THE SLITE MARL, SILURIAN OF GOTLAND, SWEDEN: AN ATLAS OF MICROFACIES AND THEIR LITHIFICATION

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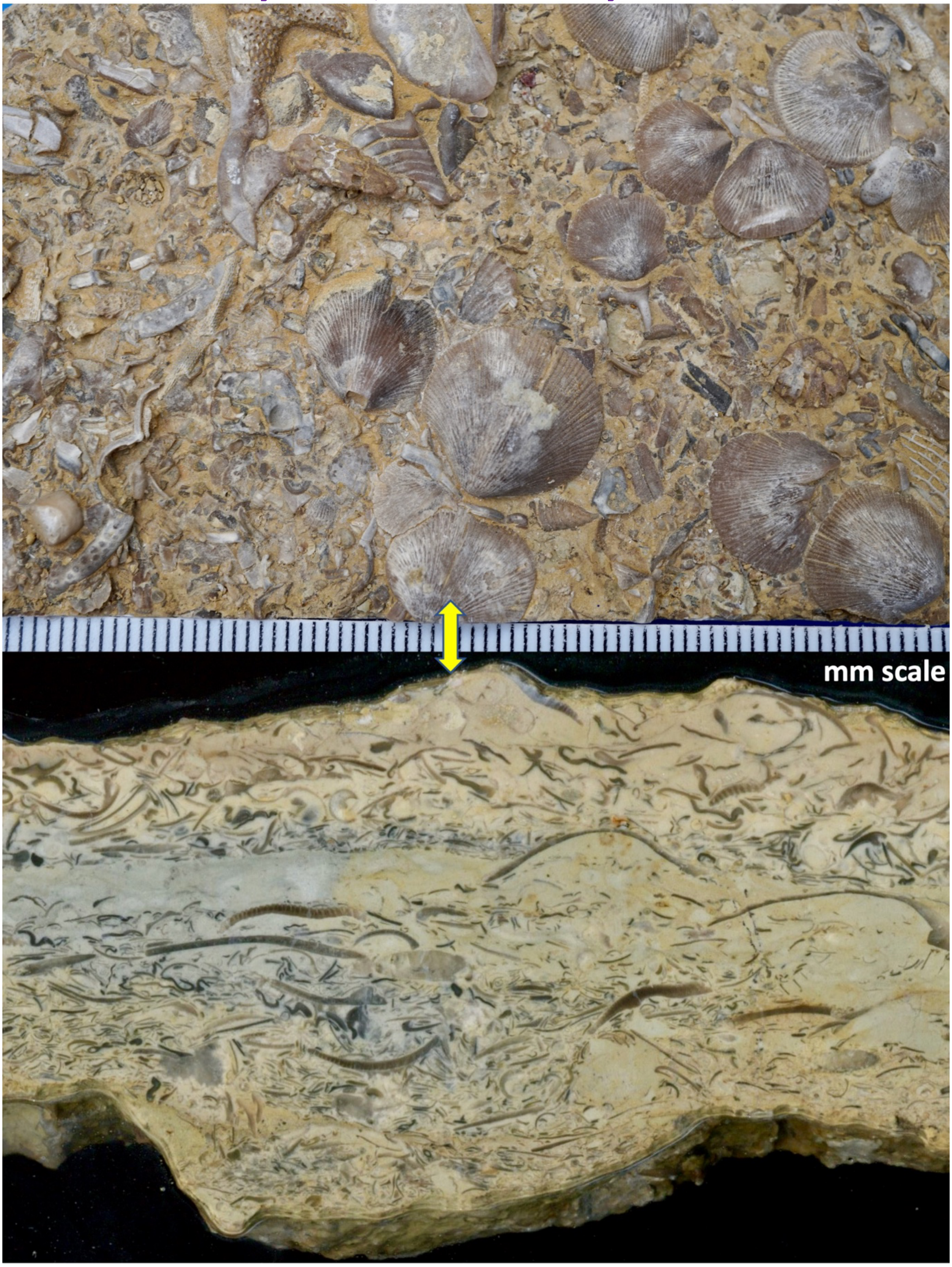

COVER PHOTO: Surface view (upper) and vertical cross-section view (lower) of a piece of fossiliferous limestone from bedded limestone of a unit locally called the “Slite Marl”. This specimen comes from the Follingbo site, which is an uninspiring ditch locality of Wenlock age (Silurian) in the western part of the island of Gotland, Sweden; Gotland is one of the most fossiliferous places on Earth. Despite its disappointing appearance in the field, Follingbo has yielded some amazingly exquisite pieces of limestone with excellent fossil preservation and some very interesting sedimentary features, that are described in this atlas, along with some comparative material from Gotland and elsewhere.

Of this specimen, the upper surface preserves numerous whole fossils and fossil fragments, and their beautiful appearance in this photo is an indication that they were covered by soft mud, that was weathered away in the outcrop to reveal the fossils. The cross-section view shows the sample is made of several layers with some sharp changes in the layering, that may be indicative of energy change from layer to layer. It is possible that some layers were partially to completely lithified before later layers were deposited, although this photo is somewhat ambiguous because it does not show equivocal evidence of the state of lithification of the material. But fear not! This atlas contains a more detailed view of samples from this site, that reasonably demonstrate the lithification state was variable. You are invited to explore these images and judge them for yourself.

Photo file: A-01-SliteMarlAtlas-FrontCover.

<u>This document is a compendium of annotated images and interpretations intended as a palaeontological and sedimentological research tool</u>

SUMMARY

The island of Gotland, in the central Baltic Sea, belongs to Sweden, and is awash with the most remarkable fossil sites, being the home to some of the best Silurian-age fossil reefs and bedded limestones in the world. For many years, I have explored fossilised calcified sponges called stromatoporoids, that are abundant on Gotland. Stromatoporoids were one of the most successful fossil groups in Earth history, and were abundant components of fossil reefs from the Middle Ordovician to Late Devonian Periods, approximately 100 million years (100 Ma) of time, together with some possible Early Ordovician cases, and some rare finds in the succeeding Carboniferous rocks. The perceived wisdom was that individual stromatoporoids needed a small hard substrate, such as a bit of shell, to settle on, and then spread across the substrate. However, there are numerous cases where there is no evidence of such shell substrates, and for years I had the suspicion that stromatoporoids were capable of growing directly on the fine particulate sediment that made up the sea floor. I expressed the view that this perceived ability to grow directly on soft sediment was part of the reasons why stromatoporoids were so successful in Earth history. These ideas are documented in numerous papers, in particular Kershaw et al. (2018), which you are invited to read to see the arguments. Over some years, I was able to assemble enough information that indicates stromatoporoids were capable of growing on a range of substrate consistencies, from soft carbonate muds to partly lithified muddy carbonates, to totally lithified sediments; this recognition led me to realise that such lithification is a widespread and long-ranging feature of the ancient Palaeozoic carbonate sediment sea floors. Note that stromatoporoids are rarely found on siliciclastic sediments (sands, silts & muds), so really we are dealing with carbonate sediments here, *viz* limestones.

This atlas spins off from the study of the relationship between stromatoporoids and their substrates, and the principal target for examination here is a unit of bedded limestones that remarkably does not contain stromatoporoids, for reasons that are not understood. These bedded limestones are the Slite marls, a unit of limestones of Wenlock (middle Silurian) age, from two sites; Follingbo in western Gotland, and Slitebrottet in eastern Gotland.

So there are two questions that arise: #1) what was the nature of the ancient sea floors of these bedded limestones, and #2) why do they not contain stromatoporoids? #1 is illustrated here in some detail in hand specimens and thin sections, while #2 is considered briefly (it's difficult to understand). To provide further perspective, some other aspects of sea-floor lithification are also examined.

The Follingbo samples illustrated here were collected over a number of years from 1975 to 1993 and were of only passing interest to me because they do not contain stromatoporoids, yet were always of attraction because of the beauty of the material. Eventually I realised I had to try to understand these limestones, as part of developing understanding of stromatoporoids. The result is this atlas, that focusses on the Follingbo and Slitebrottet material, and makes comparisons with other limestones, including some stromatoporoid-bearing strata.

The Follingbo and Slitebrottet samples reveal a range of four consistencies in the muddy limestone, as it was on the sea bed during the Silurian:

1) Clear evidence of unconsolidated soft muddy carbonate sediment, shown because overlying shell-rich carbonate sediment has no recognisable boundary with the underlying muddy carbonate; if the muddy carbonate was

even slightly lithified, there is great likelihood of a sharp contact, but there is none. Note that this was found rarely, but may turn out to be more common if investigated further.

2) Clear evidence of nearly soft substrates, composed of calcareous clay-bearing muds, that have contemporaneous shells sticking out of the muds and then entombed in further sediment. Such shells sticking out of tops of bedding surfaces can only be realistically explained if the shells were harder than the sediment in which they were embedded, and were partially exhumed by currents that removed part of the softish muddy calcareous sediment the shells are buried within. Shells are not so strong, so the idea that the sediment was relatively easily eroded, to leave shells sticking out, is consistent with a slighty consolidated sediment on the sea bed.
3) Clear evidence of solid sediment that has been eroded, and also burrowed, but the burrows have sufficient integrity that the sediment was not soft, but likely to have been partially lithified. Proving this is a bit difficult, but you can see the photos and consider the arguments. It is possible these layers were fully lithified but, depending on the characteristics of the burrows, allow an interpretation of partial lithification.
4) Clear evidence of fully lithified limestones, that were likely lithified below the sea floor and then exposed by erosion of overlying material. These are verified by the presence of intraclasts as rounded pebbles, many of which have mineralised margins, and contain uncommon encrusters, altogether indicative of hardground formation.

The lack of stromatoporoids in the Slite marl samples is mystifying. My best interpretation is these beds were laid down in water that was too deep for stromatoporoids, partly indicated by the concomitant lack of calcareous algae in these beds. However, there are rare small tabulate corals, and pieces of crinoid stems. It has been long understood that tabulate corals had a greater depth range than stromatoporoids, and this evidence is consistent with these beds being too deep for stromatoporoids. Crinoids grew commonly in association with stromatoporoids, and are well known to have possessed porous calcite skeletons, indurated with organic tissue. When they died and the tissues decayed, crinoids are likely to have had about half the density of calcite. So when the crinoid skeletons disaggregated on decay of their soft tissue, the pieces are likely to have been able to float and be transported some distance. Thus, for the Slite marl samples, I envisage a current-swept sea floor that had periods of quiet, interrupted by energetic events, in a shallow marine shelf, that was nevertheless too deep for the development of reef-building fossils.

Note that the prime aim of this document is to present images and my interpretations, so the document is open-ended as a file for observation and discussion. It has not been peer-reviewed, therefore expresses my own views, but benefits from discussions with others, some of whom are named in the document. Therefore please look at the images and judge for yourself whether you think these interpretations are consistent with the evidence. You must remember that even if there is consistency of evidence with interpretation, that does not mean the interpretation is correct!! There are so many papers out there, published in peer-review journals, where authors, reviewers and editors (bless them all, wherever they are) have not emphasised this basic scientific principal, leading in some cases to theories being accepted as fact, but without the verification needed.

This atlas contains some photos of samples belonging to others, who are thanked for these photos in the respective captions. However, all the samples explored in detail are deposited in the Natural Riksmuseum, Stockholm, Sweden. I have provided my own sample number, but these will be catalogued under different numbers in the museum.

Although I have carefully checked this document for mistakes, I cannot guarantee there are no errors, so please accept my apology if you find them (and please contact me to tell me!).

References

Below are a few references relevant to this atlas. I have provided only a few sources, rather than the huge lists of references commonly found in papers. If you want to explore this topic, you will be able to find plenty of information if you search for it!

Calner, M., Jeppsson, L., Munnecke, A., 2004. Silurian of Gotland, Part 1; Review of the stratigraphic framework, event stratigraphy and stable carbon and oxygen isotope development. *Erlanger geologische Abhandlungen*, Sonderband **5**, 131 pages.

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Mori, K., 1969. Stromatoporoids from the Silurian of Gotland, I. *Stockholm Contributions in Geology*, **19**, 1-100.

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CONTENTS LIST

PART A: SLITE MARLS AT FOLLINGBO AND SLITEBROTTET

PART A-1: Introductory images

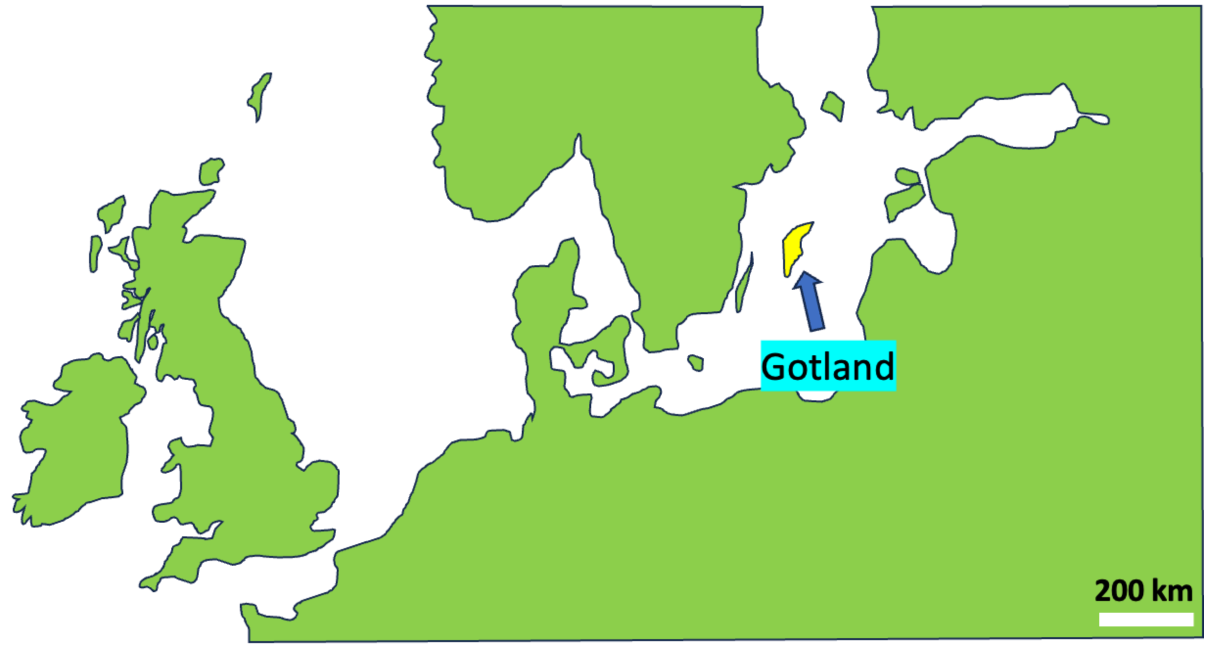


Fig. A1.
Upper: Map of northern Europe showing location of Gotland.
Lower: Outline map of Gotland showing locations of Follingbo and Slitebrottet. Follingbo site is on a small E-W-orientated road north of Follingbo village, near the junction with the 143 main road. This small road links the 143 road with the smaller

road that runs past the famous Allekvia field station from Visby to Endre and towards southeast Gotland. Slitebrottet is a limestone quarry in eastern Gotland. The precise details of the site are given in Laufeld (1974). To visit Follingbo you need to look in the ditch immediately north of this small road, walk along the ditch and look for small slabs of limestone lying loose on the ground surface. There are photos of the site in Figs. A9 and A10, taken in September 2023; it's a really exciting place. There is a geological map from the Swedish geological survey, that covers this area, but I could not reproduce it because of copyright. There is a good description of the stratigraphy of Gotland in Calner et al. (2004) that is available online, so I did not reproduce this in this atlas; that reference is easy to find. Regarding Slitebrottet, I have not visited this site since 1991 so not sure of access details at the time of writing this atlas; however it is located as the easternmost quarry of the Slite quarries, nearest to the coast. *Photo file: A-02a-GotlandMap.*

Fig. A2: View of Slite marls in the excavated wall of the large cement-works quarry near Slite; the bedded nature of these limestones is clearly visible. This, and Fig. A3 photos, were taken from the main road that passes between two large quarries. The quarry in these photos is the main large quarry; the Slitebrottet quarry site, from which samples were collected, is behind the viewer's position. *Photo file: A-02b-SliteQuarry-DSC03655-Mod.*

Fig. A3: Closer view of the bedded limestones of the Slite marls from Fig. A2; although there is not a lot of detail to see here, it is clear that the limestones had slightly varying lithologies, including limestones and muds. Figs. A2 & 3 were taken in September 2023. *Photo file: A-02c-SliteQuarry-DSC03656-Mod.*

Fig. A4: View across the landscape, looking southwest, from the higher ground of purer limestone bedrock, near to Follingbo. The Follingbo road ditch site is located a couple of km to the right of this photo, on the lower ground that represents the Slite marls. Photo taken in 2004. *Photo file: A-02d-SliteFmView-DCP_8927.*

Fig. A5: The church at Hejdeby, located a couple of km north of the former Allekvia Tingshus field station. This picture was taken at sunrise, looking east (obviously!) and catches the peaceful atmosphere of Gotland in the early morning summer. The church is built on the Slite marl. Photo taken in 2004. *Photo file: A-02e-HejdebyChurch-DCP_9373.*

Fig. A6: View of the former Allekvia Tingshus field station, built on the Slite marl, and located on the road from Visby to Endre at the small hamlet of Allekvia, comprising a collection of houses and a farm. The main building was used as accommodation for visiting geologists between 1972 until 1993, when the field station was moved to another place. In the period from 1975 to 1991, I spent an accumulated total of several months in this building, and feel great nostalgia towards it (although nostalgia is not what it used to be). The upper left two windows were where my favourite bedroom was located. The right-hand building was occupied for many years by Erik Karlqvist, the caretaker, with whom I had many conversations, despite neither of us knowing the other's language; the left-hand building was a storehouse. The water supply was pumped groundwater from 8m below the building, in the Slite marl, and the water, although OK to drink, tasted of iron, rather unpalatable, so lots of tea and coffee was drunk. Tingshus in Swedish means courthouse in English, and this building was constructed as a courthouse. The circuit judge and his family lived upstairs during trials, while downstairs is/was a constructed courtroom and anterooms. It was unmodified throughout the years it was used by geologists as a field station and really was a remarkable place to stay as a field geologist. The main building is now a guesthouse; the other two are private houses. Photo taken in September 2017. *Photo file: A-02f-AllekviaTingshus-DSC00897.*

Fig. A7: In 1980 Mt St Helens volcano blew up in Washington State, NW USA; for a couple of years there were some spectacular sunsets around much of the world; this one, the colour of which pretty much accurate, was taken from just outside the Allekvia field station in August 1981. Sunset on the Slite marl, how poetic. *Photofile: A-02g-GotlandSunset1981-06-Mod.*

Fig. A8: Early daylight on the Slite marl. This picture was taken in September 1976 from the road just west of the Allekvia field station, only a few km from Follingbo, and shows wheatfields across the Slite marl, and a church poking through the mist. This ground mist sat about 1.5 m above ground level; exactly in line with a driver's head sitting in a car, who could see only fog, and had to either stretch down to look below the mist, or stretch up to look over it, for safer driving; it was fun. I stopped to grab this photo while on the way to Visby to meet the early morning ferry from the mainland, to pick up Kei Mori (the famous Japanese geologist who wrote what is still the definitive monograph of Gotland stromatoporoids) and his young son; we had several days fieldwork together on Gotland, and each night we dined and rested on the Slite marl. *Photo file: A-02h-WheatField-DCP_9372-Mod.*

Fig. A9: This is it, folks: the Follingbo 3 locality in the Slite marl, that yielded the specimens illustrated later in this atlas. You would drive past this and not know there was anything here. There are some loose pieces of limestone lying on the ground left of the ditch; these are the target, and every piece is really interesting! North is to the left. *Photo file: A-02i-Follingbo-DSC04024-Mod.*

Fig. A10: Another exciting photo of the Follingbo 3 site. You can just about see some loose pieces of limestone lying on the ground just right of the ditch. North is to the right. Figs. A9 & 10 photos were taken in September 2023. *Photo file: A-02j-Follingbo-DSC04023-Mod.*

Fig. A11: A bedding plane view of a piece of Slite marl limestone picked up in September 2023 during a field course from Erlangen University (southern Germany), run by Prof Axel Munnecke. The surface of this sample shows lots of shell material. You can see a large brachiopod on left, and part of an orthoconic nautiloid internal mould upper left. This sample was collected by one of the students who kindly allowed me to photograph it. Sorry I don’t know the person’s name, but am grateful for the photo. *Photo file: A-02k-Follingbo2023-Sample2-DSC04016-Mod.*

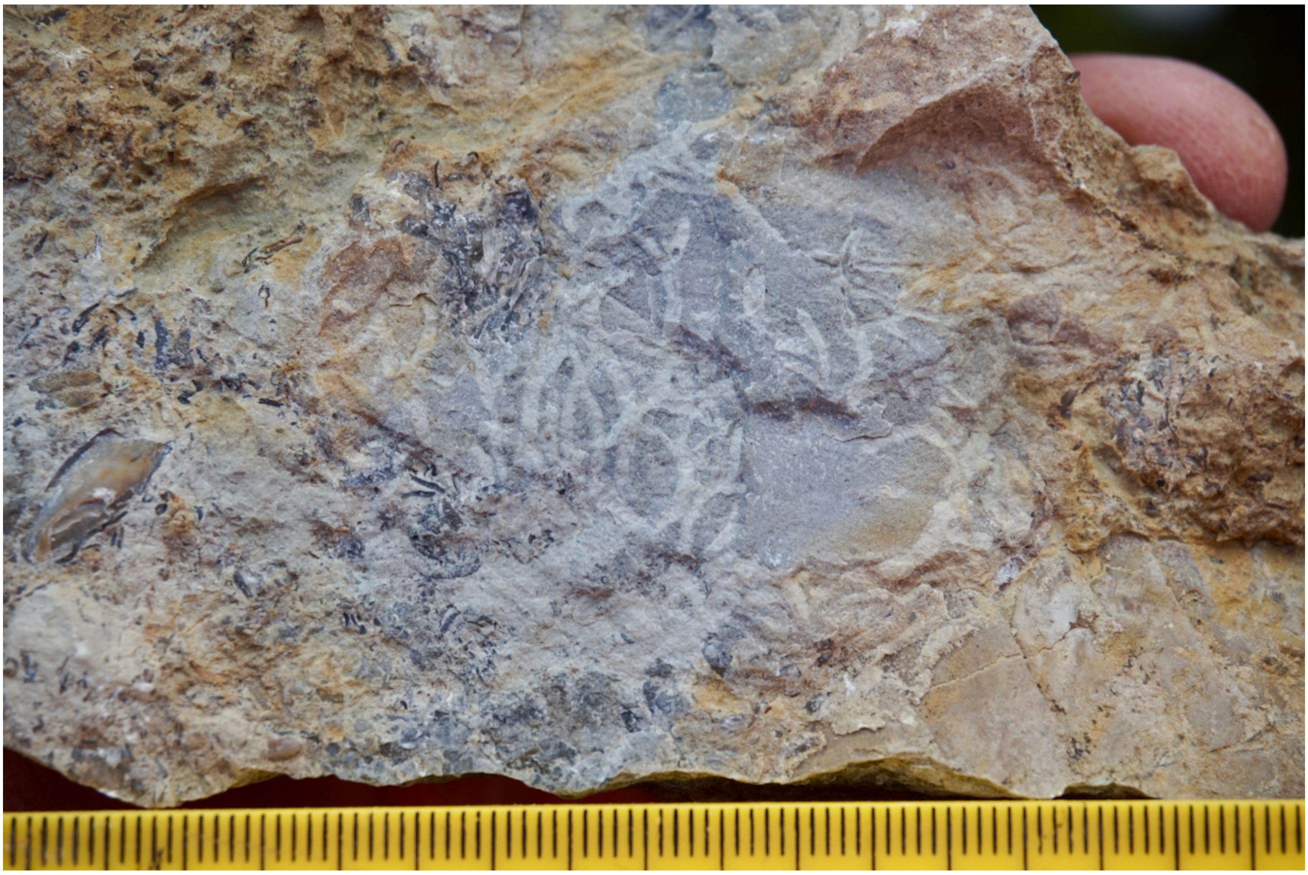


Fig. A12: Bedding plane view of horizontal burrows in Slite marl, from another sample picked up by an Erlangen student. Later in this atlas are photos of burrows in vertical cross section, which give some information about substrate lithification. Thanks to the person whose sample this is, for the photo. *Photo file: A-02l-Follingbo2023-Sample2-DSC04021-Mod.*

Fig. A13: Bedding plane view of a sample from Follingbo 3, picked up by an Erlangen student. The photo shows crinoid ossicles scattered across the bedding surface, indication of the presence of crinoids in this fossil assemblage. Thanks for the photo, to the person who picked up this slab. *Photo file: A-02m-FollingboSample3-DSC04027-Mod.*

Fig. A14: Oblique view of a sample from Follingbo 3, picked up by an Erlangen student. The photo shows a favositid tabulate, lower left, uncommon in this assemblage; also on the bottom of the photo, centre-right, is a gastropod internal mould; gastropods had aragonitic shells and these were dissolved to leave the internal mould, in contrast to the calcite shells of other fossils. Thanks for the photo, to the person who picked up this slab. *Photo file: A-02n-FollingboSample7-DSC04046-Mod.*

PART A-2: Details of my own samples from Follingbo 3

SAMPLE 1

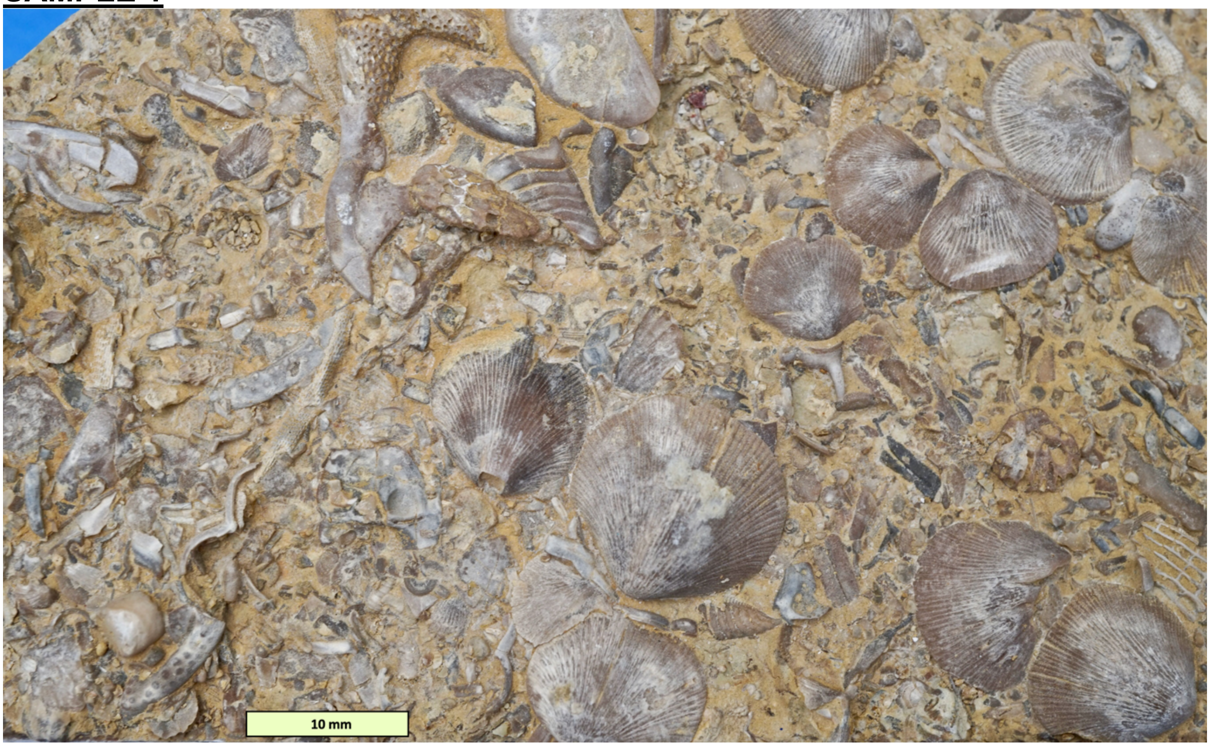
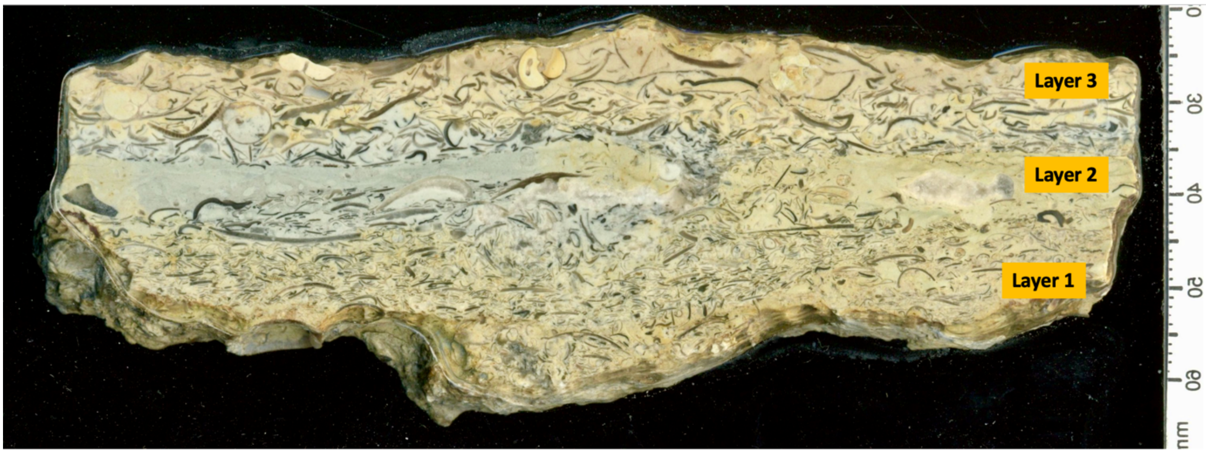


Fig. A15: This is the same specimen as shown in the cover photo of this atlas. Bedding plane view illustrating brachiopods, trilobites, bryozoa. As explained in the cover photo caption, this surface must have been covered in mud that was weathered away in the outcrop, indicating the strata of these beds contain limestones and layers of mud. *Sample Follingbo3-01. Photo file: A-03a-Follingbo3-01-i.*



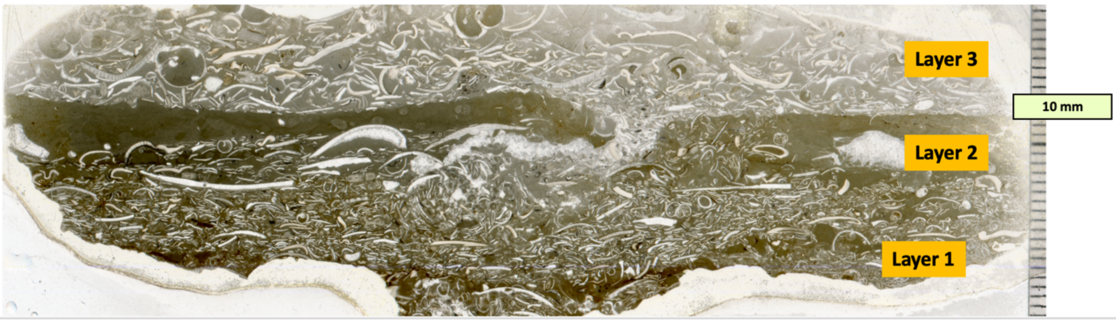


Fig. A16: Vertical cross-section views of specimen in Fig. A15.
Upper photo: a polished block.
Lower photo: a thin section cut from the polished block face. Note there are three layers visible. Layer 1 is a wackestone containing many separated brachiopod valves, that are commonly convex-up, indicating they were transported here, possibly by a storm. Layer 2 is a micritic layer with little shell material; Layer 3 is another shelly layer, but the shells are more chaotically arranged than in Layer 1, interpreted here evidence of a storm input with little sorting, thus a rapid event of transport and deposition. The break in Layer 2 in the middle is explored further in Fig. A17. *Sample Follingbo3-01. Photo file:* A*-03b-Follingbo3-01-ii.*

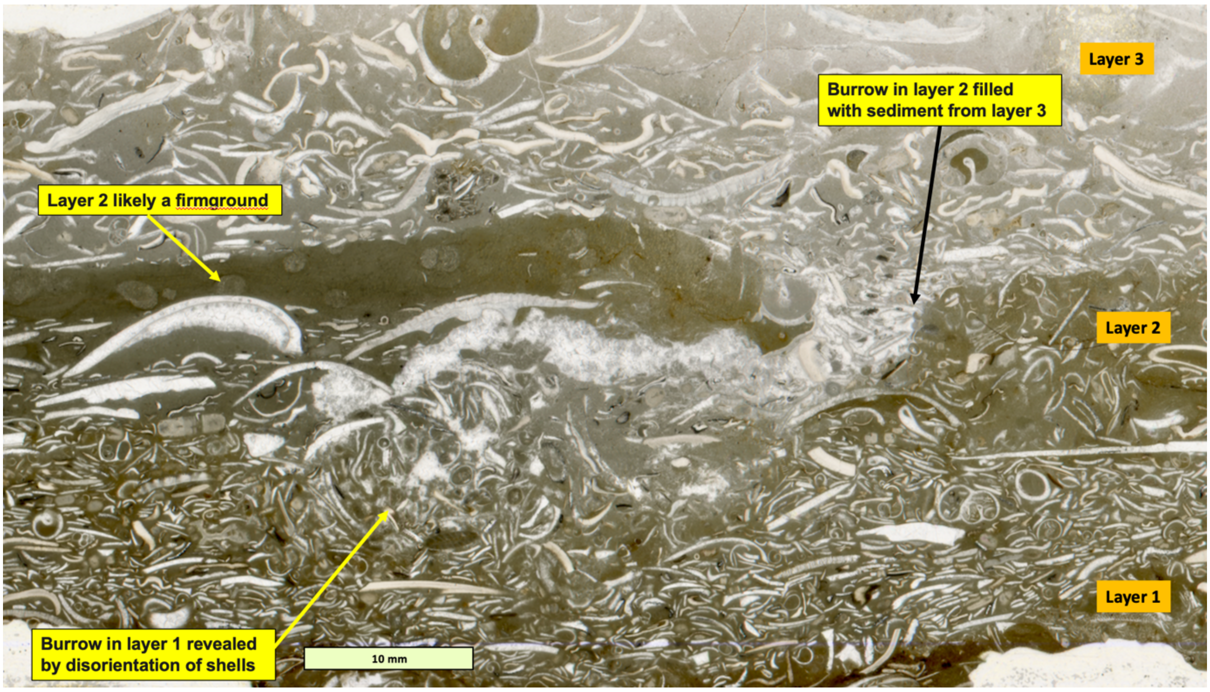


Fig. A17. Detail of the central part of the thin section in Fig. A16. As the labels indicate, Layer 2 has been cut through, and shell material occupies the cut part. The cut is interpreted as being due to a burrowing animal that passed from Layer 3 down through Layer 2 into Layer 1; the disturbance of shells in Layer 1 seems to indicate that Layer 1 was still poorly consolidated at the time when Layer 3 was deposited; so when the burrowing occurred, both Layers 1 and 3 were poorly consolidated. However, the sharp cut in Layer 2 is taken to indicate that Layer 2 was more consolidated and may have been a firmground consistency. Layer 2 also has small round spots, considered here to be cross-sections through burrows in the micrite of Layer 2. Note that in Layer 3 are gastropod shells that have total infillings of a darker micrite, and seems likely to indicate that these shells were reworked from another layer, not included in this sample, and further demonstrate the poorly consolidated nature of the sediment in this piece of rock, when these events happened. *Sample Follingbo3-01. Photo file: A-03c-Follingbo3-01-iii.*

