

SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 759

AVHANDLINGAR OCH UPPSATSER

ÅRSBOK 72 NR 21

SVEN LAUFELD, BJÖRN SUNDQUIST
AND
HÅKAN SJÖSTRÖM

MEGAPOLYGONAL
BEDROCK STRUCTURES
IN THE SILURIAN OF GOTLAND



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C DAVIDSONS BOKTRYCKERI AB, VÄXJÖ 1978

Dedicated to
RAGNAR NILSSON
on his 75th Birthday

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ABSTRACT

Laufeld, S., & Sundquist, B., & Sjöström, H., 1978: Megapolygonal bedrock structures in the Silurian of Gotland. *Sver. Geol. Unders. C 759*.

A bedrock structure consisting of 0.5–1.2 m wide and 0.3–1 m high polygonal ridges, 5–15 m across, is described from Bungeör, an islet between Fårö and mainland Gotland. The megapolygons, which occur in limestone in the uppermost, Middle Wenlockian part of the Slite Beds, have a central crestal fissure. The fissures are surface expressions of polygonal master joints. A thin section study shows one major difference in composition between the rock in the polygon ridges and the rock in the "basins" inside the polygons. The limestone at the ridges contains about six times as much micrite as that inside the polygons. The micrite is proved to be of secondary origin. Its position indicates an early, Middle Wenlockian jointing. An analysis of the joint directions suggests a local cause of the polygonal jointing. Similar joint patterns occur in other parts of Gotland, and e.g. Wisconsin, in limestones overlying shallow-buried reefs and mounds. Centrifuge model experiments indicate that polygonal joint patterns are formed on top of buried reefs. It is proposed that mapping of polygonal bedrock structures might become an important tool in reconstructing the palaeogeography of reef areas in various parts of the Phanerozoic succession.

INTRODUCTION

In 1973, Arne Philip of Visby showed Sven Laufeld an aerial photograph of Bungeör, an islet located between the Isle of Fårö and the main island of Gotland, and pointed out a megapolygonal pattern on the southeast shore of this islet. Arne Philip then took a new and better photograph of the islet from a low flight altitude, which showed in detail the appearance of the polygonal structure. This picture prompted a field study, since structures of this kind have never been reported from Gotland, and we could only speculate about the cause of the polygonal pattern. Matters were complicated because Bungeör is owned by the Swedish Defence Authority and located inside an area of restricted access. However, we were granted permission to do field work there together with some colleagues and spent a day on Bungeör in 1974. The purpose of the present paper is to describe the megapolygonal structure at Bungeör and to interpret its origin. In addition we will discuss some similar structures outside the Bungeör area.

Björn Sundquist is responsible for the petrographic descriptions, discussions and interpretations, Håkan Sjöström for the centrifuge model experiments, and Sven Laufeld for the remaining parts of the paper and for the coordination of the project.

LOCATION AND GEOLOGY OF BUNGEÖR

Bungeör (Gotl. *Bunge aur*) is an islet (c. 600×450 m) located at the southeast of Fårösundet, 1.3 km east of the easternmost tip of Gotland and 1.5 km south of the Isle of Fårö (Figs. 1,2). Bungeör is fairly flat and only the small central part of the islet reaches more than 5 m a.s.l. For further topographic data, see the topographic map sheet (1:50 000) 7 J Fårösund SO & NO, the geological map sheet (1:50 000) Aa 171 Kappelshamn and the economic map sheet (1:10 000) Gotlands län, Bungenäs.

The Silurian bedrock succession of Gotland, which includes Late Llandoveryan (Telychian), Wenlockian and Ludlovian (Eltonian – Whitcliffian, incl.) sedimentary strata, dips towards the southeast. Stratigraphically as well as geographically a large part of the Wenlockian is represented by the Slite Beds (stippled in Fig. 1) which crop out on northern Gotland as a 20 km wide belt striking northeast-southwest.

Hede subdivided the Slite Beds into a number of topoformations (*sensu* Jaanusson 1976:310) and members (summarized in Hede 1960:49–50). For a review of Hede's stratigraphy and his publications on the Slite Beds, reference is made to Laufeld (1974a:8–10). Useful information on the Slite Beds is given also in publications by Martinsson (1967), Mantén (1971), Bassett & Cocks (1974), Sivhed (1976), Brood (1976a, b), and Laufeld & Jeppsson (1976; with

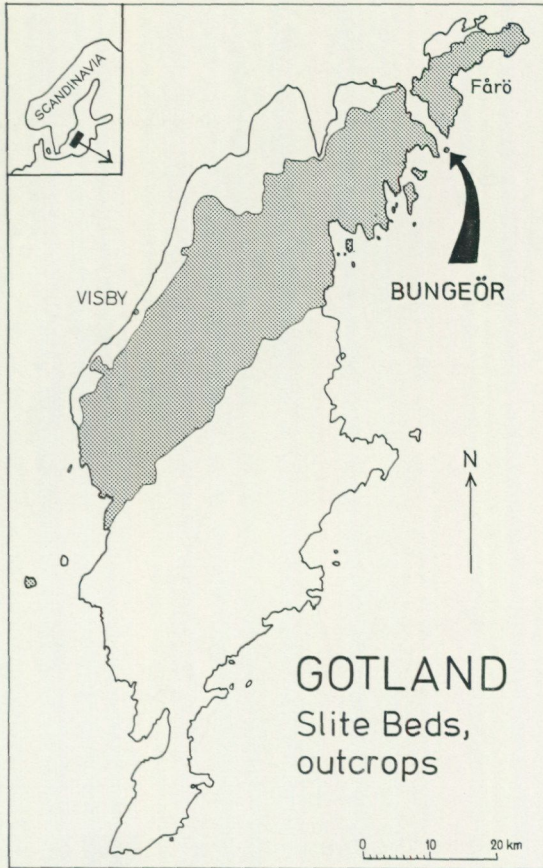


Fig. 1. Map of the island of Gotland in the Baltic showing the location of Bungeör. Area of Slite Beds stippled. Simplified from Hede 1960, Fig. 9.

a diagram showing the stratigraphy of the Slite topoformations and members) and references therein.

