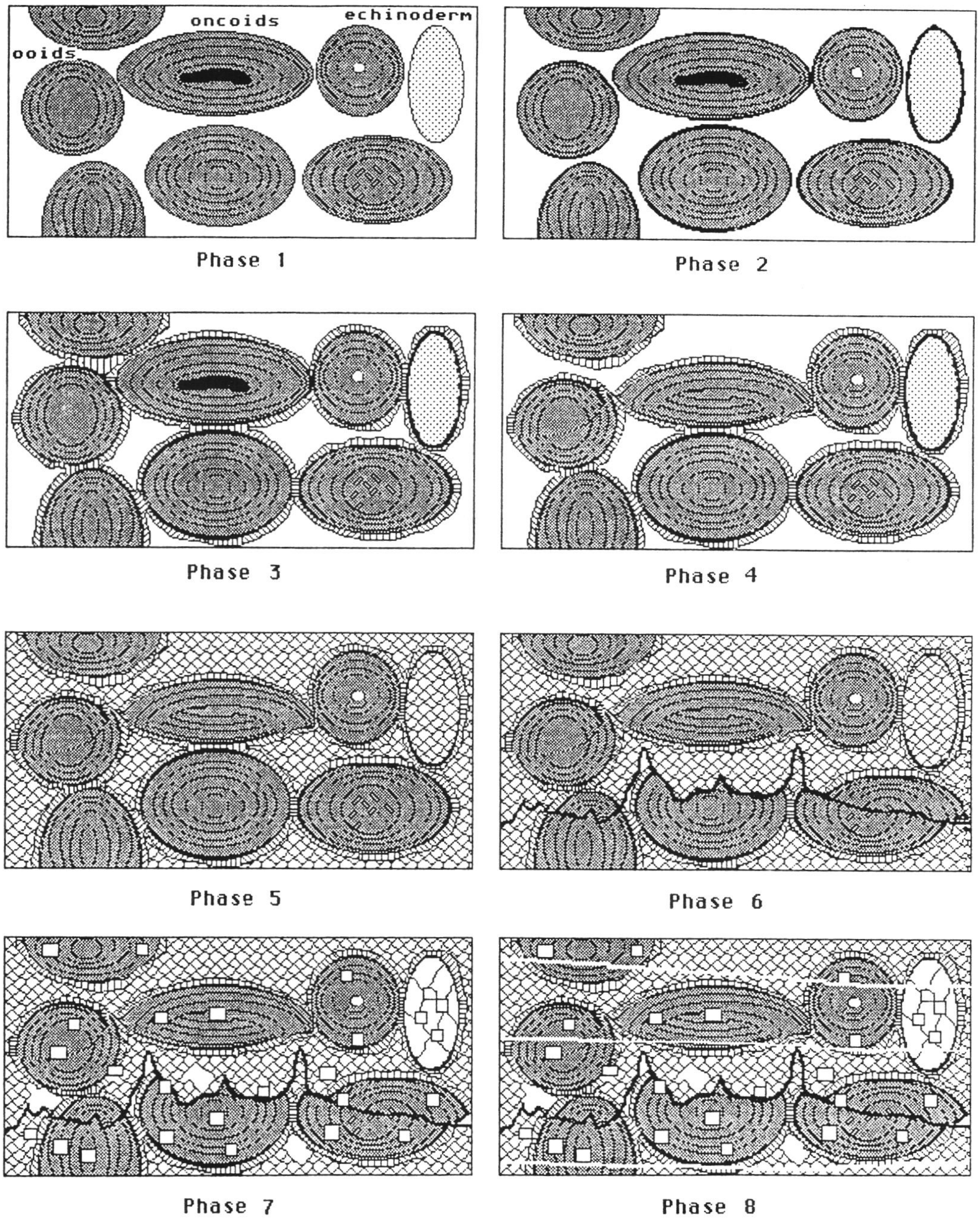

Fig. 7. Interpretation of the course of diagenesis within the ooidal, oncoidal grainstone of beds 16,20 and 22 from the subsurface samples in the Wadi Sirhan-3 area.
During phase 1 the particles were deposited: in phase 2 they became bored and micritized; during phase 3 cements coated all the grains; in phase 4 aragonite dissolved and particles with voids became deformed; in phase 5 pores were filled by blocky cement; during phase 6 pressure caused sutures; in phase 7 dolomite and anhydrite replaced some of the calcite; in the last phase 8 the solid limestone fractured and fissures were closed by calcite.

fragments and created a loose framework during early diagenesis when other particles remained unconnected. Prismatic cements were deposited around particles, fixing them to each other before the bulk of the pore space was closed with blocky calcitic cement (e.g. bed 1). Aragonitic particles or biogenes and bioclasts were dissolved either before or after the growth of the first cements. Pores, in contrast, were filled at a later stage of diagenesis by coarse blocky calcite (bed 6). Much of the cementation and most of the closing of pores probably took place under the influence of a terrestrial environment, while first lithification of the carbonate muds and sands probably occurred within the marine realm of the very shallow sea. Some of the sandstones below and above the shallow water carbonates were also influenced by a marine environment, as indicated by the common occurrence of marine trace fossils in several layers. Most of the sands were deposited within the coastal area on both the marine and the fluviatile/terrestrial sides of the tidal realm.

The formation of the common solution sutures and stylolites have been explained by the sediment load of the overburden. The features of partial or total dolomitization of the limestones as well as local displacement of calcite by anhydrite are products of later phases of diagenesis that may have occurred at an unknown time after consolidation and lithification of the limestones. Most of the fissures and cracks that became filled by calcite formed at the very last stages of diagnesis up to the moment of exposure of the rocks and the beginning of weathering.

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