DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2001/72

On the diagenesis of the Upper Jurassic reservoir rock from the Abadia structure of the Torres Vedras-Abadia area, Portugal

Project FRACARES

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MINISTRY OF ENVIRONMENT AND ENERGY

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Contents

Summary and conclusion

The present contribution summarises the result of a petrographic study carried out on Jurassic rock samples from wells situated in the Lusitanian Basin north of Lisbon, Portugal. The core samples used were obtained from the following wells: Abadia 1A, Abadia 2, Abadia 4, Abadia 6A, Abadia 8, and Abadia 11. As regards the geological setting see FRACARES (1999). Most of the samples include micritic limestones of the Montejunto Formation (Upper Oxfordian) that act as oil reservoir, but a few oolitic/oncolitic limestone samples of the Cabaços Formation (Lower Oxfordian) have also been studied. The marls of the Cabaços Formation are believed to be sources of oil.

The objective of the study was to make a preliminary account of the diagenetic history of these rocks based on a simple petrographic investigation of core pieces and thin sections; the latter were manufactured from the core pieces. Among more sophisticated methods only the oxygen and carbon isotopic ratios of rock matrices and sparry calcite in fractures were determined on a number of samples (cf. Table 4).

The diagenetic history of the micritic limestones of the Montejunto Fm.

Because the Abadia 1A samples differ by their texture and content of fossils from the remaining Montejunto samples (cf. Table 2 and 3) it was assumed to be reasonable to examine these four samples separately. However, it appeared that the two groups of micritic limestones had experienced practically the same diagenetic development since the carbonate ooze was deposited on the sea floor. The most important changes of the rocks (for the present K and Φ) that have taken place from the time of deposition until present day are as follows:

1. *Early lithification* (compaction/dewatering/incipient cementation).
2. *First generation of fractures*, mostly hairline-like.
3. *Precipitation of sparry calcite cement* in foraminiferan tests, in fractures, and in some dismicrite-like structures.
4. *Start of calcite recrystallization processes* of matrices, fossils, and cement crystals. Processes that have more or less influenced the rocks during a very long period of time, in which the following diagenetic events took place.
5. *First period of chemical compaction* with formation of stylolites that have their teeth orientated in a vertical direction.
6. *Second generation of fractures*, mostly high-angle dipping, being multiple or simple "recrystallization veinlets".
7. *Second period of chemical compaction* with formation of stylolites that have their teeth horizontally orientated. The bulk of these stylolites are formed, at least partly, in the contact between sparry calcite of second generation of fractures and surrounding micritic/micro-sparitic matrix. Low-angle dipping slickensides and calcite-filled "pull-aparts" were probably formed during this period too.
8. *A phase of leaching*, during which aggressive fluids (probably formed because of the diagenesis of underlying organic matter) have entered the rocks via the stylolitic joints, but also via fractures that have not been completely mineralised.
9. *Oil emplacement.*

The first three events, including precipitation of cements in fossils etc., are assumed to have taken place very early in the diagenetic history, in the diagenetical marine or syngenetic stage, whereas the remaining events have taken place in a shallow burial, or epigenetic stage, to an intermediate burial stage. The result of the $\delta^{13}C$ and $\delta^{18}O$ measurements confirms to a certain degree these assumptions: If we use the equation of Shachleton (1967) uncritically to calculate the temperatures of calcite precipitation, we get an oxygen isotopic temperature interval of 40-70°C for the micritic matrix (the original lime ooze that has been neomorphically altered), and an interval of 77-91°C for the calcite cements of the younger generation of fractures.

The diagenetic history of the oncolitic and oolitic limestones of the Cabaços Formation.

Originally these sediments have been deposited in a highly saline lagoon environment and a deeper, more open marine lagoon environment respectively. The diagenetic history of the rocks shows some resemblance to the diagenetic history of the above micritic limestones, as they have also been subjected to two phases of chemical compaction and a rather late diagenetic phase of leaching. It is interesting to note that such a burial dissolution, which was probably brought about by diagenetic alterations of organic matter, has favourably influenced the present reservoir quality (K and Φ) of both types of rocks.
The most important diagenetic events that have contributed to the reservoir quality are listed below in chronological order:

1. *Early lithification,* including consolidation by compaction and denaturing of lime mud, and precipitation of inter/intra-granular magnesium (?) calcite cement, plus transformation of aragonite into calcite.
2. *Fracturing* with formation of fine, hairline-like fractures.
3. *Start of calcite recrystallisation processes,* affecting both allochems and matrices. Recrystallisations seem to have played an important part up to the second phase of chemical compaction. However, neomorphic calcite crystals were probably formed during most of the diagenetic history, even at the time when the sediment was only partly consolidated (step one above).
4. *First period of chemical compaction*, an incipient one, with formation of micro-stylolites between the coated grains (ooids and oncoids).
5. *Second period of chemical compaction* with formation of stylolitic joints that cross the investigated rock samples. Small tension gashes in oncoids are probably formed during this period.
6. *First phase of leaching*, an important one considering the present reservoir quality (K and Φ). Small pores and vugs were formed in the stylolitic joints and in inter-granular pores. Fine fractures were solution-enlarged during the same phase.
7. *Precipitation of calcite cement crystals* in stylolite-associated pores/vugs in the oolitic rocks, and in inter-granular pores in the oncolitic rocks.
8. *Second phase of leaching* resulting in an insignificant corrosion.

The early lithification (step one above) may have taken place in a marine stage, the fracturing (step two) in a shallow burial stage, and the remaining events in a shallow burial to an intermediate (epigenetic) burial stage.

Introduction

Background

In the Abadia structure that has been honeycombed by 21 wells the fractured limestone of the Montejunto Formation (Middle to Upper Oxfordian) acts as an oil reservoir. The underlying shaly limestones of the Cabaços Formation (Lower to Middle Oxfordian) are believed to be the source rocks.

The Montejunto limestone shows an extremely poor reservoir quality with low porosities and permeabilities (Φ = 0.1-4.0 %, K < 0.01 mD). The porosity of the rock matrix is thus playing a negligible part, and practically no oil staining is observed here. The shows of heavy oil seem only to be related to fractures that are only partly mineralised (with calcite spar) or have been attacked by leaching. Therefore, a macroscopic core description of the Montejunto limestones has been carried out in order to explain the structural elements that have contributed to the fracture porosity, cf. FRACARES (1998), in which a preliminary chronology of structures, or elements of fracture porosity, is shown. Further information on the regional setting and the structural model of the study area is found in FRACARES (1999) and Jacobsen (2000).

Purpose of project

As a supplement to the above macroscopic core description, the intention of the diagenetic study is, if possible, to provide a brief overview of the diagenetic phenomena in the reservoir rocks of the Abadia structure, and to answer the following question: what diagenetic processes have occurred in the rocks from the time of deposition until the present day?

Materials and methods

The microscopic investigation that forms the basis of the description of the diagenetic history was based on core material from the following wells of the Abadia structure:

Abadia 1A
Abadia 2
Abadia 4
Abadia 6A
Abadia 8
Abadia 11

Seventeen small core samples, brought home from the GPEP's core storage, were photographed and macroscopically described, cf. Appendix 1. One one-inch plug was drilled from each core sample. The plugs were cleaned for water, salts, and hydrocarbons by means of methanol and toluene in a soxhlet extractor and prepared for thin sections, cf. Table 1.

In 6 of the rock samples from the Montejunto Formation the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios were determined in rock matrix and fracture cement respectively.

Sample no.	Well	Formation	Depth in metres
1A-1	Abadia 1A	Montejunto Fm	143.9
1A-2	Abadia 1A	Montejunto Fm	158
1A-3	Abadia 1A	Montejunto Fm	161.5
1A-4	Abadia 1A	Montejunto Fm	182.5
2-1	Abadia 2	Cabaços Fm	255
2-2	Abadia 2	Cabaços Fm	275
2-3	Abadia 2	Cabaços Fm	c. 334
2-4	Abadia 2	Bathonian Stage?	c. 393
4-1	Abadia 4	Montejunto Fm (?)	161.45
4-2	Abadia 4	Montejunto Fm	285
4-3	Abadia 4	Montejunto Fm	298.9
6A-2	Abadia 6A	Montejunto Fm	c. 223
6A-1	Abadia 6A	Montejunto Fm	239.80
8-1	Abadia 8	Montejunto Fm	476.5
8-2	Abadia 8	Montejunto Fm	493.8
11-1	Abadia 11	Montejunto Fm	266.44
11-2	Abadia 11	Montejunto Fm	297

Table 1: List of core pieces and thin sections used in the diagenetic study.

The classification of the rock sections (thin-sections) follows Folk (1962) and Friedman (1965), the latter in the expanded version proposed by Randazzo & Zachos (1984). In the description of cements the nomenclature of Bathurst (1976) is usually used. The crystal size scale is from Folk (1965):

ECxn	Extremely coarsely crystalline	> 4 mm
VCxn	Very coarsely crystalline	1-4 mm
Cxn	Coarsely crystalline	0.25-1 mm
Mxn	Medium crystalline	62-250 µm
Fxn	Finely crystalline	16-62 µm
VFxn	Very finely crystalline	4-16 µm
Axn	Aphanocrystalline	< 4 µm

Grouping of core samples according to texture

Concerning the early, pre-burial diagenesis belonging to the marine or syngenetic diagenetic stage the investigated rock samples may have been affected in different ways, depending on the original hydrodynamic conditions (bottom currents and infaunal activities of organisms): the degree of an early cementation depending on the number of pore volumes of water that flow through the sediment. Thus, a possible calcite cementation may be more pervasive in a carbonate sand/silt deposited in shallow water compared to an argillaceous carbonate ooze deposited in the deeper part of the neritic zone. Therefore, because the present rock fabrics of the samples to a certain degree reflect the hydrodynamic conditions at the time the sediments were deposited, it is reasonable to treat the samples in groups according to the texture when the diagenesis of the reservoir rocks are reviewed. According to the macroscopic core description (cf. Table 2) the seventeen small core pieces could be arranged in the following three groups:

(1) *Marly micritic limestones of the Montejunto Fm.*

# 1A-1	of well Abadia 1A;	depth: 143.9 metres.
# 1A-2	of well Abadia 1A;	depth: 158 metres.
# 1A-3	of well Abadia 1A;	depth: 161.5 metres.
# 1A-4	of well Abadia 1A;	depth: 182.5 metres.

(2) *Micritic limestones, fossiliferous and non-fossiliferous, of the Montejunto Fm.*

# 4-1	of well Abadia 4;	depth: 161.5 metres.
# 4-3	of well Abadia 4;	depth: 298.9 metres.
# 6A-1	of well Abadia 6A;	depth: 239.8 metres.
# 6A-2	of well Abadia 6A;	depth: c. 223 metres.
# 8-1	of well Abadia 8;	depth: 476.5 metres.
# 8-2	of well Abadia 8;	depth: 493.8 metres.
# 11-2	of well Abadia 11;	depth: 297 metres.