It is sufficient here to point out that the 100 m thick Slite Beds are composed of two main facies types. In the northwestern area there are reefs and mounds enclosed by bedded limestones which have a low argillaceous content. The area has fairly high relief. To the southeast (and south) the Slite Beds are represented by the Slite Marl, which occupies a topographically low area with almost no relief. As can be seen in Fig. 2, Bungeör is located at the transition between these two lithofacies types. The bedded and reef limestones shown in Fig. 2 are 30 m thick and all belong to the youngest formation (unit g which locally is named Ryssnäs Limestone) of the Slite Beds. However, the lower part of unit g is synchronous with the uppermost part of the Slite Marl. It is evident that the limestone outliers in Fig. 2 represent carbonate buildups in the "Slite Marl" sea.

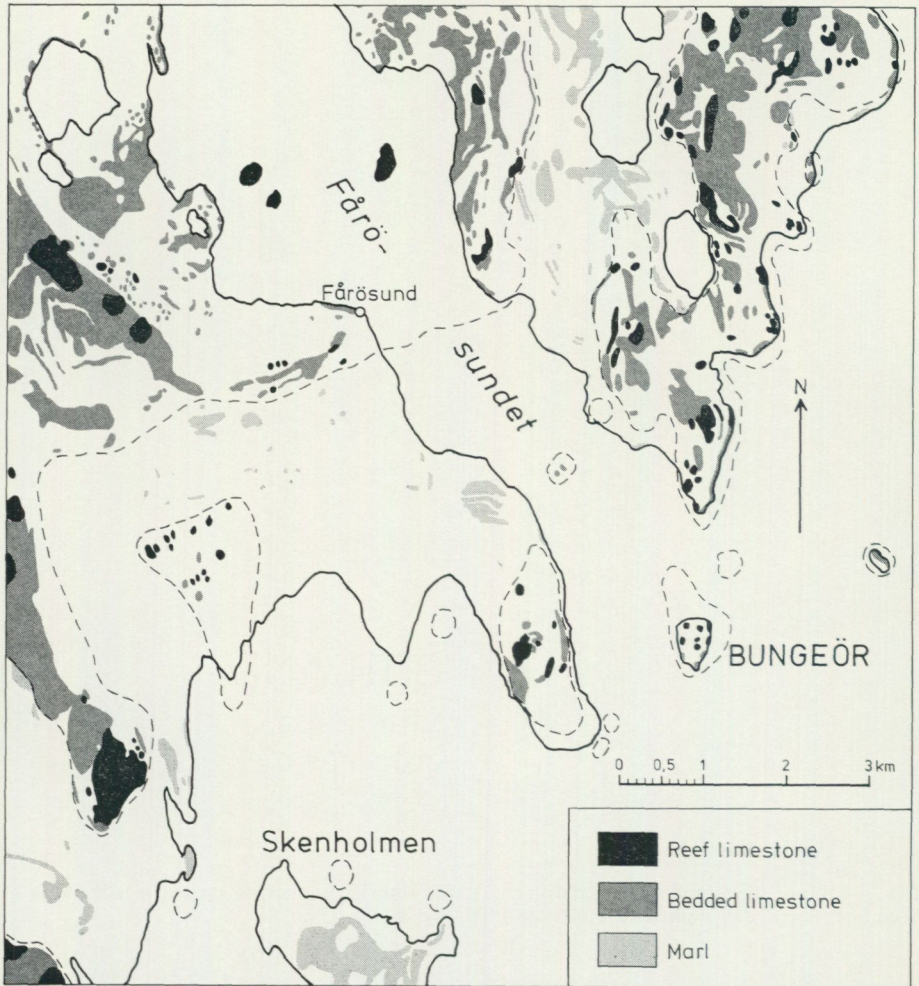


Fig. 2. Bedrock map of Bungeör and adjacent areas. The map area is located in the Slite Beds at the transition (marked with a broken line) between the northwestern limestone area and the southeastern Slite Marl area. Note especially all reef exposures. The small areas in the sea encircled by a broken line are submarine outcrops of Slite reefs (and adjacent bedded limestones) as revealed by analysis of the nautical chart Östersjön Nr. 331 (1:200 000). Bedrock exposures are compiled from the geological map sheets Aa 180 Fårö (Hede 1936) and Aa 171 Kappelshamn (Hede 1933).

Hence, Bungeör is surrounded and underlain by Slite Marl. In the northern part of Bungeör there are some small exposures of reef limestone. In the south bedded limestones are exposed, especially just outside the beach ridges in the far southeast where the polygonal structure was discovered (Fig. 3). These limestones are of Middle Wenlockian age and are correlated with the *Cyrtograptus lundgreni* Zone.

THE MEGAPOLYGONAL STRUCTURES

The aerial close-up photo, Fig. 4, reveals that the polygons are bed-rock structures with positive relief. Field study provided the following information.

The polygons are between 5 and 15 m across and consist of 0.5–1.2 m wide ridges of limestone. Some of the ridges reach a height of slightly more than 1 m but most are 0.3–0.5 m (Fig. 5). The ridges are made up of a bedded bioclastic limestone like that constituting the bedrock between the polygons. All ridge crests have a central fissure which is almost vertical and perpendicular to the bedding planes. These fissures are surface expressions of master joints and each can be traced downwards to a conspicuous joint (Fig. 5C). Hence, it is evident how the polygons were formed. At first joints formed in a polygonal pattern. Solutions percolated the joints and cemented the calcareous beds on both sides of the joint to a distance of roughly 0.25–0.6 m from the joint plane. When erosion of the limestone took place it was selective and the more resistant rock along the joints was left as a large-scale honeycomb structure, whereas the less indurated limestone ("the honey") inside the polygons disappeared. But it is still not known when the joints were formed and why they form a polygonal pattern. To answer the first question the texture and composition of the limestones at a fissure (joint) and inside a polygon were compared.

PETROGRAPHY

MATERIAL AND METHOD

Two surface samples, A and C (Fig. 4) were taken close to the fissures, and two, B and D, were taken inside the polygons. Although samples A and C had a stratal position ca. 5 cm above that of samples B and D, we consider any discrepancy in their ages to be very small. The coarse texture of the rocks suggests fairly rapid sedimentation, so for all practical purposes we regard the samples as synchronous.