SAMPLE 2

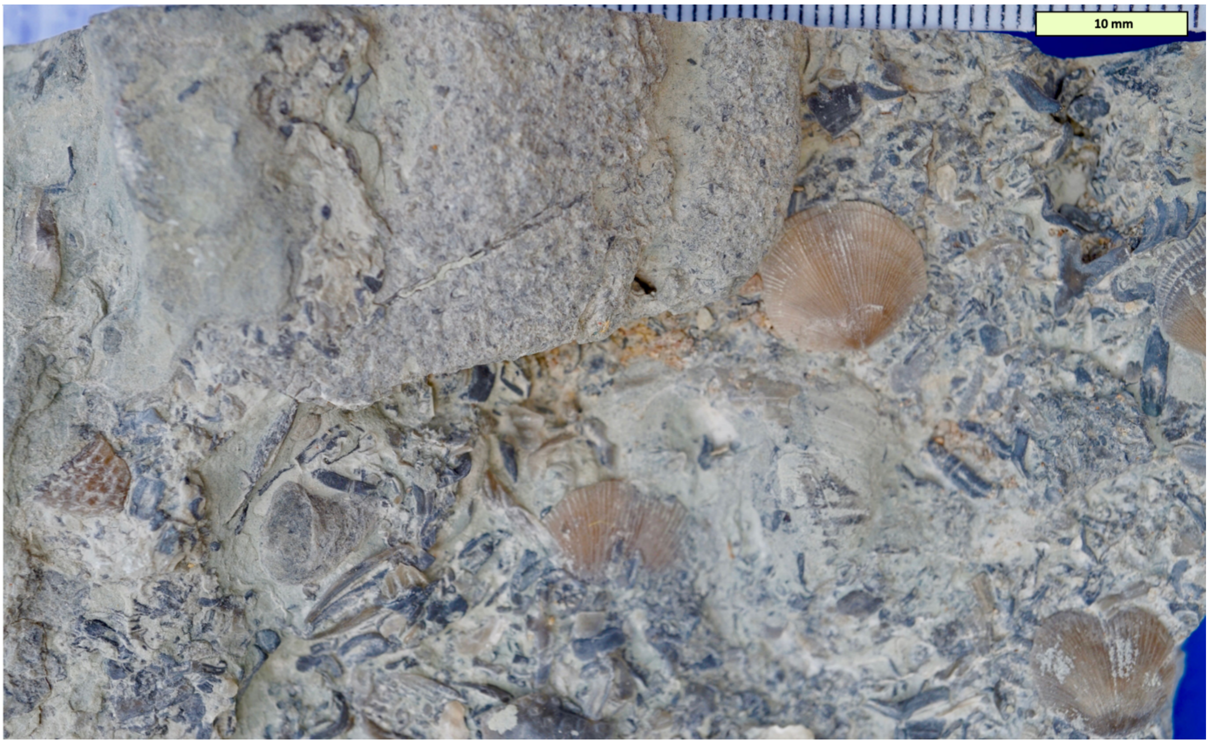


Fig. A18: Top view of block showing shell material. The upper left quarter of the photo shows a micrite area, that is part of an intraclast lying on the top of the block and illustrated in Fig. A19. *Sample Follingbo3-02. Photo file: A-04a-Follingbo3-02.*

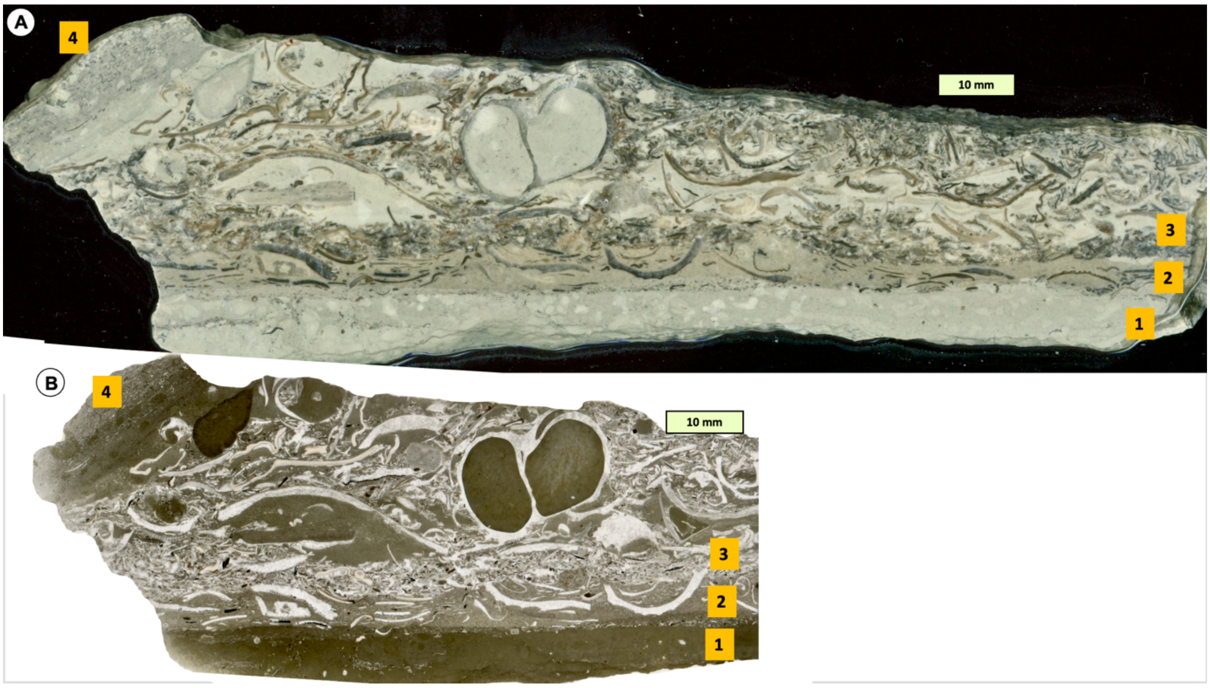


Fig. A19.
Upper: Vertical cross-sections of polished block
Lower: Thin section cut from the polished block.
1: lowest layer comprising carbonate mudstone, with an eroded top. This layer has burrows, presumed to be horizontal burrows, filled with a lighter gray-coloured micrite, that is presumed to have filled the burrows after they were vacated. Note this

lighter burrow fill is lighter coloured also than the overlying layer 2 matrix, and therefore may be an indicator of a missing layer between layers 1 and 2, that could have been eroded before layer 2 was deposited.
2. wackestone with some disarticulated brachiopod valves, some convex-up, others convex-down; this layer is interpreted as having undergone little sorting, and may represent a short-term storm event depositing micrite with disarticulated shells.
3. Wackestone-packstone, poorly sorted, with disarticulated brachiopods and a couple of gastropods (see more in Fig. A20).
4. area of laminated micrite with internal lamination at a steep angle to the bedding, thus interpreted as part of a lithoclast, that is also shown in upper part of Fig. A18. *Sample Follingbo3-02. Photo file:* A-04b-Follingbo3-02.

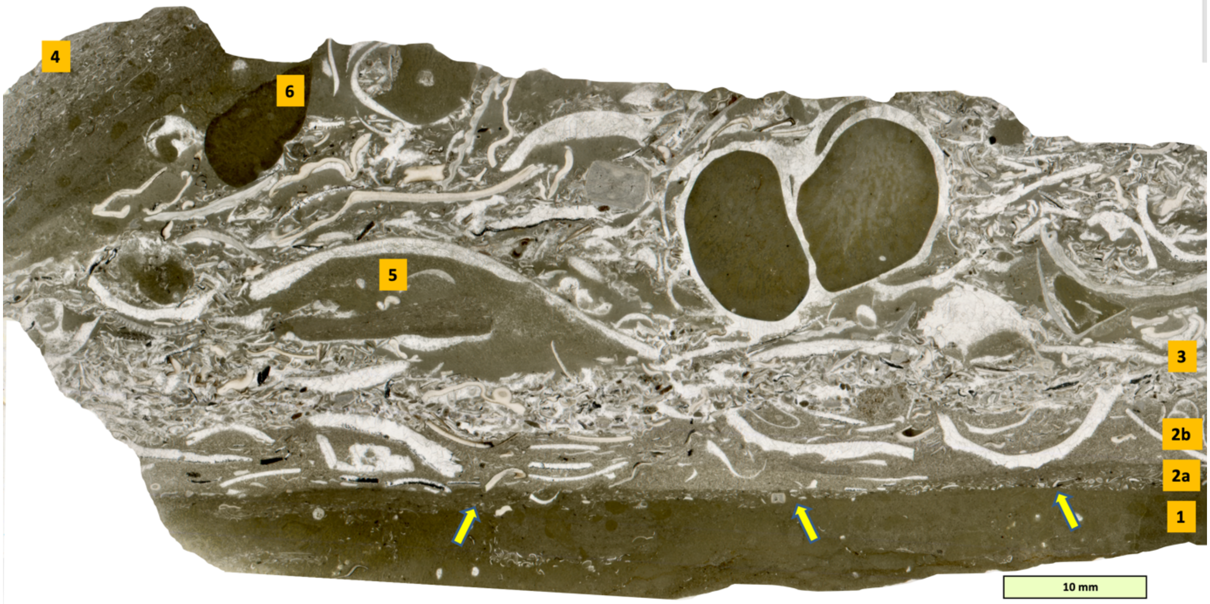


Fig. A20. Enlargement of Fig. A19, showing more details of the contact between layers 1 & 2, revealing Layer 2 to contain a thin lower sublayer (2a), and the top of Layer 2 (top 2) is eroded, and may have been partially lithified. 3 & 4 as in Fig. A19.
5. disarticulated shell with micrite adhering to its concave side, interpreted as a lithoclast that contains both the disarticulated shell and its sediment infilling.
6. small dark rounded lithoclast with a mineralised margin (see Fig. A29 for more details of 6). The three yellow arrows indicate locations of details explored in enlarged images in the following figures. *Sample Follingbo3-02. Photo file: A-04c-Follingbo3-02.*

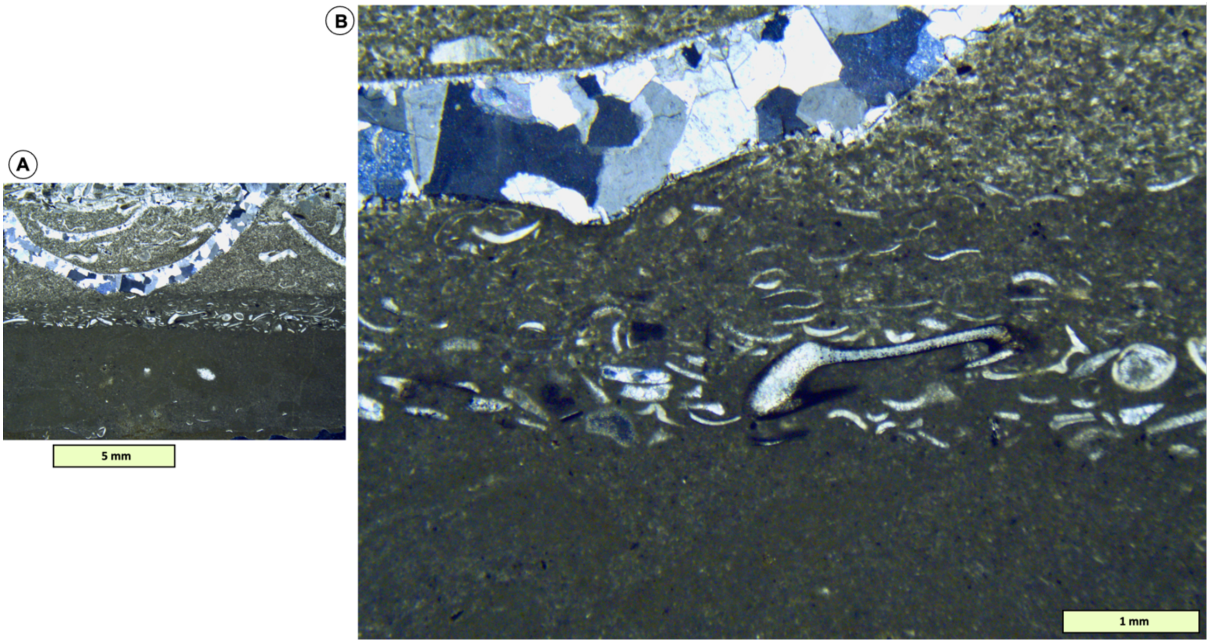


Fig. A21. XPL view. Enlargement of the bottom right area of Fig. A20 (by the right-hand yellow arrow in Fig. A20). The photo shows recrystallised curved disarticulated shells (probably bivalves) and three layers of sediment. Lower layer = Layer 1 in Fig. A20: dark fossil-poor micrite, with a diffuse upper margin in contact with Middle layer (micrite rich in shell debris). The Middle Layer (Layer 2a in Fig. A20) likewise has a diffuse upper margin in contact with the Upper Layer (Layer 2b in Fig. A20, light-coloured micrite with some shells). These diffuse upper contacts of the Lower and Middle layers are interpreted here to indicate that these bed surfaces (of the Lower and Middle layers) were only partly solidified when the Middle and Upper layers, respectively, were deposited. Fig. A22 gives a more detailed view of the Middle-Upper layer contact.
Sample Follingbo3-02. Photo file: A-04d-Follingbo3-02.

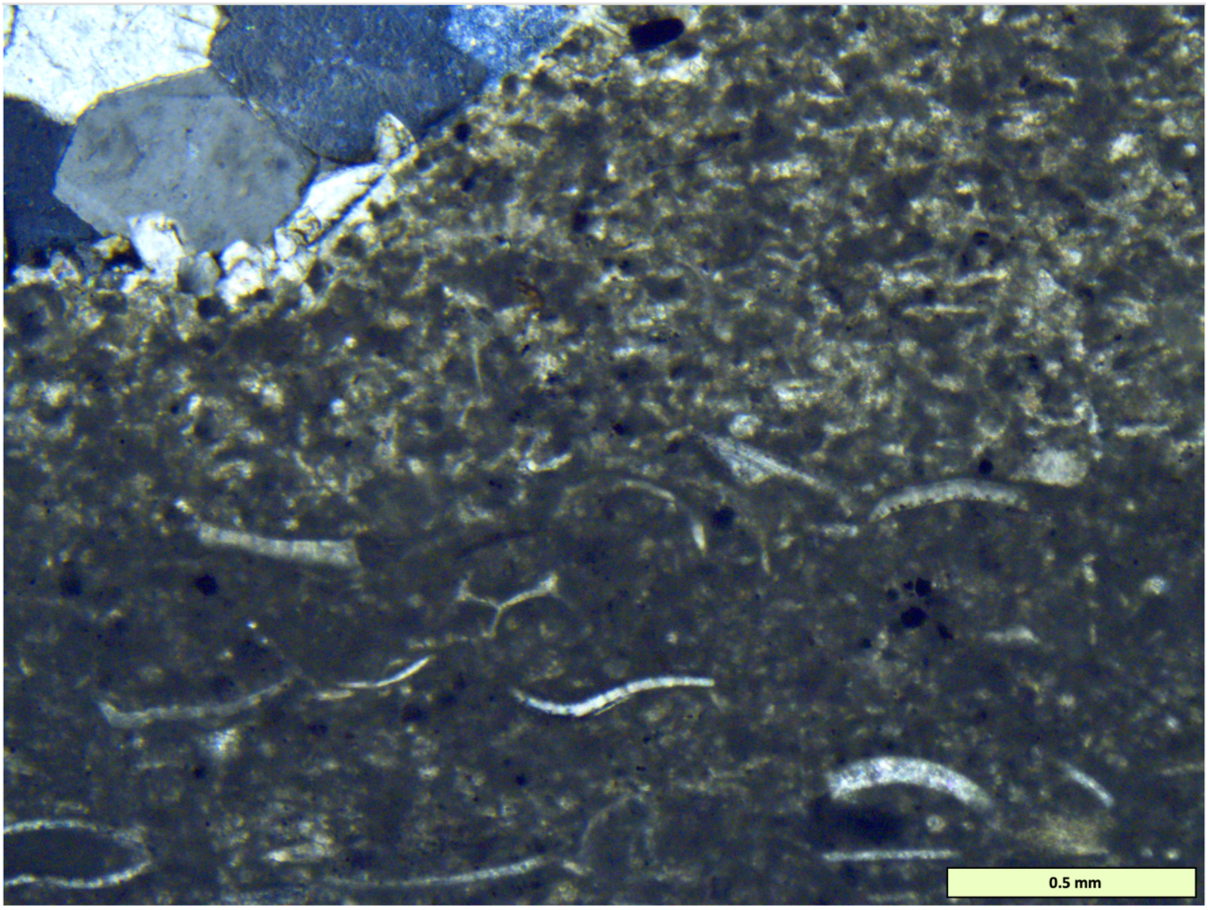


Fig. A22. XPL view. Following from previous photo, this shows more detail of the contact between the Layer 2a and 2b described in previous images. The diffuse contact shown here is interpreted to indicate that the top of Layer 2a was not fully solidified when the Layer 2b was deposited.
Sample Follingbo3-02. Photo file: A-04e-Follingbo3-02.

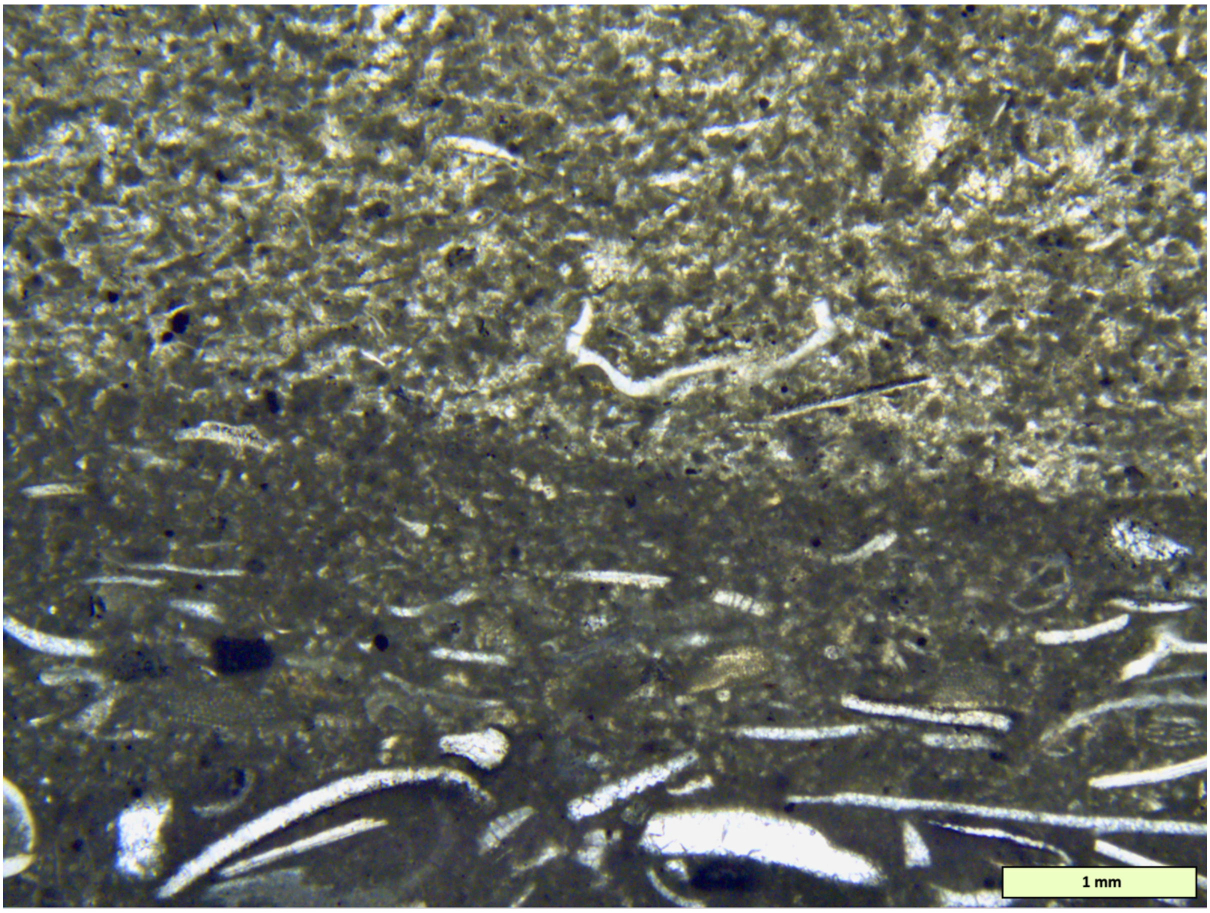


Fig. A23. PPL view. Another view of the contact between Layers 2a and 2b further along the layer, showing it is a little more sharp here, possibly the surface of Layer 2a was more firm. This variation reveals the difficulty of making decisions about the nature of the firmness of the substrate.
Sample Follingbo3-02. Photo file: A-04f-Follingbo3-02.

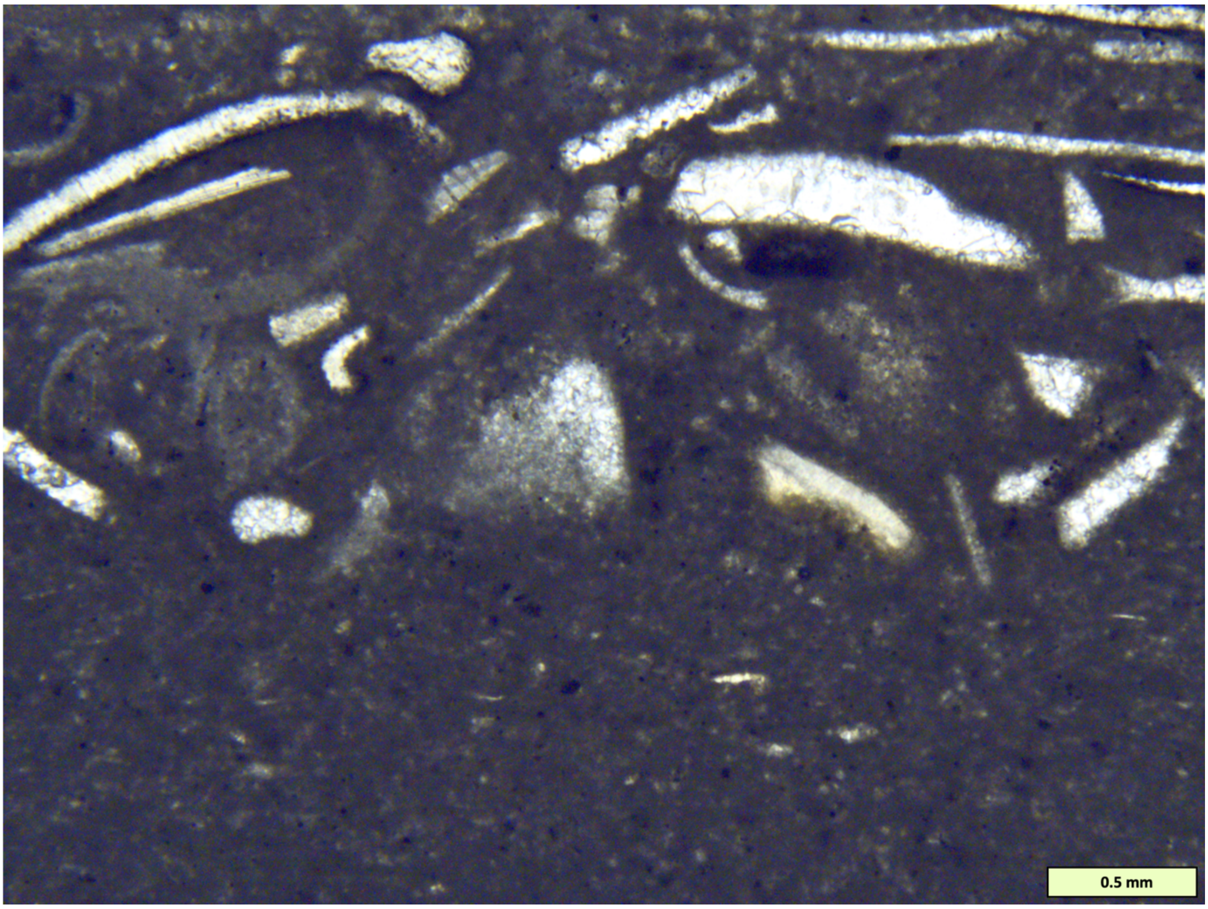


Fig. A24. PPL view. More detail of contact between Layer 1 and 2a, wherein there is little contrast between the two layers, which makes it difficult to interpret whether or not the Lower Layer was partly solidified when Layer 2a was deposited.
Sample Follingbo3-02. Photo file: A-04g-Follingbo3-02.

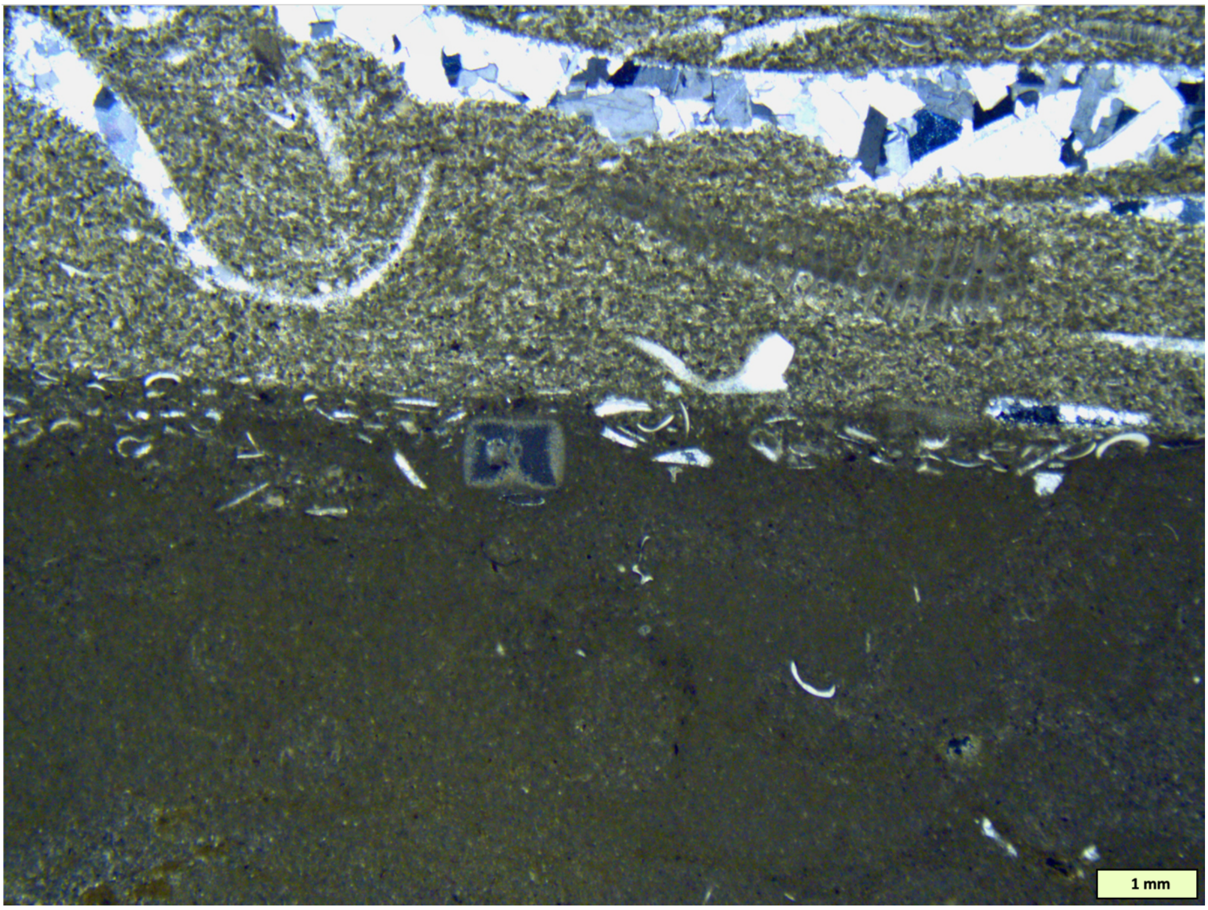


Fig. A25. XPL view. Detail of area of central yellow arrow in Fig. A20, showing Layers 1, 2a and 2b. A crinoid ossicle is prominent in the middle.
Sample Follingbo3-02. Photo file: A-04h-Follingbo3-02.

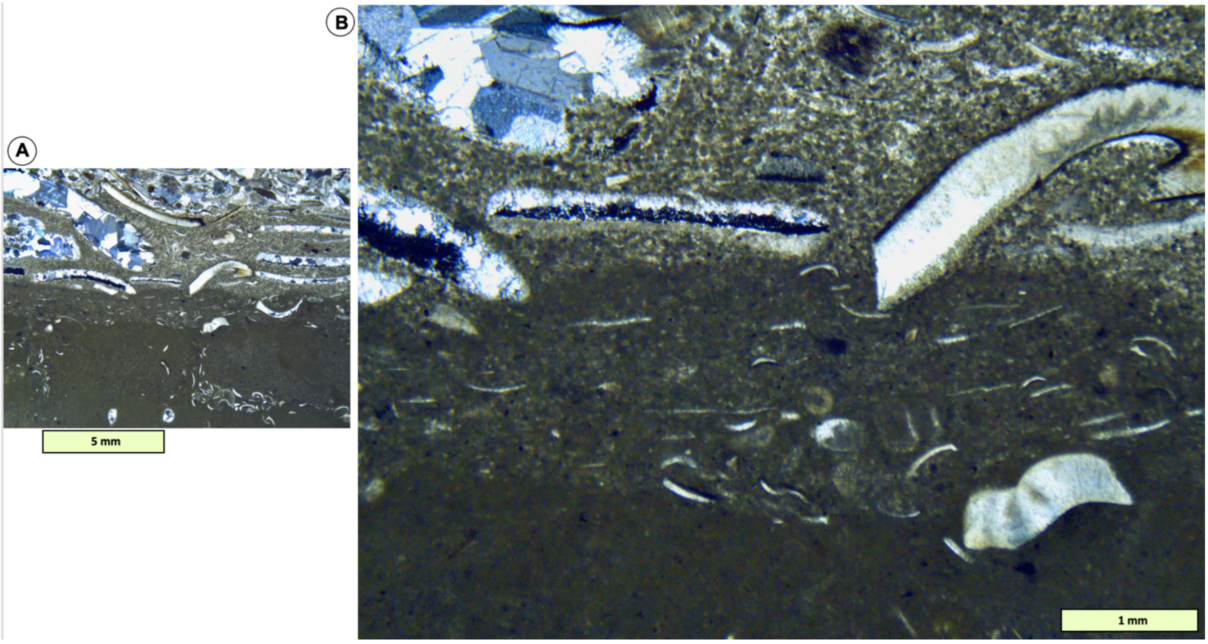


Fig. A26. XPL view. Enlargements of area of left-hand yellow arrow in Fig. A20. Note the trilobite fragment in centre-right has a sharp lower edge crossing boundary between Layers 2a and 2b. Interesting question is why the shell crosses this

lithological boundary; it may be that the shell fragment was hit against the partially lithified substrate of Layer 2a, embedding into it, by current transport across the surface of Layer 2a, when Layer 2b was deposited. It is also possible that the Layer 2a sediment was soft when shells were transported across its surface.
Sample Follingbo3-02. Photo file: A-04i-Follingbo3-02.

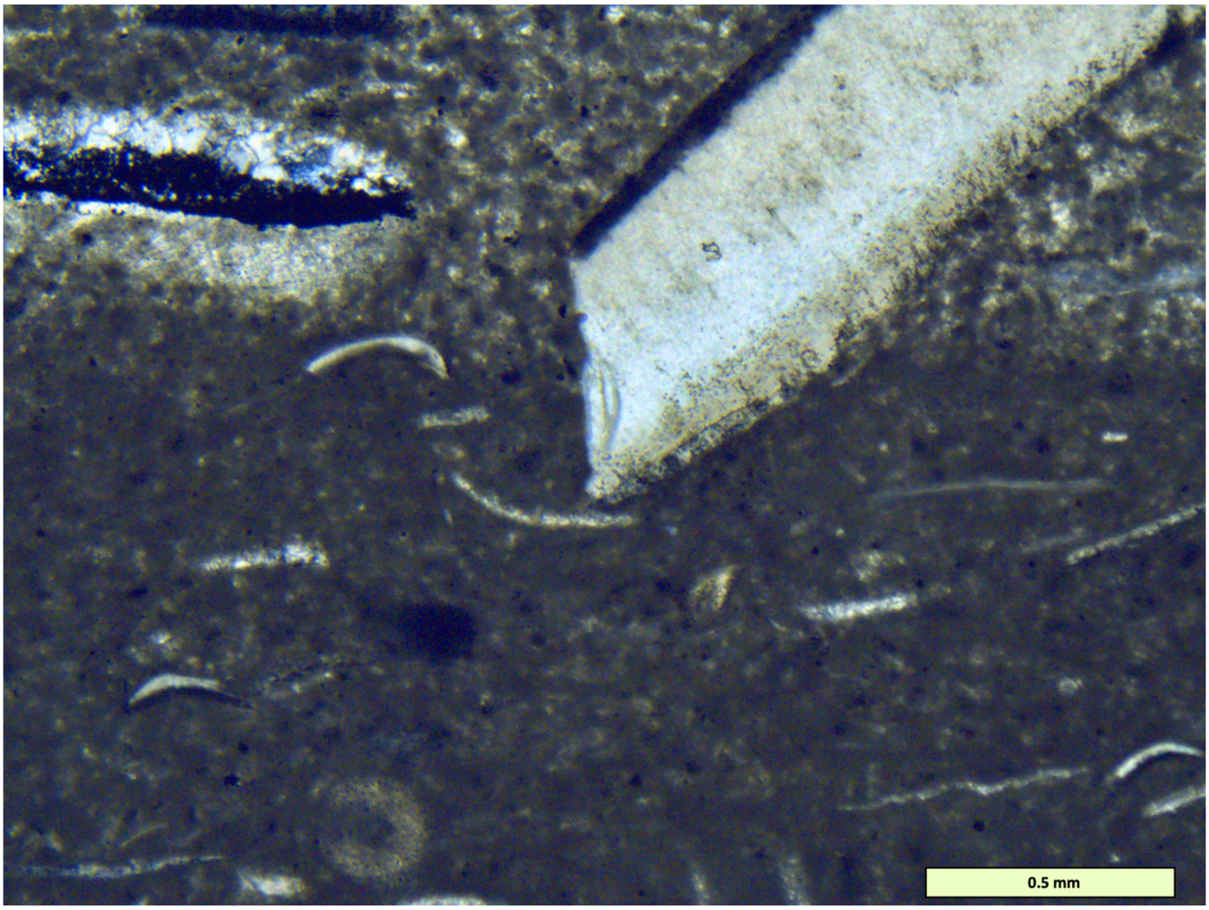


Fig. A27. PPL view. Enlargement of Fig. A26 showing the trilobite fragment crossing the lithological boundary between Layers 2a and 2b. See caption of Fig. A26 for interpretation.
Sample Follingbo3-02. Photo file: A-04j-Follingbo3-02.