(2a) *Brecciated micritic limestone of the Montejunto Fm.*

# 4-2	of well Abadia 4;	depth: 285 metres.

(2b) *Dyke-related Mxn-Cxn limestone of the Montejunto Fm.*

# 11-1	of well Abadia 11;	depth: 266.4 metres.

(3) *Oolitic/oncolitic micrite/micrudite of the Cabaços Fm.*

# 2-1	of well Abadia 2;	depth: 255 metres.
# 2-2	of well Abadia 2;	depth: 275 metres.
# 2-3	of well Abadia 2;	depth: c. 334 metres.
# 2-4	of well Abadia 2;	depth: c. 393 metres.

The study of the corresponding thin sections seems to confirm this sample grouping, when the texture and content of fossils are considered, cf. Table 3. The rock textures of sample groups (1) and (2) are almost identical, but their contents of fossil-elements are different: the samples of group (1) contain no shells/shell-fragments of macrofossils, except for spicules of calcite and a few echinoderm fragments and no benthic foraminiferans, whereas the samples of group (2) show a larger assortment of macrofossils and many thick-walled tests of benthic foraminiferans. Thus, the richer fossil assemblage of benthic fossils in the rocks of group (2) makes it reasonable to assume that the sediments of these rocks were originally deposited in a shallower depth of water compared to the sediments of the rocks of group (1). However, another reason to the dissimilarity of the two fossil assemblages may be due to the fact that the conditions for life were very poor at the sea bottom in the sites where the sediments of group (1) were deposited.

The fossiliferous micrites to sparse biomicrites of the Montejunto Fm. belonging to sample group 1

Following rock samples are included in group 1: 1A-1, 1A-2, 1A-3 and 1A-4.

Rock type

We are dealing with grey-coloured, massive limestones, that are cut through by multiple fractures filled by sparry calcite (veins), rather indistinct, hairline-like fractures, and more or less well-developed stylolites. Scattered framboids (of pyrite) are commonly seen in the micrite matrix (cf. Fig. 1).

Rock matrix

With high magnification of the light microscope the fine-grained matrix of the rocks is observed to be a sutured mosaic of Axn to VFxn calcite crystals. Both the original matrix of lime mud and the tests/shells of the fossils (see below) are altered by neomorphism being replaced by micrite and/or microspar. Therefore, the contacts between fossil skeletons and surrounding matrix are either indistinct or completely obliterated. In many fossils the intragranular sparry calcite cements have also been attacked by micritisation. In places the matrix forms irregular blurs or streaks of VFxn to Fxn calcite with a xenotopic to hypidiotopic sutured mosaic fabric. A renewed aggrading neomorphism seems to have taken place here. The recrystallisation has apparently spread laterally from former sparfilled fractures into the micritic matrix (Fig. 2).
The rock matrix is rich in scattered, authigenic pyrite grains that appear as both single crystals and nice framboids. The latter are aggregates of small interlocking crystals. In places, pyrite has taken shape of fossils (monactine/triactine spicules and foraminiferans), like a cast formed by a filling in of a former fossil mould (Fig. 3). Pyrite grains that have grown at the expense of the surrounding calcite are found primarily in the micritic matrix itself, but they have also been precipitated in the intra-skeletal spar of many fossils, or grown from the matrix across the micritised fossil tests into the intra-skeletal spar. Tiny little pyrite grains are commonly seen in the insoluble residue accumulation of stylolites (see below). A few framboids are observed to post-date an "old", poorly preserved generation of fractures: the recrystallised spar of these fractures being more or less replaced by pyrite. Relatively very few pyrite grains are observed in the younger generation of distinct wide fractures. Here, the pyrite is either connected with the micrite-residuals of these peculiar fractures (see below) or they are found in the intercrystalline boundaries of the coarsely grained fracture-spar.
Small, scattered silica grains are commonly seen in the matrix. They have grown at the expense of surrounding Axn calcite. The silica crystals are from about 20 µm to about 100 µm in size. Many silica grains are more or less equant with a finely serrated outline, but most are longish, fibrous, sometimes needle-like, chalcedony crystals. Tiny little silica crystals are also found embedded in the organic-like insoluble residue accumulations of stylolites (see below).
A few “randomly” scattered rhombohedral carbonate crystals of dolomite have replaced both micrite of matrix and sparry calcite crystals of fossils. The dolomite(?) crystals are up to 50 µm in size. Many of them look old, and seem themselves to be more or less micritised. Relatively small

rhombohedrals, probably also of dolomite, are observed in some of the joints of microstylolites and solution seams (see below).

Fossils

The skeletal microstructure of the fine-grained fossils is more or less obliterated because of micrite replacements, but the fauna/flora elements listed in table 3 could be identified and their abundance roughly estimated. Pelagic foraminiferans are very common, especially the tiny fragments of their tests. Because of the micritisation their original shape is usually revealed by the intragranular sparry cement, which in turn has been more or less micritised too. The micritisation of the cement is so radical in places that the former foraminiferans appear as indistinctly outlined peloids of calcite being somewhat more coarse-grained compared to the surrounding micrite matrix.
Spicules, both monaxons and triaxons, of spar and/or microspar are rather common. They are probably sponge spicules that have been diagenetically altered (Fig. 4). A few other fauna elements are also seen in a very limited number: echinoderm fragments, radiolarian-like tests of silica, and minute calpionellid-like structures. Several of the above fossils are partly or totally replaced by pyrite (Fig. 3). Fossils that are believed to belong to the vegetable kingdom are represented by small fragments, or plant residues, of a black to dark blood-red colour when observed in transmitted light. These residues are found in all the samples but they are relatively common in sample 1A-3.
Longish plant residues and sponge(?) spicules are usually "randomly" orientated. However, in one of the samples (1A-3) these grains are rotated into one and the same plane, probably the original bedding plane. This grain orientation may have been produced by primary sedimentary processes and/or by the compaction of the non-lithified ooze.

Deformation structures

Fractures: The rock sections are crossed and penetrated by high-angle dipping multiple and simple fractures that are mineralised by calcite (Fig. 1 and 5). Two generations of fractures exist: an older poorly preserved one of small fracture widths, and a younger more well preserved one of larger fracture widths. The fractures of the former generation look indistinct, especially when observed under crossed nicols, because a recrystallisation of calcite crystals has taken place along the fracture surface. In places, an aggrading neomorphism has spread from the sparry cement out into the surrounding rock matrix. With low magnification most of the fractures of the older generation resemble hairlines. One of these poorly preserved thin fractures is observed to cross a planktic foraminiferan without any displacement of the test. The sparry calcite of the younger fracture generation shows a xenotopic to hypidiotopic fabric; fracture cements with an idiotopic fabric showing plane intercrystalline boundaries and plane compromise boundaries were observed only sporadically in one of the samples (1A-1). Twinned stress laminae are commonly seen in the more coarse-grained calcite crystals (Fig. 6). Dusty inclusions and residuals of spar crystals and/or micrite are seen frequently in the fracture cements, both embedded in the single crystals and in groups of crystals. The cement crystals seem to have engulfed and more or less replaced surrounding calcite during their growth. In that way several of the fractures have almost got a woody appearance (Fig. 7) because of their contents of rows of darker fibrous micrite inclusions that run parallel to the margin of the fracture. These fracture "trunks", that are usually multiple with thinner branches, resemble the "dashed veinlets" or "recrystallisation veinlets" described by Mišík (1968). According to this author they are characteristic for marly limestone and originated by recrystallisation from parallel hair veinlets.

In a few places an authigenic clay mineral with low birefringence, probably a kaolinite, is observed in the spar of the younger distinct fractures. The presence of calcite residuals inside the clay grains seems to indicate that clay has grown, at least partly, at the expense of the calcite crystals.
In one of the samples (1A-4) the micritic matrix is disturbed in several places by some small dismicrite-like structures, i.e. small angular patches of sparry calcite and kaolinite-like clay (cf. Folk 1959). The structures may represent original cavities formed because of minor movements or disturbances when the original lime ooze was only semi-congealed, perhaps contemporaneous with the "old" generation of hairline-like fractures, and subsequently filled in with calcite spar and calcite-replacing clay.
Stylolites: Several, mostly very poorly developed pressure dissolution structures, represented by both stylolites and solution seams, cross or penetrate the rock sections. Even though it is difficult to demonstrate the directions of the stylolitic teeth (the axes of columns), as none of the thin sections are prepared parallel to any of the presumed axes of linear stress, the presence of the two generations of chemical compaction being observed on the corresponding core pieces is certified on two of the thin sections (1A-2 and 1A-3). The older generation includes microstylolites and solution seams formed as a response to a more or less vertically orientated direction of stress, probably a simple consequence of overburden, whereas the relatively more well-developed solution seams and stylolites/microstylolites belonging to the younger generation have been formed as a response to an almost horizontally orientated direction of the stress axis. The supposed bedding plane, i.e. the horizontal direction of the rock sections, could be deduced from the orientation of longish skeletal grains and plant residuals and from the orientation of distinctive fractures that could be recognised in the core pieces, from which the thin sections were manufactured.
Many of the "old" microstylolites and solution seams are so thin that they are invisible to the naked eye (Fig. 8). One of the samples (1A-4) is relatively rich in "old" indistinct irregular microstylolites that form interconnected networks. When a microstylolite or a solution seam is crossed by a similar structure, formed during the later phase of chemical compaction, its surface is always, as expected, observed to be displaced a little. Usually, the "old" microstylolites/solution seams cut the "old", rather indistinct, thin fractures, but are themselves cut by the younger, more distinct fractures. However, in a few cases it looks as if both the spar of the older fracture and the microstylolite have been more or less obliterated during a later phase of recrystallisation, a micritisation.
The relatively more distinct stylolites/solution seams that belong to the second phase of chemical compaction are found both in the micritic rock matrix and in the contact between sparry calcite of larger, high-angle dipping fractures and surrounding micrite (Fig. 6 and 2). In a few cases one and the same pressure dissolution structure is observed to change from a wavy thick solution seam inside the micritic matrix to a "normal" stylolite with teeth in the contact between fracture spar and rock matrix.
Usually, the stylolites and solution seams show an insoluble residue accumulation of an oil-like matter (bitumen?) and subordinate clay that contain many small, probably authigenic pyrite crystals and fewer tiny little silica crystals. Scattered small rhombohedrals, probably of dolomite, are also observed in the seams in several places. In a few places they are observed to overlay microstylolites, indicating that the precipitation of that mineral took place contemporaneous with or after the stylolitisation. The dolomite(?) crystals of the younger generation of stylolites/solution seams look more well-preserved and "fresh" compared both to those found in the older generation of microstylolites/solution seams, and the few scattered ones in the micritic matrix.

Porosity

Generally, all the rock sections are massive (cf. the macroscopic description of corresponding core pieces), only a few small, scattered, irregularly outlined pores are found in the micritic matrix, and few moulds from planktic foraminiferans. However, in one of the samples (#1A-4) an insignificant leaching seems to have taken place after the first phase of chemical compaction, as small pores are developed in the surface of some of the microstylolites. Such stylolite associated pores and vugs were observed macroscopically in two of the core pieces (cf. Table 2).