100 grams of each rock sample were treated in dilute acetic acid for insoluble residue analysis. The percentages of CaCO_3 and $\text{CaMg}(\text{CO}_3)_2$ were calculated by means of chemical titration. From each sample one thin section was made perpendicular to bedding. The sections were point-counted. The number of points counted varied between 496 and 564 due to the different sizes of the sections. In counting the skeletal particles, the grain-solid definition of Dunham (1962:111) was used (Fig. 6).

MICRITE, SPAR AND ALLOCHEMS

Folk's (1959) strictly defined nomenclature for the constituents of limestones is now in common use. He (1959:4) divided the non-terrigenous constituents into allochems and orthochems. The former was further split into intraclasts, ooids, fos-



Fig. 3. Aerial photograph of Bungeör showing location of megapolygonal structures in the bedded Slite limestone (unit g) at Bungeör 1 in the far southeast of the islet. Photo Arne Philip 1972-10-06, 8:20 AM. Approved for publication by the Defence Staff 1972-12-12.

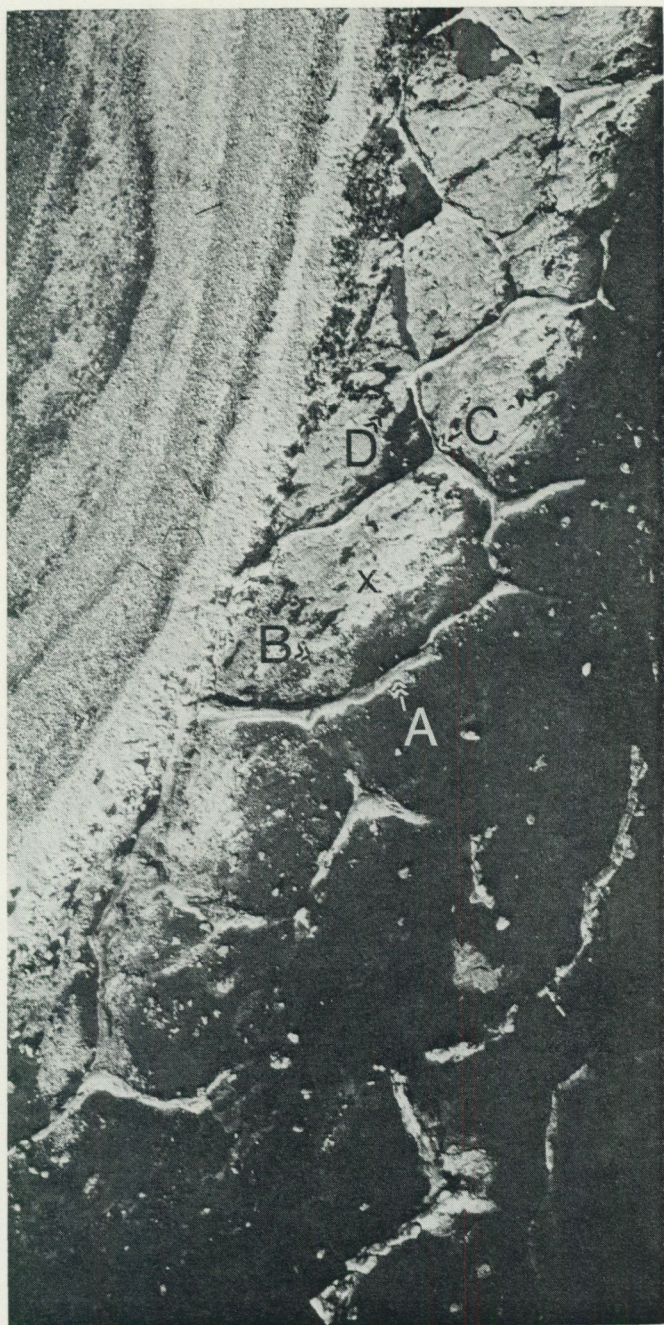


Fig. 4. Aerial photograph of the megapolygonal structures outside the beach cobble. Note remnants of submarine polygons. The letters refer to our sampling sites. Photo Arne Philip 1973-10-06, 13:07-15:07 AM. Approved for publication by the Defence Staff 1975-01-16.



SAMPLE	INSOL. RESIDUE %	CaCO ₃ %	CaMg (CO ₃) ₂ %	Micrite		Spar		Allochems		Echinoderms			Bryoz.	Brach.	Arthr.	Algae	Others & N.I.	No. of points
				20%	40%	20	40%	20	40	60%	20	40	60%	10%	10%	10%	10%	
A	0.20	98.0	1.7	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	564
B	0.01	96.8	1.0	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	496
C	0.30	94.8	2.1	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	542
D	0.02	98.0	1.0	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	██████████	512

Fig. 6. Composition of samples. "Others" in the last column include pellets, intraclasts, and molluscs. The coenitids are included in "Bryozoa". For sampling sites, see Fig. 4.

sils, pellets, and pseudo-allochems. The orthochem constituent was divided into microcrystalline calcite ooze (micrite, grain diameter 1–4 microns), sparry calcite cement (spar, grain diameter more than 10 microns) and others (i.e. minerals formed by post-depositional replacement or recrystallization). Later (1962, 1965, 1974) Folk developed this terminology further, introducing (Folk 1965:37) the term microspar (grain diameter 5–10 microns). The genetic differences between the orthochems are important. Micrite may be an *in situ* precipitate and hence a cement, but part of it may also be a primary sediment. Spar, however, is always secondary in origin and forms a cement. Microspar is also secondary, being the neomorphic product when micrite is diagenetically altered to a coarser crystalline mosaic. Aggrading neomorphism can proceed until complete recrystallization has taken place to give a coarse calcite spar (see Folk 1965:23 for discussion). Such neomorphic spar is often difficult to distinguish from cement spar, but because the origin of the spar affects interpretation of the original sediment this distinction is essential. Fabric criteria for recognition of true cement were summarized by Bathurst (1971a:417).

In 1962 Dunham proposed a classification of carbonate rocks based on the grain-to-grain relation and the presence or absence of carbonate mud. This classification refers to the depositional texture of a rock (i. e. the sediment). It is therefore evident that the diagenetic history of a rock must be understood before its site of deposition can be categorized.