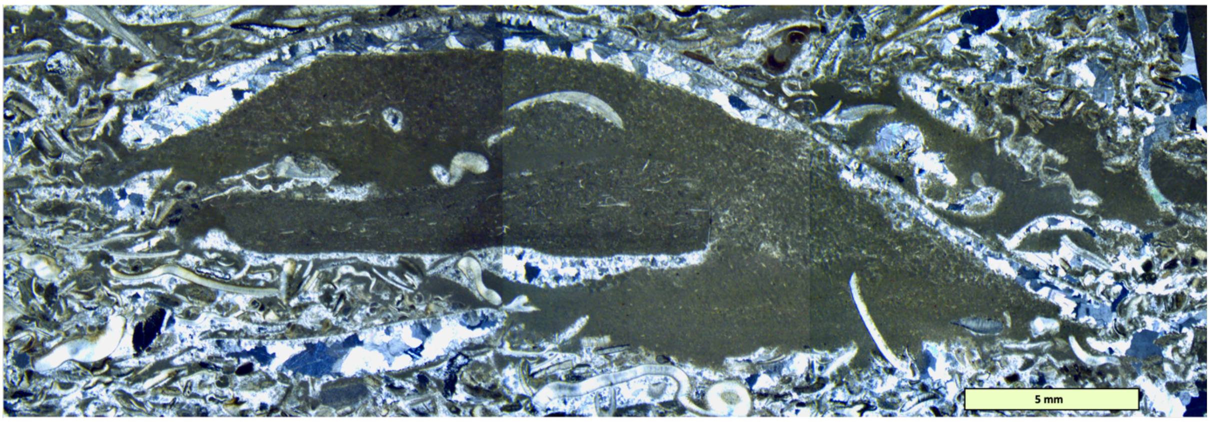


Fig. A.28. XPL view. Enlargement of Fig. A20 of bivalve shell with adhered micrite and small shell fragments; this looks like a lithoclast comprising a shell with sediment

and fragments. Note the small shell sticking out of the micrite on its lower side, in lower right quarter of photo; this may indicate there was more slightly hardened mud beneath the shell that was winnowed away as the fragment was moved across the substrate by currents.
Sample Follingbo3-02. Photo file: A-04k-Follingbo3-02.

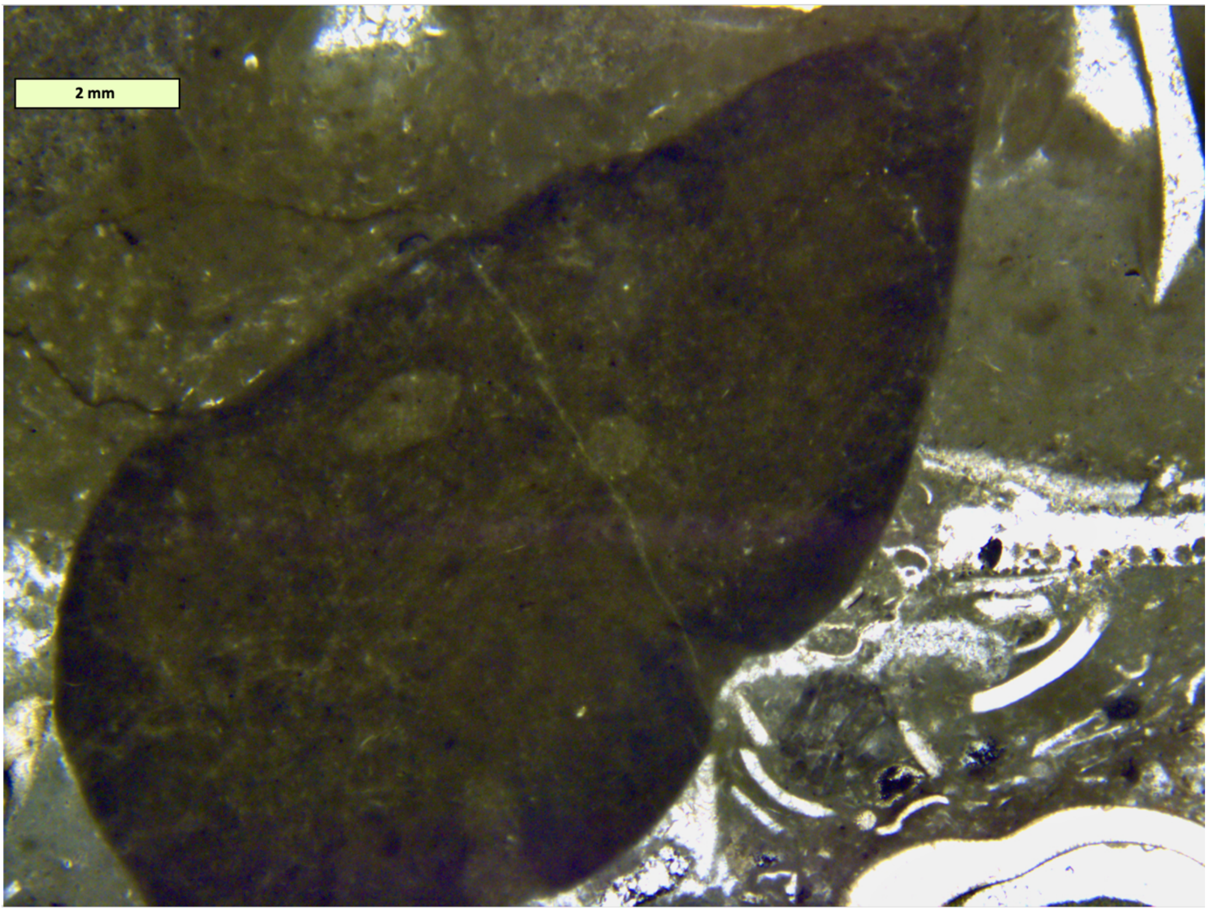


Fig. A29. PPL view. Enlargement of the dark-coloured lithoclast shown as point 6 in Fig. A20. Note the variegated internal structure, looks like it is a piece of burrowed micrite that was lithified and exhumed from substrate and then transported into the location of this sample.
Sample Follingbo3-02. Photo file: A-04l-Follingbo3-02.

SAMPLE 3

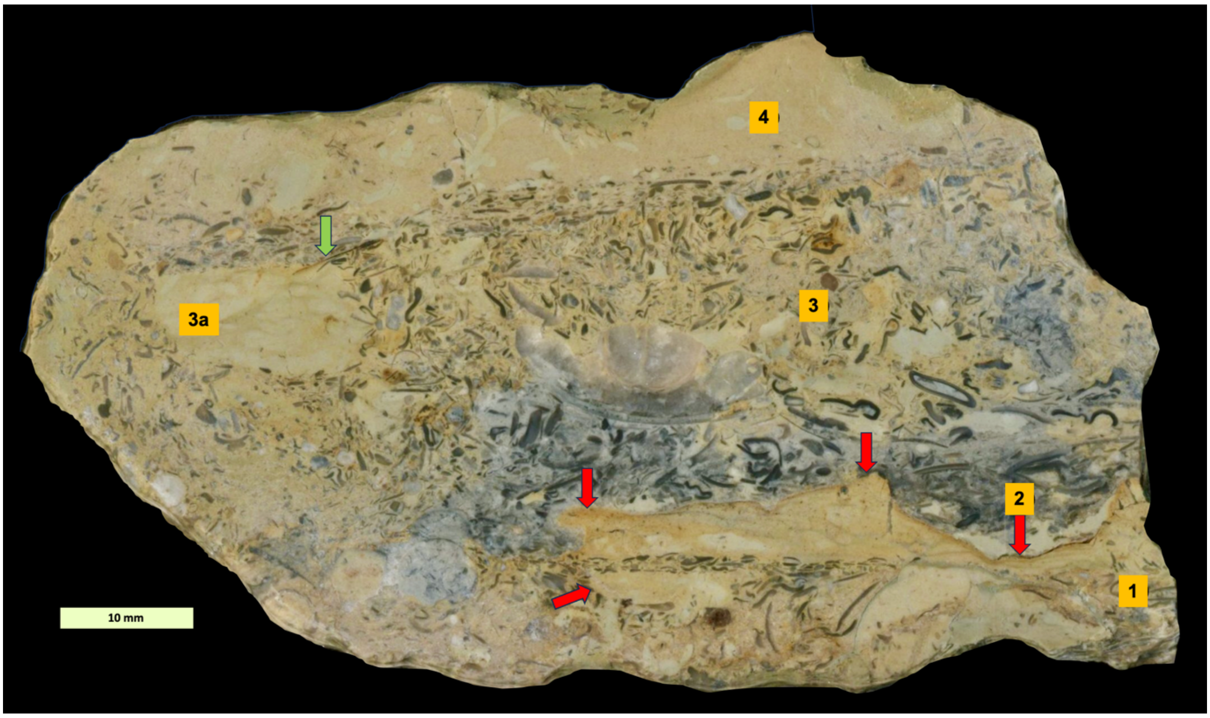


Fig. A30. Polished block vertical section of a piece of limestone from Follingbo 3, showing a prominent erosion surface (red arrows, 2) cutting into the lowest sediment layer (1). Layer 3 is a poorly sorted bioclastic micrite wackestone-packstone deposited, including a micrite lithoclast (3a, see green arrow). Layer 4 is calcareous mudstone with fine burrows, the burrow infills are lighter coloured than the substrate, indicating infill into the burrows from a later deposited mudstone.
Sample Follingbo3-04. Photo file: A-05-Follingbo3-04.

SAMPLE 4

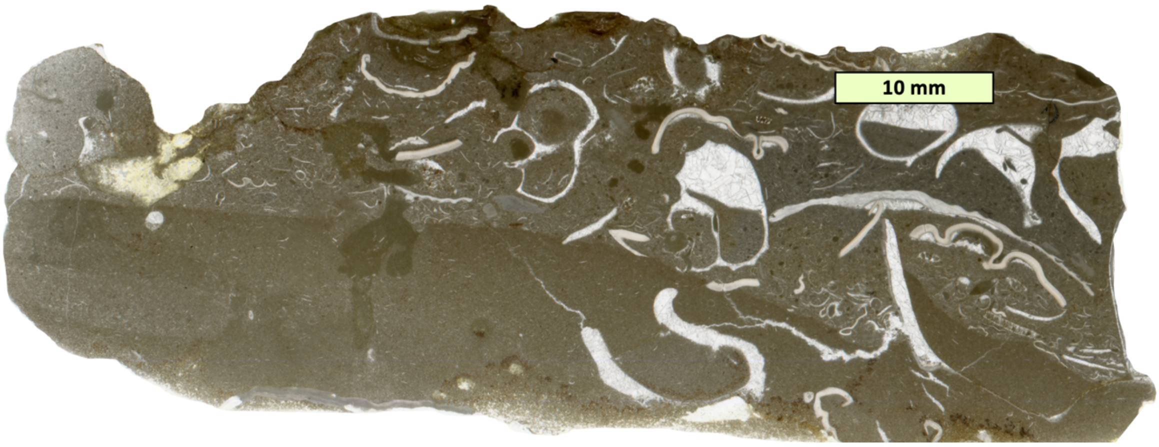


Fig. A31.
Upper: Polished block vertical thin section of piece of Follingbo 3 limestone, showing lower half contains some shells, but upper half is richer in shells.
Lower: Thin section scan of the same surface, showing the contact between lower and upper halves is a sharp boundary.
Sample Follingbo3-05-i. Photo file: A-06a-Follingbo3-05-i.

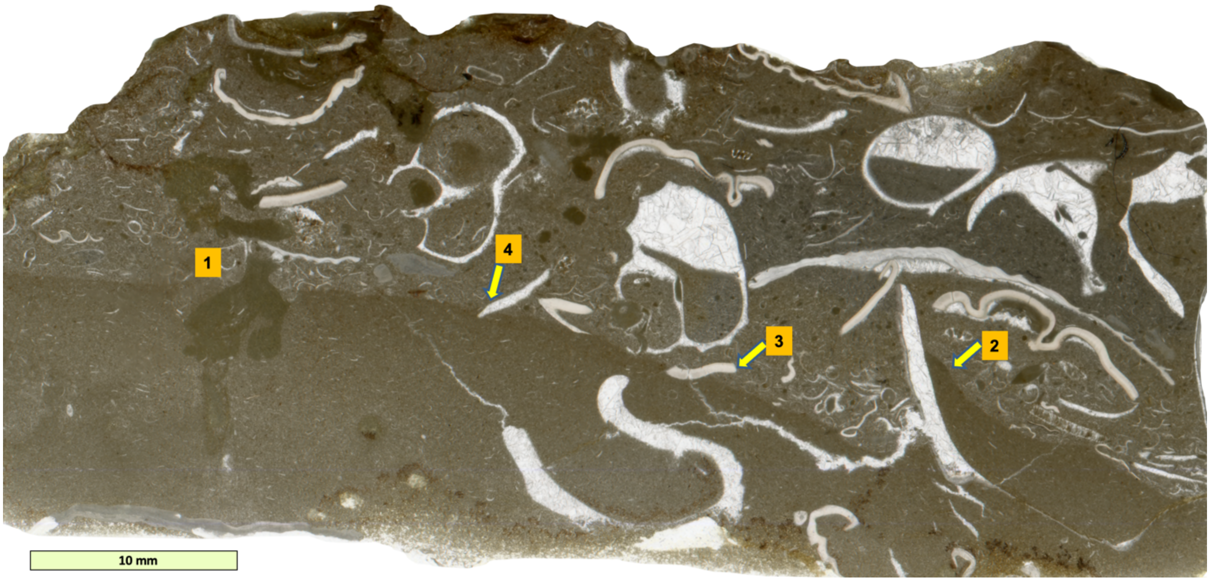


Fig. A32. Enlargement of previous photo showing some more details. 1 = a presumed burrow that cuts both the lower and upper layers, thus formed after both were laid down. This burrow has sharp boundaries, and could potentially be a boring into fully lithified mudstone, but this does not have to be the case; instead it could be a burrow into partially lithified sediment. 2 = unusual case where part of lower layer darker mudstone is swept up against right side of the shell fragment, not level with top of the lower layer on left side of the shell; see Fig. A33 for more details. 3 = small trilobite fragment partially embedded into the lower layer top; see Fig. A34 for more details. 4 = bivalve shell partially embedded into the lower layer top; see Figs. A35 & 36 for more details.
Sample Follingbo3-05-i. Photo file: A-06b-Follingbo3-05-i.

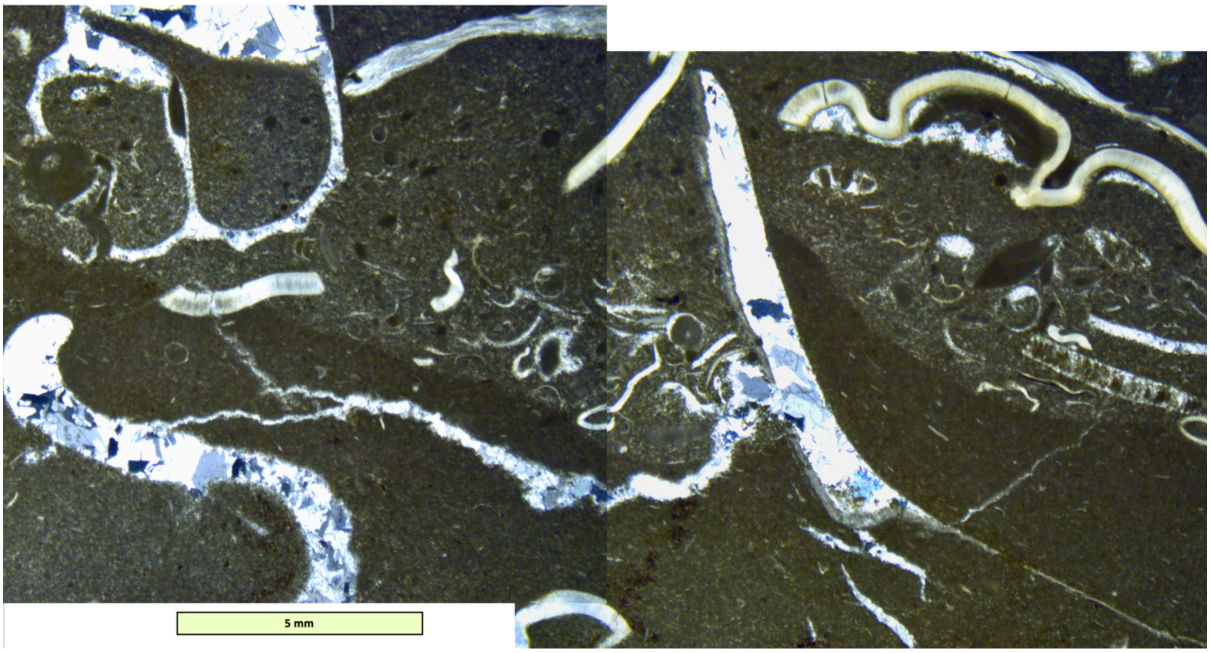


Fig. A33. XPL thin section detail of Fig A32, point 2, showing dark muds of lower layer riding up the right side of the shell fragment that is partially embedded into the lower layer muds. Note also that the tiny shell fragments within the lower layer mud are aligned with the curved shape of the right-hand upward-curving mud. The left

side of the shell has the lower mud top surface at a lower level. This arrangement is here interpreted to indicate current flow from right to left, mud remained mobile and was swept up onto the right side of the shell, while the left side of the shell was protected and mud did not accumulate there; there could even be some scouring on the left side caused by eddy currents swirling around the shell that was sticking up out of the lower layer muds. If this interpretation is correct, then the lower layer mud was mobile and deposited, after which it stuck to the side of the shell.
Sample Follingbo3-05-i. Photo file: A-06c-Follingbo3-05-i.

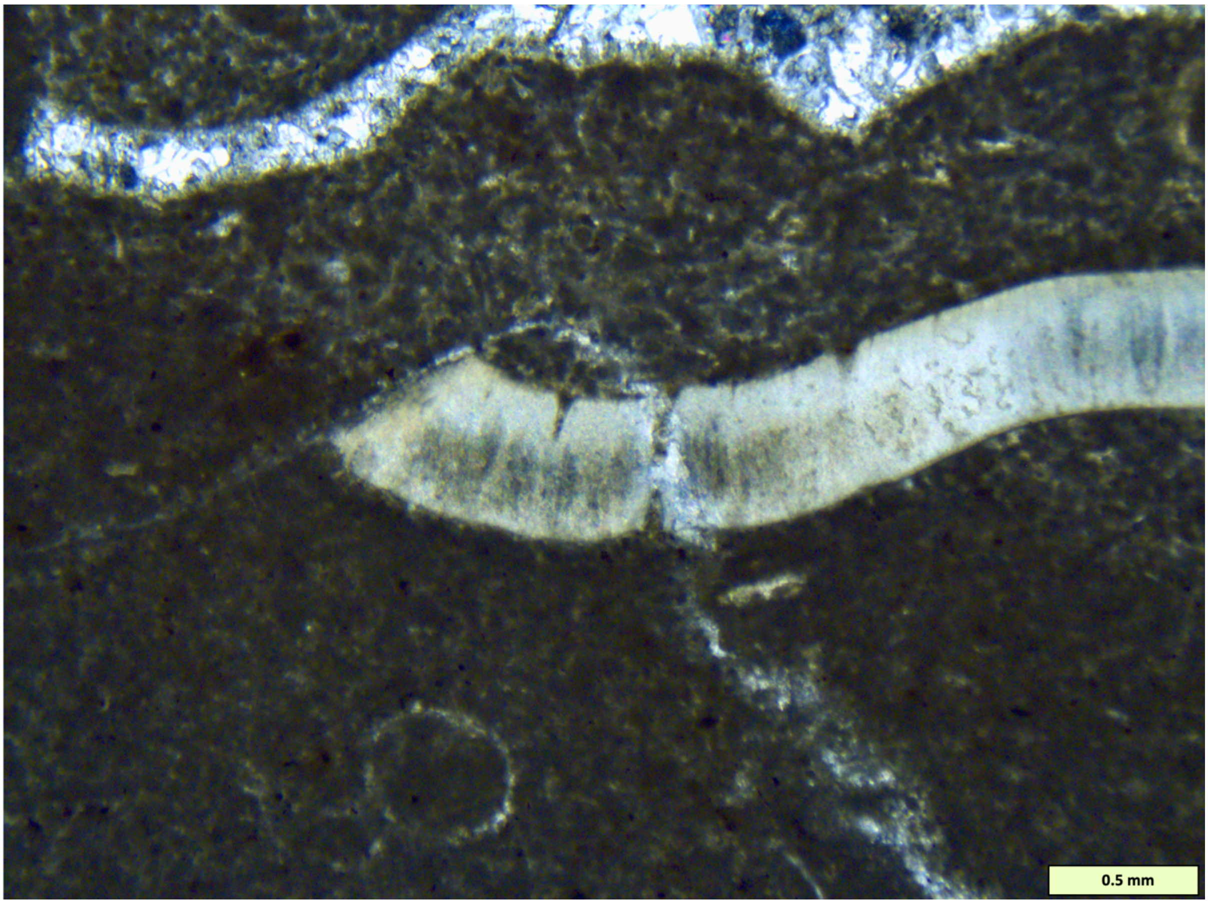


Fig. A34. Enlargement of point 3 in Fig. A32, also visible on left side of Fig. A33. Shows a trilobite shell fragment embedded into the lower mud layer, and I propose that it was transported and stuck into the lower layer mud top by current transport from the right. This would be consistent with the interpretation proposed for Fig. 33 view.
Sample Follingbo3-05-i. Photo file: A-06d-Follingbo3-05-i.

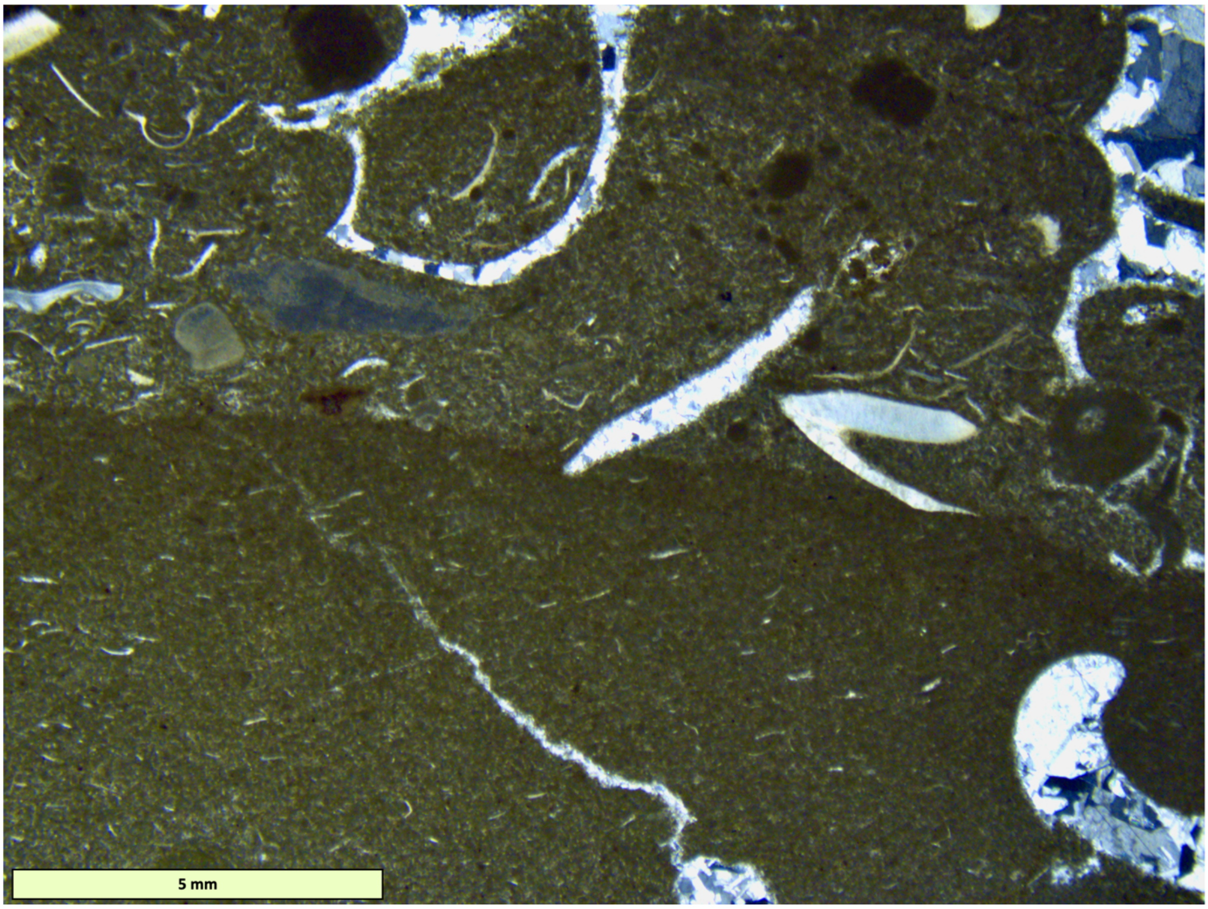


Fig. A35. Enlargement of Point 4 in Fig. A32, showing a recrystallised shell (probably a bivalve), with its tip embedded into the lower mud layer, interpreted as having been transported across the mud substrate and was jabbed into the soft mud by current movement. See Fig. A36 for detail.
Sample Follingbo3-05-i. Photo file: A-06e-Follingbo3-05-i.

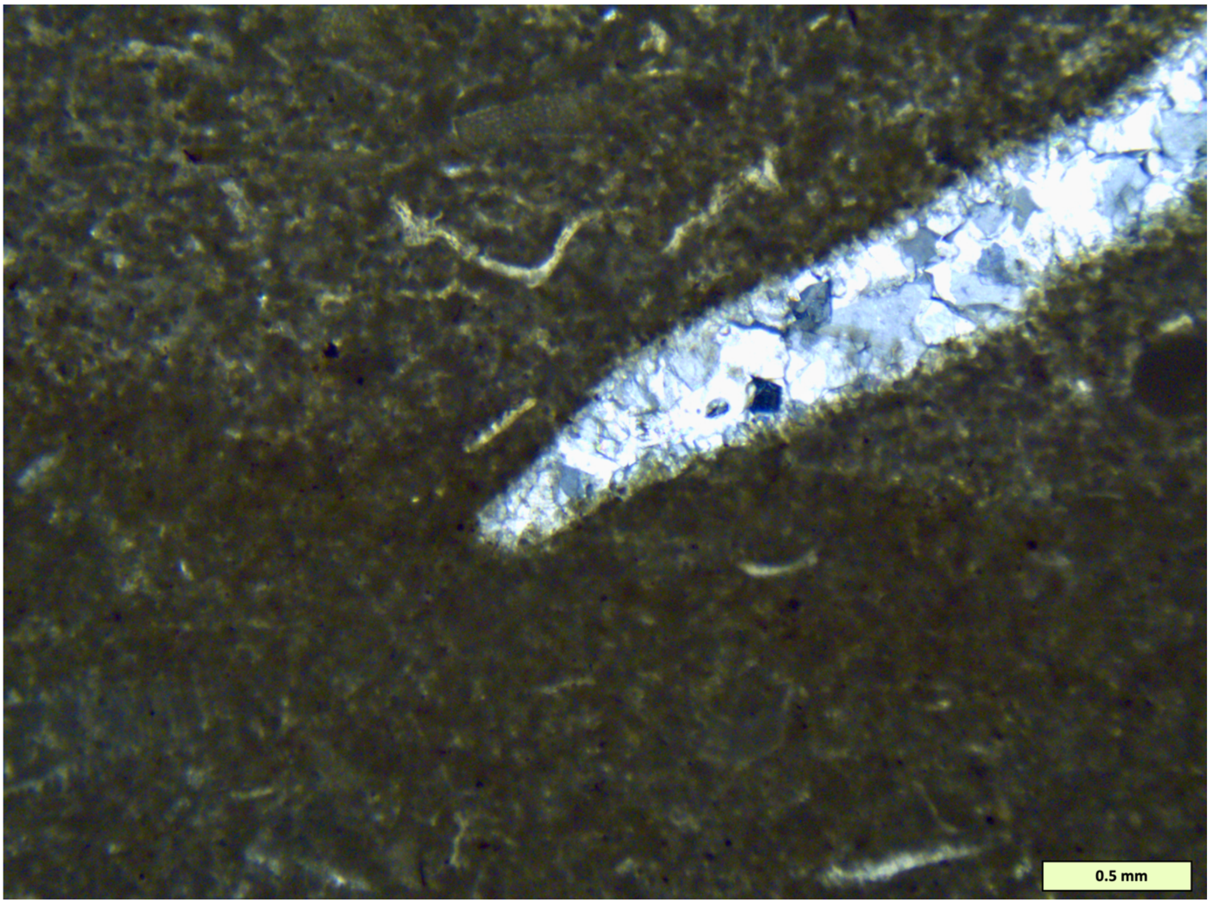


Fig. A36. Enlargement of previous photo showing detail of shell fragment partly embedded into the lower mud layer, which is interpreted as having been soft when the shell was deposited.
Sample Follingbo3-05-i. Photo file: A-06f-Follingbo3-05-i.

Overall, Sample 4 shows a sequence of events that can be interpreted as follows:

A) Lower mud layer was deposited in fairly quiet environment, and was soft sediment.
B) Points 2, 3 & 4 are compatible with the idea that the lower mud layer was unconsolidated so that it was swept up against the side of the shell in point 2, and then two shell fragments were pushed down into the mud surface in points 3 & 4, by currents flowing from right to left.
C) Later, after both the lower and upper layers of sediment were deposited, the sediment became at least partly lithified and was then burrowed (point 1 in Fig. A32) and filled with later mud from a younger layer not present in this specimen.

SAMPLE 5

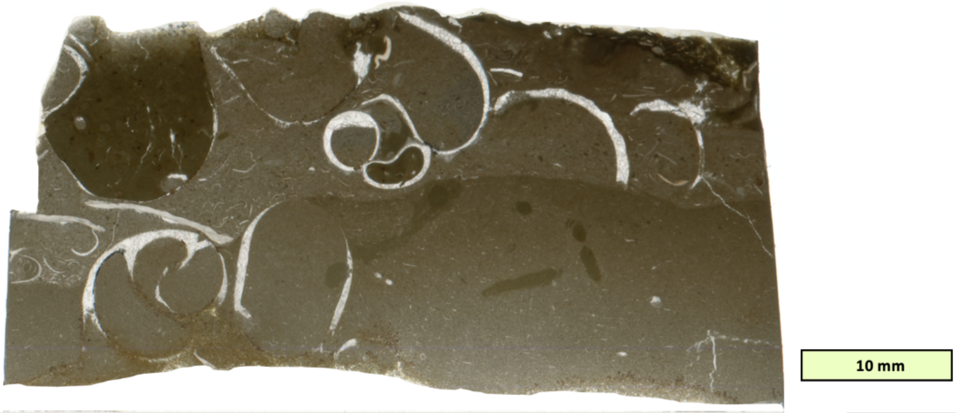


Fig. A37.
Upper: Vertical section of polished block showing two layers of carbonate mudstone with a subtle contact, seen better in Lower layer. The three coloured arrows are explained in Fig. A38.
Lower: Vertical thin section scan of polished block face, showing the two carbonate mudstone layers more clearly. Note in the upper layer the left-hand gastropod has a dark micrite infill; it seems it was derived from a prior deposit. In both layers are burrows infilled with a darker micrite than is present in both layers, indicative of filling from sediments not preserved in this section.
Sample Follingbo3-05-ii. Photo file: A-07b-Follingbo3-05-ii.

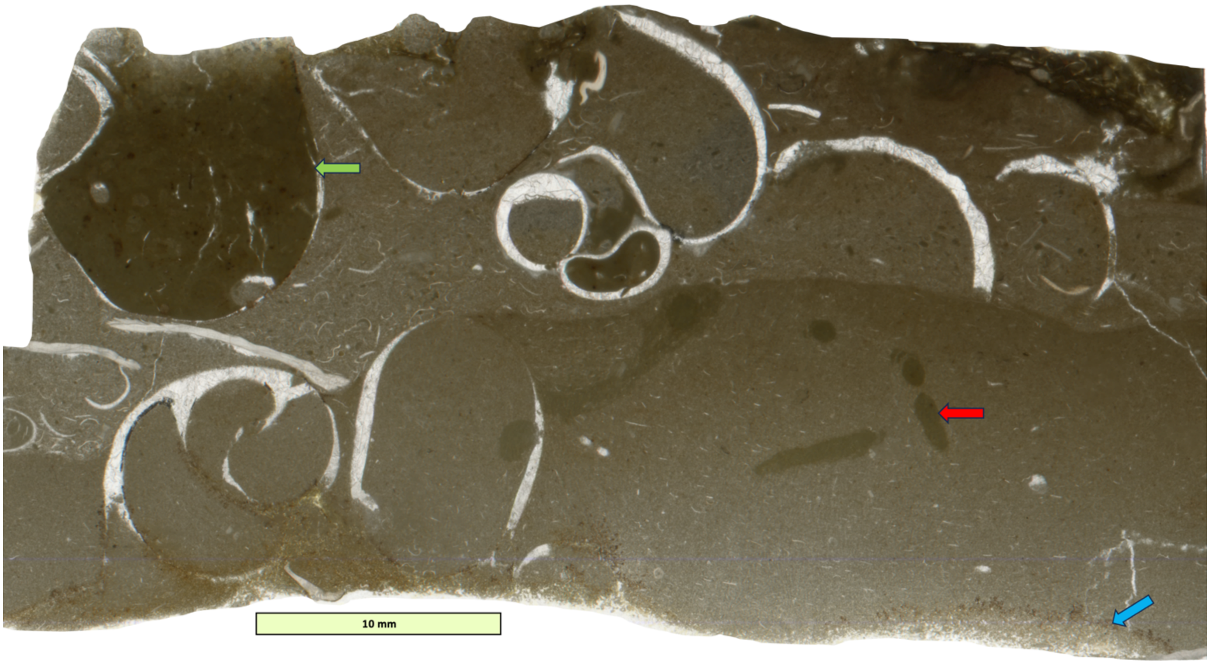


Fig. A38. Enlargement of Fig. A37, highlighting the dark infill of the left-hand shell (green arrow), the burrows with dark fill (red arrow) and weathering of the margin of the block (blue arrow) that may have occurred in the modern times on the outcrop. On left side, the upper surface of the lower layer has 2 shells embedded, but partly protruding above its surface; these shells are interpreted as indicating the lower layer was partly eroded so that some of the mud was removed before the upper layer was deposited; because the shells are not eroded, this arrangement is interpreted to indicate the mud was soft or slightly consolidated when the erosion occurred. Burrows in the lower layer do not cross into the upper layer, so presumably these burrows entered the lower layer before the upper layer was deposited.
Sample Follingbo3-05-ii. Photo file: A-07c-Follingbo3-05-ii.