The diagenetic events arranged in relative time

From the above it is obvious that quite a lot of diagenetic events have influenced the rocks, slightly or highly, from the time of deposition until present day. The events that were found during the examination of both the core pieces and the thin sections are listed below:

Several events of neomorphism, both degrading and aggrading ones are observed. The term degrading is used e.g. for a process where sparry calcite is ± replaced by a sutured mosaic of Axn calcite, and the term aggrading e.g. for a process where Axn calcite (micrite) during a coalescive neomorphism is ± replaced by a sutured mosaic of Fxn calcite (cf. Folk 1965). Each of the observed events listed below may have taken place during more than one period of time:

- Micritisation of carbonate mud.
- Micritisation of skeletal structures.
- Micritisation of intra-skeletal sparry calcite.
- Micritisation of sparry calcite of "old" fractures.
- Micritisation of carbonate rhombohedrals of dolomite(?).
- Micritisation of "old" microstylolitic joints.
- Aggrading neomorphism of micrite.
- Aggrading neomorphism of "old" fractures (that is neomorphism of micrite close around original thin fractures, and eventually also of former calcite filling (passive cement)).
- Aggrading neomorphism of younger fractures (the micrite around the original thinner veins being ± replaced by a Fxn-Cxn spar).

Two or more phases of precipitation of "passive" calcite cement, i.e. precipitation of cement in open spaces, represented by:

- Precipitation of microspar and/or spar in foraminiferan tests.
- Precipitation of sparry calcite in fractures. (The cements of the younger distinct fractures show fabric-criteria for "passive" cement in places).

Two phases of fracturing:

- An older generation of rather thin, indistinct fractures.
- A younger generation of more distinct fractures.
- To which must be added the fact that later on a few calcite-filled veins (pull-aparts) were formed still on sliding surfaces (slickensides), probably contemporaneous with the younger stylolites.

Two phases of chemical compaction with formation of:

- An older generation of microstylolites and solution seams.
- A younger generation of (tectonic) stylolites and solution seams.

One or more phases of precipitation of calcite replacing kaolinite-like clay:

- Precipitation of kaolinite(?) in sparry calcite of younger fractures.

- Precipitation of kaolinite(?) in sparry calcite of dismicrite-like structures.

One or more phases of precipitation of pyrite crystals:

- Precipitation of pyrite in micrite of rock matrix.
- Precipitation of pyrite in micritised foraminiferan test walls.
- Precipitation of pyrite in spar/microspar of sponge-spicules.
- Precipitation of pyrite in intraskeletal spar/microspar.
- Precipitation of pyrite in neomorphic spar of older fractures.
- Precipitation of pyrite in micrite-residuals inside younger fractures.
- Precipitation of pyrite in insoluble residue accumulation of older stylolites/solution seams.
- Precipitation of pyrite in insoluble residue accumulation of younger stylolites/solution seams.

One or more phases of precipitation of silica crystals:

- Precipitation of quarts and fibrous chalcedony in micritic rock matrix.
- Precipitation of quarts and fibrous chalcedony in micritised foraminiferan test walls.
- Precipitation of very small silica crystals in insoluble residues of older microstylolites/solution seams.
- Precipitation of very small silica crystals in insoluble residues of younger stylolites/solution seams.

Two or more phases of precipitation of small, scattered rhombohedrals of dolomite:

- Precipitation of dolomite in micritic rock matrix.
- Precipitation of dolomite in micritised fossils.
- Precipitation of dolomite in intra-skeletal sparry cements.
- Precipitation of dolomite in insoluble residue accumulation of older generation of micro-stylolites.
- Precipitation of dolomite in insoluble residue accumulation of younger generation of stylolites and solution seams.

One or two phases of leaching with:

- Formation of small pores along the surface of stylolites, both along indistinct "old" microstylolites (observed in thin-section 1A-4) and along more distinct younger tectonic stylolites (observed macroscopically, cf. Table 2).
- Formation of pores and small vugs in the sparry cement of younger distinct fractures.

Far from all of the above diagenetic events could easily be arranged in relative time, but the following relations between pairs of events could be established with certainty:

1. A first phase of fracturing was followed by a second phase of fracturing.
2. The first phase of fracturing was followed by an aggrading neomorphism of the calcite along the fractures.
3. Formation of the neomorphic spar of the "old" fractures was followed by a precipitation of calcite replacing pyrite crystals.
4. Formation of neomorphic spar of "old" fractures was followed by the second phase of fracturing.
5. Precipitation of intra-skeletal calcite spar (in foraminiferans tests) was followed by a phase of micritisation. The opposite case, where the test walls of empty foraminiferans were micritised before the sparry cements were precipitated inside the chambers of the tests, is not likely, as the cement crystals are usually more or less "attacked" by micrite too.
6. Precipitation of intra-skeletal sparry cements was followed by a precipitation of calcite replacing pyrite crystals.

7. Precipitation of intra-skeletal sparry cements was followed by a precipitation of calcite replacing, rhombohedral dolomite crystals.
8. Precipitation of calcite spar of dismicrite-like structures (in sample 1A-4) was followed by a precipitation of calcite replacing kaolinite(?) crystals.
9. Micritisation of fossils was followed by a precipitation of calcite replacing dolomite crystals.
10. Micritisation of rock matrix, the former lime mud, was followed by a precipitation of calcite replacing dolomite crystals.
11. Precipitation of some of the calcite replacing dolomite crystals in the micritic rock matrix was followed by a (renewed) micritisation.
12. Micritisation of fossils was followed by a precipitation of calcite replacing silica crystals.
13. Micritisation of rock matrix, the former lime mud, was followed by a precipitation of calcite replacing silica crystals.
14. Micritisation of fossils was followed by an aggrading neomorphism of micrite.
15. Micritisation of rock matrix was followed by an aggrading neomorphism of micrite.
16. The first phase of fracturing was followed by two phases of chemical compaction.
17. A first phase of chemical compaction with formation of microstylolites and solution seams was followed by a second phase of chemical compaction with formation of tectonic stylolites and solution seams.
18. The first phase of chemical compaction was followed by the second phase of fracturing.
19. Both the first and the second phase of chemical compaction were followed by a phase of leaching, being a rather insignificant dissolution of calcite along microstylolites and stylolites (observed in sample 1A-3 and 1A-4).
20. The second phase of fracturing was followed mostly (see below) by the second phase of chemical compaction.

The following is a discussion of cases where pairs of diagenetic events could not so easily be arranged in relative time:

1. First phase of chemical compaction is observed to post-date a first phase of fracturing (cf. above). However, in a few places recrystallisations have blurred that relationship. In two places the formation of a first phase microstylolite was seemingly followed by a (renewed?) recrystallisation, an aggrading neomorphism, along an "old" intersecting fracture. Furthermore, in one of the samples (1A-4), where an "old" fracture is crossed by an "old" microstylolite, it looks as if both the fracture-spar and the microstylolite have been more or less obliterated simultaneously during a later phase of micritisation.
2. In a few places, where a stylolite with ± horizontally orientated teeth is seen along a "young" distinct sparfilled fracture, it is difficult to state the relationship in relative time between the two diagenetic events, because locally an apparently renewed recrystallisation of the sparry calcite crystals of the fracture has spread laterally across the stylolite. Residuals of insoluble residue accumulations of the stylolite are usually found inside the calcite crystals that have grown during an aggrading neomorphism.
3. Concerning the formation of the few moulds from foraminiferan tests it is important to stress that we are not dealing with "true" moulds formed because of a dissolution of the skeletal structures, the test walls, themselves. In fact, the pores described as moulds seem to be small voids bound by the interior sides of the skeleton walls of foraminiferan tests, that have never been filled with lime mud or sparry calcite cement. The original microstructure of the skeleton walls themselves has been obliterated by micritisation.

4. The relative time of precipitation of some of the ubiquitous pyrite grains was also difficult to prove in proportion to a few other mineral phases: For instance, some pyrite crystals arefound in the crystal contacts of the coarse-grained spar of the younger generation of distinct fractures. Whether these pyrite crystals were precipitated before or after the spar is impossible to say. However, the fact that pyrite-crystals are also observed in the micrite, that appear as residuals in the same fractures, may indicate that the micrite replacing, but not pyrite replacing, spar crystals were precipitated after the pyrite. Other pyrite grains appear as casts from fossils taking the shape of both monaxene/triaxene spicules and planktic foraminiferans. Here the pyrite grains may have been either "passively" precipitated in former fossil moulds (cf. above), or they may have totally replaced the former spar/microspar of the spicules and the intra-skeletal spar/microspar of the foraminiferans. The last-mentioned occurrence is probably the most credible one as the above spar/microspar is frequently observed to be replaced partly by pyrite. Many pyrite grains occur in the insoluble residue accumulation of stylolites and solution seams belonging to both phases of chemical compaction. Pyrite is relatively more common here compared to the surrounding rock, which may be due to a concentration resulting from the loss of surrounding soluble carbonate during the chemical compactions. However, it is not at all inconceivable that many of the small pyrite crystals of stylolites and solution seams were precipitated contemporaneous with, or after, the chemical compaction, their growth being dependent on the presence of the organic matter of the insoluble residue accumulations.
5. Tiny little silica grains are commonly seen in the insoluble residues of stylolites and solution seams (of both generations of chemical compaction). Like the pyrite, silica may have been concentrated in the seams due to carbonate losses during the chemical compactions. However, the very frequent occurrence, in most places, of silica crystals embedded in the residue accumulations of stylolites/solution seams compared to the sparse occurrence of silica crystals in the surrounding micritic matrix seems to indicate that most of the former crystals are precipitated contemporaneous with, or after, the chemical compactions.

In accordance with the above time relations between pairs of diagenetic events the following "flow-chart" for the diagenetic evolution of the marly micritic limestones of the Montejunto Formation can be made. The diagenetic events, that are assumed to have been unimportant for the creation of the present reservoir quality (Φ and K) of the rocks, are omitted here:
Original sediment → Early lithification (compaction/dewatering/incipient cementation) → Formation of first generation of thin, mostly hairline-like fractures, and in places dismicrite-like cavities → Precipitation of sparry calcite cement in foraminiferan tests, and in fractures and dismicrite-like structures → One or more phases of recrystallisation: micritisation of matrix and fossils, and aggrading neomorphism of carbonate close around the thin fractures → A phase of chemical compaction, being a response of a ± vertical direction of stress axis → A phase of leaching, with formation of pores along microstylolites → Formation of a second generation of mostly high-angle dipping fractures, being multiple or simple "recrystallisation veinlets" → A second phase of chemical compaction, here with a ± horizontal direction of stress axis, with formation of relatively more distinct stylolites and solution seams, and in places also low-angle dipping slickensides. The twinning of the calcite cement crystals in the younger fractures has probably taken place during the same phase → renewed phase of leaching with formation of pores along stylolites. A possible formation of pores and small vugs in the sparry cement of younger distinct fractures (cf. description of core pieces) may have taken place during the same phase → Oil emplacement → Present rock.

The first three diagenetic events, including the precipitation of sparry cements in fossils and fractures, are assumed to have taken place in the diagenetical marine or syngenetic stage, whereas the remaining events have taken place in the shallow burial, or epigenetic stage, to the intermediate burial stage.

The fossiliferous micrites to sparse biomicrites of the Montejunto Fm. belonging to sample group 2

Following rock samples are included in group 2: 4-1, 4-3, 6A-1, 6A-2, 8-1, 8-2 and 11-2, plus the brecciated limestone of sample 4-2 and the dyke-related limestone of sample 11-1.