Fig. 5. Close-up photos of three polygonal ridges. A. Well-preserved symmetrical ridge with a bifurcation where it plunges into the sea. The wild beast is 25 cm high. Note the fissure along the central part of the ridge. B. Irregular polygon ridge with a wide central fissure. Erosion has just started carving out this ridge. Note that the bedding planes in the limestone are perpendicular to the fissure. C. Transverse section of a well-developed polygonal ridge. Note the fissure at the hammer and the deep joint in the central part of the ridge. Bedding is horizontal.

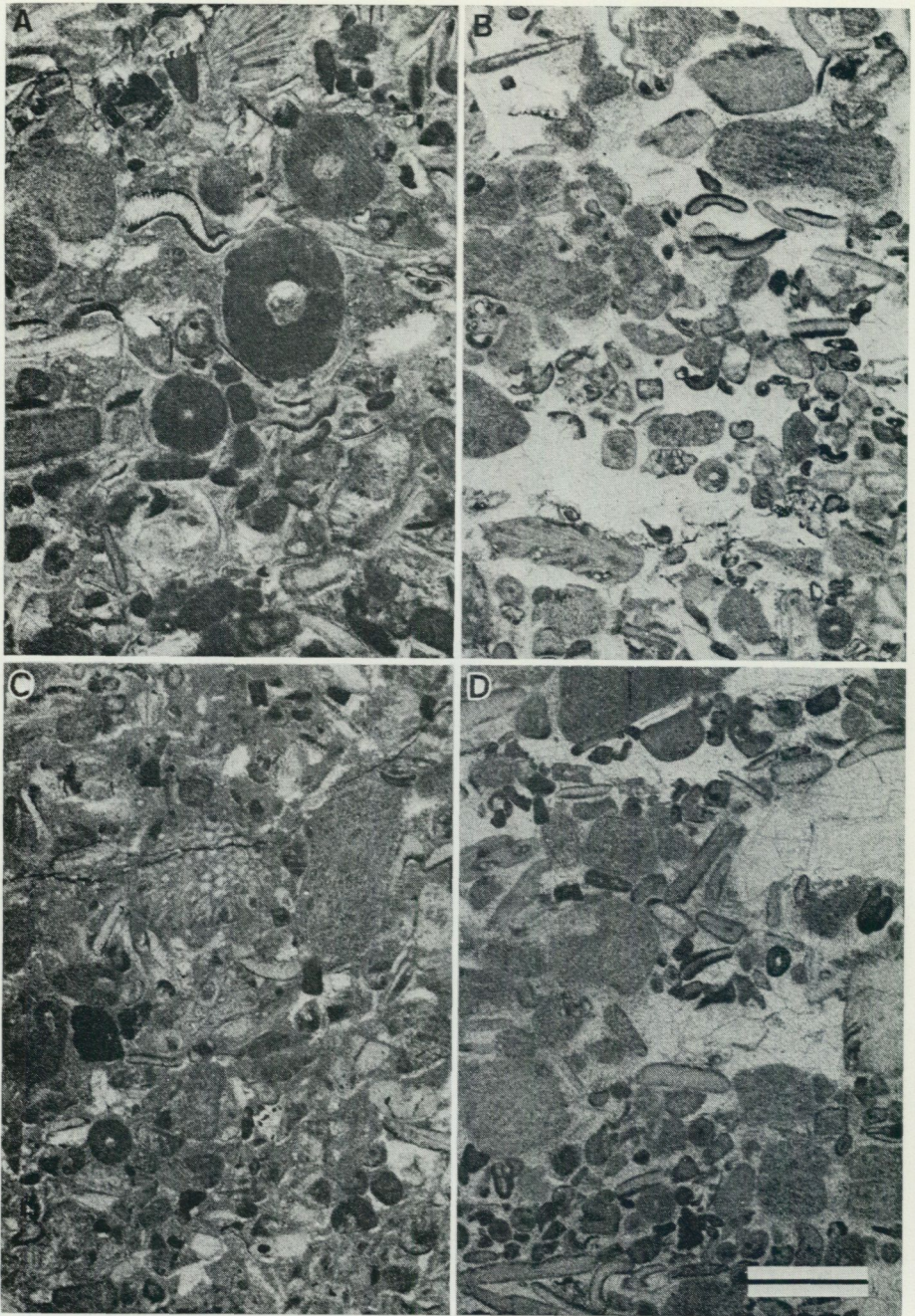


Fig. 7. General appearance of studied samples. Letters on the photographs are the same as sample designations. Thin sections in plane light. All same scale, bar equals 2 mm. All photos in correct up-orientation. Compare with Figs. 4 and 6.



Fig. 8. Negative prints of thin sections in plane light. A is sample A, B is sample B. Both same scale, bar equals 2 mm. Arrow in lower right in B points at broken shell, shown in higher magnification in Fig. 9A. Both photos in correct up-orientation.

For various reasons, many workers have not adopted Folk's definition of micrite in terms of crystal size. Instead, micrite has come to include crystal sizes up to 30 microns (Leighton & Pendexter 1962:35) or even 50 microns (Bissell & Chilingar 1967:161). Micrite has also been used as a synonym for carbonate matrix and carbonate mud (e. g. Leighton & Pendexter 1962:35). In Dunham's classification (1962:113) the distinction between grains and mud is 20 microns. For skeletal carbonate rocks Jaanusson used a size limit of 100 microns for the distinction between matrix and sand (see Jaanusson 1972:218 for discussion). Heckel (1974:99) included particles less than 62 microns in the term lime mud, thus following the normal usage of "mud" as including the clay and silt fractions.

In this study spar is used for calcite crystals that are translucent and forming a cement or neomorphic mosaic, and micrite for calcite crystals of such a small size that they appear dark in light microscope and which fill pores or form a matrix. Allochems are normally larger than 100 microns.