SAMPLE 6

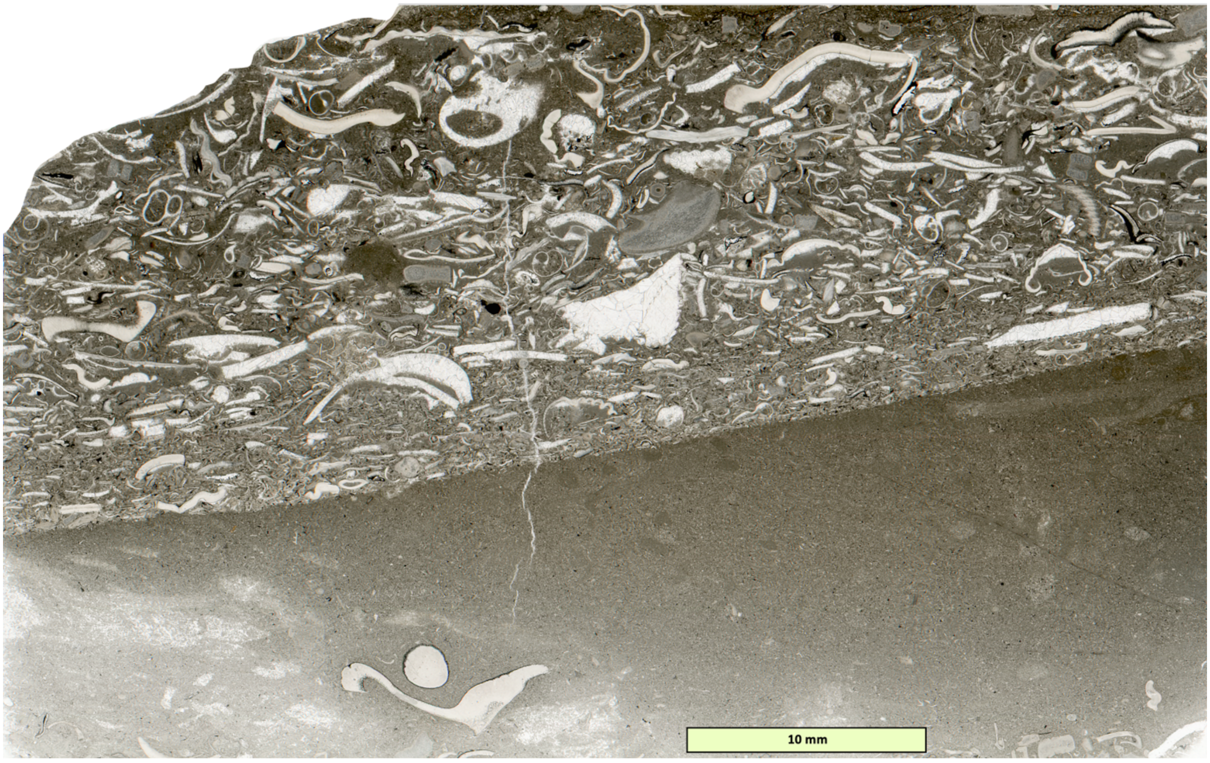


Fig. A39. Vertical thin section view of two layers of sediment in Follingbo 3.
Upper: Poorly sorted shell debris, with overall approximately horizontal alignment of shell material, likely due to transport across sea floor, and likely eroding top surface of lower layer.
Lower: Carbonate mudstone with vague burrows, seen best on right-hand side. The lighter patches on left side are where the thin section was too enthusiastically lapped by the thin section technician (me), so here it is very thin, losing detail. Centre-bottom is a fossil ghost [ha, ha]; it is actually a shell, probably a gastropod, cut obliquely.
Sample: Follingbo3-07-i; Photo file: A-08a-Follingbo3-07-i.

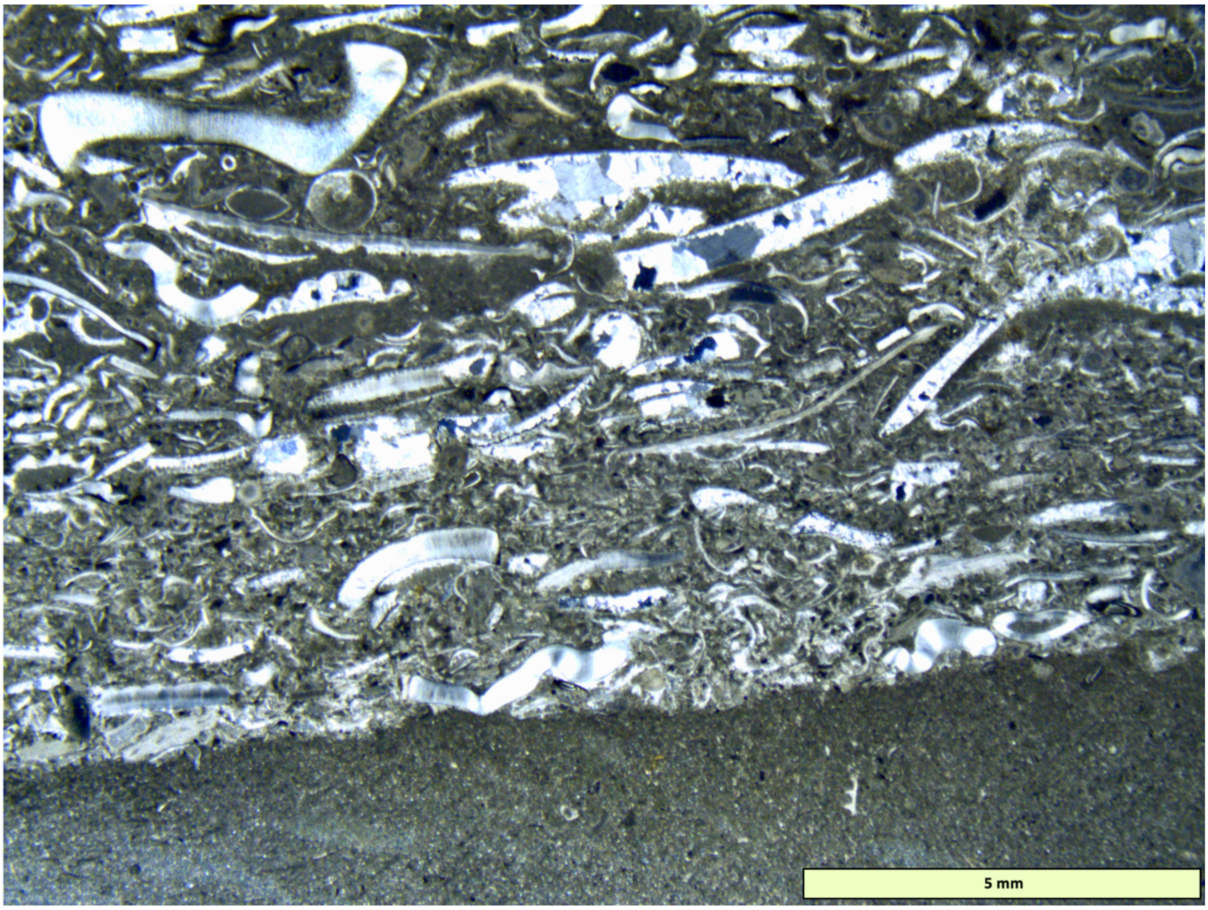


Fig. A40. XPL view. Enlargement of Fig. A39, showing details of bioclastic material, lots of trilobite fragments, and sharp contact between lower and upper layer; this contact may represent erosion of either a soft, partially lithified, or possibly even fully lithified, carbonate mud sediment; it is difficult to determine the consistency of the lower layer from this photo (but see Fig. A41).
Sample: Follingbo3-07-i; Photo file: A-08b-Follingbo3-07-i.

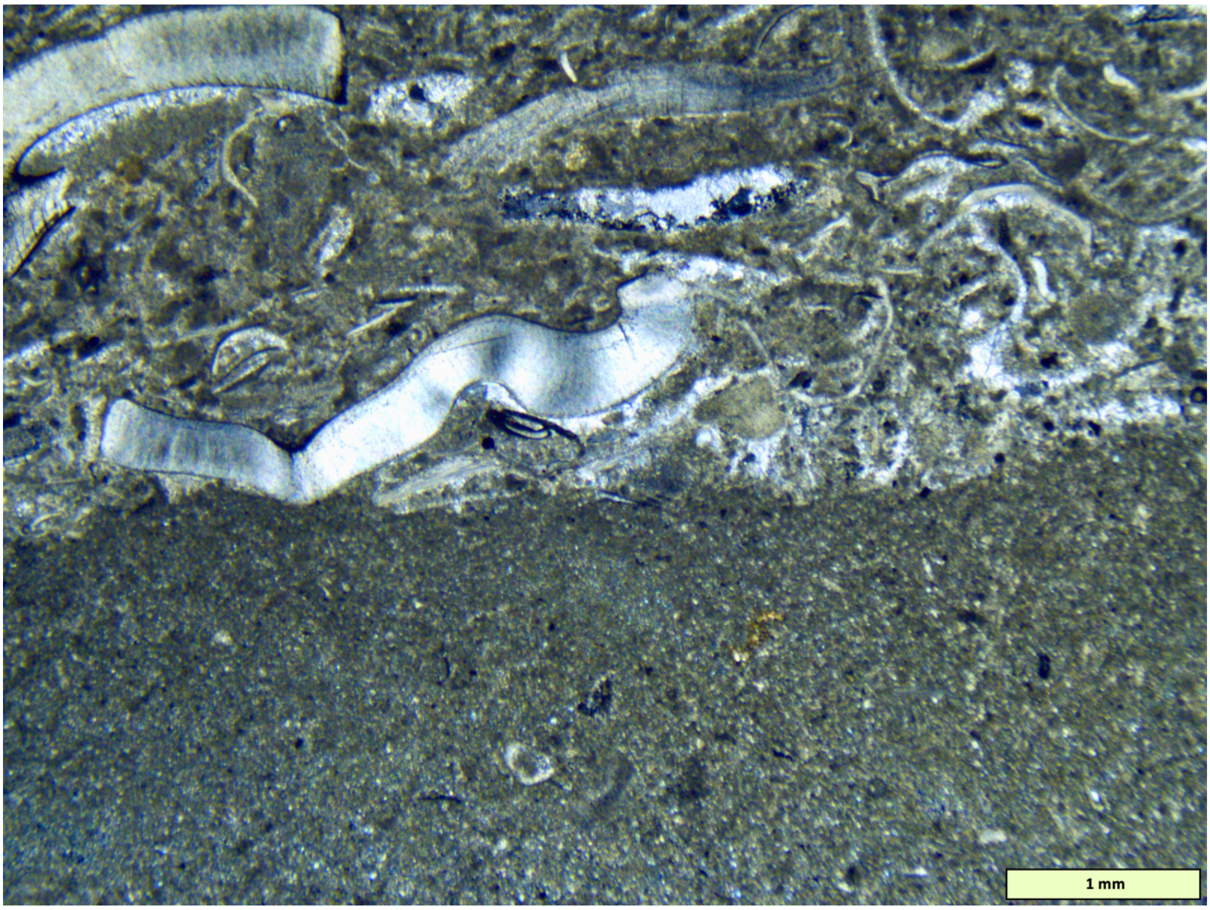


Fig. A41. Enlargement of Fig. A40, showing micro-irregular contact between lower and upper layers. It seems more likely that the lower layer was at least partly lithified before erosion, but it is rather difficult to prove this.
Sample: Follingbo3-07-i; Photo file: A-08c-Follingbo3-07-i.

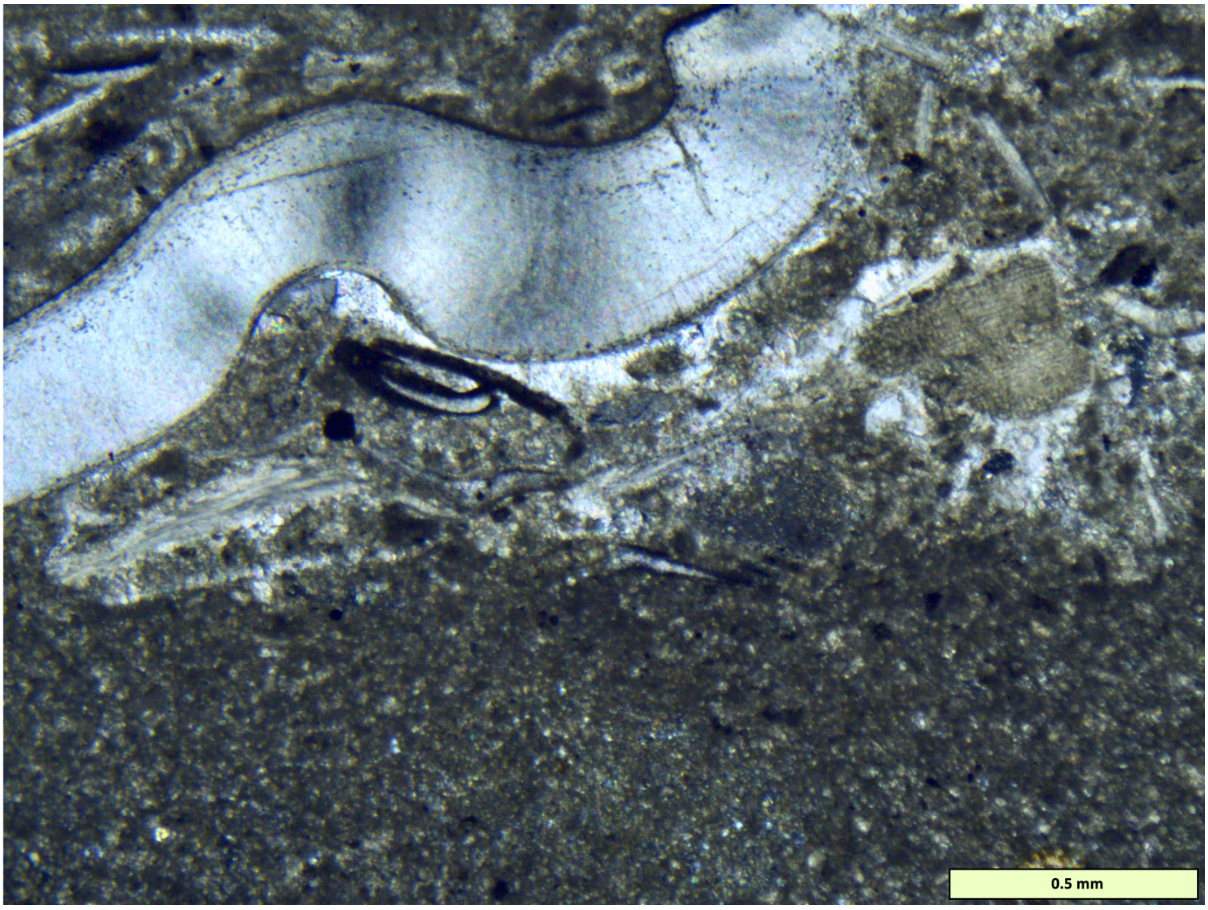


Fig. A42. Detail of Fig. A41, showing contact between lower and upper layer. Here the sharpness of the boundary between these two facies is not so clearly defined as in the previous lower-resolution figures. It leaves some uncertainty as to the nature of the consistency of the lower layer at the time when the upper layer was laid down. *Sample: Follingbo3-07-i; Photo file: A-08d-Follingbo3-07-i.*

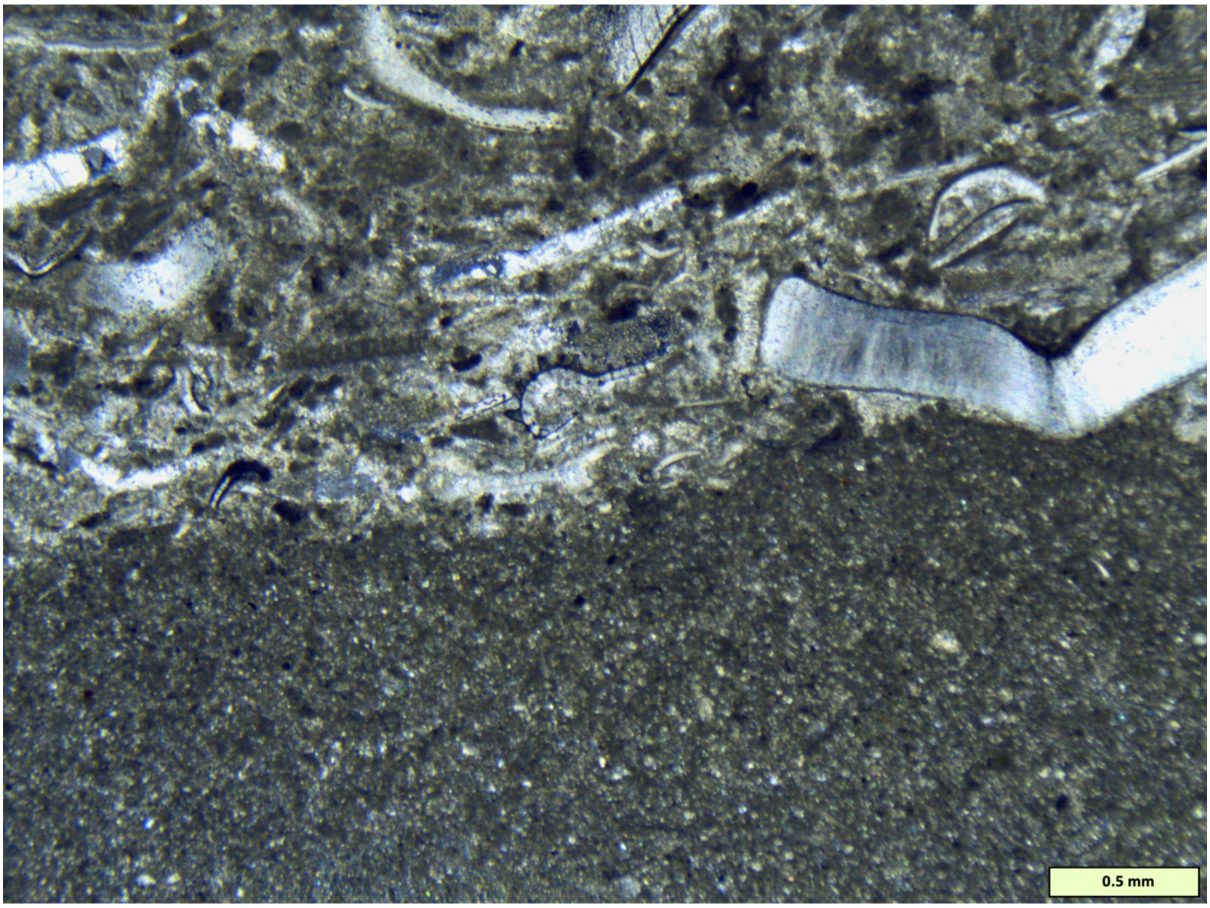


Fig. A43. Another detail at same scale as Fig. A42, showing a sharper appearance to the contact between lower and upper layers. Here a mass of fragmented shell material is in direct contact with the lower layer, giving impression that the shell material may have acted as erosional tools to erode the surface of the lower layer. If this is true, then it could be explained if the top surface of the lower layer was slightly consolidated when the upper layer was deposited. Something to think about !!
Sample: Follingbo3-07-i; Photo file: A-08e-Follingbo3-07-i.

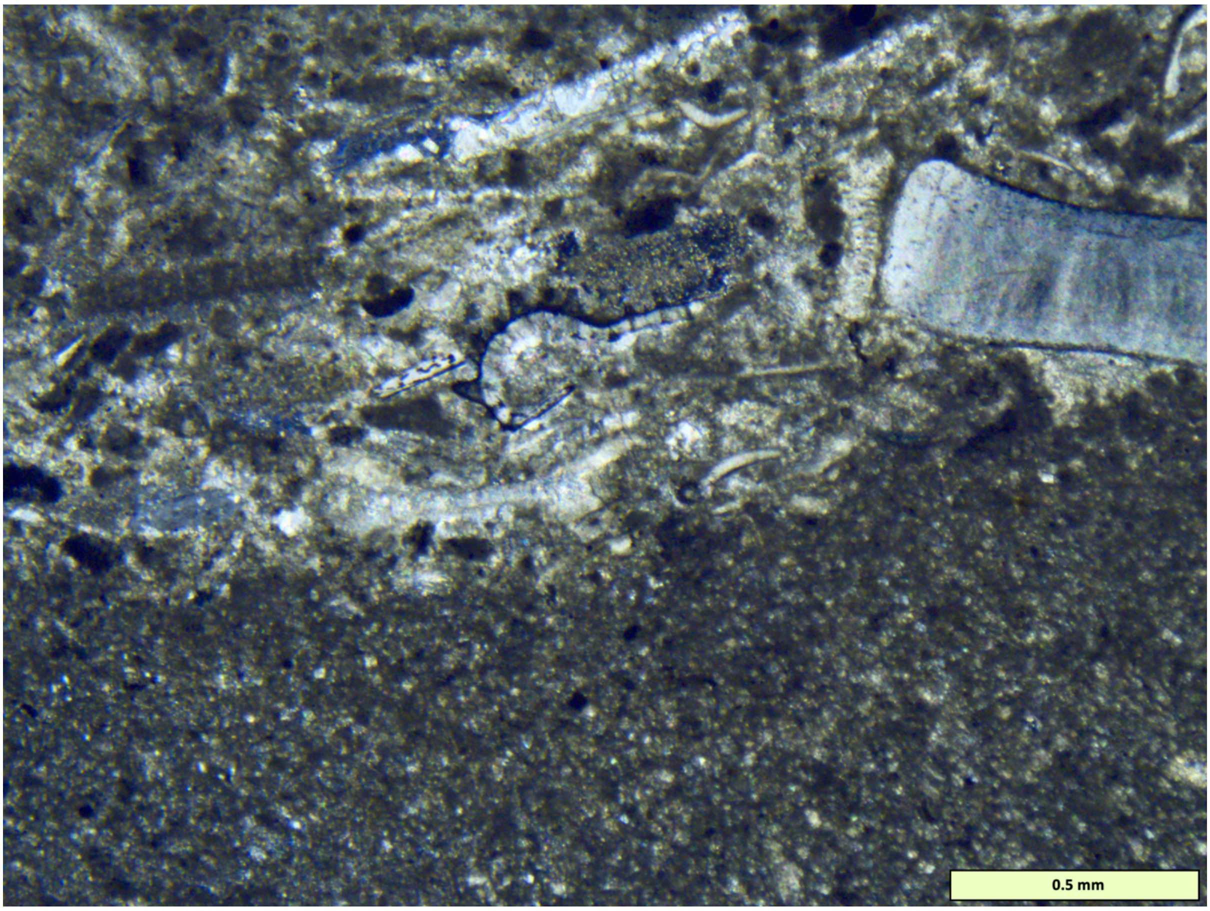


Fig. A44. Another example similar to Fig. A43.
Sample: Follingbo3-07-i; Photo file: A-08f-Follingbo3-07-i.

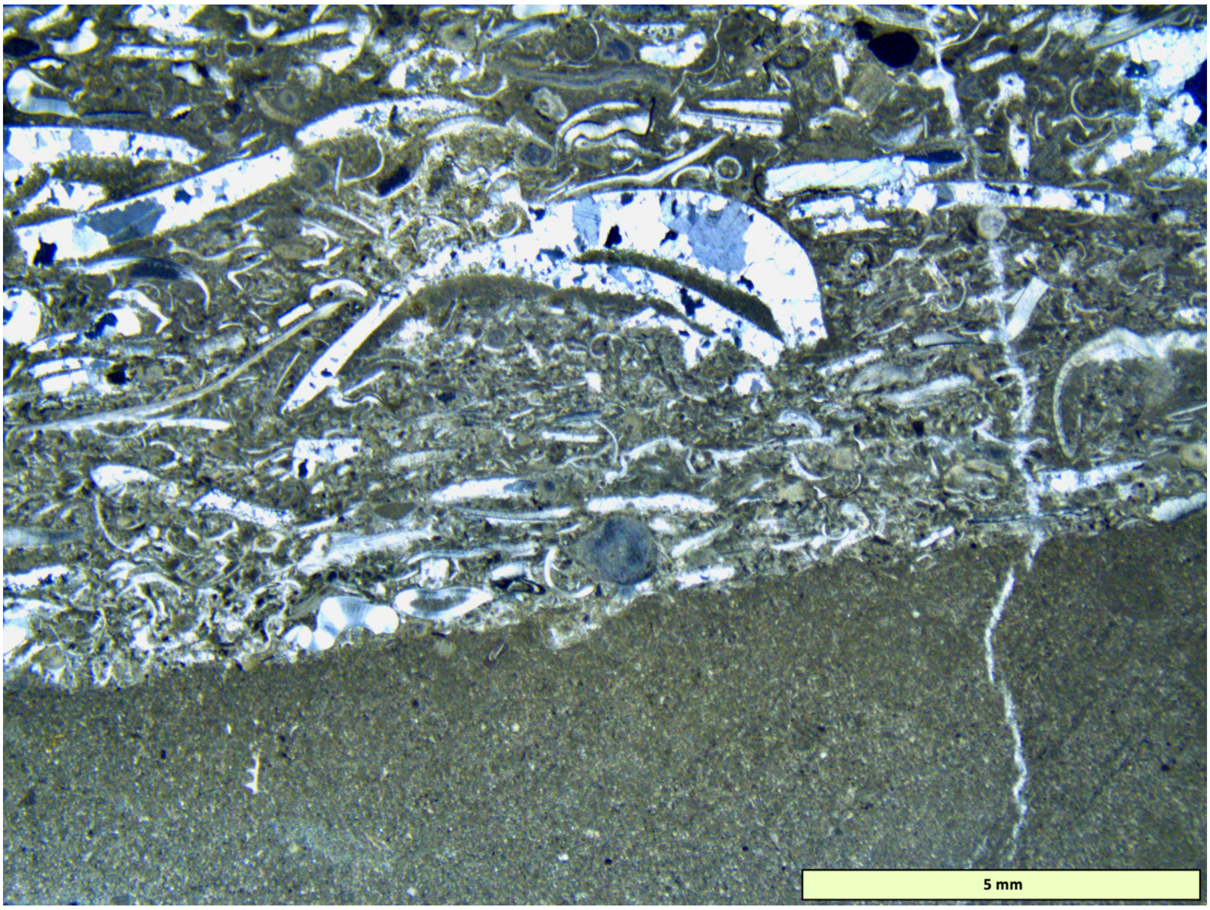


Fig. A45. General view of the contact between the lower and upper layers. Look at the small shell fragment in the centre, that is partly embedded in the lower layer, details in next two photos.
Sample: Follingbo3-07-i; Photo file: A-08g-Follingbo3-07-i.

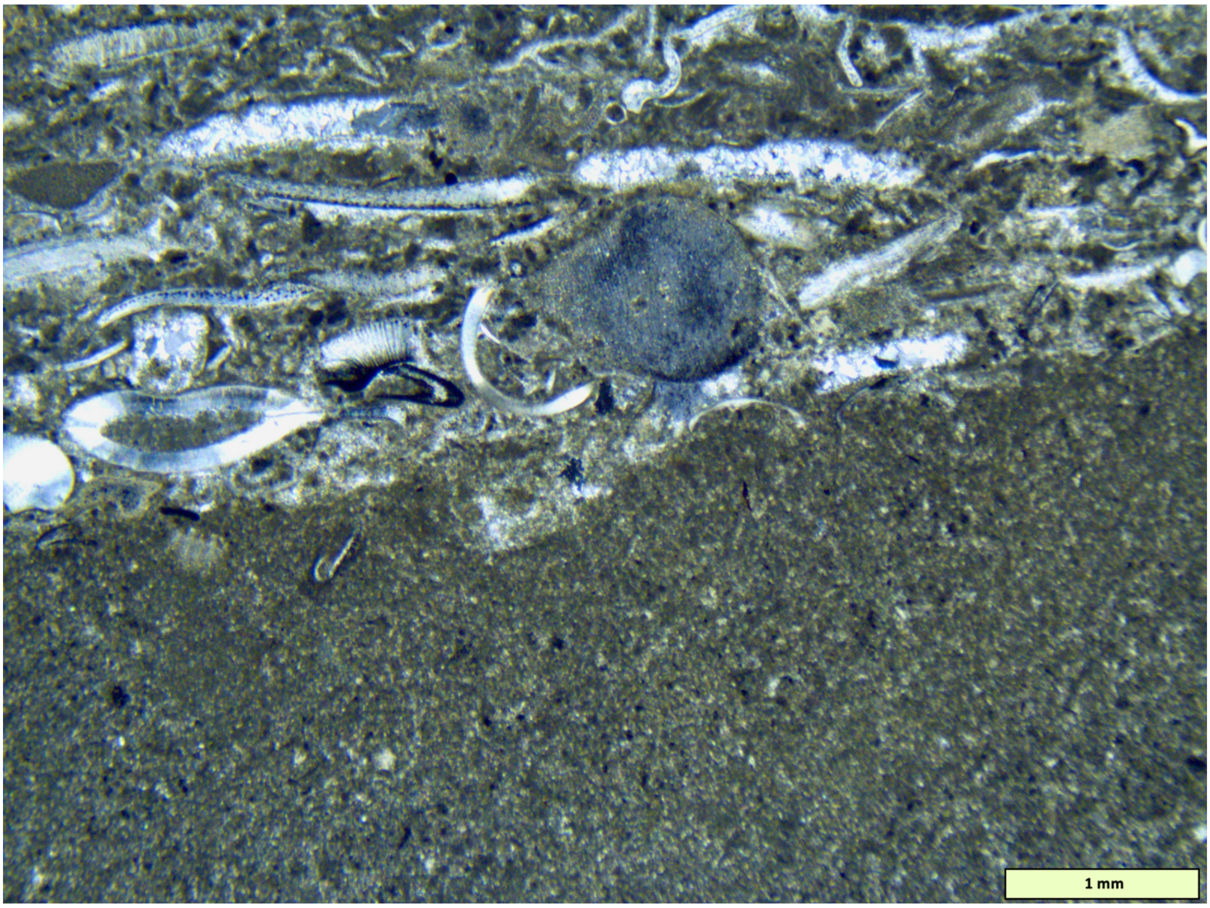


Fig. A46. Detail of centre of Fig. A45, showing the small angular shell fragment (that is recrystallised); its left side is partly embedded in the lower layer but right side is lying on top of the lower layer surface. See Fig. A47 for more detail.
Sample: Follingbo3-07-i; Photo file: A-08h-Follingbo3-07-i.

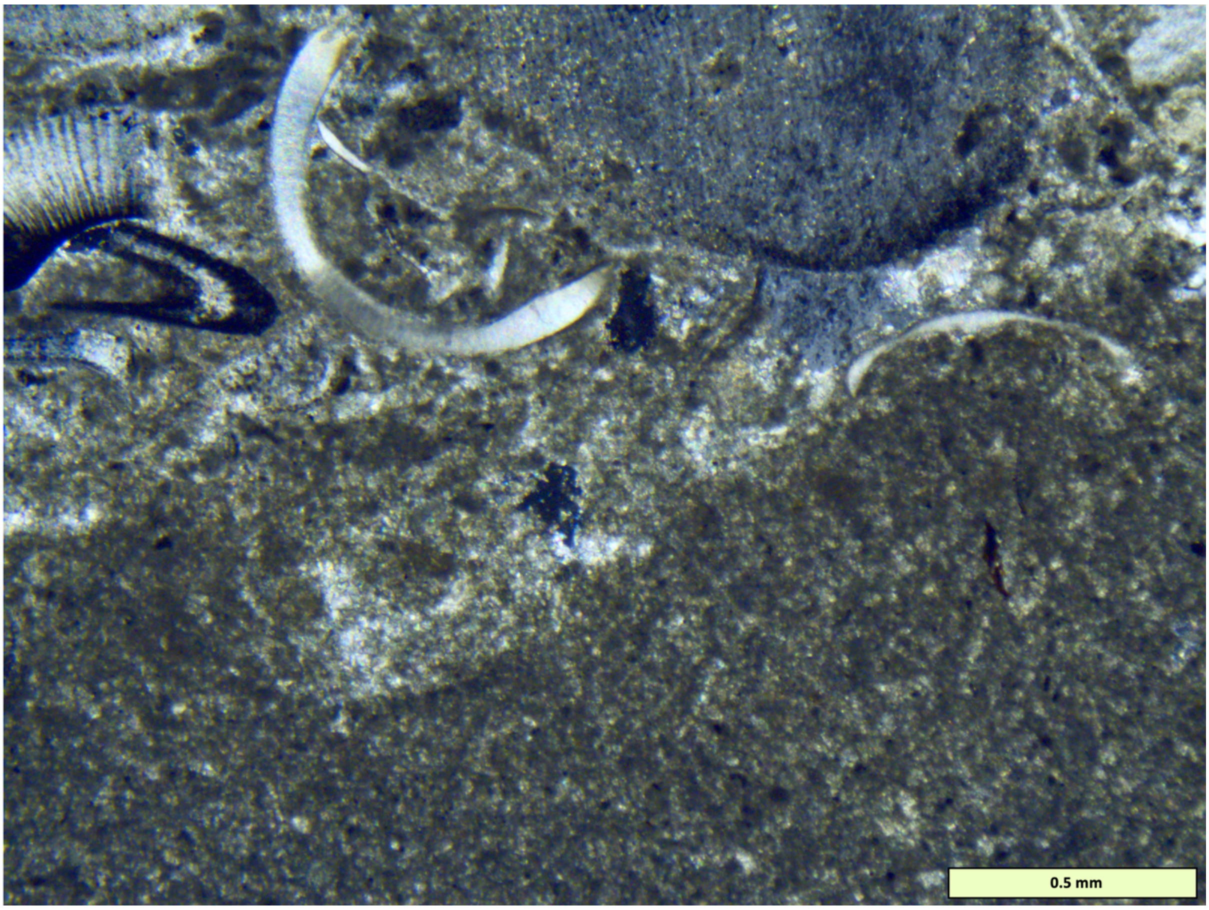


Fig. A47. Detail of angular shell fragment (recrystallised) partly embedded in the lower layer mud. At this higher resolution, the shell fragment is more difficult to define because it is recrystallised, but its left-hand edge was broken and not rounded and is fully embedded into the lower layer mud. This arrangement can be explained if the lower layer was made of poorly consolidated mud and the shell fragment simply pushed into it as the current carrying the shells of upper layer flowed across the surface of the lower layer in a storm, from right to left.
Sample: Follingbo3-07-i; Photo file: A-08i-Follingbo3-07-i.

Overall, Sample 6 shows evidence that the lower layer was poorly consolidated at the time of deposition of the upper layer.

SAMPLE 7

Fig. A48. Small polished slab of vertical section of Follingbo3-10-i sample showing:
On left: a large gastropod with geopetal infill. The sediment infill looks same as the matrix.
In centre: cross-section through what is probably an orthoconic nautiloid (with siphuncle in its middle); the shell is largely dissolved and lost, but its sediment infill is different from the matrix. This arrangement is interpreted to indicate this shell was exhumed from another sediment elsewhere, so it had died, been infilled and then transported to this location for deposition.
Lower right: single shell valve with some sediment adhering to its concave surface; this whole feature may have been a lithoclast, possibly from the same site as the orthocone, since the sediment is the same colour as the infill of the orthocone.
Centre right: another shell that is not so clear to see, but has a geopetal, details of which can be seen in Fig. A49.
Sample: Follingbo3-10-I; Photo file: A-09a-Follingbo3-10-i.

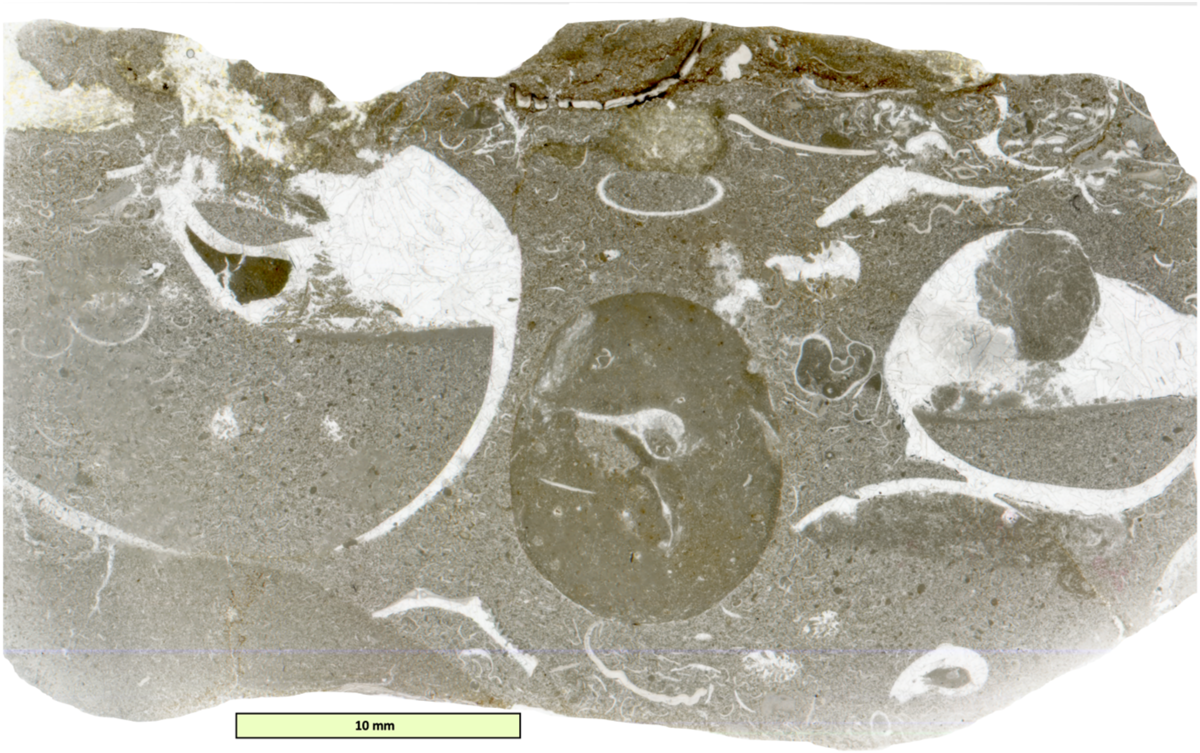


Fig. A49. Vertical thin section parallel to and close to the plane of the face in Fig. A48, showing detail of the features described in Fig. A48. This photo also shows some evidence of a lower layer of micrite, indicated by the sloping sharp contact on lower left of photo.
Sample: Follingbo3-10-ii; Photo file: A-09b-Follingbo3-10-ii.