Rock type

The rocks are micritic limestones, being hard and massive, and pale grey to bluish-grey in colour. They are cut by calcite-mineralised fractures, single as well as multiple ones, of varying widths, and by pressure-dissolution joints. According to Folk (1962) the rocks can be classified as fossiliferous micrite to sparse biomicrite, in places packed biomicrite, with pelmicrite playing a minor part, cf. Table 3. The fossils are very fine-grained and include mostly foraminifer tests and organic remains. Besides fossils the matrix contain scattered pyrite framboids and/or crystals.
Three of the samples show a bioturbated texture with trace fossils that have some resemblance to *Chondrites* (this trace fossil is most common in sample 6A-2). The micrite of the trace fossils is a little more dark-coloured compared to the surrounding micrite matrix, and the density of pyrite crystals and brownish-red organic grains is also somewhat higher in the traces.

Rock matrix

With greater magnification of the petrographic microscope the micritic matrix, in which the skeletons etc. are embedded, shows an inequigranular, xenotopic, sutured mosaic fabric; however, an inequigranular, fogged mosaic fabric is also commonly seen. The calcite crystals of the matrix vary in size from Axn to VFxn, but is mostly Axn, cf. the size scale shown on p. 3. A recrystallisation of the original carbonate ooze has for certain taken place: it has been converted into a micrite, which in turn has suffered an aggrading neomorphism in places. The micritisation of the matrix has spread into the skeletal structures, and the intra-skeletal sparry calcite cement (inside the foraminifer tests) has also been more or less "attacked" by micrite. In places where the skeletons – mostly planktic foraminifers with intra-skeletal spar – have been replaced by Axn-VFxn calcite during the neomorphic alteration the rock has got a fogged mosaic fabric. In some of the rock samples (samples 4-3 and 6A-1) where such a fabric is commonly seen, i.e. where numerous indistinct outlined peloids are found, one cannot preclude the possibility that we are dealing with a former ooze, rich in both microfossils (tests of foraminifers) and pellets, that has been neomorphically converted into micrite and microspar.
Authigenic pyrite crystals are commonly seen scattered "randomly" in the Fxn to VFxn matrix, but in many places pyrite is also observed to have replaced poorly preserved fossils, intra-skeletal sparry cements, and spar of thin "old" strain-recrystallisation fractures. Relatively few pyrite crystals are found in the coarsely crystalline spar of the large "younger" veins, whereas relatively many tiny little crystals are found in the insoluble residue accumulation of the stylolitic joints. In places, pyrite is observed to have partly replaced the reddish-black coloured organic grains. Pyrite is also found in a few of the small silica crystals, where it seems to post-date the silica. The bulk of the many pyrite grains consists of small, scattered single-crystals, but several nice, up to about 400 µm large,

spherical crystal-aggregates (framboids), built up of small interlocking crystals, are found in all the investigated samples.

Small 10 to 200 µm large silica grains are also commonly seen. They occur mostly scattered in the matrix, but in places they are also found in fossils and in the intra-skeletal sparry cement. The silica crystals seem to have replaced the calcite during their growth, as residuals (inclusions) of calcite are found as often as not in some of the crystals. The bulk of the silica grains are 10 to 50 µm large, more or less equant crystals with an irregular, finely serrated outline when seen in thin-section, but several larger crystal-aggregates as well as longish, fibrous chalcedony-like crystals are seen. Also small silica grains are observed embedded in the insoluble residues of the stylolitic joints. One of the latter, in sample 11-2, is extremely rich in very small silica crystals.

Rather few dolomite rhombohedrals, being from 20 to 50 µm in size, were observed in five of the samples. They occur scattered in the matrix of the rocks, where they seem to have grown at the expense of the Axn-VFxn calcite. Some of these dolomite crystals look "old", as they are themselves partly replaced by calcite, being more or less micritised. Smaller, 10 to 30 µm large euhedrals are precipitated in the surface of stylolites. In a few places, dolomite crystals are observed to overlay the stylolitic joint, as if the dolomite is precipitated contemporaneous with, or after, the stylolitisation (the chemical compaction).

In one of the samples, a few aggregates of kaolinite (?) crystals are found in association with calcite veins. It looks as if the authigenic clay minerals have attacked both the micritic rock matrix and the fracture spar during their growth.

Fossils

As stated above in the introductory remarks, the carbonates of sample group 2, represented by the four wells Abadia 4, 6, 8 and 11, show a richer fossil assemblage compared to the carbonates of sample group 1 from Abadia well 1A, cf. Table 2.

Planktic, thin-walled foraminifers, being uniserial and/or biserial types, as well as *Globigerina*-like types, are common to very common. Thick-walled benthic foraminifers are rather common to common, as are the spicules built up of VFxn-Fxn calcite. Fragments of pelecypods, that resemble *Inoceramus*, and echinoderms are rather common. The remaining two fauna elements (cf. Table 3): brachiopods, planktic bivalves (a juvenile stage), and mollusc-fragments of unknown origin, are far less common. The blood red to black coloured (when observed under the light microscope), irregular, organic fragments are very common in all the samples. They are probably plant-remains.

All the fossils in all the samples are very poorly preserved due to one or more phases of micritisation that have affected both fossils with associated sparry cement and surrounding fine-grained matrix. The numerous small, more or less spherical bodies, mostly of micrite and/or microspar, are supposed, as far as the majority is concerned, to be former spar-filled or sediment-filled foraminifer tests that have been neomorphically altered. These structures vary in appearance from defuse peloids of micrite/microspar to perfect "unwalled calcispheres" of spar.

Deformation structures

Compaction: In some of the samples the longish skeletons, i.e. the organic, plant-like grains and the filaments (juvenile bivalves), are orientated parallel to each other. This bedding-plane parallelism may be due to primary sedimentary processes, but it is likely that the fossils have also been rotated during the compaction of the sediment prior to lithification.

Fractures: Both the appearance of the fractures and the presence of small displacements indicate that we are dealing with at least two generations, or events, of fracturing:
An earlier generation of thin, high-angle dipping (the fracture surface being more or less vertically orientated) and rather indistinct hairline-like fractures. Under the microscope these fractures are observed to consist of indistinctly outlined "strings" of microspar, that seems to be formed during a recrystallisation, an aggrading neomorphism, along a former micro-fracture, probably contemporaneous with the neomorphic alteration of the former carbonate mud matrix. The microspar itself of the hairline-like fractures shows irregular, almost sutured contacts between the crystals (a xenotopic fabric). Very small, if any, displacements of the rock have taken place along these fractures, which is obvious as fossils are usually crossed by the fractures without any interruption or breakage. This is observed among several plant-like grains and foraminifer tests.
The fractures of the younger generation are far more distinct, being of greater fracture width (up to several mm), and filled in with a coarse-grained spar of a xenotopic to hypidiotopic fabric. In places they are only partly spar-filled, and the inter-crystalline pores and vugs are here filled with residuals of oil. Most of the fracture planes show high-angle dips; only in sample 4-3 the fractures are observed to dip from an almost vertical to an almost horizontal direction. The younger fractures are partly multiple, and in places they resemble "dashed veinlets" (Mišík, 1968) as the coarse-grained spar contains darker-coloured micritic enclosures, arranged in rows parallel to the margin of the fracture, being remnants of the micritic matrix. Such a woody fracture is probably formed by an aggrading strain-recrystallisation along a bundle of closely packed veinlets. In fact, many of the cement crystals of the larger fractures seem to have suffered from stress, as twinned lamellae are commonly seen, and many crystals without stress twins also show an undulatory extinction under the polarising microscope. The strained calcite cement crystals may have been formed during the very latest phase of chemical compaction (see below), which occurred under a stress direction almost at right angles to the fractures, i.e. in a more or less horizontal direction.
One of the samples (no. 8-2) is crossed by a very distinct, still younger, spar-filled fracture that dips about 45° degrees. It is bound by slickensides, for which reason it is obvious to assume that the fracture-like structure is a calcite-filled cavity, a "pull-apart", formed along a sliding surface (cf. e.g. the "enduits de calcite" described by Arthaud & Mattauer, 1969), which in turn was developed contemporaneous with the youngest phase of chemical compaction, during which the tectonic stylolites were formed, cf. below.

Stylolites: Pressure-dissolution structures are commonly seen. From their orientation in space, being most easily seen in the core pieces from which the thin-sections are manufactured, and their relationships to other diagenetic structures it is obvious that they represent two generations: (A) An earlier one of stylolites and solution seams with the surfaces (the stylolitic joints) orientated more or less horizontally, the stylolites having their axes columns, the teeth, orientated in a more or less vertical direction, and (B) A younger generation of stylolites, and a few solution seams, with the surfaces more or less vertically orientated, the teeth of the stylolites being more or lees horizontally orientated. It seems as if the pressure-dissolution structures of the "old" generation are formed as a response to compression forces (main stress) orientated at ± right angles to the bedding plane (the "normal" load of overburden), whereas the structures of the "young" generation are formed as a response to stress that has acted in a ± horizontal direction (the "tectonic stylolites" being formed).

Compared to the stylolites of the younger generation, the stylolites of the older one are generally much more poorly developed, many are, in fact, "incipient" microstylolites, as they appear only as thin, wavy strings of a relatively more dark-coloured micrite that cross or penetrate the thin-section. In a few places, a wavy to zigzagging string of pearls of tiny pyrite grains is observed, which probably indicates the site of an incipient stylolite, or solution seam, otherwise invisible under the microscope.

The older stylolites and solution seams are observed to post-date the older phase of fracturing, and pre-date the younger phase of fracturing. The stylolites belonging to the younger generation are usually formed along the younger, more well-developed fractures, i.e. in the contact between the fracture spar and the surrounding fossiliferous micrite and biomicrite. It is beyond doubt that they post-date the fracturing.

In the more well-developed stylolitic joints the insoluble residue accumulations is observed to consist of organic and clay-like matters. Here the rock is relatively rich in very small silica and pyrite crystals, and sometimes also in small rhombohedrals of dolomite. Even some concentration of pyrite and silica may have taken place here during the process of chemical compaction with its loss of carbonate. It looks as if the small minerals have been precipitated in the stylolitic surfaces contemporaneous with, or after, the insoluble residuals were accumulated.

In a few places (e.g. in sample 8-2) a deformation of the fine-grained, micritic matrix has taken place close along the pressure-dissolution structures. Here the calcite seems to have been strain-recrystallised during the phase of chemical compaction, like a "stretched metamorphic" quartz. Because of the strain the small, micro-sparry calcite crystals are now elongated in a preferred direction. The leaching which took place via the stylolitic joints has also attacked these strained crystals. The insoluble residues of the latter may have acted as conduits for aggressive fluids, that were developed because of the diagenesis of underlying organic matter, cf. the passage below.

Porosity

Both the macroscopic investigation of core pieces (cf. App.1 in Progress Report no.2) and the petrographic description of the thin-sections, by the use of a polarising microscope, confirm that the rocks are of very poor reservoir quality (very low Φ and K values). The rocks look extremely massive except for the presence of some scattered, inter-crystalline vugs and pores, mostly oil-filled, in the larger fractures with very coarsely crystalline calcite cement, and small pores developed in the stylolitic joints. In places, the latter are more or less interconnected so, locally, they resemble solution-enlarged, thin, wavy to zigzagging fractures. There is no doubt that a phase of leaching post-dates the chemical compaction.