TEXTURE AND COMPOSITION

The gross textures of samples are illustrated in Figs. 7 and 8. Most of the allochems are well rounded and of sand size but the sorting is poor. Elongate fragments are oriented horizontally or subhorizontally and reach a maximum length of about 5 mm. Dolomite is present as euhedral grains concentrated in the micrite matrix. The texture of all samples is grain-supported, and since mud (*sensu* Dunham) is present the rocks are all packstones. Using Folk's (1959) classification based on the kind of allochems present and their relative abundance, together with the spar-micrite ratio, samples A and C would be termed biomicrudites and samples B and D biosparrudites. Stylolite seams occur in all samples but are only of millimeter-size. Micritic envelopes on grains are found in every thin section but are not abundant. The most striking feature of samples B and D is their original high porosity compared with samples A and C. Using the terminology of Choquette & Pray (1970), the porosity types present in samples B and D are fenestral and vug. Vug pores occur also in A and C but are very subordinate in abundance compared to samples B and D. All these pores are filled completely with spar.

The composition of the samples is summarized in Fig. 6. The amount of insoluble residue in each sample is very small, but in B and D it is only a tenth of that in A and C. The residue consists of pyrite, limonite, clay aggregates, and dolomite rhombs. The micrite content exceeds that of spar in samples A and C, while the reverse is true in samples B and D. Microspar (*sensu* Folk) makes up c. 10 % in A and C but only c. 0.5 % in samples B and D. Fossils are by far the dominant component of the allochems, and the most abundant group are echinoderms (crinoid debris). Pellets and intraclasts together make up only a small component and ooids are absent.

EVIDENCE OF EARLY JOINTING

The distributions of micrite and spar in samples A and C compared with samples B and D differ greatly. If the rocks are synchronous, as postulated, these distributions cannot be primary. Therefore, either all rocks originally had a high content of micrite matrix or the micrite present in A and C is secondary. The former possibility, which must imply subsequent aggrading neomorphism in B and D and not in A and C, is less probable because of fabric criteria. In B and D there are two generations of cement (Fig. 9A–B), there are no relict structures present, peloids and micrite coats are not altered to spar, the spar–particle contacts are sharp, and the intercrystalline boundaries of the spar are planar. These criteria are among those used by Bathurst (1971a:417, 1971b:296) indicative of an original cement spar. It means that no more micrite than is present now has ever been present in samples B and D.

By elimination then, it can be concluded that the micrite in A and C must be secondary. This is supported by the presence of a first generation cement in these samples (Fig. 9). This cement, which could not have been developed if micrite was originally present, consists of thin scalenohedral calcite linings on the skeletal grains. On some grains the cement-rims are not uniform in thickness but are preferentially developed on the lower surface of the grains, like the gravitational cement of Müller (1971:301) characterizing the vadose zone. In interpreting the diagenetic environment, reference should also be made to the study by Dunham (1969) on vadose silt (compare with his Fig. 17, p. 158).

To conclude, it is evident that the original sediment was a skeletal sand, with the depositional texture of a grainstone and that the micrite was introduced to the sediment *via* the joints after the first generation cement and before the final porefilling cementation. Therefore the joints must be early. The micrite was filtered off during the lateral passage of the first 0.25–0.6 m of the semi-lithified sediment and this "injection" transformed the textures to that of packstone.

JOINT SYSTEMS

An analysis of the joint directions was made, even though the petrographic analysis suggested that the joints in the polygonal ridges were formed in Wenlockian time. Measurements of these calcite-filled master joints are plotted in black in Fig. 10. The dotted areas in the figure represent measurements of unfilled subsidiary joints in a "basin" (marked by x in Fig. 4) inside the polygon.

The number of observations of the (dotted) small unfilled joints is fairly small, but most of these joints are aligned in the E–W quadrant and a WNW–ESE direction is conspicuous. All the small joints measured are almost vertical. The same is true of the master joints. There are two main alignments in the distribution of master joints, one NNE–SSW, another ENE–WSW. Minor concentrations of master joint directions also occur roughly perpendicular to these two sets.