Fig. A50. Vertical section of polished block parallel to and close to the faces illustrated in Figs. A48-49, showing more of the same features.
Sample: Follingbo3-10-iii; Photo file: A-09c-Follingbo3-10-iii.

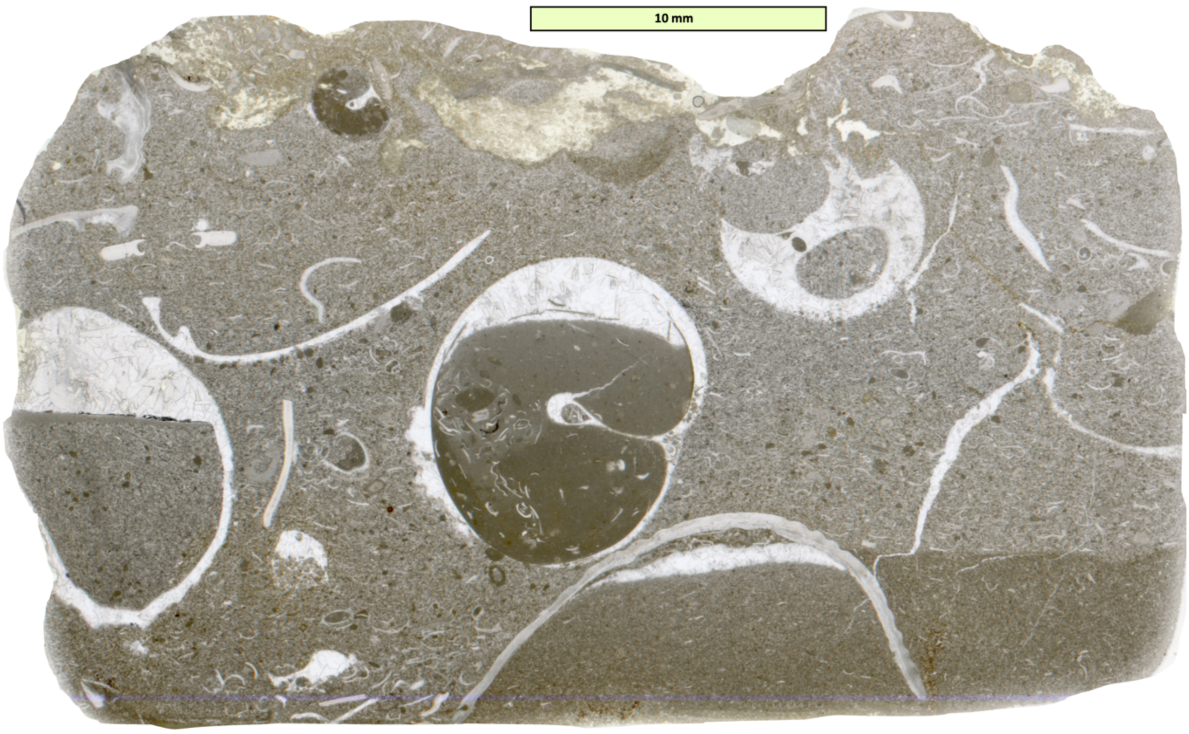


Fig. A51. Vertical section of polished block parallel to and close to the faces illustrated in Fig. A50, showing more of the same features. Note that in the lower right of this image is a boundary between a darker micritic lower portion and lighter tone of the rest of the matrix. The fact that the boundary between the darker lower and lighter upper matrix does not extend across to the left side of the central lower shell likely indicates an uneven contact between the lower and upper layers. *Sample: Follingbo3-10-iii; Photo file: A-09d-Follingbo3-10-iiii.*

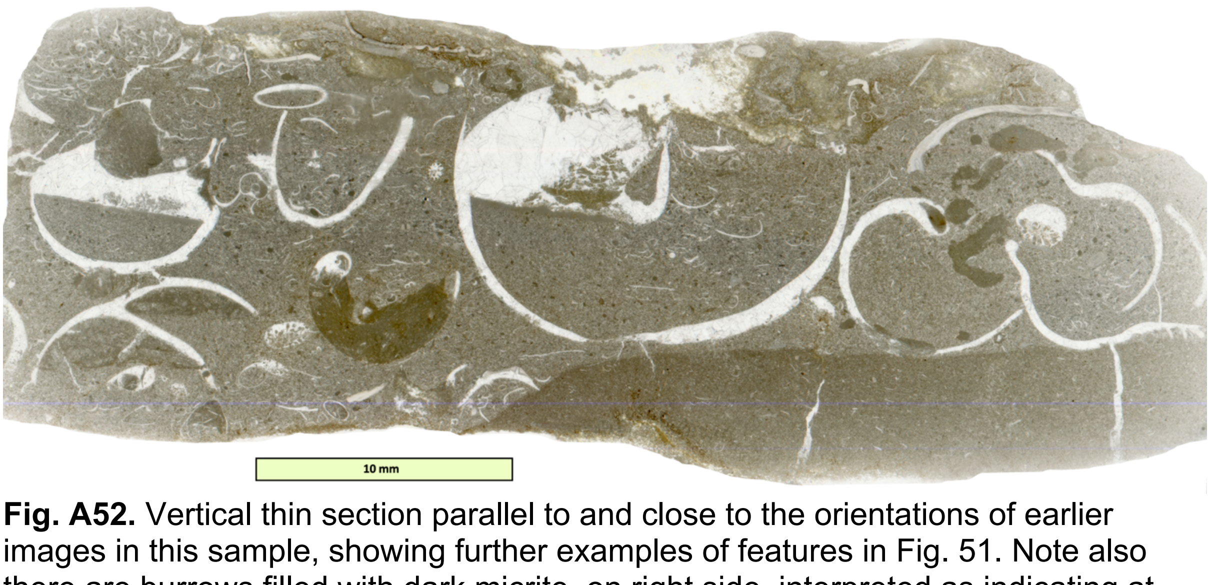


Fig. A52. Vertical thin section parallel to and close to the orientations of earlier images in this sample, showing further examples of features in Fig. 51. Note also there are burrows filled with dark micrite, on right side, interpreted as indicating at least partial lithification of the upper layer micrite when the burrowing occurred. *Sample: Follingbo3-10-v; Photo file: A-09e-Follingbo3-10-v.*

SAMPLE 8

Fig. A53. Vertical thin section view showing:
Lower layer: darker micrite with sharp upper surface;
Upper layer: lighter micrite with more shell material.
Dark elliptical object: crossing boundary between lower and upper layers.
Sample: Follingbo3-12-i; Photofile: A-10a-Follingbo3-12-i-1.

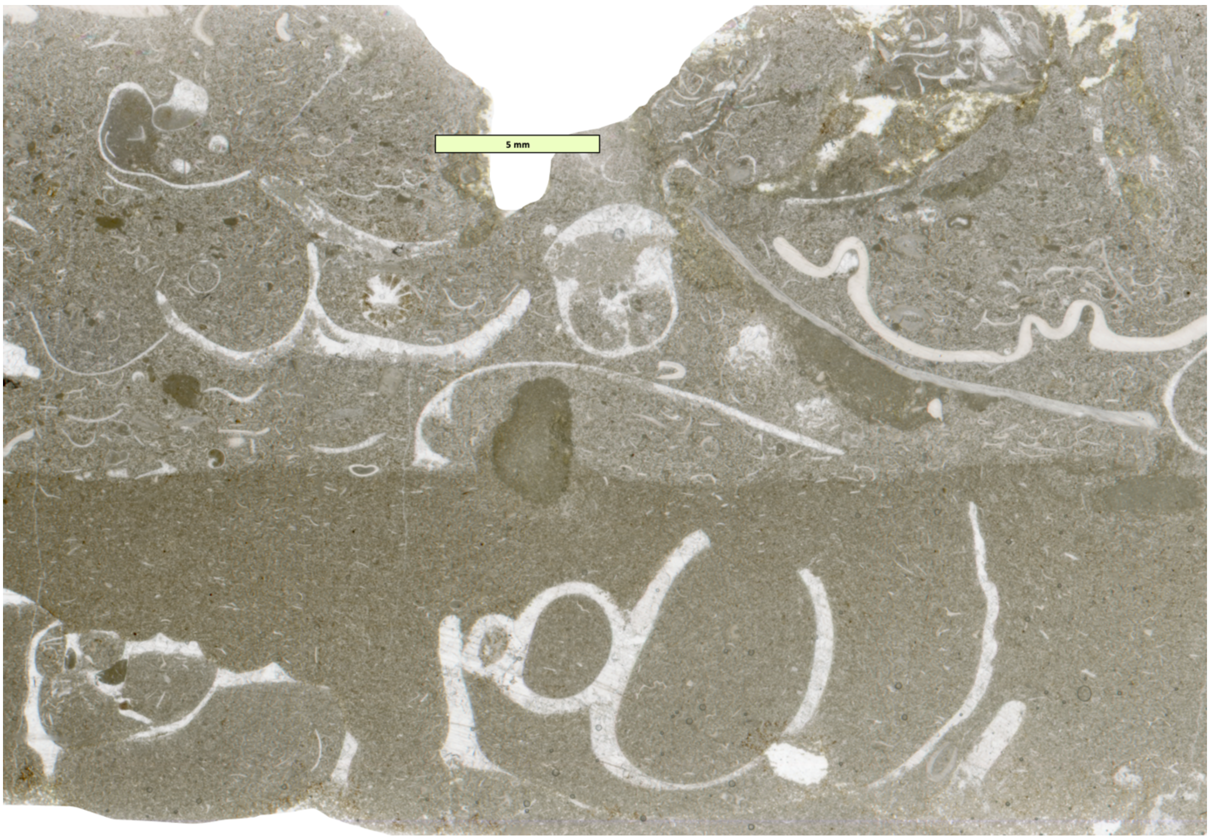


Fig. A54. Enlargement of centre of Fig. A54, showing more detail of the contact between the two layers and the dark elliptical object that crosses the contact. Note that the upper surface of the lower layer is slightly undulose; it is not clear whether the lower layer was partly consolidated when the upper layer was laid down, or whether the lower layer was soft sediment. The dark object may be a lithoclast, that was transported as the upper layer material was carried across the surface of the lower layer. Note that this interpretation as lithoclast is more likely than a burrow because its margins are somewhat irregular and that the object has a darkened rim, which may be mineralisation of a lithified clast of mudstone eroded from elsewhere

and transported here. If it is a lithoclast, then its presence embedded partly in the upper part of the lower layer is an indication the lower layer was sufficiently soft to accommodate this impact without showing any associated sedimentary structure. Note that in left part of photo is another very small dark rounded object that could be another lithoclast, rather than a burrow, given its slightly irregular shape.
Sample: Follingbo3-12-i; Photofile: A-10a-Follingbo3-12-i-2.

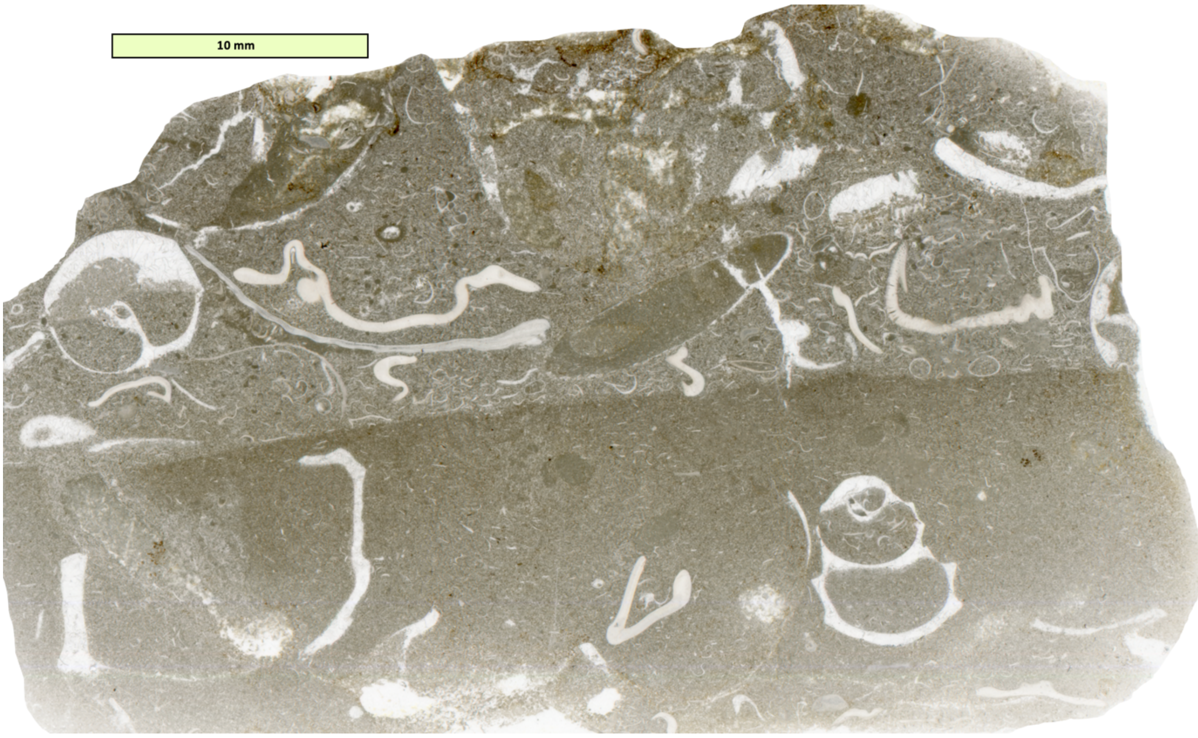


Fig. A55. Another vertical thin section of this specimen, parallel and close to those shown in Figs. A53 & 54. Note the lower layer has a few irregular darker areas, with sharp margins, and these may be lithoclasts of micrite.
Sample: Follingbo3-12-ii; Photofile: A-10c-Follingbo3-12-ii.

SAMPLE 9

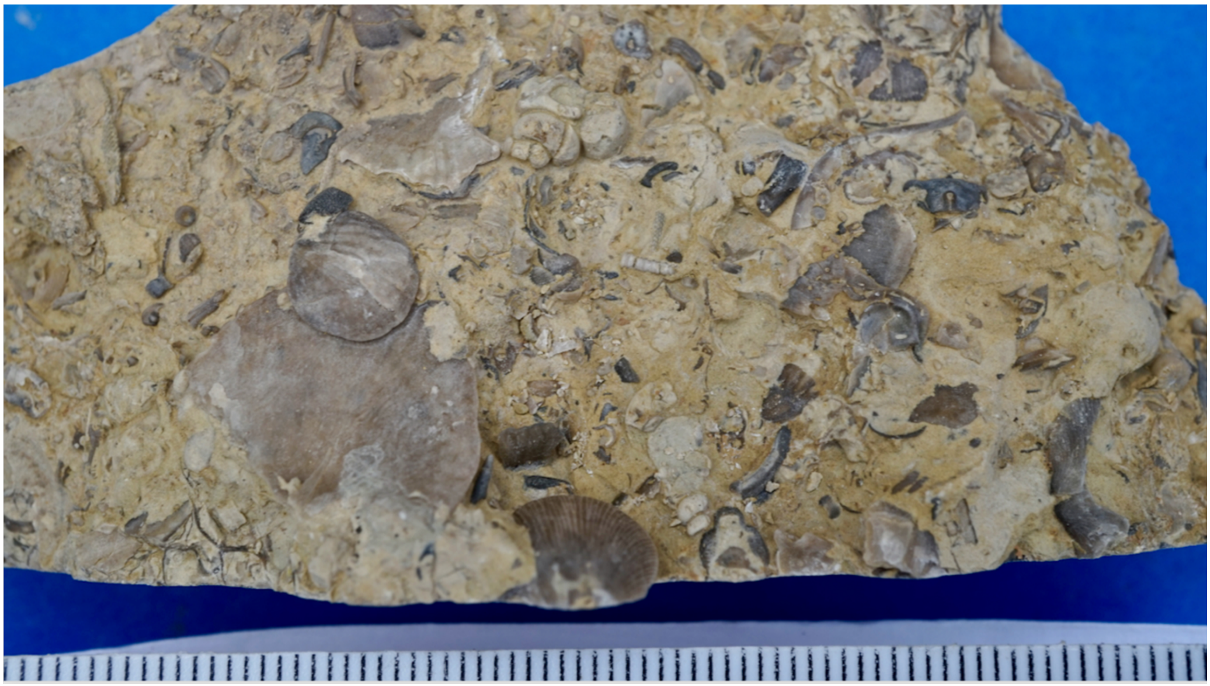


Fig. A56. Lower surface view of a piece of Follingbo limestone showing a mixture of shell debris and whole shell valves, presumably transported by storm action.
Sample: Follingbo03-14; Photofile: A-11a-Follingbo03-14-ii-i.

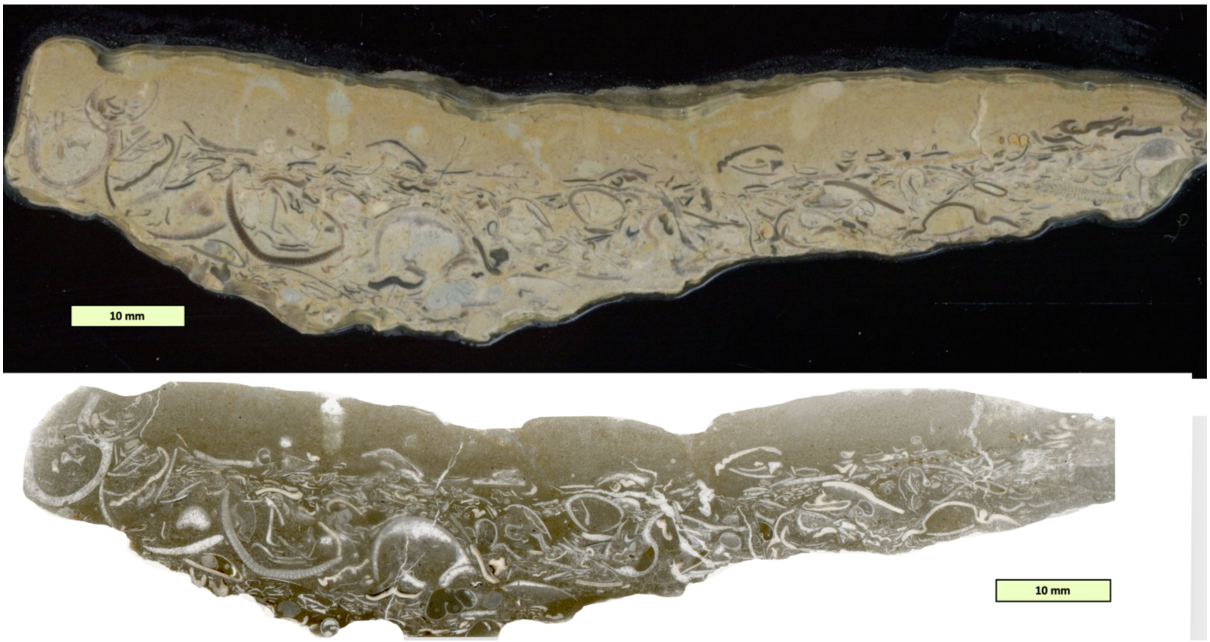


Fig. A57.
Vertical section of polished slab showing lower layer of poorly sorted shell material, shown in Fig. A56 in lower surface plan view. The poor sorting and mixture of complete, disarticulated and broken shell material is interpreted here as representing a storm deposit. Note the upper layer of micrite contains almost no shell material, but has some burrows with infills of lighter-coloured micrite and indicates the upper layer was likely partly consolidated when the burrows formed. It is possible that these burrows, like other burrows in this atlas, were lined with organic tissue that is not preserved. Such linings are common in modern worm burrows whereby the worms

maintain their burrows by lining with soft tissue, and thus may give a misleading impression of partial consolidation, yet the sediment may have been unconsolidated. There are no obvious features in this specimen to discriminate between these two possibilities.
Sample: Follingbo03-14-ii; Photofile: A-11b-Follingbo03-14-ii-ii.

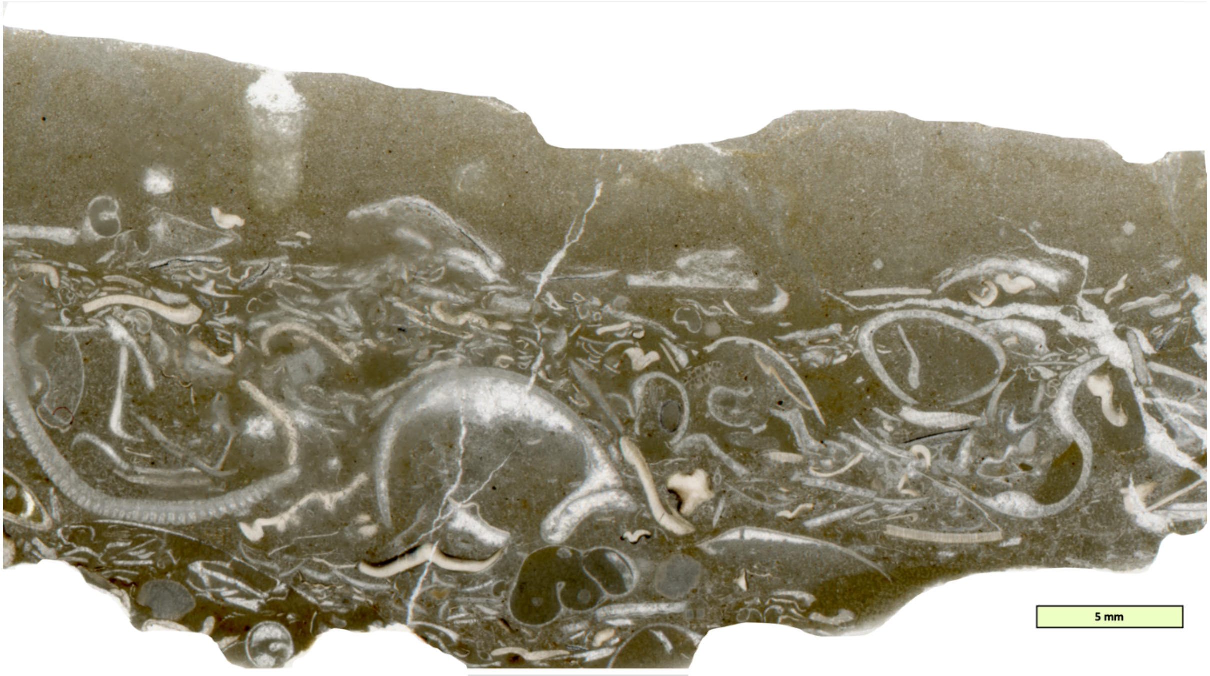


Fig. A58. Enlargement of part of previous image showing more details. Burrows in the upper layer contain a soft micrite that is eroded out during thin section-making, in the case on left side. Note in centre lower part is a gastropod shell with a dark micrite infill, which may have been derived from an earlier deposit, that was eroded, to exhume this shell.
Sample: Follingbo03-14-ii; Photofile: A-11c-Follingbo03-14-ii-ii.

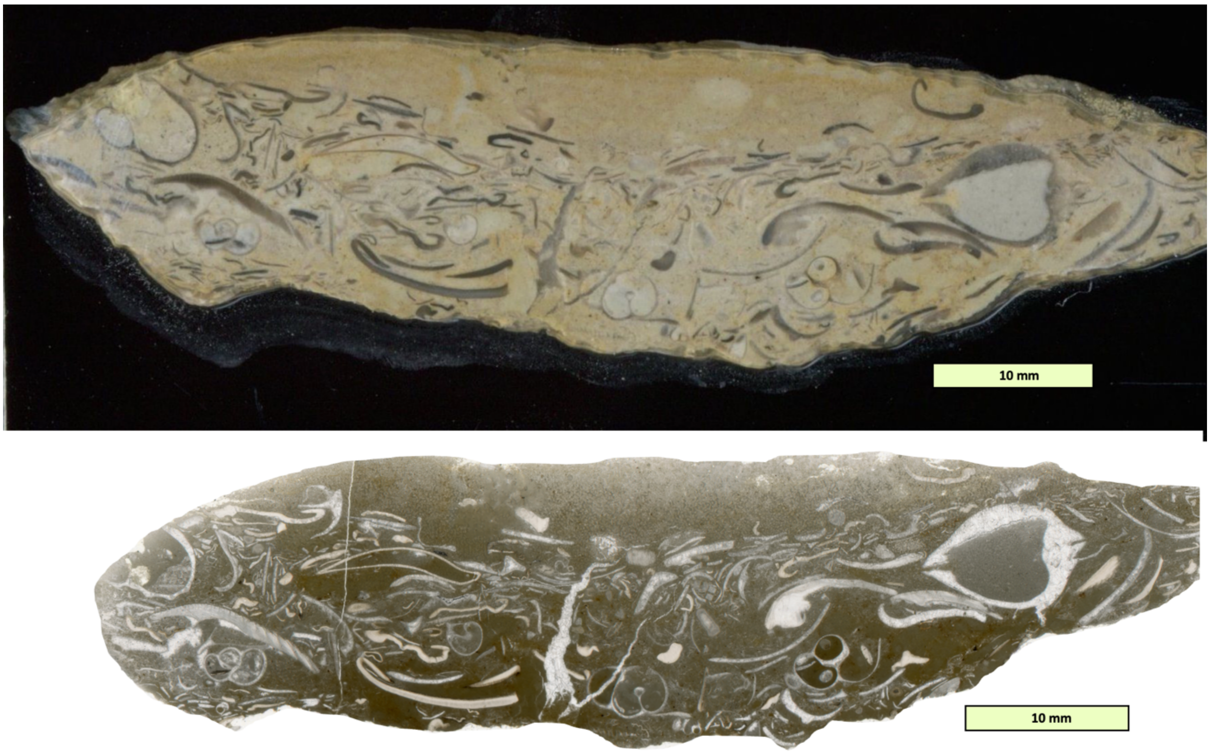


Fig. A59. Another image from a parallel thin section to the previous images in Figs. A57 & 58, showing more of the same features.
Sample: Follingbo03-14-i; Photofile: A-11d-Follingbo03-14-i.

SAMPLE 10

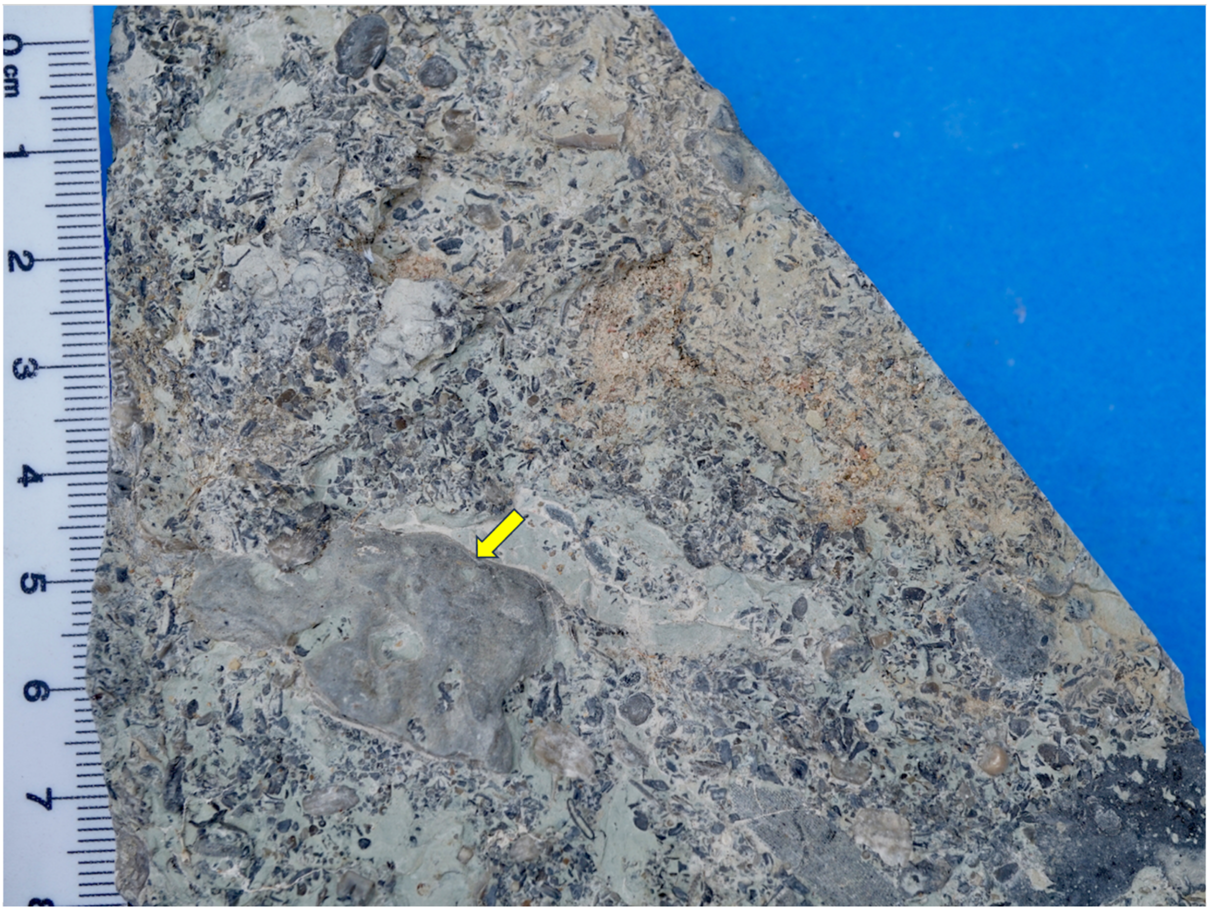


Fig. A60. View of lower surface of a piece of Follingbo limestone, with a micritic lithoclast (yellow arrow, enlargement shown in Fig. A61), shown in thin section in Figs. A62 & 63. Shell debris in this picture clearly shows a great degree of damage, consistent with an interpretation that this is a storm deposit.
Sample: Follingbo3-15; Photofile: A-12a-Follingbo3-15-i.

Fig. A61. Enlargement of micritic lithoclast (yellow arrow) from Fig. A60. Note irregular shape of the lithoclast.
Sample: Follingbo3-15; Photofile: A-12b-Follingbo3-15-ii.

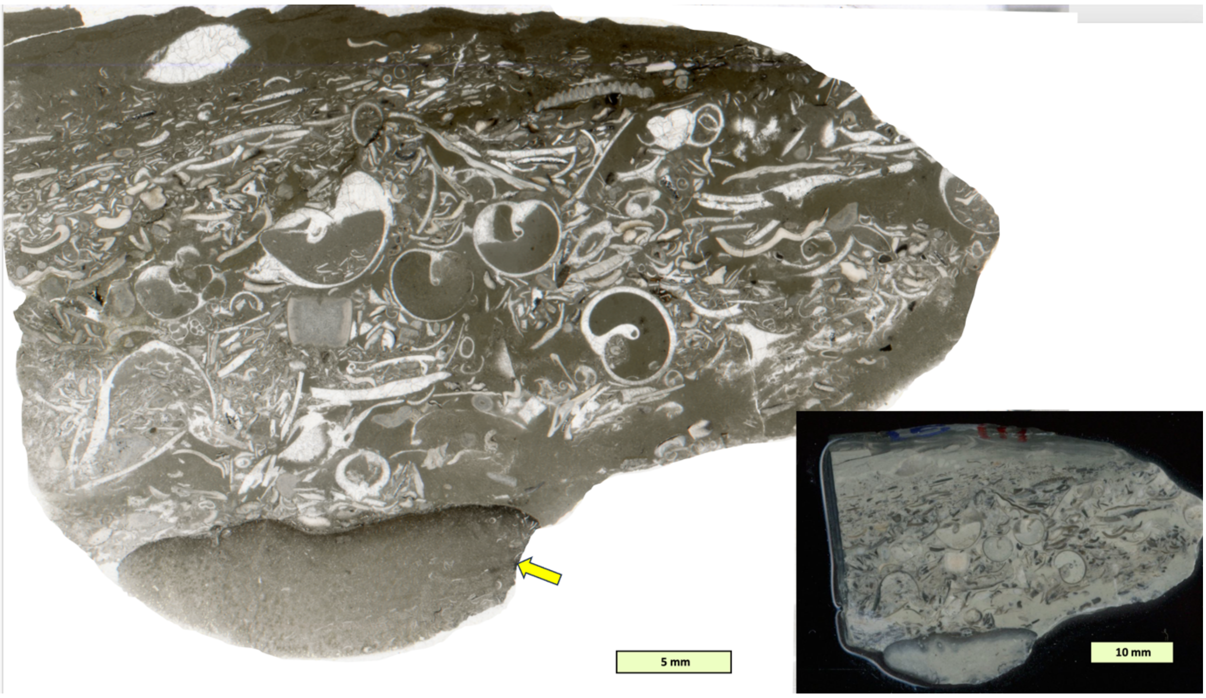


Fig. A62. Vertical thin section showing the lithoclast (yellow arrow) has a mineralised margin (dark outer edge). Note that the lower edge of the sample lacks the mineralised margin, probably the lithoclast was eroded. Note the shell material in this section comprises a mixture of complete shells and debris, and is a poorly sorted deposit that would be consistent with a high energy rapid event, such as storm

action. Inset shows the hand specimen from which this thin section was made, next photo shows an enlargement.
Sample: Follingbo3-15-iii; Photofile A-12c-Follingbo3-15-iii.