The Axn to VFxn matrices with fossils are non-porous when examined under the polarising microscope, only a few moulds from planktic foraminifer tests were observed in one of the samples (sample no. 6A-2), and a few 80 to 100 μm large, irregular outlined pores in the micritic matrix of two of the samples.

Samples of group 2a and 2b

Sample no. 4-2 from the Abadia 4 well: This sample belongs to the Montejunto Formation, and is also a micritic limestone, but it differs from the other samples discussed above, as it seems to be strongly brecciated (cf. Appendix 1 and the picture on the title page of the present contribution).

The thin-section of Figure 9 shows a massive, non-porous rock made up of angular rock fragments like a tectonic breccia, with carbonate veins being spar-filled fractures, of which many are multiple, and a few "dashed veinlets". At first sight, two different rock types seem to exist: (A) A pale grey fossiliferous micrite to microspar (Axn-VFxn), in which ostracod carapaces and filament-like fossils (cf. sample 4-3 from the same well) are almost obliterated because of recrystallisations of both original mud matrix and fossils. The rock contains small, scattered pyrite grains, and a few tiny little authigenic silica grains. (B) The other rock-type is darker grey to olive-grey as the crystals of the matrix are smaller (Axn). The rock is a fossiliferous pelmicrite with the same scattered ostracod- and filament-like fossils, and it contains scattered grains of pyrite and plant-like organic matter. The former rock type may be a neomorphically altered, by aggrading neomorphism, version of the latter (cf. the diagenetic considerations below).

Sample no. 11-1 from the Abadia 11 well: The rock of sample 11-1 is a dyke-related, Mxn-Cxn, massive and dark grey coloured limestone with a xenotopic fabric. Both the core piece (cf. Appendix 1) and the thin section (Figure 10) show an area close around a contact between an amygdaloidal basalt and limestone. The latter may represent a calcite vein in a basaltic rock, or the contact between the two rock types shows the outermost part of a dyke or a vein of basalt that has intruded the country-rock of fossiliferous micrite and sparse biomicrite. A dark, sulphide-like mineral is precipitated along the contact, for which reason the surface of the contact, which shows a dip of about 60°, has got some resemblance to a stylolitic joint, when observed with the naked eye. The crystals of the limestone grow in size in the direction against the basalt, and nearest to the basalt they form a vein-like structure (cf. Fig. 10).
The basalt is grey to pale ochre-yellow and consists of poorly preserved feldspar laths, that resemble plagioclase, and olivine crystals, plus several opaques, embedded in an aphanitic groundmass. The amygdales, being former vesicles, are built up of calcite, in places of both calcite and silica; here the silica seems to post-date the calcite as residuals of calcite are observed in places in the silica crystals. Some of the vesicles are still non-mineralised. Both the carbonate crystals and the silica crystals seem to be strained, as they show an undulatory extinction. The basalt is intersected by several "thin", almost hairline-like fractures, filled in with calcite. In many places, the calcite of both the amygdales and the fractures has been "attacked" by aggressive fluid(s): A phase leaching seems to post-date the precipitation of the sparry cements.

On the diagenetic events arranged in relative time

From the macroscopic description of the small core-pieces, from where the thin-sections were manufactured (cf. Table 2 and Appendix 1), it was found that an early phase (perhaps more phases) of fracturing is followed by a later phase (perhaps more phases) of fracturing, and an early phase (perhaps more phases) of chemical compaction is followed by a later phase (perhaps more phases) of chemical compaction, the latter being locally connected with low-angle sliding surfaces with slickensides (cf. sample 8-2). One or more phases of leaching are observed too, as a late-diagenetic dissolution of the rock has taken place in the stylolitic joints. These diagenetic events could thus be arranged in relative time in the following way (→ means followed by): First generation of fractures, mostly hairline-like → First generation of stylolites, having their teeth vertically orientated → Second generation of fractures, usually more well-developed → Second generation of stylolites with the teeth horizontally orientated, the bulk of the stylolites being formed, at least partly, in the contact between sparry calcite of "younger" fractures and surrounding micritic and micro-sparitic matrix → A rather insignificant phase of leaching, during which aggressive fluids have entered the rock via the stylolitic joints, but also along fractures that have not been completely mineralised by sparry calcite. The aggressive fluids were probably formed in connection with the diagenesis of underlying organic matter. On organic matter maturation and subsequent hydrocarbon degradation, see e.g. Mazzullo & Harris, 1992.

Examination of thin-sections by petrographic microscope confirms the above diagenetic history, but it also reveals more supplementary information: Thus it is most likely that one or more calcite-recrystallisations (aggrading neomorphisms *sensu* Folk, 1965) have taken place in the former matrix of lime ooze and of the calcite cement in the fractures. In the latter case the neomorphism seems to have spread laterally into the matrix from the fracture-joints; the characteristic "dashed veinlets", showing parallel rows of micrite residuals in coarse-grained fracture spar, have in many places been formed in this way, cf. Figure 11. Many of the fractures of the oldest generation are observed to be indistinctly outlined the contact to the surrounding matrix being poorly defined, because of the neomorphic alteration. Even the stylolitic joints, formed as a response on the ± vertically orientated stress because of loading of overburden, have in many places an "old appearance" as if a recrystallisation of the matrix has obliterated the seams (Fig. 12). A strain-recrystallisation with formation of numerous twins is usually seen in the coarsely crystalline spar of the younger generation of relatively well-developed fractures. These twinnings may have taken place contemporaneous with the chemical compaction brought about because of a ± horizontally orientated stress. Many of the vertically orientated stylolitic joints from this diagenetic period are formed in the contact between the coarsely crystalline spar and the surrounding matrix, cf. Figure 13.

Authigenic grains of silica, pyrite and dolomite are commonly seen. The insoluble residue accumulation of the more well-developed stylolitic joints is relatively rich in small silica and pyrite grains. Some concentration has also taken place here among the rhombohedral dolomite crystals. The relationship in time between the precipitation of the dolomite and the stylolitisation may be difficult to outline; in a few places a dolomite crystal is observed to overlay the insoluble residues, indicating that the crystal is precipitated contemporaneous with or after the chemical compaction of the rock. However, in some other places the dolomite seems to predate this compaction, cf. Figure 14. In the latter case the presence of relatively more dolomite crystals in the stylolitic seams may be due to the fact that the relatively less soluble dolomite, as compared to calcite, has been concentrated here because of the chemical compaction, during which the surrounding calcite was dissolved. The relative time in the diagenetic history of the precipitation of pyrite and silica grains is also difficult to prove in proportion to other diagenetic events. Even where silica and pyrite are found together, i.e. they are both a part of one and the same grain, it proved difficult in thin-section to make out if one of the mineral types has eventually grown at the expense of the other, or if silica was precipitated before or after the pyrite, or if the two mineral types were precipitated contemporaneously.

In the brecciated limestone of sample 4-2 (cf. above) numerous silt to granule sized rock pieces seem to have infiltrated the fissures between the larger, angular rock fragments *before* the sparry calcite cement was precipitated here, as geopetal-like structures are seen in places, cf. Figure 15. The large calcite crystals above the geopetal sediment show an undulatory extinction under crossed nicols, as if they have later suffered from stress. The presence of geopetals supports the assumption that we are dealing with a usual tectonic breccia. However, the spar of the veins is not quite "passively" precipitated, actually, as it has more or less attacked the surrounding micrite: residuals of micrite being found in many of the sparry calcite crystals. Furthermore, the spar also shows a xenotopic fabric, with anhedral crystals, which is not typical for a "passive" cement, precipitated in a cavity. Therefore, we are probably dealing, at least partly, with a so-called recrystallisation breccia (cf. Carozzi, 1960), i.e. after a "normal" brecciation the calcite cement, which was precipitated in the fissures between the angular rock fragments, spread laterally at the expense of the surrounding calcite of the fragments during a period of aggrading neomorphism. This is confirmed by the occasional presence, of residuals of dissolution seams inside coarsely grained spar crystals. A phase of chemical compaction must have taken place prior to the precipitation of the sparry cement, at least before the supposed recrystallisation of that cement.

A few fine, spar-filled fractures seem to be developed *after* the brecciation of the rock, as they can be followed across more than one angular rock fragment without any displacements of the fracture-surface (cf. Fig. 9). Indeed, with great magnification of the microscope it looks as if the coarsely crystalline spar of the veins between the angular rock pieces was precipitated *after* the spar of the fine fractures, residuals of the latter in places being seen inside the large spar crystals, but as it is not likely that a fracture could be formed prior to a brecciation without getting broken up, it is probably formed after the brecciation phase, but before the above recrystallisation of the coarsely grained spar, assuming that the rock is primarily a tectonic breccia, not just a recrystallisation breccia.

On the stable oxygen and carbon isotope ratios

The $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios were determined on 6 samples with a Varian M-250 mass spectrometer and related to the PDB standard. The results of the analyses are shown in Table 4 and in Figure 16. The samples marked with an M and a ■ are from the micritic rock matrix, and the samples marked with a C and ● are from the sparry calcite of the younger generation of fractures. Sample no.11-1C is from the coarsely crystalline calcite near the basalt. It should be emphasised here that even though these samples were carefully removed from the rocks by means of a scalpel under a dissection microscope, some of the samples of sparry fracture-calcite, if not all, have probably been contaminated by some micritic material, as the fracture-spar usually contains fibre-like residuals of micrite (cf. the description above of these peculiar "recrystallisation veinlets").
The $\delta^{13}C$ values, being from about 1.0 to about 1.6, seem to indicate that the formation of the sparry calcite in the fractures did not take place in a freshwater environment (e.g. Milliman, 1974). It should be noted (cf. Fig. 16) that the diagenetic trend from matrix to sparry cement of the samples roughly parallels the straight line fitted by least squares for all the samples (sample 11-1 being included). Note also that for one and the same rock sample the cement is substantially lighter in oxygen than the surrounding micritic matrix, whereas the corresponding decline of the $\delta^{13}C$ values is relatively small.
Assuming that the isotopic composition of the precipitating pore water was more or less unchanged during an increasing depth of burial for the sediment (with an increasing temperature) and the water had a composition close to present marine water, which is about 0‰, the temperature for the precipitation of late-diagenetic sparry calcite can be calculated from the following equation:

$$T\ (°C) = 16.9 - 4.38\ (\delta_C - \delta_W) + 0.10\ (\delta_C - \delta_W)^2 \quad \text{(from Shackleton, 1967)}$$

It is tempting to do that considering the very low $\delta^{18}O$ value of the coarsely crystalline calcite picked out of sample 11-1 adjacent to a basaltic rock, which may have affected the surrounding limestone severely during its intrusion, especially as regards temperature. However, the $\delta^{18}O$ values of interstitial fluids are likely to change, probably increase, with increasing burial (with increasing temperature), and therefore the $\delta^{18}O$ values in Figure 16 will most likely reflect the deep burial diagenetic condition when the sparry calcite was precipitated rather than the temperature itself at that time (cf. Heydari & Moore, 1988). When using the equation above, regardless of such considerations, and with the δ_W value uncritically put at 0 ‰, we got an oxygen isotopic temperature interval of 40-70°C for the micritic matrix, and a temperature interval of 77-91°C for the fracture-calcite, not including the T-value of 106°C for sample 11-1C. According to Heydari and Moore these temperatures, being less than 100°C, should show a normal *temperature*-dependent trend toward lower isotopic values.