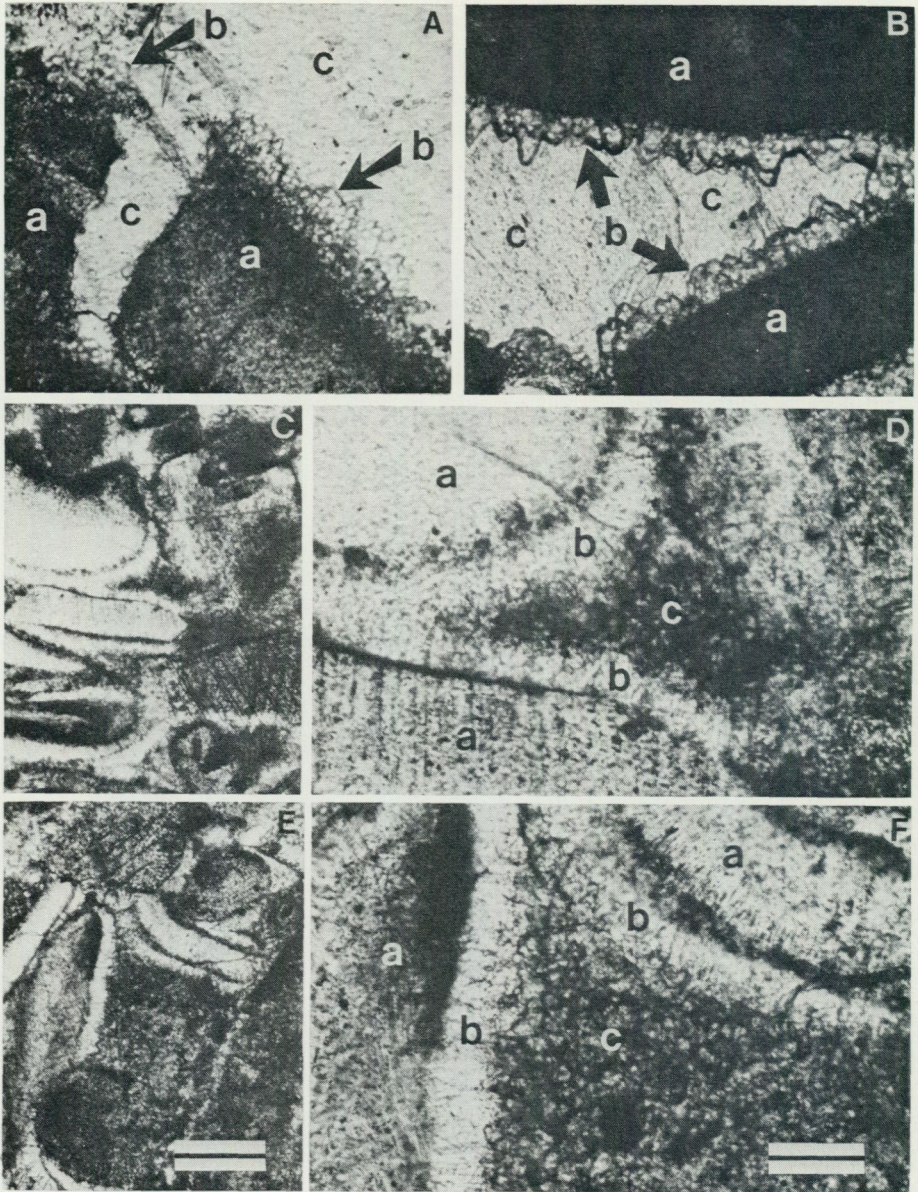


Fig. 9. Significant differences in near-fissure and mid-polygon samples illustrated by samples A and B but valid also for samples C and D. All photos in correct up-orientation. Thin sections in plane light.

A: Broken shell (a) showing the original surface lined with scalenohedral calcite crystals (b). Inside the fracture there are no such crystals but instead the fracture, as well as the remaining pore-space, is filled with clear calcite (c) which was precipitated subsequent to b. Thus the fracture developed after the precipitation of the first generation cement (b) and before the final pore filling (second generation) cementation (c). Hence, there is a discontinuity in the cementation of this rock. Sample B.

B: Analogous to photo A. Skeletal debris (a) being lined with first generation cement (b), the remaining pore-space later filled with a second generation cement (c). Sample B.

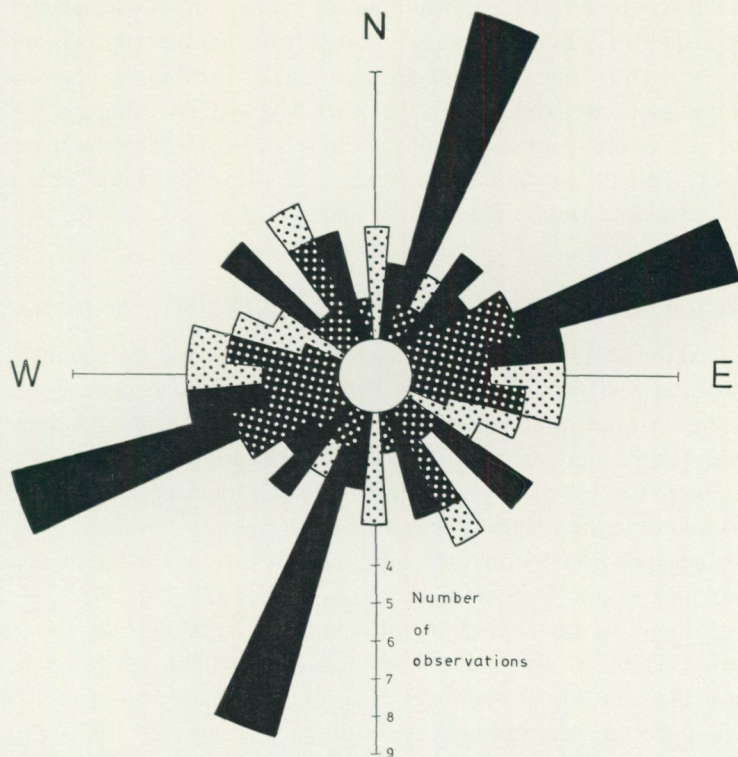


Fig. 10. Diagram showing joint directions in the Slite limestone in the southeastern part of Bungeör. Black areas represent calcite-filled master joints along the centre of polygonal ridges. $N=51$. Dotted areas represent subsidiary joints ($N=37$) in a "basin" between polygonal ridges. Thus white dots represent overlapping areas. The class width is 10° .

When Fig. 10 is compared with data from earlier studies of joint directions on Gotland some interesting differences become obvious. Kaufmann (1931:293, Figs. 2 and 5) showed that on northernmost Gotland there are two groups of master joints (calcite-filled). One dominates and strikes NE-SW, the other E-W. For small unfilled joints there are less pronounced distribution peaks in the directions perpendicular to the master joints. As shown by Kaufmann (1931, Figs. 2-3) the bedrock of Gotland is cut by master joints having a narrow and very conspicuous distribution maximum NE-SW. Manten (1971:52, Fig. 50) pointed out a group of master joints striking ENE-WSW in north-central Gotland. He stated that this direction occurs also on northwesternmost Gotland,

C-F: C and E are overview pictures, D and F are close-ups. Skeletal debris (a) lined with first generation cement (b). Contrary to sample B (photos A and B) the remaining pore-space is filled with micrite (c). Sample A.

A, B, D, and F same scale, bar in F equals 100 microns. C and E same scale, bar in E equals 400 microns.

although this was by reference to Kaufmann's publication in which only NE-SW and E-W groups of master joints are reported from that part of the island.

As can be seen in Fig. 10 there are two major distribution peaks of master joints on Bungeör, one NNE-SSW, the other ENE-WSW. There is no NE-SW maximum and virtually all sectors of the circle are represented by master joints. This suggests that the polygonal structures were caused by some local influence in Silurian, probably Middle Wenlockian time.

LARGE POLYGONAL STRUCTURES IN RECENT CARBONATES

Kendall & Skipwith (1969) reported large (400 m across) polygonal structures on Recent intertidal sand flats at the Persian Gulf. The structures were interpreted as the surface expression of cracks in the cemented surface (a hardground) under a very thin sediment cover. According to Kendall & Skipwith (1969:874) the cracks were formed during subaerial exposure, by desiccation or from accumulation of gases in the sediment below the hardground.