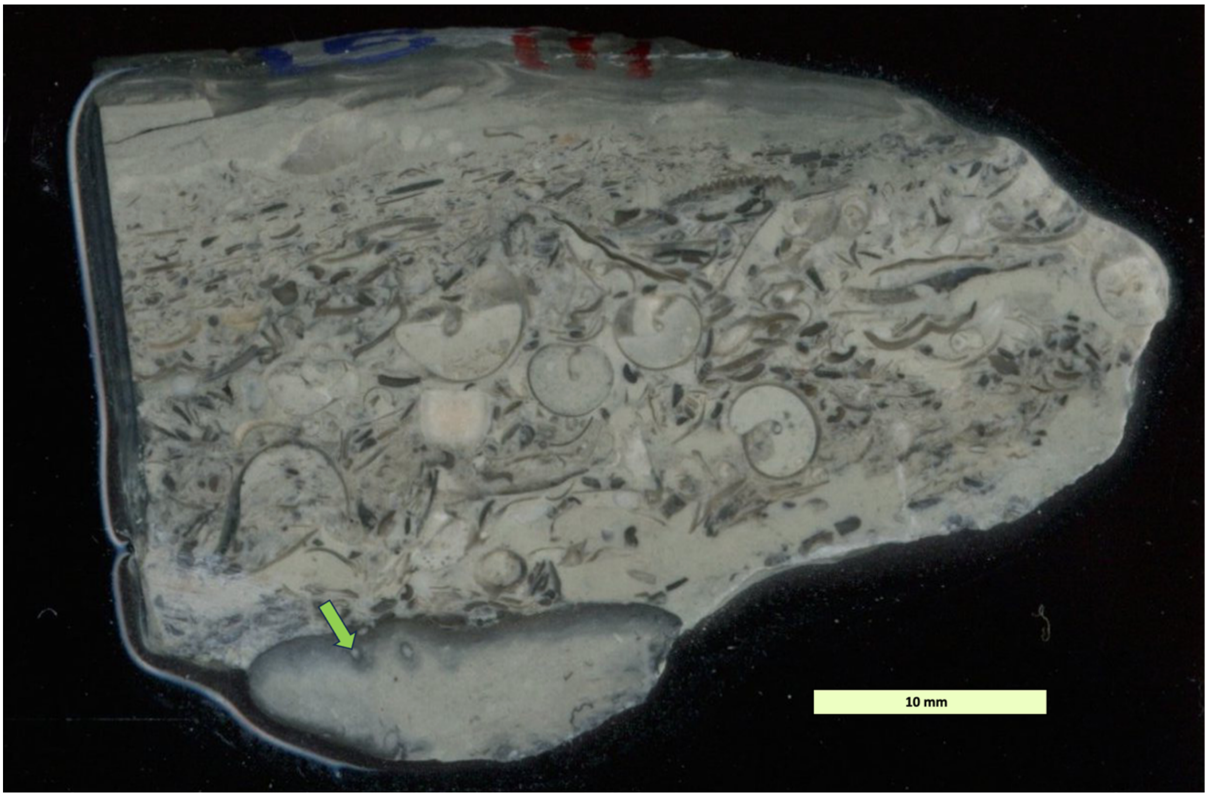
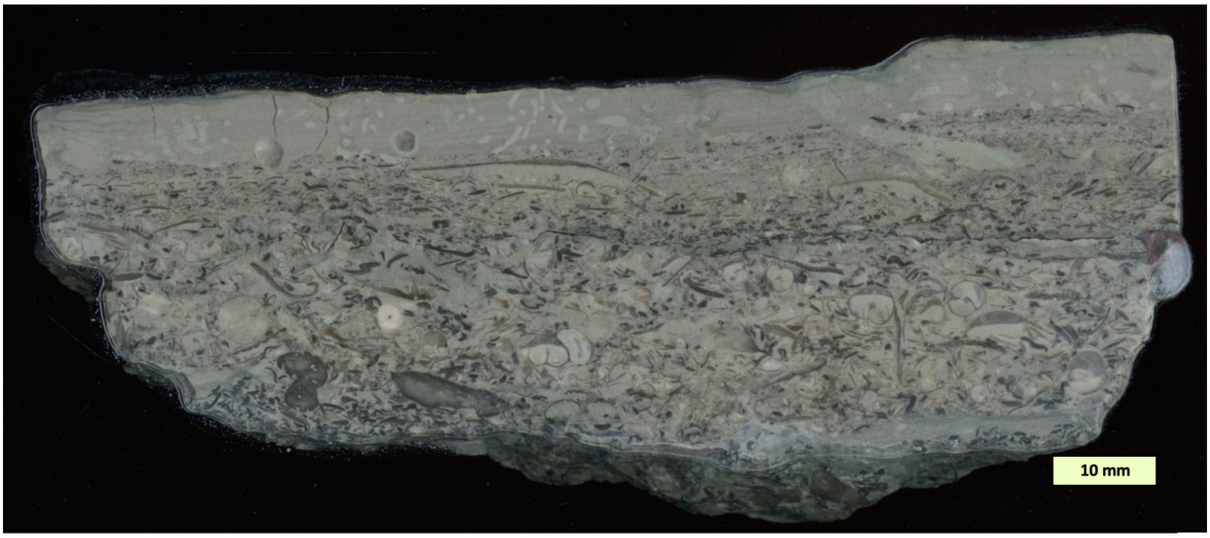


Fig. A63. Vertical section of polished block from previous figure, indicating the lithoclast has a mineralised margin and also has some internal circular structures interpreted as burrows (green arrow). This photo also shows clearly the upward-grading nature of the deposit, consistent with deposition from a waning current, such as my happen during a storm event.
Sample: Follingbo3-15-iiii; Photofile: A-12d-Follingbo3-15-iiii.

Fig. A64. Another vertical section of polished block from this sample. Here another lithoclast is highlighted (yellow arrow), and a sharp line (red arrow) between a lower gray-coloured packstone-wackestone layer and an upper wackestone-packstone

layer. These features demonstrate the dynamic environment in which these deposits were formed.
Sample: Follingbo3-15; Photofile: A-12e-Follingbo3-15-v.



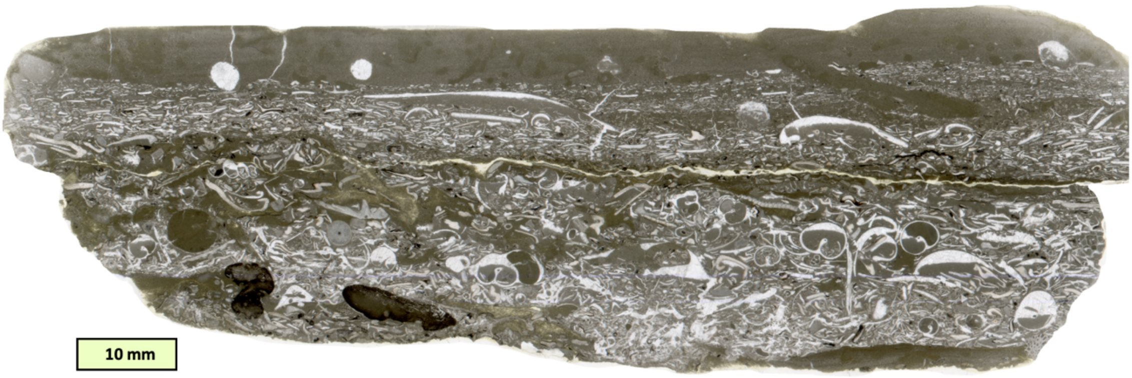


Fig. A65. Vertical section of polished block showing:
Lower: 2 small lithoclasts, bottom left, and an upward-graded deposit of shell deposit.
Upper: Micrite layer with small burrows with a lighter-gray fill.
Sample: Follingbo3-15; Photofile: A-12f-Follingbo3-15-vi.

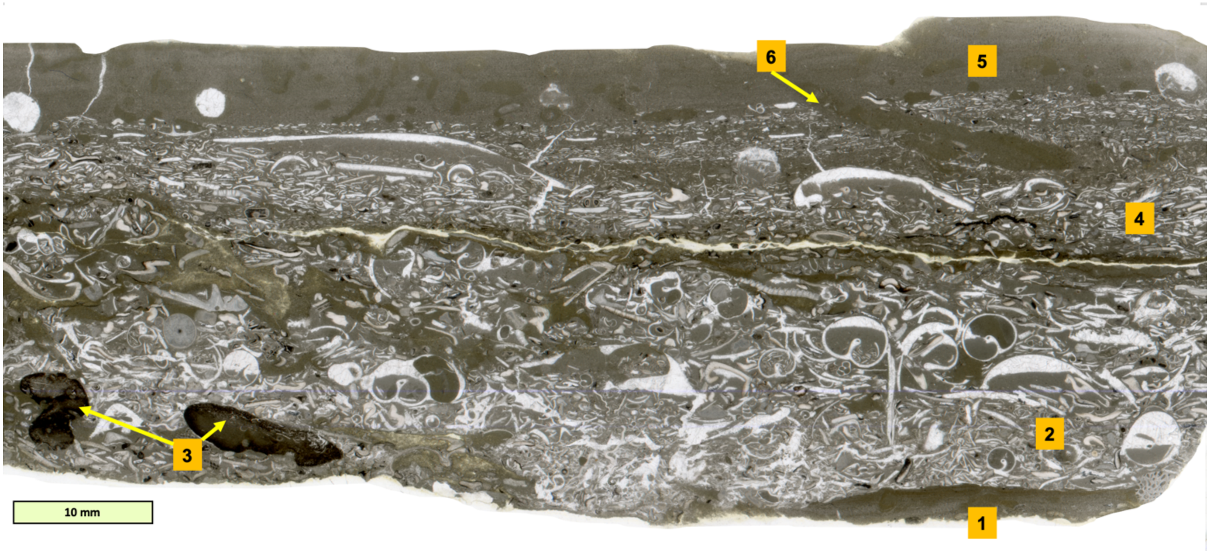


Fig. A66. Enlargement of Fig. A65, showing more details of this sample.
1: Part of a lithoclast at bottom of sample.
2: Poorly-sorted packstone.
3: Highlights the two small lithoclasts, lower left.
4: shows changes in the layering as the sequence developed. Note this sample has a horizontal fracture about halfway up the specimen; on the left edge it looks like this is an erosion surface that has formed a horizontal weakness in the specimen.
5: The upper layer of micrite is uniform with no shell debris included. Faint burrows are visible. This deposit is interpreted here to indicate a low energy environment.
6: a burrow from the upper (micritic) layer has penetrated into the shell debris at the top of the lower layer; this is interpreted to indicate excavation of the lower layer after partial lithification, and indicates the lower layer underwent fairly rapid lithification after burial.
Sample: Follingbo3-15; Photofile: A-12g-Follingbo3-15-vii.

SAMPLE 11

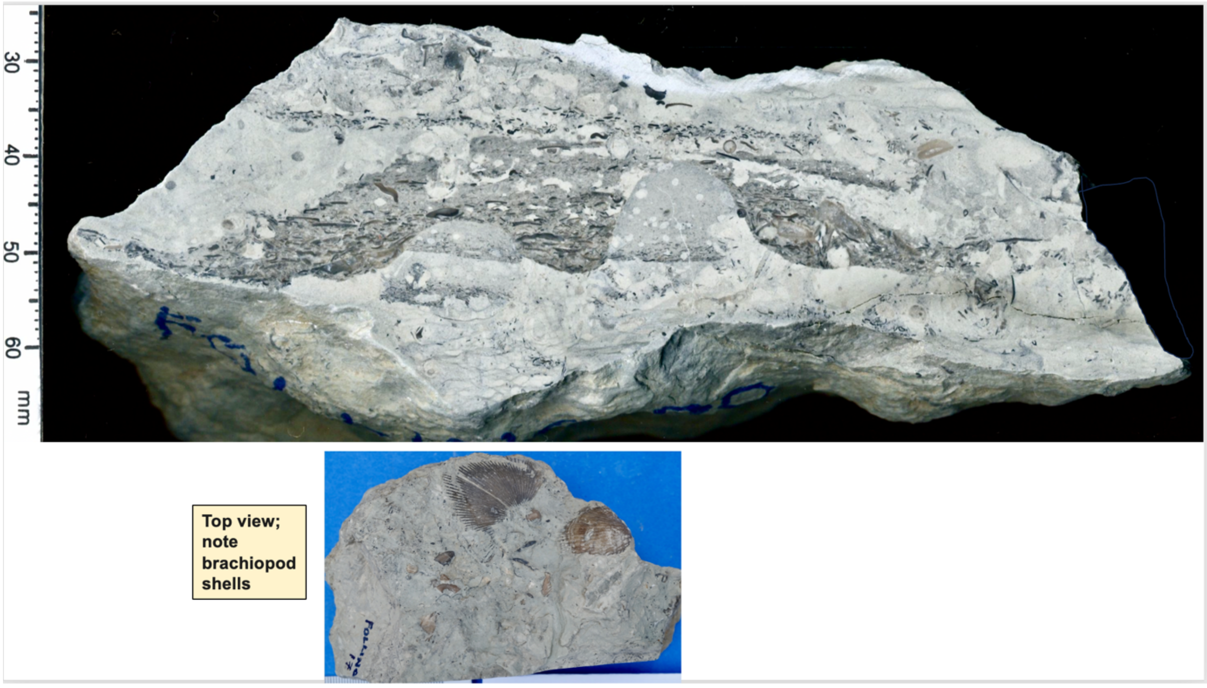


Fig. A67.
Upper: Vertical section of polished block showing undulose erosion surface and complex layering, described in thin section in Fig. A68.
Lower (inset): Shows two large entire brachiopod valves on upper surface, showing very good preservation, as undamaged valves.
Sample: Follingbo3-17; Photofile: A-13a-Follingbo3-17-i.

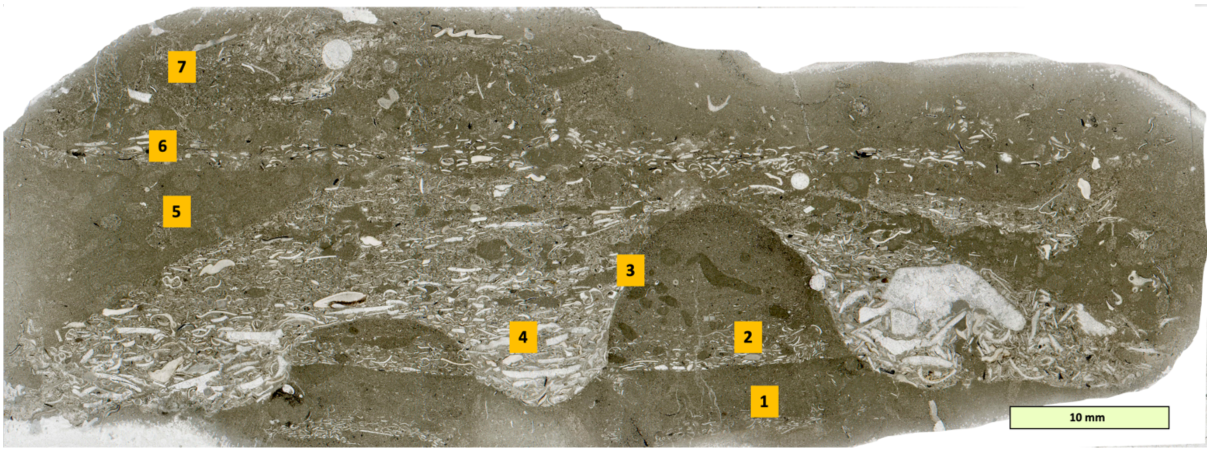


Fig. A68. Vertical thin section of a parallel plane, close to that shown in Fig. A68.
1: Carbonate mudstone at base.
2: Wackestone grading upwards to carbonate mudstone, with interpreted burrows infilled with dark micrite; their sharp edges may be evidence of partial consolidation of layer 2 matrix. However, it is possible that these dark objects are micritic lithoclasts rather than burrows, noting that Layer 4 also has dark objects, see below.
3: Undulose erosion surface eroding Layers 1 and 2, which are thus interpreted as having been somewhat consolidated prior to erosion. However, note that on the right side of the right-hand erosional dome a small circular pale object, presumed a rod-like fossil in cross-section, partly embedded in Layer 2, but also partly protruding;

this is interpreted to indicate erosion of Layer 2 matrix, to leave the harder calcite fossil protruding, thereby indicating the sediment was not fully lithified.
4: Upward fining wackestone, with small elongate dark irregular objects that may be lithoclasts rather than burrows.
5: On left side, a wedge of calcareous mudstone with mottling interpreted as burrowing. This sediment seems to have been deposited on a sloping surface of Layer 4 indicating that Layer 4 was eroded before the wedge of 5 was laid down. On right side, the facies shows interdigitation of micrite and wackestone, with curving irregular contacts, that might indicate small-scale erosion of these layers, implying partial consolidation.
6: Erosion surface across the top of Layers 4 & 5, implying removal of some material before the thin layer of shell debris was deposited.
7: Calcareous mudstone with mottling that is presumed due to burrowing, and some shell debris locally.
Sample: Follingbo3-17; Photofile: A-13a-Follingbo3-17-ii.

Overall, this sample shows the small scale complexity present in the Follingbo facies, and demonstrates the dynamic state of the environment of these sediments.

SAMPLE 12

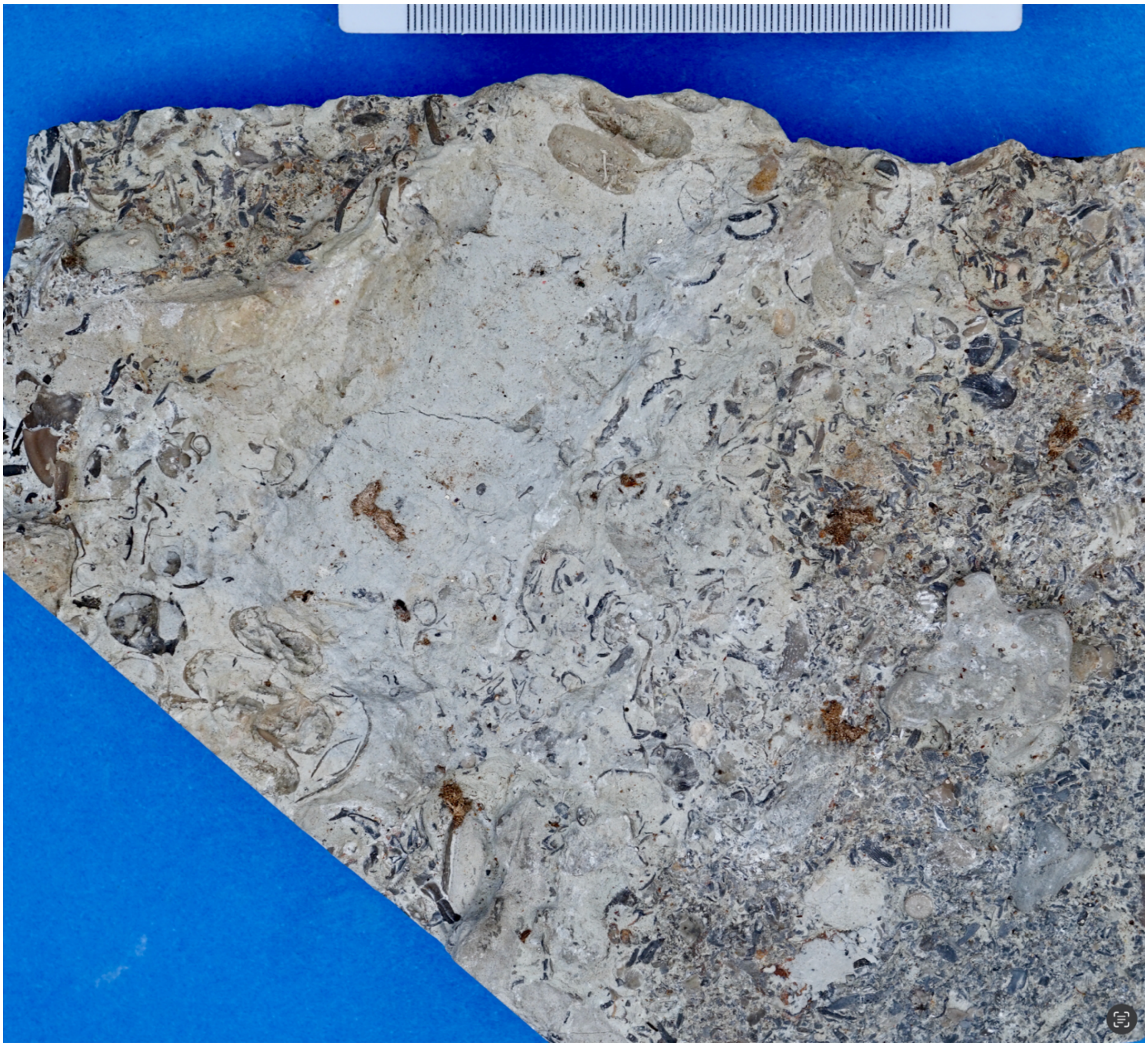


Fig. A69. Surface view of a slab of Follingbo limestone. The centre-left part of the slab is dominated by a large orthoconic nautiloid, preserved as a mould. The remainder of the surface is awash with fine shell debris.
Sample: Follingbo3-20; Photofile: A-14a-Follingbo3-20-i.

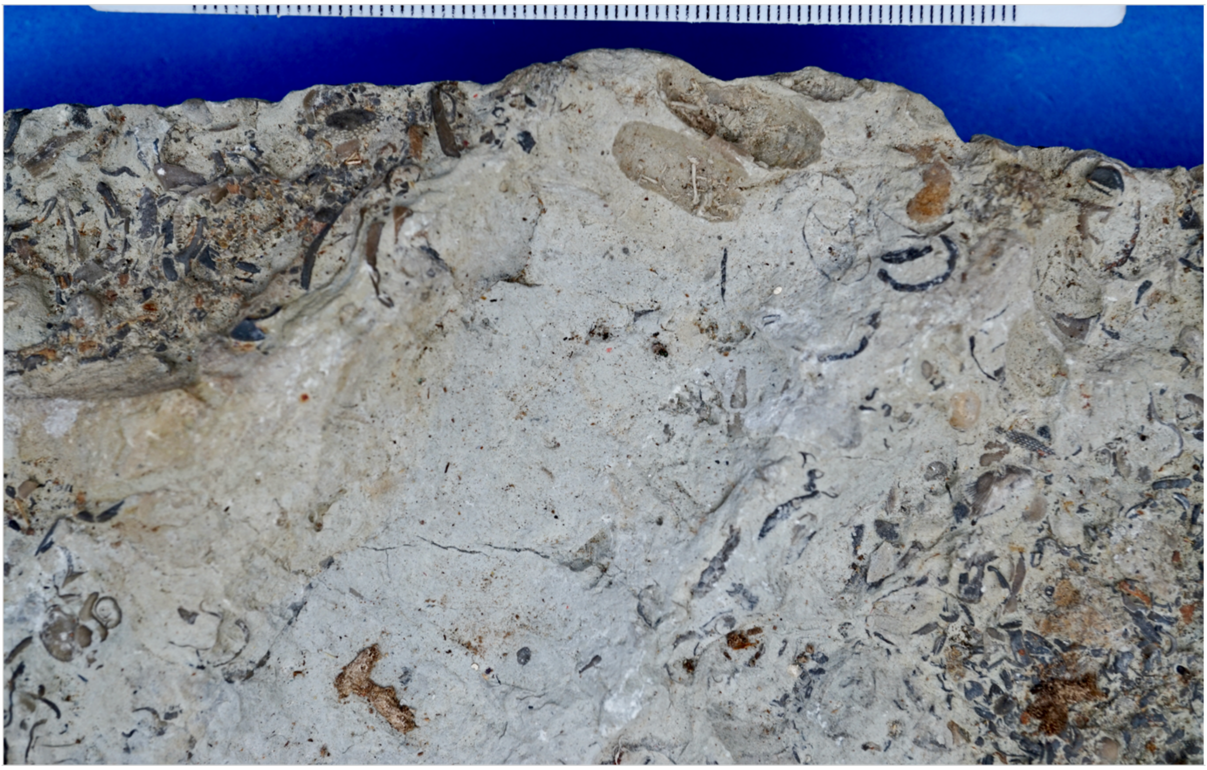


Fig. A70. Detail of the orthocone; the elliptical dark objects top-centre are impressions of the ribbing in the orthocone, all preserved as internal mould.
Sample: Follingbo3-20; Photofile: A-14a-Follingbo3-20-ii.

Fig. A71. Detail of the shell debris.
Sample: Follingbo3-20; Photofile: A-14a-Follingbo3-20-iii.

Fig. A72. More detail of shell debris and a small lithoclast of carbonate mud centre-left.
Sample: Follingbo3-20; Photofile: A-14a-Follingbo3-20-iiii.

SAMPLE 13

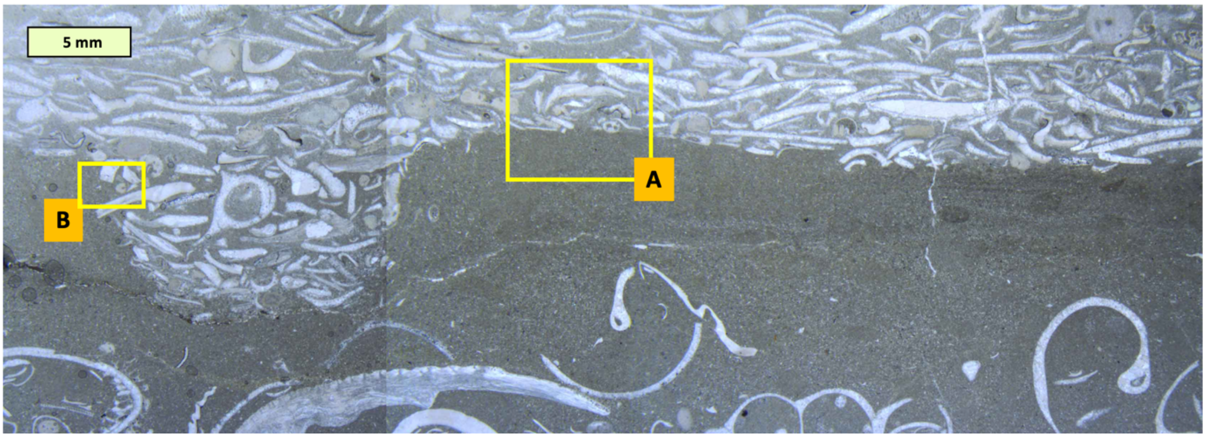


Fig. A73.
Upper: Vertical thin section scan, showing two Layers; Layer 1 is a packstone that passes up into carbonate mudstone and has an erosion surface with a hollow on the left side. Layer 2 is a packstone of shell debris.
Lower: Detail of contact area between Layers 1 & 2, showing the sharp contact. A and B are locations shown in Figs. A74 & 75 (A) and A76 & 77 (B).
Sample: Follingbo3B; Photofile: A-15a-Follingbo3B-i.

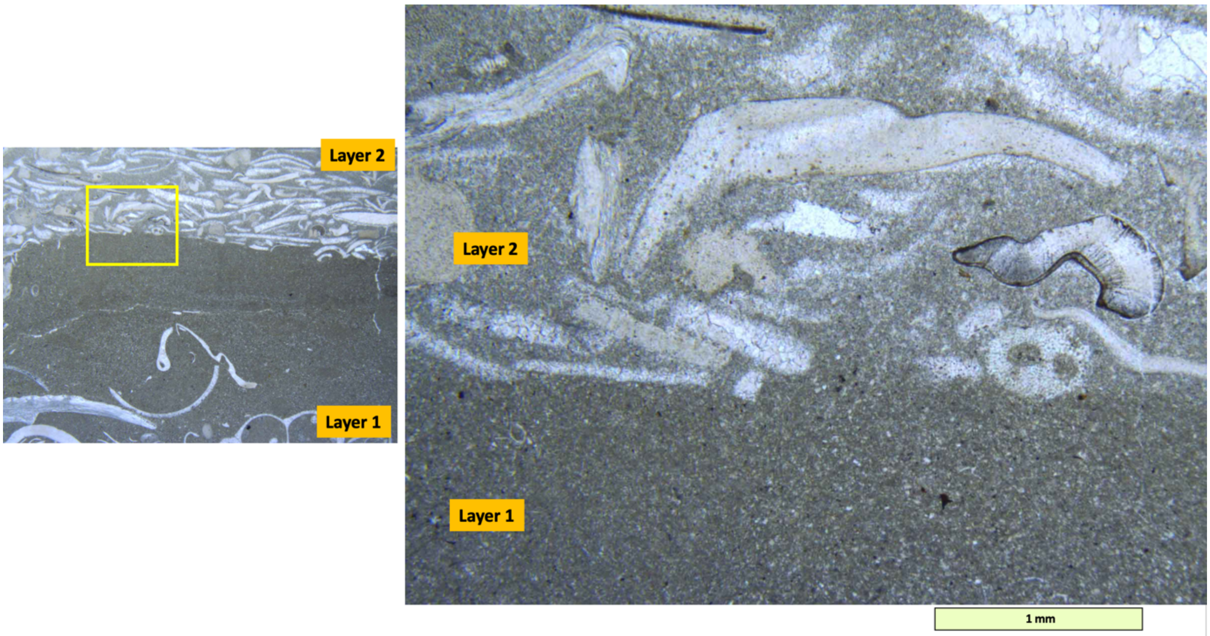


Fig. A74. In this enlargement of area A in Fig. A73, the contact between Layers 1 & 2 is not as sharp as it appears at lower resolution. See next figure.
Sample: Follingbo3B; Photofile: A-15a-Follingbo3B-ii.

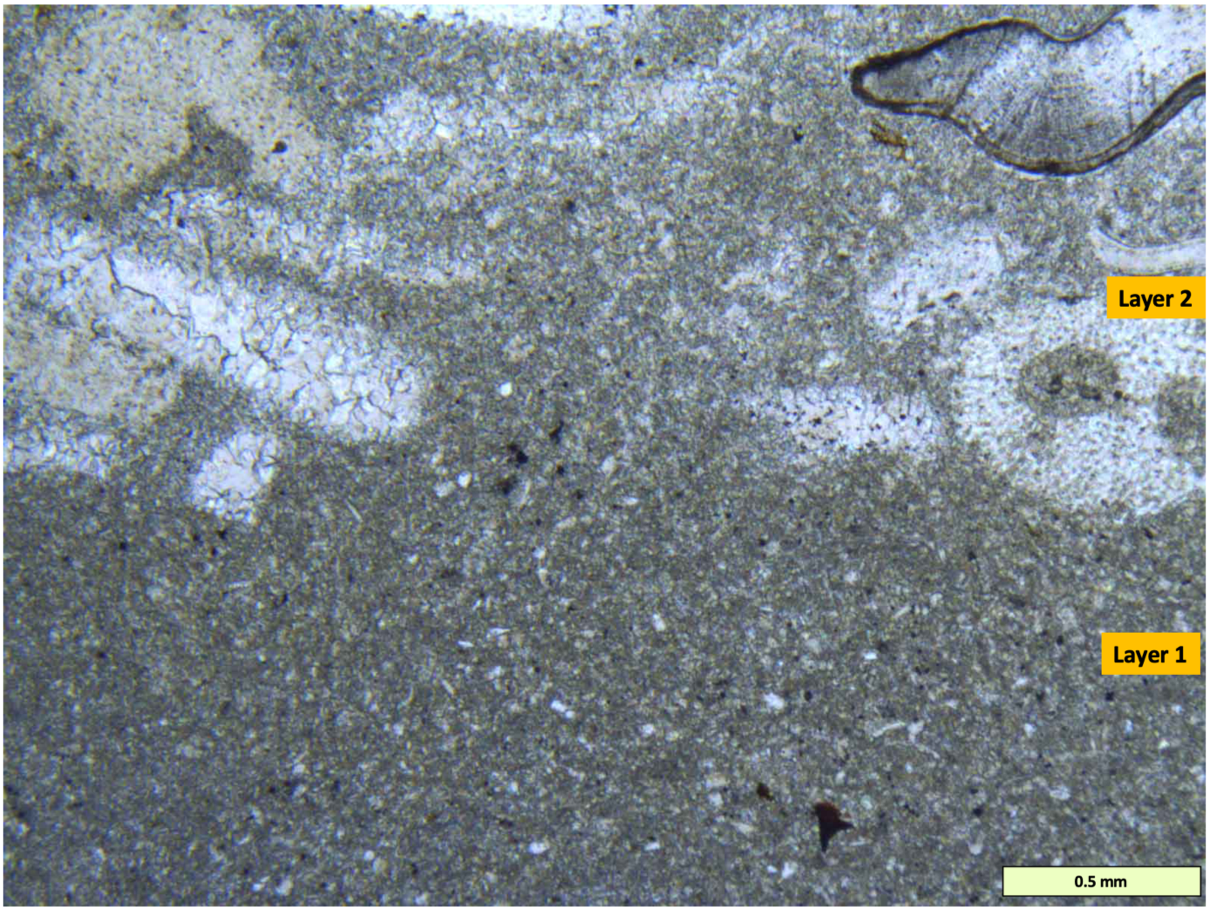


Fig. A75. Close detail of contact between Layers 1 & 2 shows there is barely a recognisable contact.
Sample: Follingbo3B; Photofile: A-15a-Follingbo3B-iii.

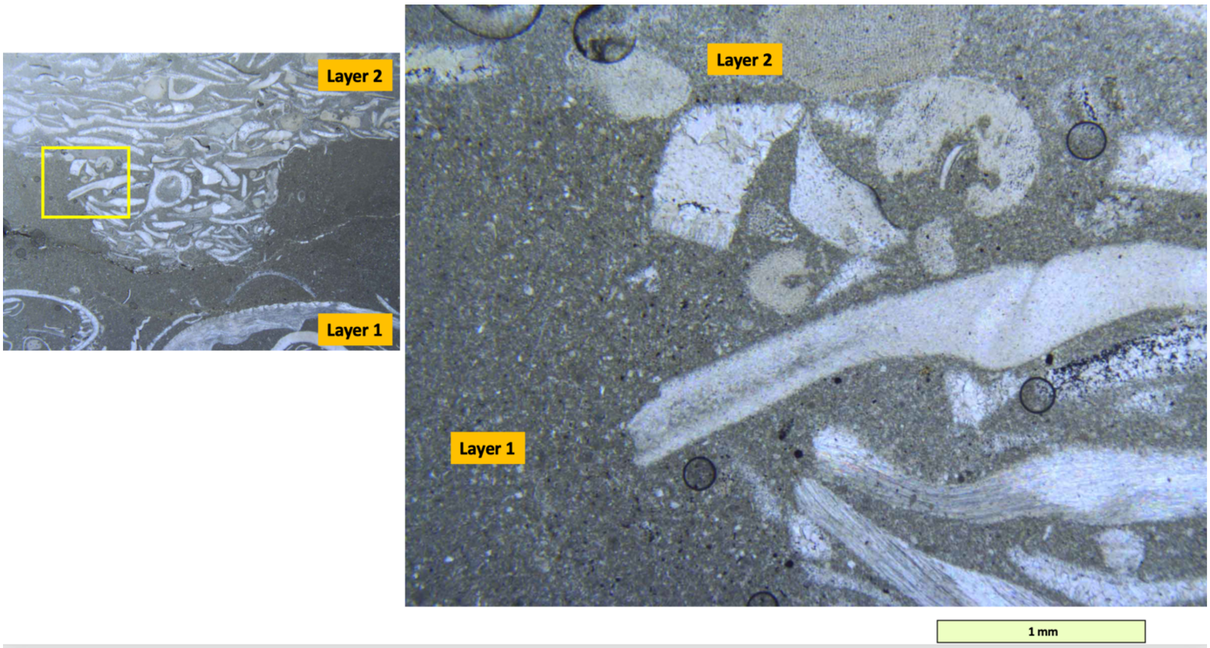


Fig. A76. In this enlargement of area B in Fig. A73, again the contact between Layers 1 & 2 is not clear, and the central elongate shell fragment in the photo crosses into Layer 1, although it is seemingly part of Layer 2 material. [sorry about the air bubbles].
Sample: Follingbo3B; Photofile: A-15a-Follingbo3B-iiii.