The oolitic and oncolitic micrites and micrudites belonging to the Cabaço Formation

Introductory remarks

The four small rock samples described below can be divided into two groups by their texture and content of allochems: One group represented by samples 2-1 and 2-2, and another group represented by samples 2-3 and 2-4, cf. Table 3.

Sample 2-1 and 2-2 from a depth of 255 and 275 m, respectively

Rock type: Macroscopically, the rocks show a faint marbled appearance because of the presence of some irregular, almost vein-like patches of sparry calcite, being characteristic of the dismicrite rock type (cf. Folk, 1959). The sparry patches tend to be orientated crudely at right angles to some thin, spar-filled fractures (Fig. 17). Both samples are pale grey coloured limestone, being hard and massive except for rather few, scattered solution vugs and pores. When the thin sections are observed under the petrological microscope the rocks appear to be built up of thinly coated skeletal grains, surrounded by a micritic matrix, for which reason they have a texture like a packed oomicrite, cf. Figure 18. However, areas of other fabric types occur locally, especially in sample 2-1, such as oomicrudite, pelmicrite, pelsparite, and sparse biomicrite, all being partly responsible for the above marbled appearance.
The coarsely crystalline calcite of the dismicrite-like patches shows a hypidiotopic to idiotopic fabric. It is observed to overlay the thin, rather indistinct outlined fractures, which indicates that it has been precipitated after the fractures were mineralised.

Rock matrix: The matrix which surrounds the coated grains consists of micrite with an aphanotopic fabric. A micritisation of an original lime mud seems to have taken place. In places, the matrix consists of microspar with a xenotopic fabric, indicating that an additional aggrading neomorphism has taken place here. It looks as if the micritisation of the inter-fossil lime mud has spread to the coats of the ooids and further into the skeletal nuclei, that have been more or less micritised. The coated grains are usually so micritised that they have got a ghost-like appearance when observed with high magnification of the petrological microscope.
Among the authigenic minerals precipitated in the matrix several tiny little pyrite-like crystals and crystal-aggregates (framboids) are found "randomly" scattered in the rocks. Several pyrite crystals have also been precipitated in the cortices of the ooids, and in the fossils themselves. A few small silica grains are also found in the matrix, being from a few teens of µm to more than 200 µm in size. They appear both as more or less equant crystals with a finely serrate outline, when observed in thin-section, and as needle-like, fibrous chalcedony crystals. In sample 2-2 a few rhombohedrals of presumed dolomite have grown at the expense of the surrounding micrite.

Allochems: Practically, both samples show the same association of poorly preserved fossils that are mostly surrounded by the above-mentioned, rather thin micritic coat. Among the faunal and floral elements that could still be recognised (many coated skeletal grains seem to have reached a peloidal stage) ostracod carapaces are very common, followed in frequency by benthic foraminiferan tests, being dominated by one single, rather thick-walled species, which has some resemblance to a miliolid one. The following elements were represented in the thin sections by one to a few specimens only: fragments of brachiopod shells, algal-like structures, echinoderm osicles, a sponge-like structure, and a gastropod.

Fractures: Two generations of calcite-mineralised fractures occur in both samples:
(1) An old generation of thin, partly multiple, and rather irregular formed fractures, that tend to have their fracture-planes orientated parallel to each other. The sparry to microsparry calcite of the fractures is xenotopic of fabric. Where such an "old" fracture is observed to cut allochems (e.g. benthic foraminiferan tests) no displacement of rock is ever observed along the fracture-plane, cf. Figure 19. Note in Figure 19b the rather indistinct contact between the spar of the fracture and the surrounding micrite matrix, as if the fracture has suffered an incipient micritisation.
(2) A younger generation of far more distinct fractures, or fracture-like structures branching off from the above-mentioned patches of rather coarsely crystalline calcite, and being extremely variably in widths. Both the calcite patches and their associated fractures are observed to cut rock matrix and allochems as if a dissolution of the rock took place prior to the precipitation of their present sparry cement.

Chemical compaction: Stylolites and micro-stylolites are commonly seen in the two core pieces. The stylolitic joints, that are rendered more visible by oil, are very irregular and in many places they form an interconnected network, when observed in cross-section. In places, the contacts between allochems consist of micro-stylolites, and the rock shows here a so-called fitted fabric. The chemical compaction post-dates the old generation of fractures, but is in turn followed by a phase of dissolution, as indicated by the presence of small vugs and pores that are formed in the stylolitic joints. In the thin-section of sample 2-2 micro-stylolites are also found in areas of dismicrite. Here the sparry calcite of the patches has more or less obliterated the microstylolites, indicating that its precipitation post-dates the chemical compaction (Figure 20).

Porosity: The rocks are generally rather massive, even several scattered solution pores of varying size are found. The pores are usually from a few μm to a few hundreds of μm across. Most of them are connected with the stylolitic joints (Figure 21) where locally they form an interconnected pore-system. It looks as if these joints with their insoluble residue accumulations have acted as conduits for aggressive fluids rather late in the diagenetic history. The remaining porosity of the rocks is connected with the sparry patches of dismicrite-like areas, some of the irregular patches being only partly filled in with coarse-grained calcite cement; in a few of them no cement is seen at all. Probably, some of these partly filled patches have never been filled completely with cement as the cement crystals, that line the vug, show perfectly developed crystal faces of rhombohedrons. However, in other partly filled patches a phase of leaching is observed to have taken place after the cement was precipitated (Figure 22). The pores of the dismicritic areas are generally very poorly interconnected.

Sample 2-3 and 2-4 from a depth of about 334 m and about 393 m, respectively

Rock type: The rocks are a grey-coloured, hard, but rather porous limestone, built up tightly packed oncoids that vary a lot in both shape and size. The interstices, i.e. the inter-oncoidal spaces, are sparsely filled in with a sparry calcite cement, and residuals of oil are seen in several of them. Thus, the rocks can be characterised as an oncolithic grainstone, cf. Figure 23. Note in the figure how the section is crossed by two streaks of higher porosity and permeability. Contrary to samples 2-1 and 2-2 only a few relatively small patches of sparry calcite are found scattered in the rock.

Rock matrix: As can be seen from the above, practically no micrite is found in the spaces between the oncoids. Tiny little pyrite crystals are rather common; they appear scattered in the rock, both in the not very widespread micritic matrix, in the micrite of the oncoids, and in the poorly preserved macrofossils (see below), but they seem to be a little more common in the contacts between the oncoids. Clay minerals that have some resemblance to kaolinite are observed in a few of the inter-oncoidal pores, but perhaps we are only dealing with remains of invaded drilling-mud.

Allochems: Here the ubiquitous, sub-rounded bodies, that make up the bulk of the two rock samples (Figure 24), have merely descriptively been called oncoids in accordance with the classification of coated grains stated by Richter (1983a and b). Most oncoids are built up of a homogenous micrite of an aphanotopic fabric without any nuclei or cortical lamination like "normal" ooids, but several show an inner part of more coarse-grained (VFxn to Fxn) calcite, the crystals growing in size centripetally from micrite (Axn). Finally, rather few of the oncoids show an intra-granular porosity, the innermost part being attacked by leaching. In relatively very few oncoids a poorly preserved shell-fragment forms a nucleus. Some fossils are surrounded by a thick coating, others by a superficial one; the latter resemble micritic envelopes (cf. Bathurst, 1976).
Among the rather few very poorly preserved fossils and fossil-fragments, that occur scattered in the rock between the nucleus-less oncoids, the following elements were recognised in the two thin-sections (the number of specimens is shown in bracket):

Brachiopod shell fragments (6)
Echinoderm fragments (5)
Bryozoan fragments (3)
Mollusc fragments (3)
Coralline algae (1)
Foraminiferan, benthic (1)

Fractures in oncoids: Even though the oncoids are tightly packed no "smearing" or "pealing off" of oncoids are observed. However, relatively few of them are crossed or penetrated by small, solution-enlarged fractures. None of these small fractures are observed to cross more than one oncoid in their course.

Chemical compaction: The rocks have a "condensed fabric" as many of the contacts between oncoids are observed (under the microscope) to consist of micro-stylolites, or residuals of micro-stylolites. A few somewhat more well-developed stylolites cross the rock pieces (sample 2-3, cf. Figure 23). They run parallel to each other, and they have both been solution-enlarged.

Porosity: The numerous inter-granular pores play a decisive part for the reservoir quality (high porosity and permeability). Locally, they form interconnected pore systems, especially around the solution-enlarged stylolitic joints. The rather few intra-granular pores, i.e. the hollow oncoids, and the small fractures play only a minor part for the quality. In some of the oncoids of sample 2-4 small moulds are seen that have probably been formed by dissolution of former monoclinic gypsum crystals, cf. Figure 24.

The allochems and the depositional environment

The descriptions above of the constituent allochems show that it is reasonable to divide the four samples into two groups (group 1 including samples 2-1/2-2, and group 2 including samples 2-3/2-4) based on the following characteristics:

1. *The content of fossils.* Group 1 limestones are very rich in fossils, but the fossil assemblage is dominated by only two taxonomic groups: ostracod carapaces and miliolid(?) foraminiferans, whereas limestones of group 2 are relatively very poor in fossils. No ostracods are seen in group 2, and only one benthic foraminiferan specimen was found.
2. *The appearance of the ubiquitous coated grains.* According to the descriptive subdivision of coated grains given by Richter (1983a and b), the coated grains of group 1 are ooids consisting of a fossil (acting as a nucleus) which is surrounded by a rather thin micritic coat, whereas the coated grains of group 2 are oncoids without any nucleus. The cortices of both types of coated grains show no growth-lines, and no pseudo-uniaxial cross is seen either with crossed nicols, indicating that they are aphano-crystalline (micrite) without preferred arrangement of the small calcite crystals.

The morphology of the coated grains, together with the content of fossils, may give us some idea of the depositional environment. However, it is important to stress that no definitive estimate can be made of the depositional environments, considering that here an about 138 m thick rock interval is represented only by four small core samples. The oncoids of sample group 2 fulfil many of the criteria of "autochthonous ooids" (Flügel, 1978) formed in a low energy environment, e.g. a lagoon or in a greater depth than the normal "allochthonous ooids". The very low content in the rocks of marine fossils, and the presence in the oncolitic micrite of moulds, that is assumed to come from dissolved gypsum crystals, speak in favour of the assumption that the oncoidal carbonates have been deposited in a protected location with slight wave action, perhaps in a lagoon environment in depths of water ranging from shallow subtidal to upper intertidal. The better sorted ooids of sample group 1 may have been deposited in a little more open marine, and lesser protected environments, considering the presence of the skeletal nuclei; however, the presence of the inter-ooidal mud (now micrite) together with the fact that the fossil assemblage is qualitatively impoverished make it more likely that the oolitic sediment was deposited in a rather protected lagoon environment, certainly not in an oolitic shoal or bar system, where an effective winnowing is to be expected. The presence of numerous ostracods together with many benthic foraminiferan tests seems to indicate that we are dealing with a sediment deposited in a shallow marine environment, not a brackish water or freshwater environment. By the way, more thin-walled carapaces are indicative for freshwater ostracods.