Similar megapolygonal structures were described from the Sabkha Matti area in another part of the Persian Gulf by Evamy (1973:336, Fig. 3A-B) who interpreted them to be caused by gravitational instability in the sediment. Artyushkov (1963a, b) also pointed out that a cemented and fairly heavy bed overlying a light and loose sediment is so gravitationally unstable that cracks are formed in the rigid hardground. According to Evamy (1973:336) this process is aided by repeated thermal expansion through insolation, and contraction caused by relatively cool water.

From the Persian Gulf Kendall & Skipwith (1969:885) and Evamy (1973:332, Fig. 2B) also reported large polygonal structures (up to 2 m in diameter) in algal mats on intertidal flats.

The polygonal structures at Bungeör could not have been formed in these ways. Algae are virtually absent from the limestone on Bungeör. Furthermore, the ridges are too straight for a biogenic origin. Nor would such an origin explain the joints. The large grain-size of the limestone, the composition of the fossil fauna and the general geological situation make it impossible to interpret the polygons as caused by desiccation. Hence, we conclude that the polygons are related to irregularities in the bedrock below, most probably buried reefs. As it would be extremely difficult to drill an exploratory well on Bungeör, it was decided to look for polygonal structures in some other areas on Gotland where buried reefs and mounds are known.

MEGAPOLYGONS IN THE SILURIAN OF GOTLAND

The large limestone area between Martebo and Bro church first attracted our attention because of the large number of domes indicating buried reefs or mounds

(Larsson & Philip, in prep.). Around Dacker 1 (Laufeld 1974b:30), a locality in unit e of the Slite Beds, a great number of joint polygons on the top of buried reefs or mounds were recorded. The size of the polygons is smaller than that at Bungeör. No ridges are developed in the Dacker area, but the bedrock was stripped of vegetation and topsoil only a few years ago.

Another area with shallow-buried mounds or reefs is located at Östergarn, where joint polygons have been recorded on Grogarnsberget and Klintsklint and at Snabben (southeast of Kuppen 1). At the latter locality there are conspicuous polygonal ridges although not as well-developed as at Bungeör.

It should also be mentioned that large bed-rock polygons occur in reef rock of Sundre (Whitcliffian) age at, e. g. Helligholmen, Holmhällar 1 and Hammars-hagehällar, but they are not always straight-sided and some of them probably represent an original, polygonal growth pattern of reef-building organisms. These will not be considered here because the areas mentioned earlier provide enough evidence of a megapolygonal joint pattern developed in bedded limestones immediately superjacent to buried reefs and mounds.

Foreign colleagues visiting Gotland were asked about polygonal bedrock structures connected with reefs and mounds. Don Mikulic (letter 10 February, 1977) drew attention to Robert Shrock's unpublished field notes from Wisconsin. When studying the Racine Dolomite in the Waukesha County Shrock wrote in his note-book (16 August, 1930): "The surface of the dome shows deeply weathered joints which divide the rock into large polygonal blocks." Shrock mentions a number of other mounds close by with prominent jointing. Mikulic has seen one of these mounds now exposed by deep quarrying and confirms that it is a reef.

The above-mentioned observations and the geological setting of the polygons at Bungeör make it highly probable that the polygonal structures were caused by a buried reef. An experimental study was performed to verify observations and conclusions.

CENTRIFUGE MODEL EXPERIMENTS

Since the early 1960's many geological structures have been simulated in experimental models by using the centrifuge techniques. Ramberg, who pioneered this field of study has described (1967) the theoretical and practical background for experiments in which the force of gravity in nature is simulated by the centrifugal force acting on the model in the centrifuge.

We have used the centrifuge in Ramberg's laboratory in Uppsala for the purpose of testing whether polygonal joints are generated above a buried reef or mound.

Seven different models (\emptyset 10 cm) were constructed, to represent ductile as well as brittle deformation of limestones on top of a buried reef or mound. To