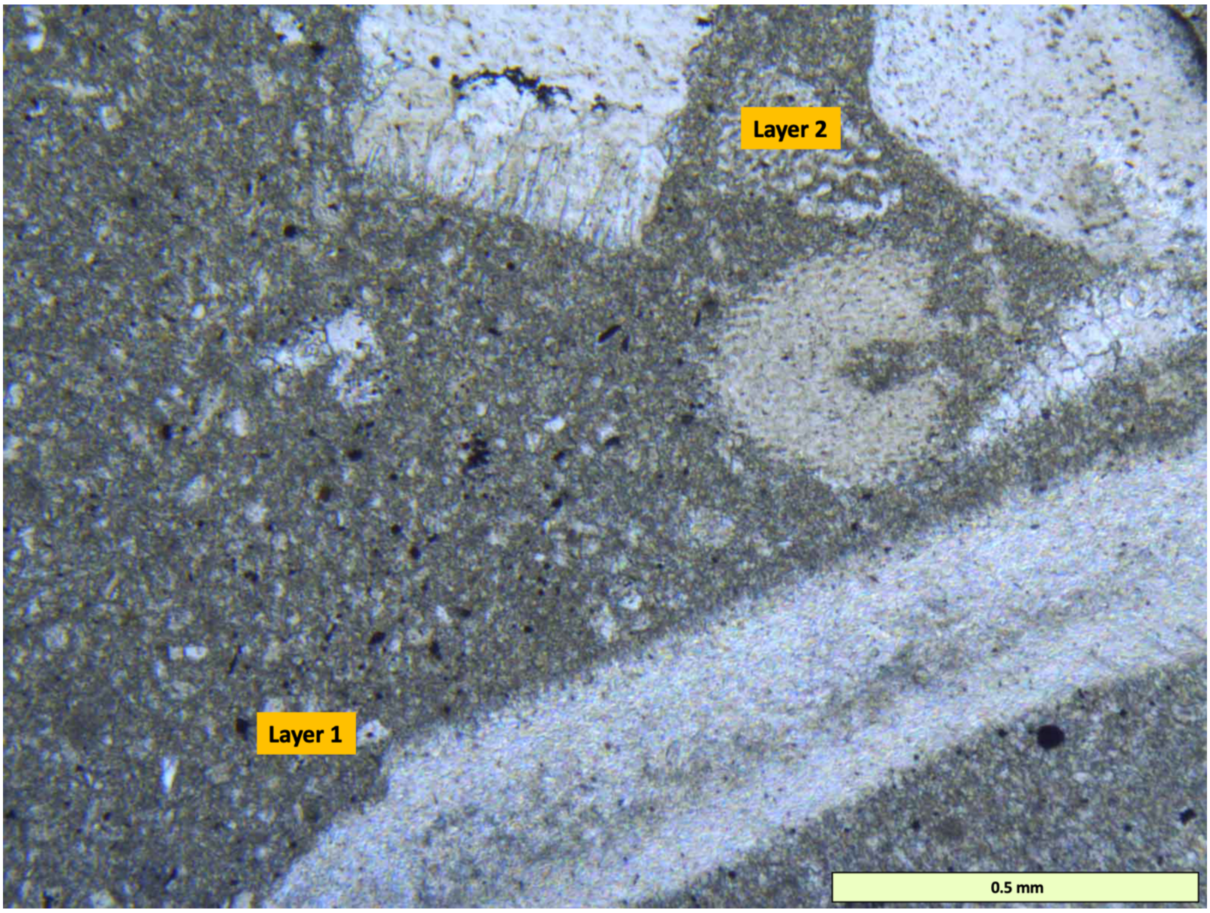


Fig. A77. Fine detail of contact between Layers 1 & 2, showing no discernible contact line. Also the large shell at bottom passes between the two Layers. *Sample: Follingbo3B; Photofile: A-15a-Follingbo3B-v*.

Overall, this sample is evidence of erosion of soft sediment, so that no erosion surface can be recognised. In the case of area B, the large shell shown in Figs. A76 & A77 seems to have been pushed into the sediment of Layer 1, because Layer 1 was soft sediment. This is the best sample in the set, to show soft sediment consistency, indicated by the lack of a sharp contact between the layers.

SAMPLE 14

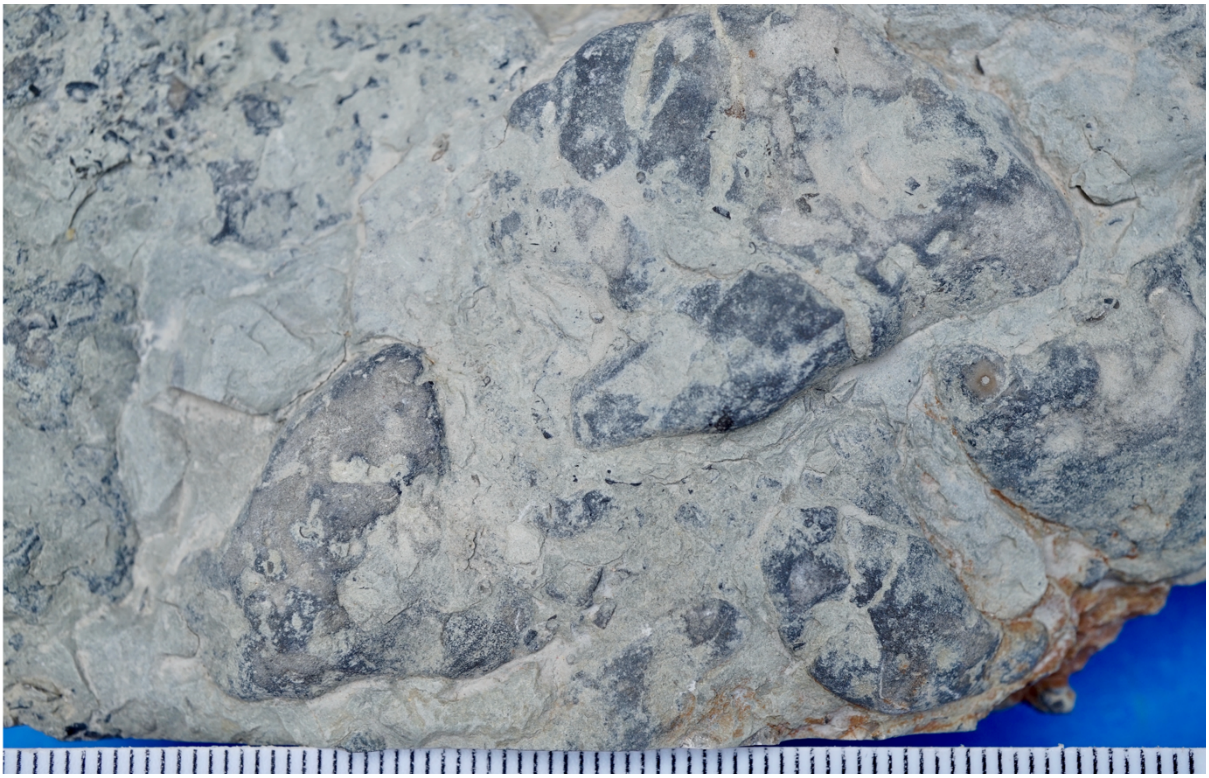


Fig. A78. Top surface view of piece of Follingbo limestone with numerous lithoclasts, that have mineralised margins and may have been eroded from a hardground elsewhere. In right side centre, the lithoclast here has a crinoid holdfast (small brown object with a tiny light-coloured centre, ca 3mm diameter).
Sample: Follingbo3-X; Photofile: A-16a-Follingbo3-X-i.

Fig. A79. Vertical thin section of sample in Fig. A78, showing the lithoclasts and shell packstone.
Sample: Follingbo3-X; Photofile: A-16a-Follingbo3-X-ii.

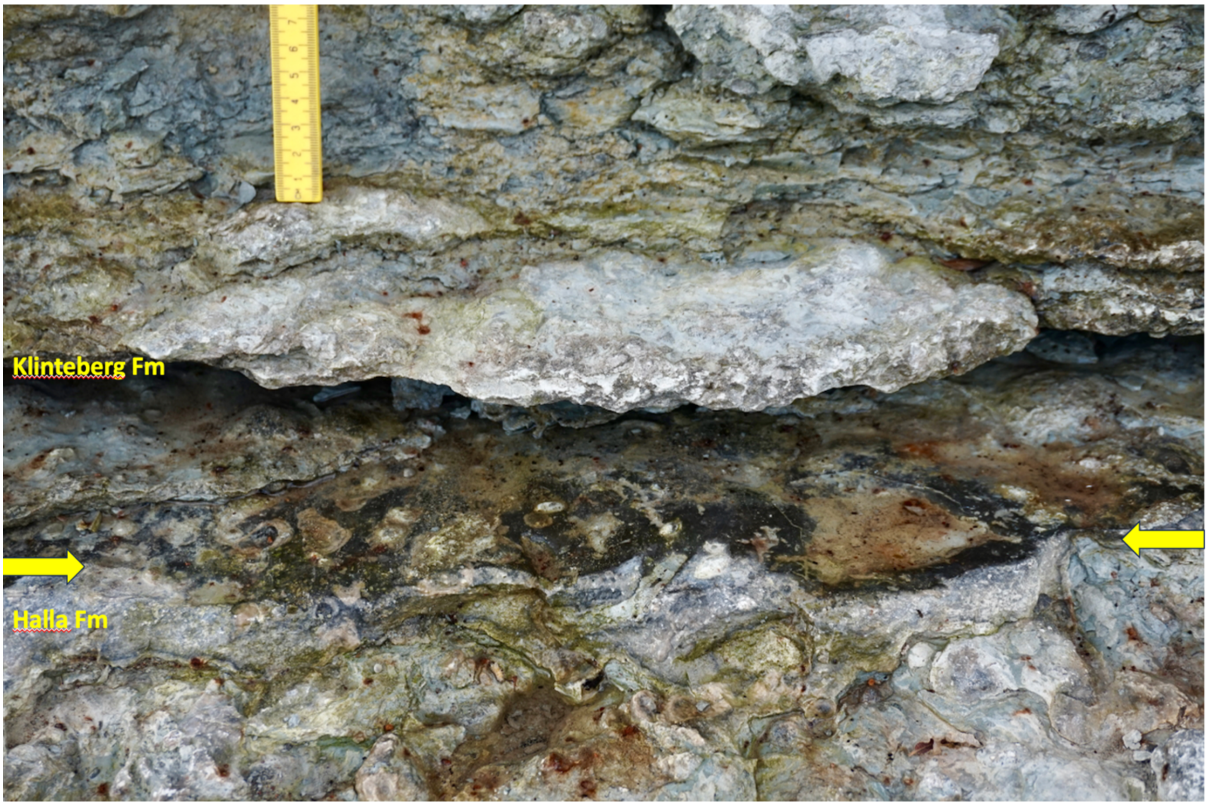


Fig. A80. For comparison with the previous photos of mineralised surfaces of limestone exposed on the sea bed for an extended period of time. Field photo from the contact between the Halla and Klinteberg Formations, with a mineralised hardground surface (yellow arrows) that mark the formations' contact. This image is provided for comparison with the lithoclasts in the Follingbo material, noting the Halla-Klinterberg boundary material is late Wenlock, younger than the Follingbo material that is Slite Group. Gothemshammar 2 locality.
Photofile: Gothemshammar.

PART A-3: Details of my own samples from Slitebrottet

What is Slitebrottet? It is a quarry site on eastern Gotland, in the Slite marl unit, as described in the introduction. Below are descriptions of 3 samples, that show some more characterstics of the Slite marl limestones. See Laufeld (1974) for descriptions of Slitebrottet site.

SAMPLE 15

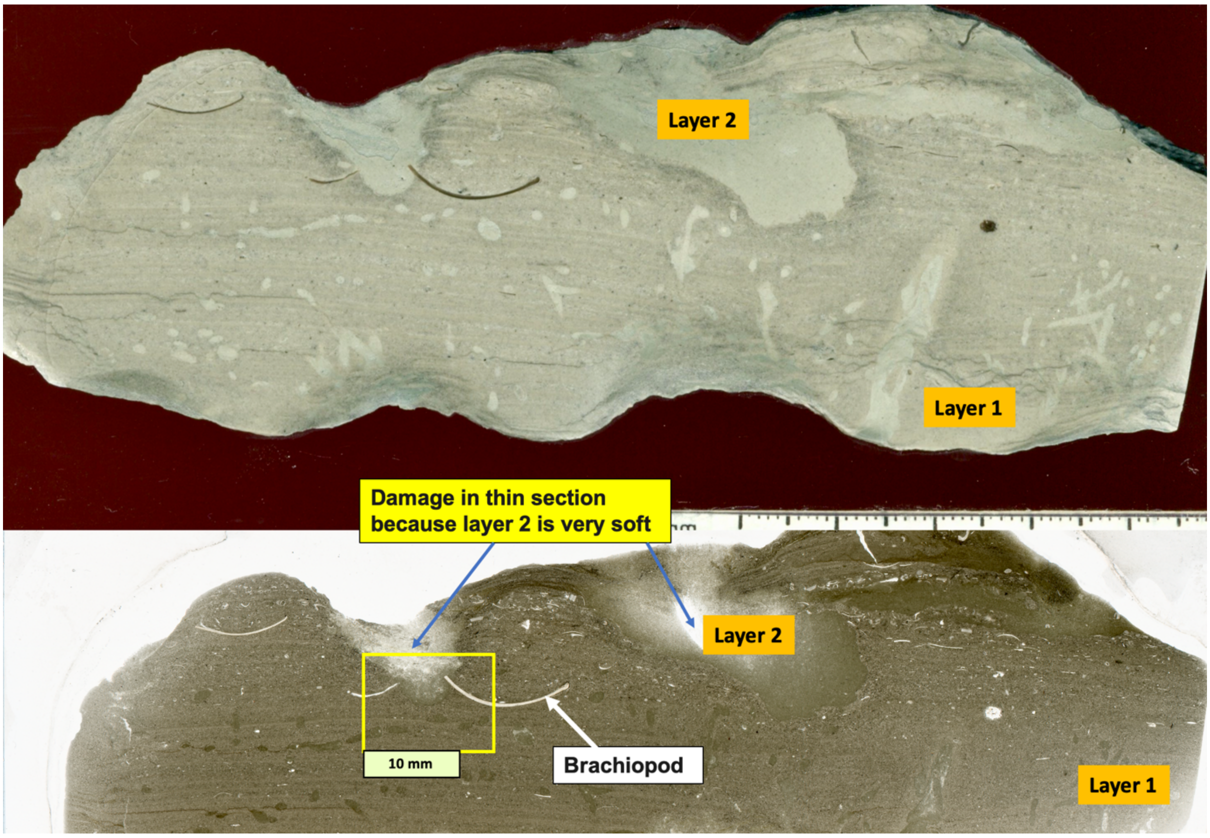


Fig. A81.
Upper: Vertical section of polished block showing two layers with an irregular erosion surface.
Lower: Vertical thin section scan of this polished block face, showing some shell valves in Layer 1 that protrude into Layer 2. Note that Layer 2 sediment was very soft and some loss occurred when thin section was made. See Fig. A82 for details in yellow box.
Sample: SL.BR.2-2-i-b; Photofile: A-17a-SL.BR.2-2-i-b-i.

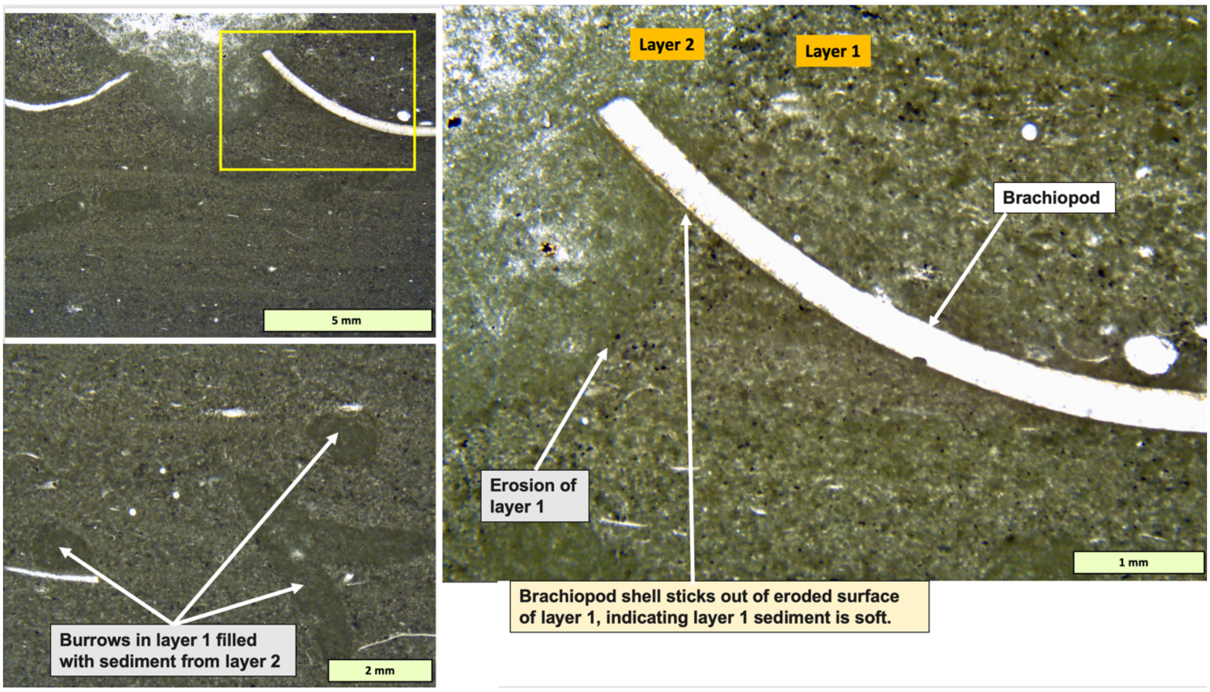


Fig. A82.
Upper Left: Detail of contact between Layers 1 & 2, showing the shell protruding from Layer 1 into Layer 2 sediment.
Upper Right: More detail of this feature, interpreted to indicate that Layer 1 sediment was very soft and eroded, so that the brachiopod shell protruded, then was covered by Layer 2 sediment.
Lower Left: Enlargement of Layer 1 with dark areas indicating burrows filled with dark sediment. These may indicate the Layer 1 sediment was partly consolidated, noting that it is unknown as to whether the burrows had soft-tissue linings or not. If the burrows were lines, then the sediment of Layer 1 may have been soft when the burrows were made.
Sample: SL.BR.2-2-i-b; Photofile: A-17a-SL.BR.2-2-i-b-ii.

SAMPLE 16

Fig. A83. Surface view of thin irregular slab of Slite Marl limestone, showing much shell debris and lithoclasts with dark mineralised surfaces.
Sample: SL.BR.2-3-i; Photofile: A-18a-SL.BR.2-3-i-i.

Fig. A84. Detail of surface showing trilobites and *Ptilodicyton* bryozoan frond (centre), plus shell debris and lithoclasts.
Sample: SL.BR.2-3-i; Photofile: A-18a-SL.BR.2-3-i-ii.

Fig. A85. Vertical section of polished face of sample in Figs. A83 & 84, showing packstone-wackestone fabrics with geopetals.
This sample is from the Slitebrottet site in western Gotland, not from Follingbo.
Sample: SL.BR.2-3-i; Photofile: A-18a-SL.BR.2-3-i-iii.

Fig. A86. Vertical thin section scan of sample illustrated in Fig. A85, revealing two layers. Note the shells strongly embedded in the lower micrite-rich layer with their tops in the upper wackestone layer. Also in centre is a shell apparently stuck onto the contact between the two layers. This arrangement is interpreted to indicate that the lower layer was partially consolidated, but subject to some winnowing of the matrix, leaving shells sticking up out of its surface, and then all was buried in Layer 2.
Sample: SL.BR.2-3-i; Photofile: A-18a-SL.BR.2-3-i-iiii.

SAMPLE 17

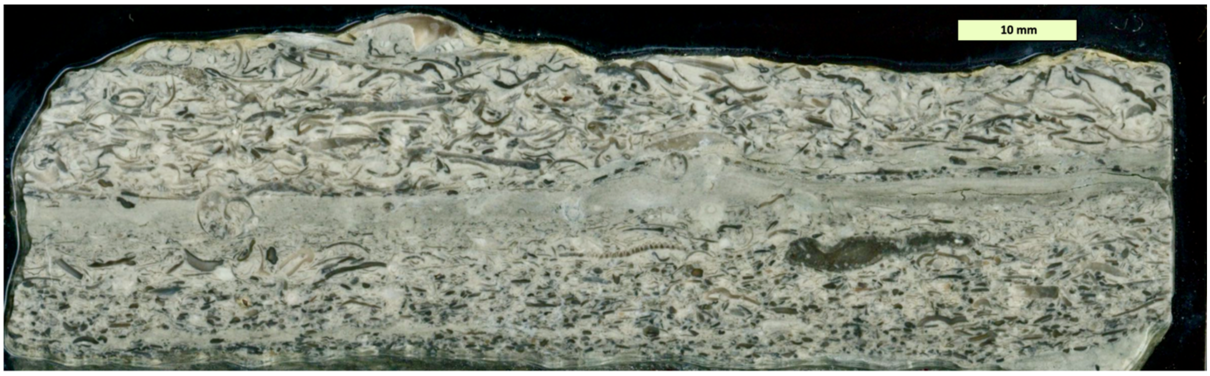


Fig. A87. Vertical section of polished block showing 3 layers, two packstone layers with a micritic layer between them. Mottling in the micrite layer is interpreted as indicating burrowing of the soft sediment, during a low energy episode between the higher energy events of the lower and upper layers.
Sample: SL.BR.2-5-I; Photofile: A-19a-SL.BR.2-5-i-i.

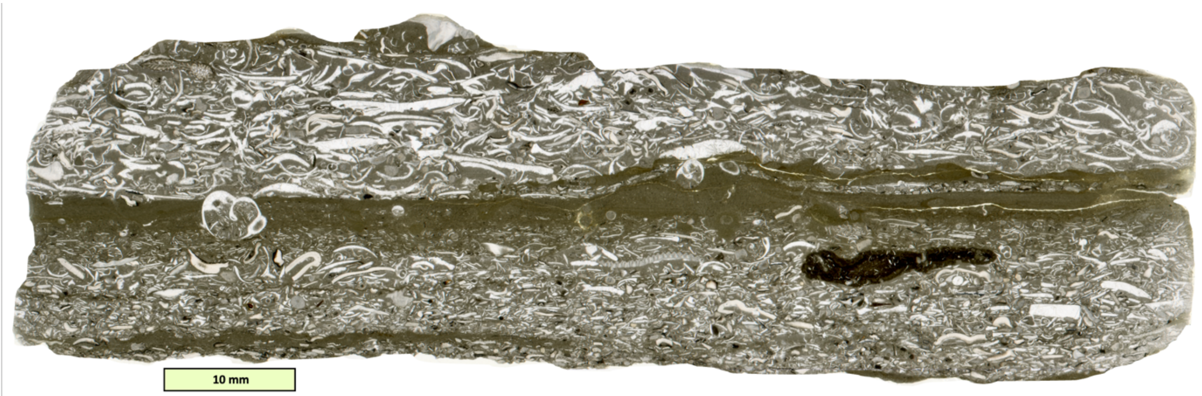


Fig. A88. Vertical thin section of the face illustrated in Fig. A87, showing upward-fining shell debris in lower layer, and an interpreted period of quiescence to deposit the central, micritic layer, followed by a small amount of erosion and deposition of the packstone in the upper layer. A lithoclast (dark) is in the lower layer on right side.
Sample: SL.BR.2-5-I; Photofile: A-19a-SL.BR.2-5-i-ii.

Fig. A89. Gotland has some very nice honey, and I found this in September 2023 on sale. “Nyslungad” means “Newly launched”; it’s very tasty.
Photo file: A-20-FollingboHoney-Mod.

PART A-4: Summary of Follingbo and Slitebrottet samples

From the details of photos shown in this section it should be possible to recognise a pattern.

1) Some of the material can be interpreted as being soft sediment when erosion processes affected it.
2) Some material indicates a partial lithification, but sufficiently soft to be eroded by subsequent current action.
3) Some material is more fully lithified, so that erosional surfaces are created, with sharp contacts.
4) Some material was fully lithified into solid rock matter and then eroded (most obvious from lithoclasts).

Some structures that may be burrows are equivocal. Some are certainly burrows, but the problem is whether the burrows were lined with soft tissue while the burrowing animals were alive. If so then it is possible that the sharp contacts between burrow and matrix may be simply indicating such soft tissue, and thus the sediment may have been unconsolidated. Otherwise, the sediment may have been partially consolidated when burrowing occurred. Proving the difference between these two possibilities may not be possible. Some of the possible burrows may instead be small intraclasts, rather difficult to be sure from 2D thin sections.

PART B: COMPARISONS

Part A presented all my material from the Slite Marl, from Follingbo and Slitebrottet sites. In this section are some comparisons with other evidence of ancient sea floor lithification processes, one from a Middle Jurassic site in England, that I worked on some years ago, and one from Gotland.

PART B-1: BACKGROUND

A famous study by Sandberg (1983) proposed the idea of changing global water chemistry through the Phanerozoic Eon, and is commonly known as the Sandberg Curve, also as the Aragonite and Calcite Seas hypothesis. Fig. B01 shows this curve.

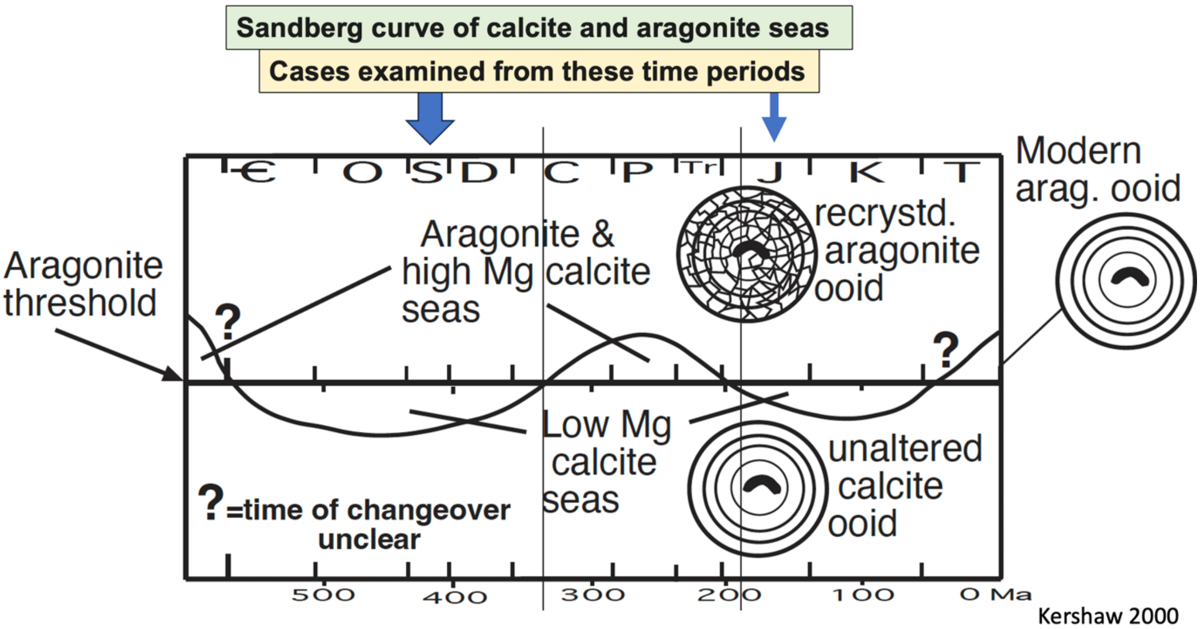


Fig. B01. Sandberg curve of aragonite and calcite seas. The study was based on the structure of ooids, and it was recognised that ooids of different ages have two states of preservation: recrystallised ooids versus unaltered ooids. The crystallised ooids are interpreted to have been composed of aragonite, or possibly high-Mg calcite (HMC), while unaltered ooids were calcite (=low-Mg calcite, LMC). These two states are recognised according to the curve in relation to the geologic timescale. You can read lots about the aragonite-calcite seas debate in various books and papers. Of great interest is that well-lithified ancient sea floors, also called hardgrounds, are more prominent in the calcite seas times. There is a good review of hardgrounds in Christ et al. (2015), Earth Science Reviews, 151,176-226, where the authors emphasise the prevalence of hardgrounds in calcite seas times. Examples illustrated in this atlas are all from calcite seas strata, shown by the two blue arrows above the diagram (the thicker arrow is the Silurian deposits that are the focus of this atlas). From Kershaw (2000).
Photofile: B-01-SandbergCurve.

Below is illustrated a well-known case of hardgrounds: the Middle Jurassic Period; the example shown is from some of my older work (Kershaw & Smith 1986).

PART B-2: JURASSIC HARDGROUND OF CENTRAL ENGLAND

Jurassic hardgrounds are well-known in the literature as a feature of calcite seas times. At Foss Cross, near Cirencester, midlands of England was exposed several tens of sq m of hardground as preparation for a landfill site, in 1980; in 1981 I sampled the site with a student. The material gives clear evidence of early lithfication processes in calcite-seas times.

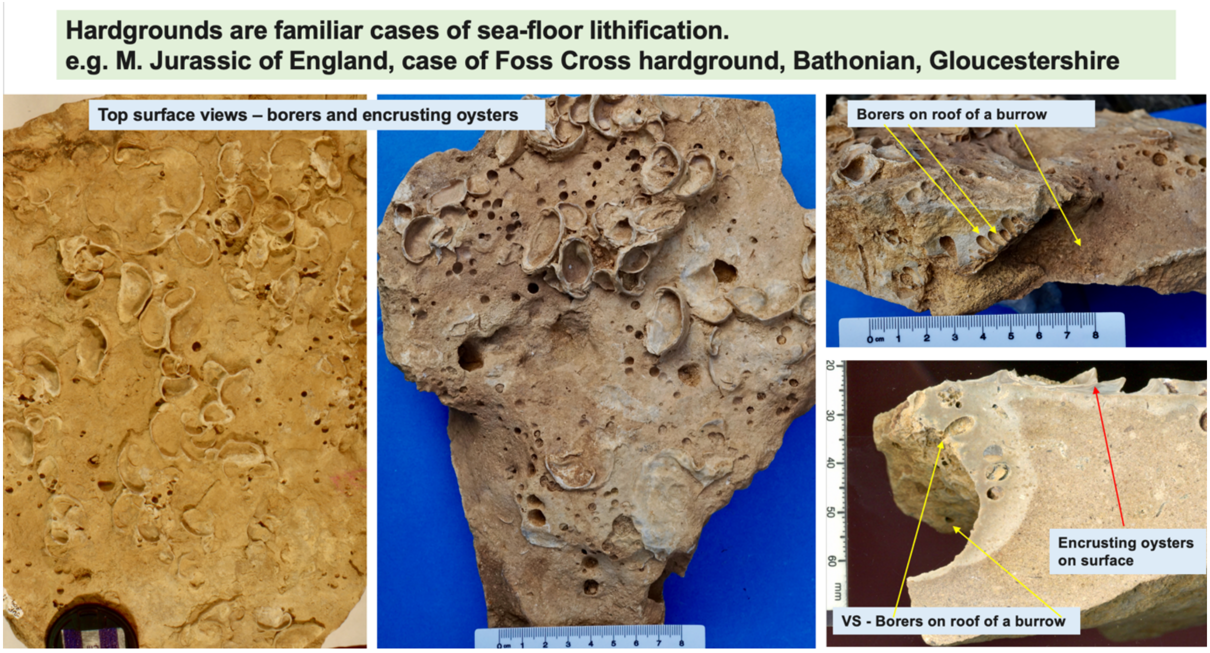


Fig. B02.

Left: Upper surface view of slab of Foss Cross hardground, showing encrusting oysters and bivalve borings. There are two taxa of oysters, a large plate-form (top) and the more common small *Nanogyra*. This specimen was donated to the National Museum of Wales in Cardiff.

Middle and upper right: Upper surface view of piece of Foss Cross hardground, showing stacks of small oysters (*Nanogyra)* and some borers of rock-boring bivalves; two of the borers have been eroded out to reveal the base of the borehole, indicating some thickness of the hardground surface was removed by erosion. The upper right photo shows the sample at an oblique angle, to indicate the large burrow; the burrow roof has rock-boring bivalve holes in its roof. This specimen was donated to the Earth Sciences Department, Cambridge University.

Lower right: Vertical section of small piece of hardground including a burrow, so it shows the upper surface of the hardground and the shape of a burrow [including bivalve borings in its roof] (I still have this sample!).

Photofile: B-02a-FossCross01.

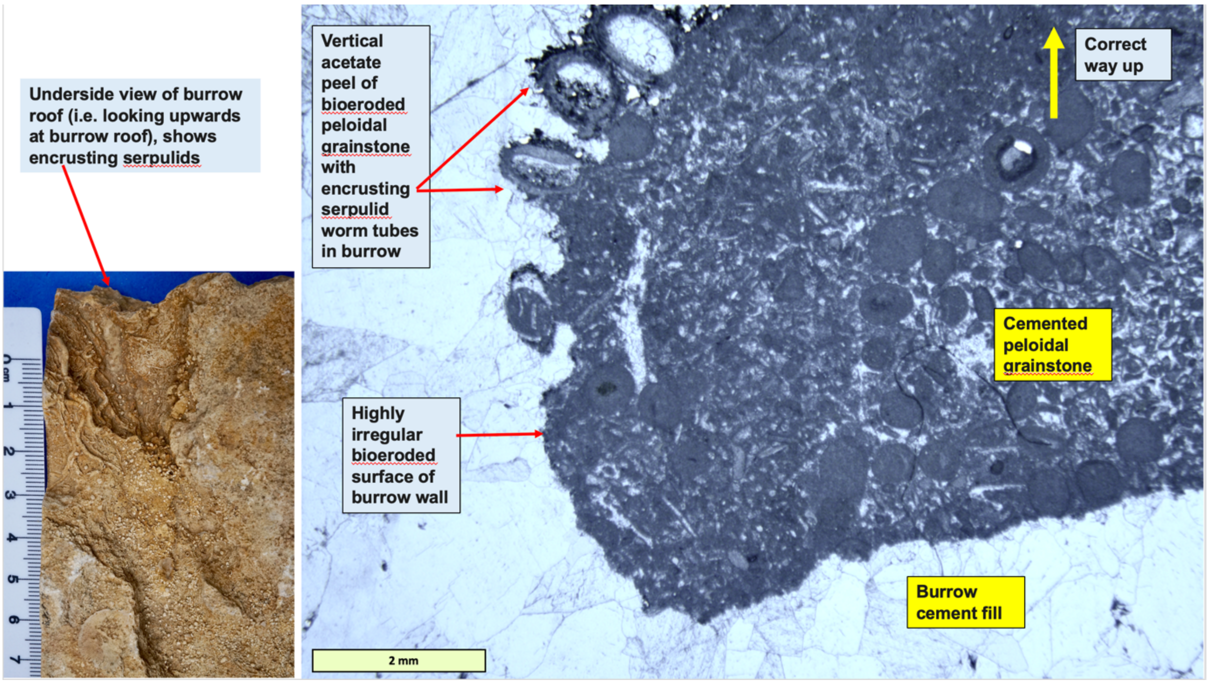


Fig. B03. The ecology of faunas associated with Jurassic hardgrounds includes the encrustation of the roofs of burrows by various organisms. In this case they are serpulid worm calcified tubes.

Left photo: shows the roof of a burrow, as if you were inside the burrow looking up; the roof is encrusted by serpulid worm tubes.

Right photo: shows vertical cross section in an acetate peel of a cement-filled burrow that preserved the irregular form of the burrow wall. You can see the highly irregular surface of the burrow wall, that is almost certainly have been caused by bioeroding organisms that nibbled away at the burrow wall to produce the micro-irregularity seen here. Then, later, the wall was encrusted by serpulids, seen here as cross-sections of tubes (which even have geopetals in them!). The limestone of the bedrock here is a peloidal grainstone; acetate peels are not always excellent to show carbonate features, but this one does show the grains well.

Photofile: B-02b-FossCross02.