Diagenetic considerations and conclusions

The old generation of fractures: The microsparry to sparry calcite of these fine fractures shows a xenotopic fabric typical for a neomorphic spar, and they cross fossils without any displacement of the rock (cf. the "dashed veinlets" described by Mišík, 1968), i.e. the recrystallisation of calcite seems to play an important part for the present appearance of these structures (cf. Figure 19). Perhaps the neomorphic alteration of the carbonate along the fractures took place contemporaneously with the neomorphic alteration of the fossils, the coated grains, and the original carbonate ooze in between these grains. If so, an early diagenesis of the sediment, including a compaction and early (marine?) cementation, that made the rock somewhat brittle → fracturing when the rock was buried further, with formation of fine fractures in the oolitic rocks → one or more phases of neomorphic alterations of the rock, which in some places (along the fine fractures and inside oncoids) was an aggrading neomorphism.

The spar-filled, irregular patches: In places, these dismicrite-like structures are rather irregular cavities, that are only partly filled with calcite-cement, either because they have never been completely filled in with cement, or because leaching has taken place after the cement was precipitated. From the description above the following diagenetic considerations and conclusions could be made about the patches:

A. The structures are formed after the neomorphic alteration took place along the thin fractures, cf. Figure 25.
B. The coarsely crystalline calcite cement shows a hypidiotopic, in places an idiotopic fabric; plane inter-crystalline boundaries are usually seen, which speaks in favour of a "passively" precipitated, space-filling calcite, not a neomorphic one.
C. A leaching seems to have taken place prior to the precipitation of the coarsely grained calcite cement. However, in places it looks as if a leaching, even though a rather insignificant one, has also taken place *after* the sparry calcite of the patches was precipitated, cf. Figures 22 and 26; note in the figures how the calcite cement-crystals are clearly corroded. That means, if we assume that only one phase of cementation took place, that a phase of leaching vas followed by a phase of cementation of coarse-grained cement, which in turn was followed by a renewed phase of leaching. On the other hand, if we assume that two phases of cementation took place, i.e. a leaching followed by a cementation-phase 1, which was followed by a renewed leaching, which was finally followed by a cementation-phase 2, you should expect to find only cement belonging to the second phase of cementation, or remains of the cement belonging to the first phase of cementation overgrown by cement belonging to the second phase. It is to be expected that the more simple course of diagenetic events of the first mentioned case that has affected the rocks, implying that the minor leaching of phase two has only attacked the rock locally.
D. The spar of the patches is observed to post-date a phase of chemical compaction, cf. Figure 20, which shows how a micro-stylolite is only preserved as residuals inside the coarsely grained spar crystals.
E. In some way, the sparry patches seem to be related to the stylolitic joints, the latter being found in the areas, or streaks, rich in patches, cf. Figure 17. Like the stylolites these streaks tend to be orientated at right angles to the fine, almost hairline-like old fractures.

In summary, concerning the irregular sparry patches, following flow chart for diagenetic history seems to apply for all samples, assuming that the above-mentioned leaching, which pre-date the precipitation of the coarsely crystalline cement, occurred contemporaneous with the formation of the many small pores in the stylolitic joints: Aggrading neomorphism along hairline-like fractures → chemical compaction with formation of stylolitic joints → phase of leaching related to the stylolitic joints → precipitation of sparry calcite, that most likely took place passively in the open spaces, previously formed → a renewed phase of leaching, being rather insignificant.

On the recrystallisation: Micritisation has played an important part in all the investigated samples: both the former inter-granular lime ooze (especially of sample 2-1 and 2-2) and the coated grains, ooids as well as oncoids, have been transformed into micrite. All original skeletal structures and

possible growth rings of the coats have been obliterated, being replaced by mosaics of tiny little calcite crystals without any preferred orientation. In places, an aggrading neomorphism (probably a coalescive one, cf. Folk, 1965) seems to have taken place with the formation of very finely to finely crystalline mosaics (cf. e.g. the description above of the of the old, fine fractures). During the recrystallisation of the oncoids (in samples 2-3 and 2-4) a great part of the inter-oncoidal grain contacts has also been obliterated, the tightly packed, but still rather little deformed oncoids being completely fused together, cf. Figure 27.
The one or more phases of neomorphism are observed to post-date the formation of the old, early diagenetic, fine fractures (of a shallow burial stage), but are themselves usually followed by a phase of chemical compaction. However, some of the micro-stylolites that cross the thin-sections, and a few of the micro-stylolitic grain contacts (in places where a condensed to fitted fabric is developed) seem to be more or less obliterated due to a recrystallisation of the calcite, indicating that some chemical compaction happened prior to recrystallisation. However, it is important to stress that both the recrystallisation and the chemical compaction of the rocks may have taken place during a long period of time, or may, in fact, have happened more than once in the diagenetic history. The fact that some of the above coarsely grained sparry cement-crystals, being precipitated after a phase of leaching, do not seem to be quite "passive" of nature (see below) seems to support this assumption.
In summary, the following conditions seem to apply for the recrystallisation of the rocks: In an early stage a wet transformation of aragonite into calcite may have taken place followed by recrystallisations and aggrading neomorphisms during a longer period of the succeeding diagenetic history, the pre-existing micron-sized $CaCO_3$ of mud, shell-walls of fossils, and coated grains being replaced *in situ* by secondary micrite and microspar. The growth of neomorphic spar may already have begun when the sediment was only partly consolidated. During these processes, contributed to an increasing depth of burial, a possible high-magnesium calcite may have been replaced by calcites of successively less content of magnesium. The above fine fractures seem to have promoted the aggrading neomorphism in a rather early diagenetic stage. In general, the neomorphoses seem to have been more or less finished before the chemical compactions took place.

On the compaction and deformation of the sediments due to loading of overburden: No shearing-off of outer, concentric coatings of the coated grains has been observed, and the compaction of the sediments has not resulted in any deformation of importance of the oncoids of samples 2-3 and 2-4, even though the latter are here very tightly packed, indicating that the sediment was consolidated, at least partly, early in the history of burial. Later on, some of the oncoids cracked; this insignificant fracturing was probably related to the phase of chemical compaction. The small intra-oncoidal fractures, or tension gashes, may have become solution-enlarged contemporaneous with the formation of the stylolite-associated pores (see below). It is likely that the tight packing of the oncoids took place before the sediment was well consolidated, but a *chemical* compaction with the formation of micro-stylolitic grain contacts (a condensed or fitted fabric) may have played some part too, as residuals of such micro-stylolites are still seen in places. One of the two inter-oncoidal contact types, which are commonly seen, consists of small fracture-like pores that are believed to be former micro-stylolites that have later been solution-enlarged. The other contact type is the above "non-existing" one, where recrystallisation seems to have obliterated the former contacts. In places the inter-oncoidal grain contacts consist of microspar, which at first sight has some resemblance to an isopachous, submarine cement rind. However, this cement do not fulfil the fabric criteria for "passive" cement, but rather those of neomorphic spar (cf. Bathurst, 1976), because it looks as if an aggrading neomorphism has spread laterally from the former grain-to-grain contacts. Besides these

microstylolitic grain contacts of the oncolitic grainstones, the poorly developed stylolitic joints that cross the investigated samples (core pieces and thin-sections) have also been solution-enlarged.
As previously mentioned, chemical compactions may either have taken place simultaneously in a short time in the diagenetic history, or, which is most likely, repeatedly during a very long period of time during which the chemical compaction began with the formation of micro-stylolitic grain contacts, continued later on with micro-stylolitic joints crossing several coated grains, and finally finished with the formation of more well-developed stylolitic joints. If the latter case was valid the following sequence of diagenetic events may have occurred: Early marine diagenesis and consolidation of original sediment → formation of hairline-like fractures → an incipient chemical compaction with formation of micro-stylolites, that post-date or are formed more or less contemporaneous with an important phase of neomorphic alteration of the rocks → formation of relatively more well-developed stylolitic joints, that cross the rock samples → phase of leaching.

On the rather late-diagenetic leaching: The bulk of the pores and small vugs of the four samples is related to stylolites. The fact that the leaching, which is responsible for the creation of the pores and vugs, has taken place *after* the chemical compaction of the rock is evident from the pores/vugs being present immediately along the stylolitic joints (cf. e.g. Figure 21). During this leaching the pre-existing inter-granular pores in the oncolitic grainstones were dissolution-enlarged, as were the scattered micro-fractures inside oncoids. The intra-oncoidal pores may have been formed in the same period. Because the rocks have probably not been exposed by a tectonic uplift to a subaerial meteoric environment in that rather late-diagenetic time, it is most likely that the stylolitic joints have acted as conduits for the movement of dissolving fluids: During the burial, aggressive fluids may have been evolved by the addition of CO_2, organic acids, and hydrogen sulphide (H_2S) from organic-matter maturation, and subsequent hydrocarbon degradation (cf. Mazzullo & Harris, 1992). After the leaching a precipitation of sparry calcite cement crystals in the pores and vugs has unfavourably influenced the present reservoir quality.
As mentioned above, some small, peculiar pores inside oncoids are believed to be moulds after monoclinic gypsum crystals by their appearance. An early, synsedimentary precipitation of gypsum can be expected to occur in a present-day, highly saline depositional environment (e.g. the intertidal pellet grainstone from Shark Bay in Australia (Logan, 1974)). If we are dealing with moulds from former gypsum crystals, these crystals must have been precipitated more or less synsedimentary, as gypsum is metastable at relatively low temperatures. In normal seawater at atmospheric pressure the transition temperature, at which anhydrite and gypsum are of equal solubility, is only about 20°C (Krauskopf, 1979). Therefore, it is obvious to assume that possible gypsum crystals were changed into anhydrite, which is more stable in the temperatures of increasing burial. If so, it is conceivable that the anhydrite crystals were dissolved during the rather late phase of leaching, leaving behind the moulds after the original gypsum crystals.

On the inter-granular sparry calcite cement: The calcite cement crystals that occur scattered in the oncolitic rocks seem all to have been precipitated "passively" in the interstices, at least at first sight,. However, in a few places it looks as if the crystals have grown partly at the expense of surrounding micrite of oncoids and shell-fragments from macrofossils, cf. Figure 28. This non-passive behaviour of the cement crystals corresponds to that of the crystals of the above sparry patches, that in places were observed to partly obliterate former stylolitic seams, even though it can be difficult in a thin-section to make out if such an obliteration is either due to replacing cement crystals, or to the dissolution of the rock, which predates the cementation. Several of the crystal-faces of the inter-

oncoidal calcite cement are more or less corroded as if a renewed, but rather insignificant, phase of leaching has affected the rock.
It is possible that *some* of the inter-granular cement crystals are precipitated long before the many stylolite-related pores and vugs were created. They may even have been precipitated in the diagenetic marine, or syngenetic stage, as poorly preserved inter-skeletal as well as intra-skeletal calcite cements, that show a close resemblance to marine cement, are, in fact, observed in the oncolitic grainstones, cf. Figure 29.