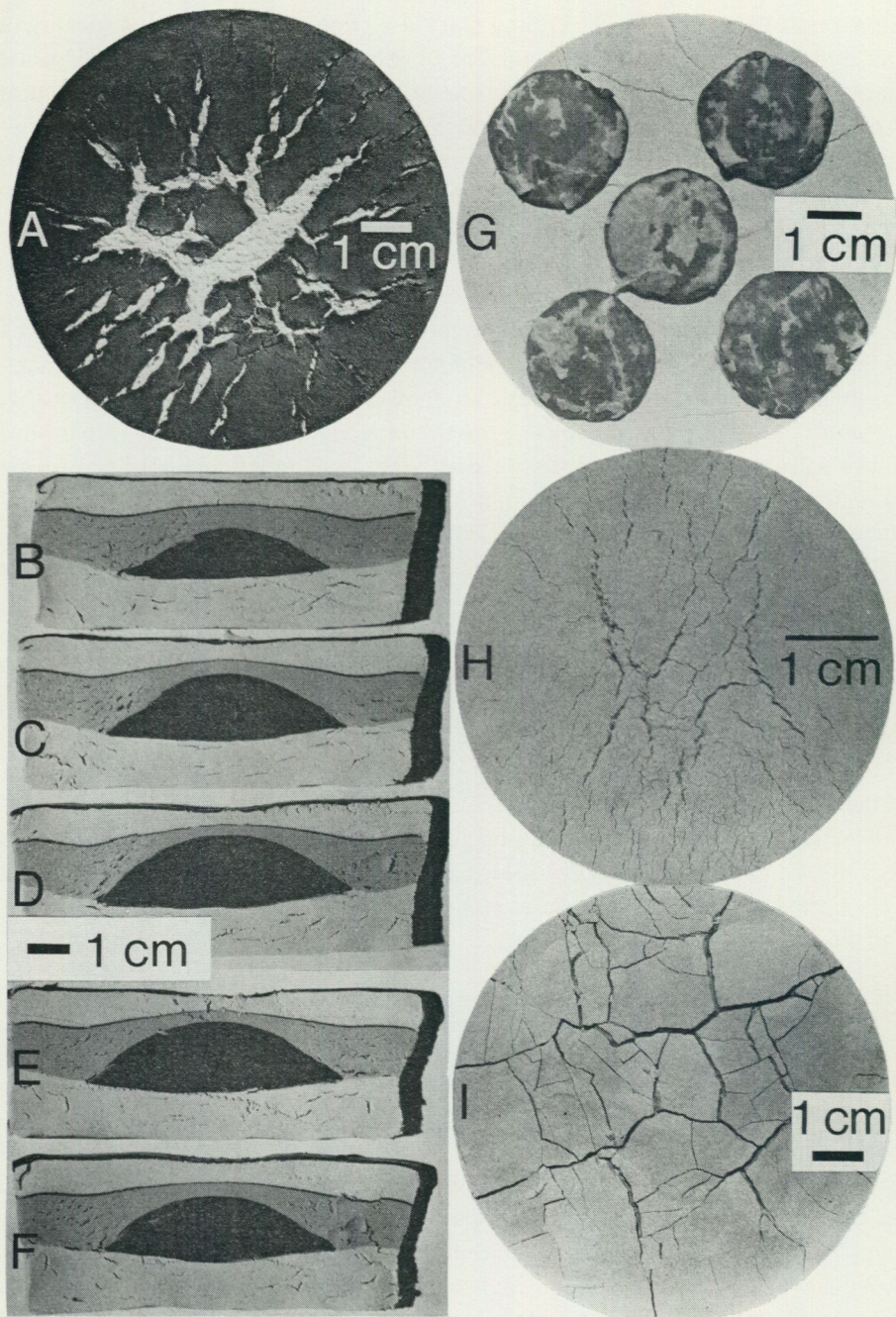


Fig. 11. Models of buried reefs or mounds run in the centrifuge.

A. Model 1: The thin black layer of plasticine on top of the buried lens has cracked in a polygonal pattern above the centre of the buried lens (not visible). Outside the central area there is a conspicuously radial pattern of joints. Acceleration 390–2 400 g, 6 minutes.

simulate ductile deformation a competent lens of plasticine (1.61–1.71 g/cm³) was placed on a less competent basal layer of painter's putty (1.8–1.9 g/cm³). The lens was covered by another flat-surfaced layer of painter's putty and a thin layer of plasticine on top (Fig. 11A–F). This type of model simulates fairly well the geology of the Bungeör area. The top layer of plasticine was excluded in another model with dome-shaped upper surface as a result of even thickness of the upper layer of painter's putty across the model (Fig. 11H). Because the models for brittle deformation are far away in several respects from the natural conditions, they were tested just to find out whether or not a polygonal joint pattern was generated. In the brittle models a plasticine lens (and 3 and 5 lenses respectively) was placed on a layer of painter's putty. This was covered by a mixture of barium sulphate and water (3.5–4 g/cm³) (plane upper surface) that was left to dry before it was run in the centrifuge (Fig. 11G,I).

The results of our centrifuge model experiments can be summarized as follows:

Where a competent lens was buried under a relatively incompetent bed tension joints were formed. The tension joints formed a polygonal pattern above the central part of the lens but a radiating pattern in lateral direction. Where a number of closely spaced lenses were buried at the same level under a brittle bed a composite polygonal joint pattern was formed above the lenses inside the circumference of all lenses and a radiating joint pattern lateral of that area. Tension joints were also formed in the upper part of the lenses when the brittle overburden cracked (Fig. 11G).

DISCUSSION

The deposition of the Slite Marl was followed by a regression in latest Slite time (in the Wenlockian *Cyrtograptus lundgreni* Zone). In the shallowing sea coarse bioclastic sediments (unit g) accumulated on top of the Slite Marl in the Bungeör area and growth of reefs started. Coarse bioclastic sediments continued to amass adjacent to these reefs and the continued shallowing of the area brought an end

B–F. Profiles of Model 1 after the centrifuge run. The plasticine is black and the painter's putty light and dark grey. Compare with A.

G. Model 4: Five plasticine lenses (c. 5 mm thick) below a 2 mm thick layer of brittle BaSO₄ and H₂O and above a 10 mm thick basal layer of painter's putty. Acceleration 390–1 400 g, 4 minutes. The photo shows the lenses after stripping of the BaSO₄-layer. Note that cracks have formed also in the upper part of the lenses.

H. Model 6: Basal layer of painter's putty, lens of plasticine, top layer of painter's putty. Differs from A–F by having the upper putty layer of equal thickness all over the model which gets a domelike appearance. The model was left drying for 17 days. Acceleration 390–2 650 g, 10 minutes. Note central polygonal cracks which are slightly irregular due to the coarse texture of painter's putty. Also the radial joints indicate that the buried lens is not circular but has an oval shape with its length axis in N–S.

I. Model 4: Same as G but with the top layer still in position. Note that closely spaced lenses yield polygonal cracks over a fairly large area and also the distinct joints resulting from completely brittle behaviour of the fine-grained material (cf. Fig. 11H).

to reef growth by an influx from north and northwest of bioclastic material that buried the reefs. Early in the diagenesis of unit g but after the precipitation of a first generation of calcite cement polygonal tension joints were formed in the bioclastic limestone above the buried reefs.

The joints were filled by micritic material that was also carried 0.25–0.6 m into the sediments lateral of the joints. The diagenesis was completed by a final pore-filling cementation of the bioclastic limestone. After a transgression in late *C. lundgreni* Zone time the Bungeör area was buried. In late Pleistocene time erosion of the then exposed unit g started. The polygonal ridges were formed because the reinforcement by the micrite gave the limestone a higher density and a better resistance to erosion.

Mapping of polygonal ridges and joints could become an important additional tool in the future palaeogeographic reconstruction of reef areas also outside Gotland, because the polygonal cracks reflect buried reefs.

Lastly we suggest that joints caused in the same way as those described herein are of great importance for the formation of sea stacks — *raukar* — on Gotland.

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APPENDIX

BUNGEÖR 1, X641584 Y169685, c. 6 600 m SE of Bunge church. Topographic map sheet 7J Färösund SO & NO. Geological map sheet Aa 171 Kappelshamn.

Shore exposure with polygonal bedrock structures in the southeastern part of Bungeör. For a detailed description, see Laufeld, Sundquist & Sjöström 1978.

Slite Beds, unit g.

References: Laufeld, Sundquist & Sjöström 1978 (Figs. 3–4 are photographs of the locality).

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