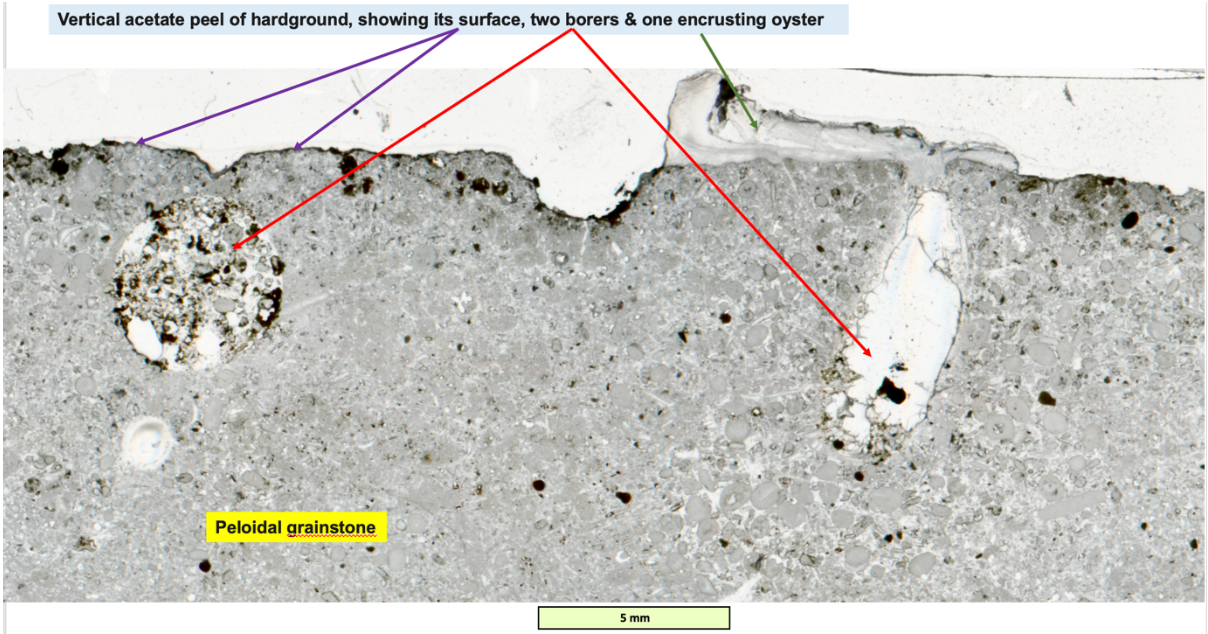


Fig. B04. Acetate peel, vertical section through top surface of hardground, showing *Nanogyra* oyster encrusting the eroded hardground surface. There are two borings in the hardground, the left one is filled with sediment from above the hardground, the right boring is empty. The peel shows the sediment is made of peloidal grainstone.
Photofile: B-02c-FossCross03.

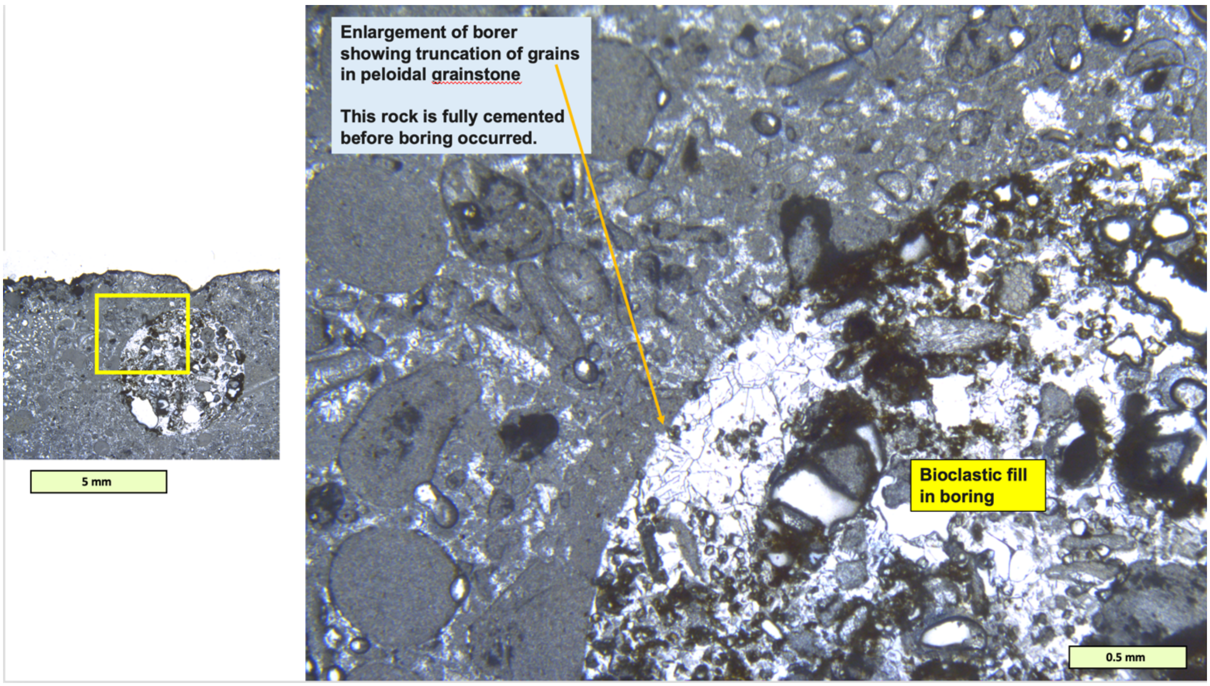


Fig. B05. Enlargement of the left-hand borehole from Fig. B04, showing the borer has truncated grains in the peloidal grainstone mass. The smooth shape of the borehole wall indicates the peloidal grainstone bedrock has been lithified before boring. Unfortunately it is not possible in this peel to see details of the cements between grains of the peloidal grainstone; more on this later.
Photofile: B-02d-FossCross04.

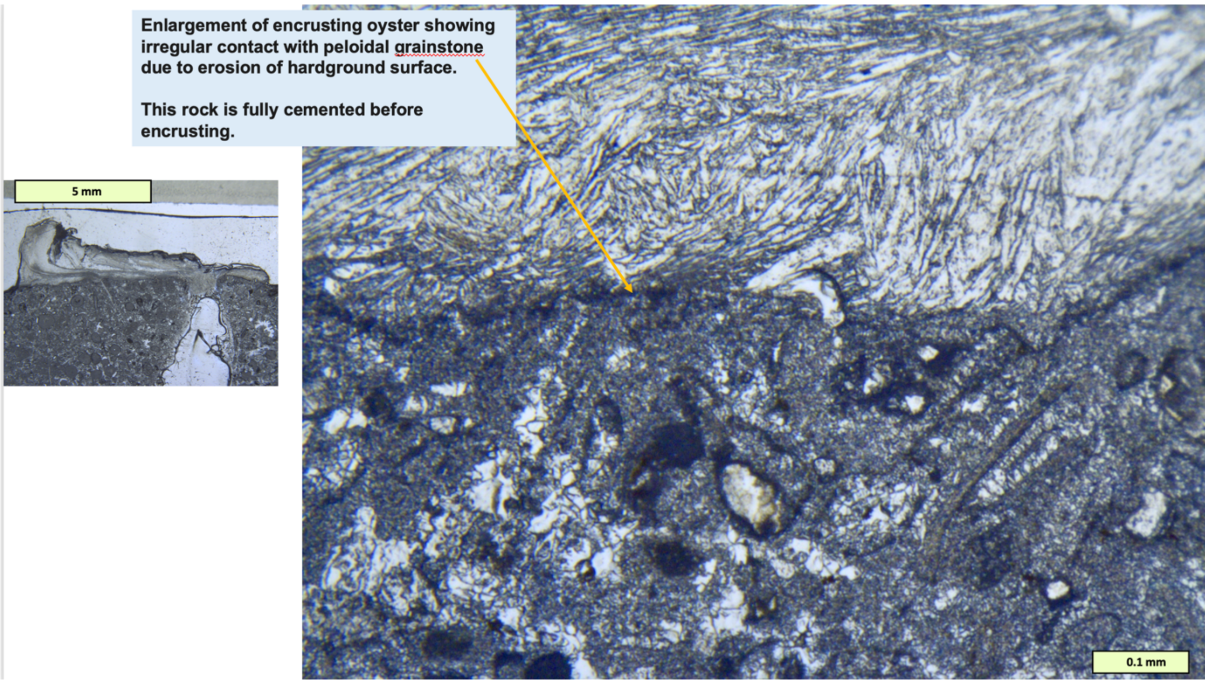


Fig. B06. Enlargement of hardground surface with encrusting oyster. Note irregular contact and the way the oyster fits tightly onto the sedimentary rock surface. Again this shows the cementation of the sediment to solid rock.
Photofile: B-02e-FossCross.

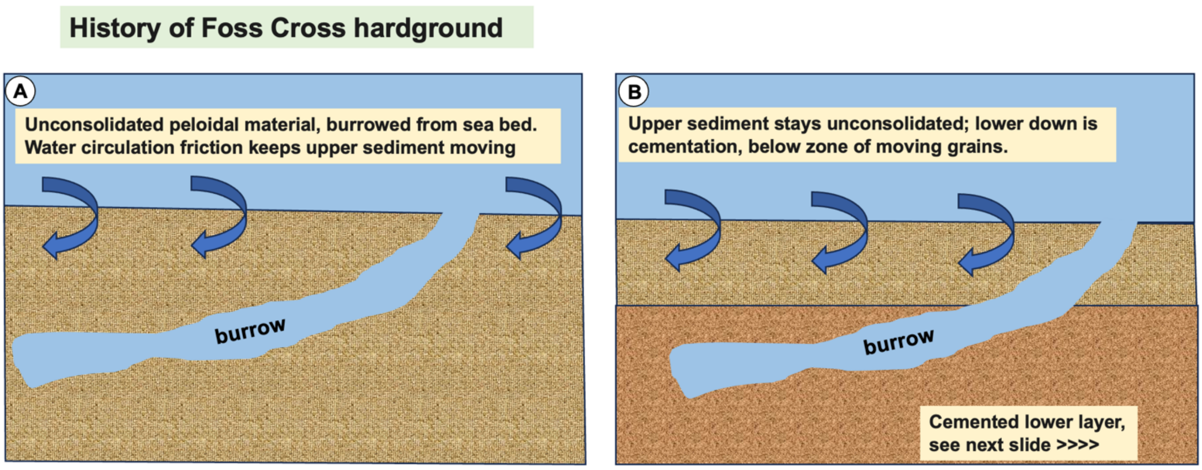


Fig. B07. These two diagrams show the first stage in process of hardground formation. After deposition of the sediment grains, water circulating in the sea above the sea floor passes through the sediment porespace and keeps the upper surface grains moving; this prevents cement from forming in the porespace. However lower down the water flow is slower and allows cement growth. Cements normally start with isopachous rims that lightly hold the grains together; later, in burial, the porespace is fully cemented. This process can be appreciated from some related samples, that do not come from the same locality as Foss Cross, see Fig. B08.
Photofile: B-02f-FossCross.

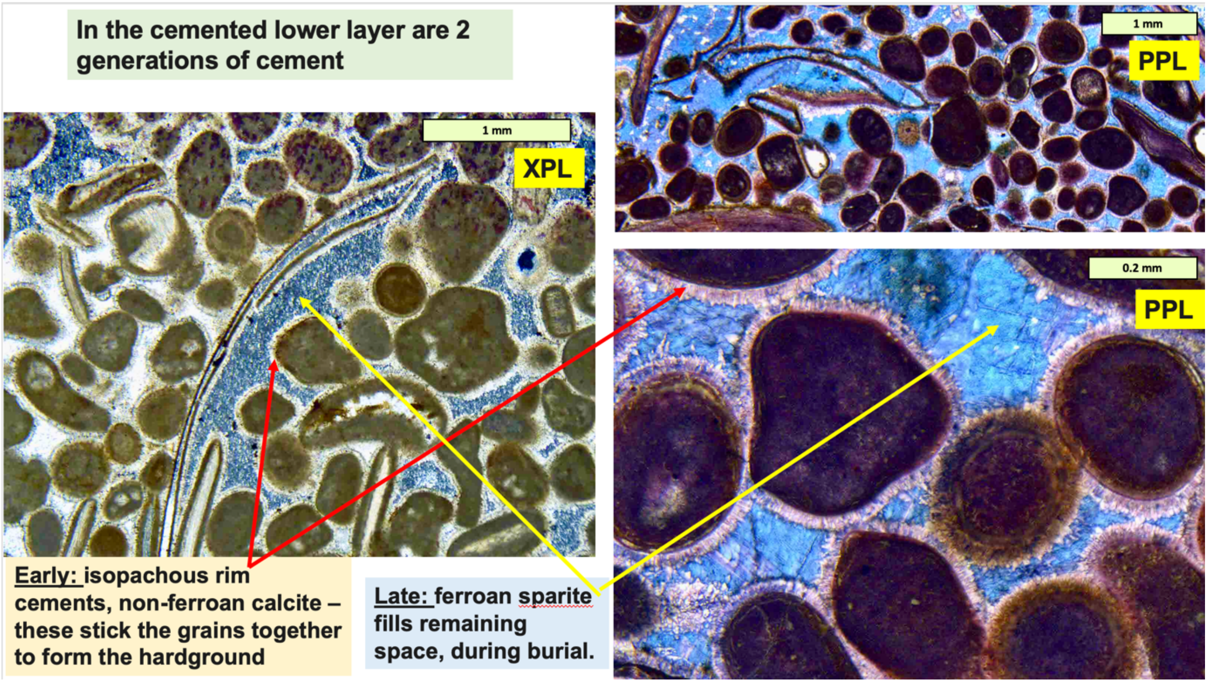


Fig. B08. Photos that show the two-stage cementation process of carbonate grainstones.
Left: XPL thin section view of grainstone; centre shows a cement crystal in extinction, highlighting the two stage cement present in this area, as shown by the labels on the image.
Right: PPL thin section view of grainstone, in this case stained with Alizarin Red S and potassium ferricyanide (ARS-KFeCN) combined stain. Non-ferroan calcite stains red, ferroan calcite stains blue. So this photo shows the non-ferroan isopachous rims on ooids and peloids; non-ferroan calcite normally forms in oxygenated environments, where no ferrous iron is present. Such isopachous rims thus hold the grains together with low strength. The remaining cement is ferroan, thus ferrous iron incorporated into the calcite, that can occur only in low oxygen conditions and represents full cementation of the material. For hardgrounds, the initial cementation stage is the isopachous cement, that can be excavated by burrowing organisms to create open burrows, such as those seen in the Foss Cross hardground.
Photofile: B-02g-FossCross.

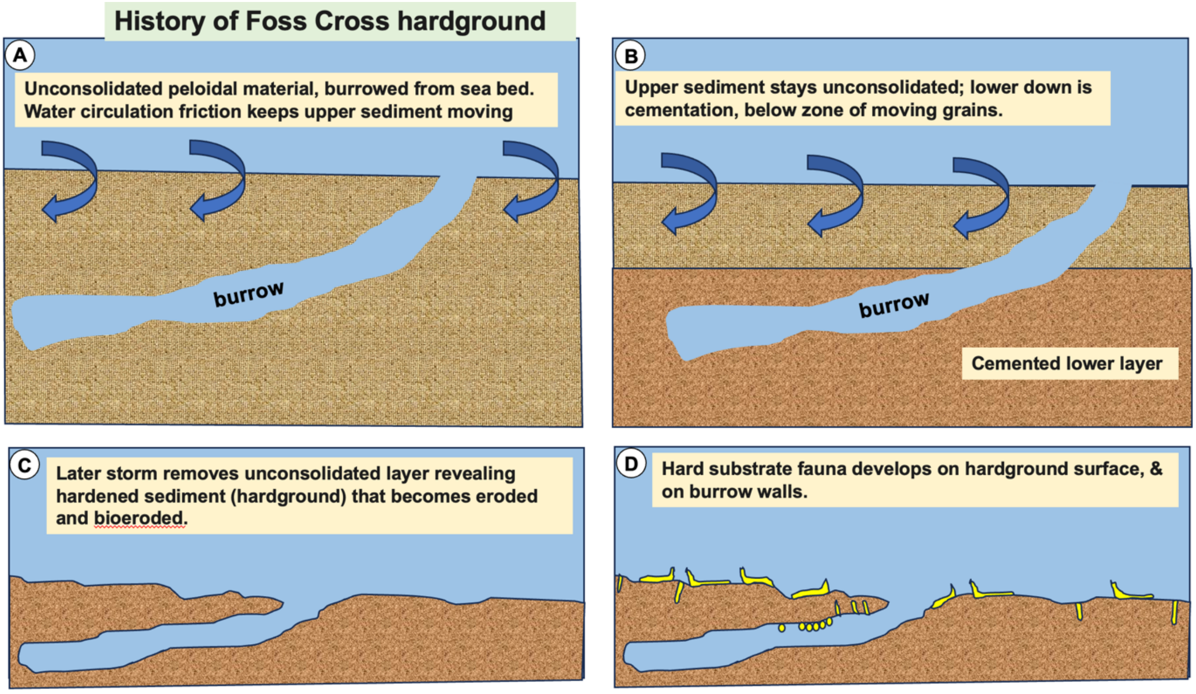


Fig. B09. Full sequence of hardground formation; although the acetate peels do not show clearly the whole sequence, the process leads to sufficient cementation of limestone below the seafloor to harden the rock and provide a substrate for encrustation and boring. Under shallow subsurface conditions on the sea floor, only the isopachous rims will develop, but depending on the position of the redox boundary in the sediment, the final cementation may occur later or earlier. Thus these 4 diagrams do not necessarily represent the full cementation process of isopachous and pore-filling cements.
Photofile: B-02h-FossCross.

Jurassic hardgrounds are iconic cases of ancient sea-floor lithification that provide a standard to judge lithification of sea-floors. In comparison with the Foss Cross hardground, the Slite marls were significantly more complex and difficult to interpret.

The second example explores the issues further, and has an important impact on the substrates of organisms such as stromatoporoids and corals.

PART B-3: UPPER VISBY FORMATION, WENLOCK, GOTLAND

The upper Visby Formation is earliest Wenlock, older than the Slite marls, and has been interpreted to demonstrate lithification sufficiently early enough to have created hard substrates for benthic organisms. The following figures demonstrate evidence of early sea-floor lithification.

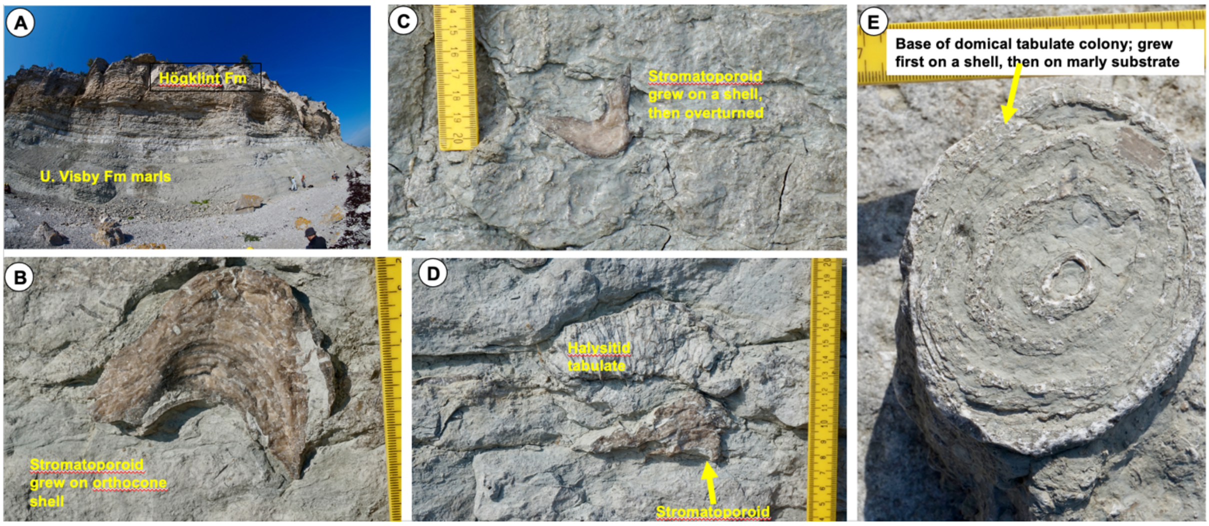


Fig. B10.
A: Field photo (fisheye lens) at Halls Huk, northern Gotland showing the sequence of shallowing from open shelf U. Visby Fm to shallower crinoidal limestones and reefs of the Högklint Fm.
B: Stromatoporoids commonly have steeply curved bases indicating growth on an object, and orthoconic nautiloids are common substrates because they form hard surfaces.
C. Although stromatoporoids grew on e.g. orthoconic nautiloids to form deep basal cavities, the sea floor was not cemented so storm action could overturn the stromatoporoid.
D. Stromatoporoids can form hard bases upon which other organisms can grow, in this case a halysitid coral.
E. Basal surface of a tabulate coral; it grew initially on a small shell fragment and then spread out over the surrounding sea floor. However, there may have been a primary growth cavity developed if the coral grew across the sea floor with little contact with the sediment.
Photofile: B-03a-UVisby.

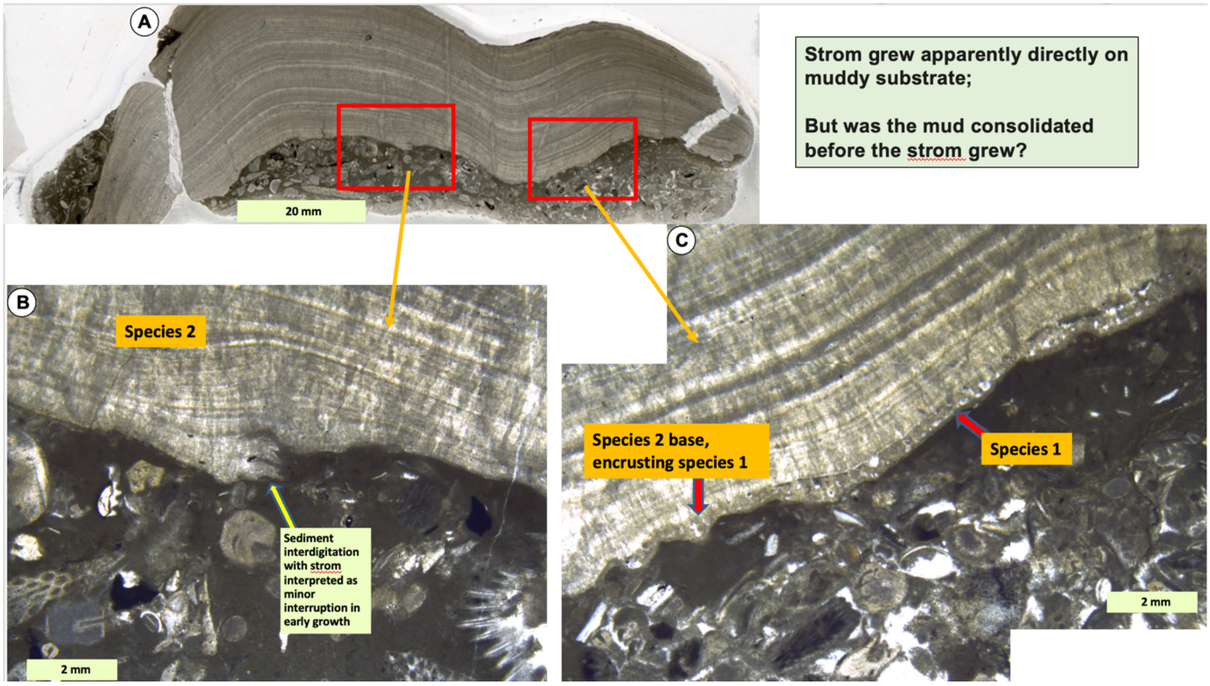


Fig. B11.
A: An example of stromatoporoid which grew on wackestone, with no evidence of a central shelly fragment that it started on. It may have grown on soft carbonate mud, or perhaps partially consolidated mud.
B: Interdigitation of stromatoporoid laminae at the base, with carbonate mud sediment, seems to indicate the sediment was soft as the base of the strom grew.
C: The undulose surface of the sediment upon which the strom grew, on the left side of the photo, could be due to partial consolidation, but there seem to be no criteria to tell whether or not it was consolidated.
This image is modified from Kershaw et al. (2018).
Photofile: B-03e-UVisby.

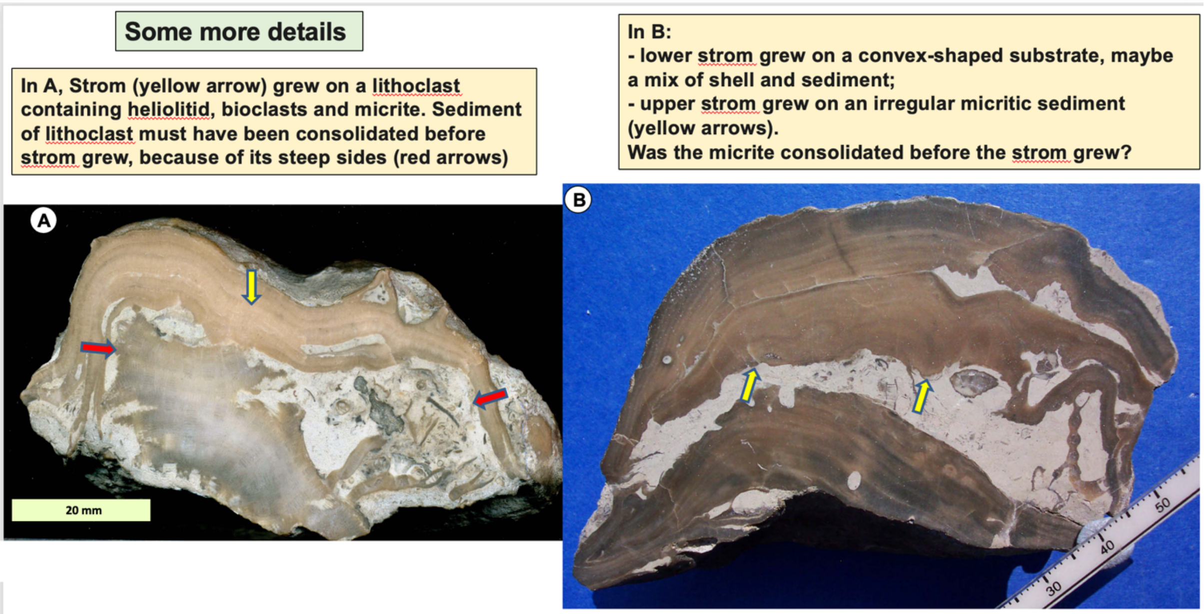


Fig. B12. These two samples show details of relationship between stromatoporoids and their bases; it seems the stromatoporoid in A grew on a lithoclast, and in B the

base of the stromatoporoid is so undulose that it could be explained as growth on a solid substrate.
Photofile: B-03d-UVisby.

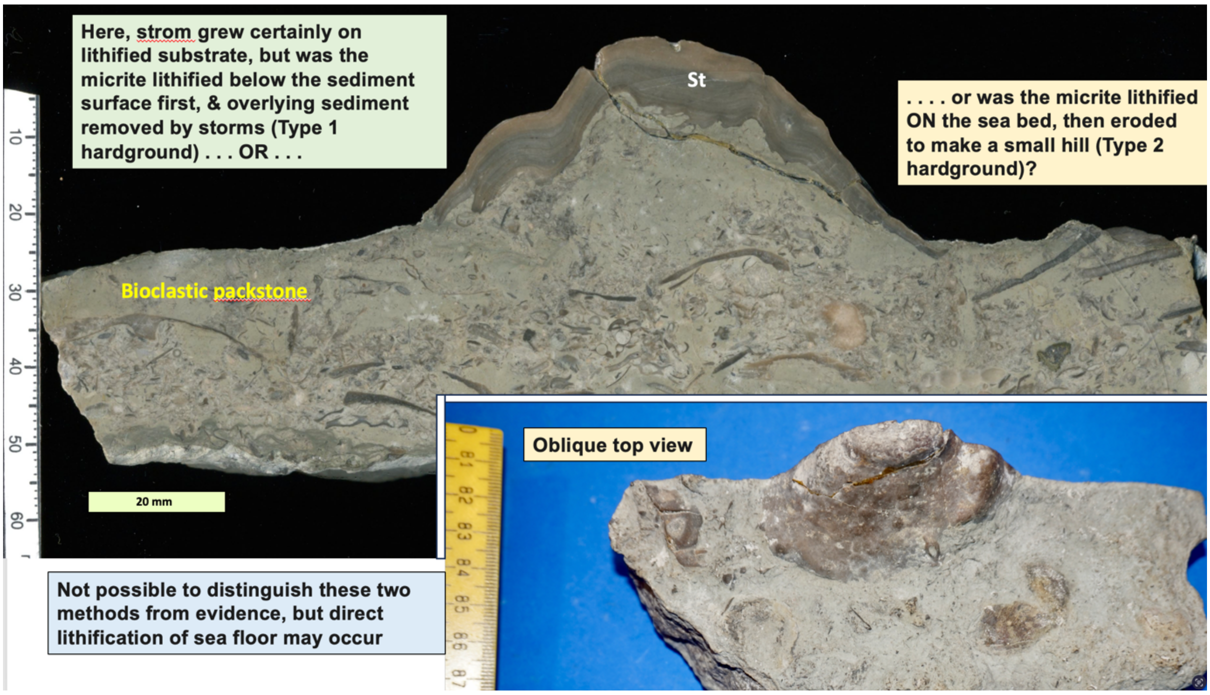


Fig. B13. In this case there is no question, the stromatoporoid grew on a solid substrate made of carbonate mud. The principal question here is whether the sea floor was directly solidified, or whether this occurred below the sediment surface and the loose overlying sediment was removed to reveal the lithified surface (as is the case for the Foss Cross hardground illustrated earlier).
Special note: the concept of Type 1 and Type 2 hardgrounds are informal terms used by Prof Axel Munnecke; I am very grateful to Prof Munnecke for his clarity of thinking regarding these ideas.
Photofile: B-03g-UVisby.

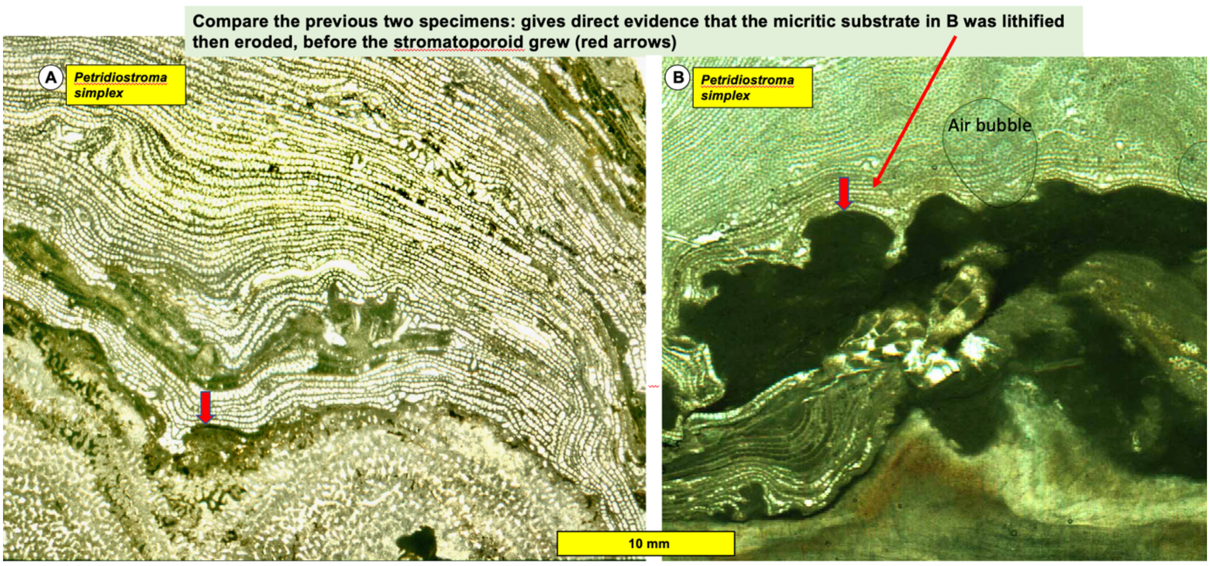


Fig. B14. Comparison between these two photos gives a clear idea about criteria to recognise lithified sediment. A shows one stromatoporoid certainly encrusting the hard surface provided by the top surface of an underlying specimen of a different species. In B almost exactly the same kind of relationship is seen, but in this case the stromatoporoid grew on sediment, that is here interpreted as having been lithified then eroded. In both photos, the stromatoporoid studied (upper part of each image) is the same taxon, *Petridiostroma simplex*, a taxon known to occur commonly as an encruster on other skeletal material.
Photofile: B-03j-UVisby.

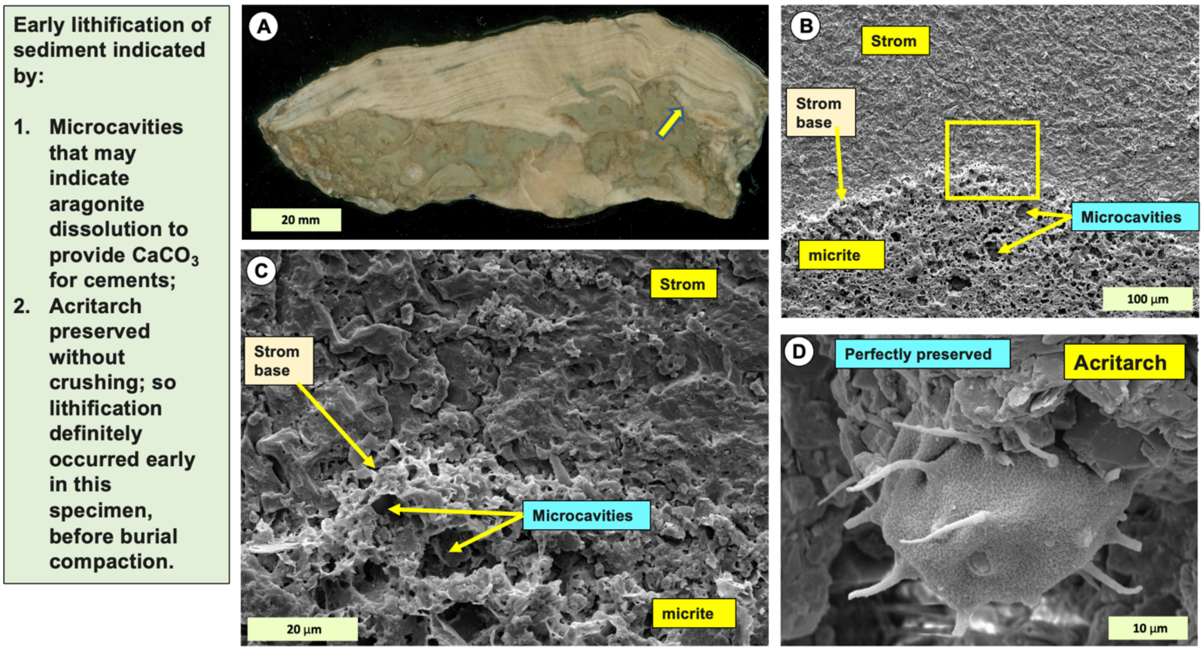


Fig. B15. In this case from the Wenlock of England, the critical photo is D that proves early lithification, because this acritarch is not crushed by compaction.
Photofile: B-03f-UVisby; this image is modified from Kershaw et al. (2018).

CONCLUSION

Images and ideas presented in this atlas show the difficulty in determining the physical state of the sea floor in these ancient carbonate sediments. Here, only three examples have been examined, but they encompass a range of lithification issues. In some cases the evidence of early lithification is unequivocal, but in others, there are alternative explanations.

Thus, in this atlas I have tried to be as scientifically honest as I can, and I am quite prepared to be wrong about the interpretations presented here in the case that other evidence exists.

Perhaps the key point is to stay open-minded about the interpretations applied, and be prepared to abandon your earlier ideas if they are demonstrated to be wrong or unsafe. There is a lot of interpretation published in literature that is not substantiated by the evidence.

Steve Kershaw
20th October 2023