The diagenetic events arranged in relative time: The mineral phases or events, that are assumed to be of importance for the present reservoir quality, have been evaluated for relative timing of their appearance. Based on these relative time-relations the "flow-chard" shown below for the diagenetic evolution of the oolitic and oncolitic limestones of the Cabaço Formation could be made with some certainty, cf. Figure 30. The following phases or events are included in this scheme:

(A) *Early incipient lithification* including a consolidation of the original sediment by compaction and dewatering of lime mud, plus perhaps some precipitation of inter-granular and intra-granular, sparry magnesium(?)-calcite cement. A transformation of aragonite into calcite may have taken place during this phase.
(B) *Fracturing*, i.e. formation of fine, hairline-like fractures. The fracturing is connected to the oomicrite of sample 2-1 and 2-2.
(C) *Recrystallisation(s)*, a neomorphism, during which a micritisation of both allochems and matrix of consolidated lime mud took place. An aggrading neomorphism with formation of sutured mosaics of VFxn to Fxn calcite were formed along the hairline-like fractures and along some of the inter-oncoidal grain contacts.
(D) *Chemical compaction - phase 1*, an incipient one with formation of micro-stylolites, mostly in the inter-oncoidal grain contacts.
(E) *Chemical compaction – phase 2*, with formation of relatively more well-developed stylolitic joints that cross the investigated rock samples. Small tension gashes in oncoids may have been developed during the same phase.
(F) *Leaching – phase 1*, an important one, during which many small stylolite-associated pores and vugs were formed, as well as several intra-oncoidal pores. Inter-granular pores and fine oncolite-fractures were solution-enlarged during this phase of leaching.
(G) *Precipitation of calcite cement* in the stylolite-associated pores and vugs (creating the characteristic dismicrite-like sparry patches in the oolitic rocks), and inter-granular pores in the oncolitic rocks.
(H) *Leaching – phase 2*, during which a rather insignificant corrosion took place of the calcite adjacent to pre-existing pores and vugs.

The incipient lithification is assumed to have occurred in a diagenetic marine, or syngenetic stage, the fracturing, i.e. the formation of the fine hairline-like fractures, in a shallow burial stage, and the remaining events in a shallow burial to an intermediate, or epigenetic burial stage. The recrystallisations seem to have played an important part in the time interval between the epoch of fracturing and the second phase of chemical compaction, but it is reasonable to assume that neomorphic calcite crystals were formed during most of the diagenetic history, from the time when the sediment was only partly consolidated. The last diagenetic event - the leaching phase-2 - may have been related to a very late tectonic phase of uplift, during which overpressured pore water was released, and pore water of another CO_2 partial pressure was introduced, a mixing corrosion *sensu* Bögli (1978) may then have been in evidence.

References

Arthaud, F. & Mattauer, M. (1969). Exemples de stylolites d'origine tectonique dans le Languedoc, leurs relations avec la tectonique cassante. *Bull. Soc. Géól. De France.* (7), XI, 1969, p. 738-744.

Bathurst, R.G.C. (1976). *Carbonate sediments and their diagenesis: Development in Sedimentology* Vol. 12. Elsevier, Amsterdam.

Bögli, A. (1978). *Karsthydrographie und physische Speläologie.* Springer-Verlag, Berlin.

Carozzi, A. (1960). *Microscopic Sedimentary Petrography.* Wiley, New York, N.Y.

Flügel, E. (1978). *Mikrofazielle Untersuchungsmethoden von Kalken.* Springer-Verlag, Berlin.

Folk, R.L. (1959). Practical Petrographic Classification of Limestones. *AAPG Bull.* Vol. 43, no. 1, p. 1-38.

Folk, R.L. (1962). Spectral subdivision of limestone types. In: W.E. Ham (Editor), *Classification of Carbonate Rocks.* AAPG, Memoir 1, p. 62-84.

Folk, R.L. (1965). Some aspects of recrystallization in ancient limestones. In: L.C. Pray and R.C. Murray (Editors), *Dolomitization and Limestone Diagenesis: a Symposium.* SEPM, Special Publication No. 13, p. 14-48.

FRACARES (1998). Technical Report # 1.

FRACARES (1999). Technical Report # 2.

Friedman, G.M. (1965). Terminilogy of *crystallization textures* and *fabrics* in sedimentary rocks. *J. Sediment Petrol.*, Vol. 35, No. 3, p. 643-655.

Heydari, E. & Moore, C.H. (1988). Oxygen isotope evolution of the Smackover pore waters, South-East Mississippi salt basin. *Geol. Soc. Amer., Accepted Abstr., Abstrs. With Program,* 20: A261.

Jacobsen, F. (2000). Core Description and Log Stratigraphy. FRACARES Report.

Krauskopf, K.B. (1979). *Introduction to Geochemistry* (Second Edition). McGraw-Hill Kogakusha, Ltd, Tokyo.

Logan, B.W. (1974). Inventory of Diagenesis in Holocene-Recent Carbonate Sediments, Shark Bay, Western Australia. *AAPG, Memoir 22*, p. 195-249.

Mazzullo, S.J. & Harris, P.M. (1992). Mesogenetic dissolution: its role in porosity development in Carbonate reservoirs. *AAPG Bull.*, Vol. 76, No. 5, p. 607-620.

Milliman, J.D. (1974). *Marine Carbonates: Recent Sedimentary Carbonates, Part 1.* Springer-Verlag, Berlin.

Mišík, M. (1968). *Some Aspects of Diagenetic Recrystallization in Limestones.* XXIII International Geological Congress, Czechoslovakia 1968, Vol. 8, p. 129-136.

Randazzo, A.F. & Zachos, L.G. (1984). Classification and description of dolomitic fabrics of rocks from the Floridan aquifer, U.S.A. *Sedimentary Geology*, Vol. 37, p. 151-162.

Richter, D.K. (1983a). Classification of coated grains: discussion. In: T.M. Peryt (Editor), *Coated Grains.* Springer-Verlag, Berlin, p. 7-8.

Richter, D.K. (1983b). Calcareous ooids: A synopsis. In: T.M. Peryt (Editor), *Coated Grains.* Springer-Verlag, Berlin, p. 71-99.

Shackleton, N.J. (1967). Oxygen isotope analysis and paleotemperatures reassessed. *Nature*, Vol. 215, p. 15-17.

Tabel 2: A synopsis of the macroscopic description of the seventeen core samples from the Abadia structure

Well no.	Abadia 1A				Abadia 2				Abadia 4			Abadia 6A		Abadia 8		Abadia 11	
Sample no.	1A-1	1A-2	1A-3	1A-4	2-1	2-2	2-3	2-4	4-1	4-2	4-3	6A-1	6A-2	8-1	8-2	11-1	11-2
ROCKTYPE																	
Micritic limestone, marly	x	x	x	x													
Micritic limestone														x	x		
Micritic limestone/breccia										x	x						
Fossiliferous micritic limestone									x		x	x	x				x
Packed biomicrite/biomicrudite					x												
Packed biomicrite							x	x									
Sparse to packed biomicrite						x											
Mxn to Cxn limestone, and basalt																x	
COLOUR																	
Pale grey						x						x					
Pale grey to bluish-grey									x		x		x	x	x		x
Pale grey, marbled					x												
Pale grey to dark grey			x														
Grey	x			x			x	x									
Grey to olive grey		x															
Dark grey																x	
Varicoloured (Pale grey/bluish/olive)										x							
PRIMARY STRUCKTURES	n.o.	n.o.	n.o.	n.o.					n.o.	n.o.	n.o.	n.o.		n.o.	n.o.	n.o.	n.o.
Coated grains, ooids						x											
Coated grains, ooids/oncoids					x												
Coated grains, oncoids							x	x									
Trace fossils (Chondrites?)													x				
FOSSILS	n.o.	n.o.	n.o.	n.o.						n.o.				n.o.	n.o.	n.o.	
Algae					x	x	x	x									
Shell-fragments, indeterminable						x		x	x		x	x	x				x
FRACTURES							n.o.	n.o.								n.o.	
Fracture density, high	x	x	x	x	x	x				x	x	x		x			x
Fracture density, low									x				x		x		
Simple fractures	x	x	x	x	x	x			x	x	x	x	x	x	x		x
Multiple fractures	x	x	x	x						x	x			x			x
Hairline-like fractures	x	x			x	x			x	x	x		x		x		x
Visible (in width), sparfilled	x	x	x	x	x	x				x	x	x		x			x
Width > 1/2mm, sparfilled	x	x	x	x	x					x	x	x		x	x		x
Irregular, varying width, sparfilled					x												
Slickensides on sliding surfaces			x	x											x		
Fracture dips: high-angle	x	x	x			?			x		x	x	x	x	x		x
Fracture dips: low-angle	x										x				x		
Fracture dips: "randomly"				x						x							
More than one event of fracturing	x	?								x	x				x		
STYLOLITES																	
Stolites (more well-developed ones)		x	x	x	x	x			x					x		?	x
Microstylolites	x	x	x	x	x	x	x			x	x	x	x	x	x		x
Solution seams				x													
Interconnected network-stylolites						x									x		x
Condensed fabric							x	x		x							
Fitted fabric					x			x									
Surfaces showing low-angle dips		x	x	x								x	x		x		x
Surfaces showing high-angle dips	x	x	x						x					x		x	x
Teeth oriented ± vertically		x	x	?							x	?	?		x		x
Teeth oriented ± horizontally	?	x	x	?					x		x			x			x
Stylolites postdate fractures	x	x	?	x	x	x			?		1)	x	x	x	2)		x
More than one event of stylolitization		x	x								x						x
POROSITY									n.o.	n.o.			n.o.	n.o.	n.o.	n.o.	
Rock is generally hard and massive	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x
Rock is hard, but rather porous							x	x									
Pores and/or vugs in fracture cements	x	x	x	x							x	x					x
Pores and/or vugs in stylolite joints			x	x	x	x	x	x			x						x
Intergranular porosity							x	x									
Pores and/or vugs ± interconnected							x	x									x

n.o. = not observed
→ = followed by
1) First generation of fractures → first generation of stylolites → second generation of fractures → second generation of stylolites
2) Fracturing → stylolitization → sliding surface associated veins

Sample number	1A-1	1A-2	1A-3	1A-4	4-1	4-3	6A-1	6A-2	8-1	8-2	11-2	4-2	11-1	2-1	2-2	2-3	2-4
Texture																	
Fossiliferous micrite				x				x	x	x	x						
Fossiliferous micrite/sparse biomicrite	x	x	x		x		x										
Fossiliferous micrite/pelmicrite																	
Sparse to packed biomicrite/biopelmicrite						x											
Fossiliferous pelmicrite, brecciated rock												x					
Mxn-Cxn limestone, and basalt													x				
Dis-oo/pel-micrite														x			
Packed oomicrite/disoomicrite															x		
Oncolitic grainstone																x	x
Fossiliferous limestone with clotted structure																	
Fossils													n.o.				
Fossils are fine-grained	x	x	x	x	x		x	x	x	x	x						
Many indeterminable fragments of macrofossils														x	x	x	
Radiolarian tests	x		x														
Calpionellids			x														
Planktic forams, common or very common	x	x	x	x	x	x	x	x	x	x	x	?					
Benthic forams						x	x	x	x	x	x			x	x		x
Miliolids														x	x		
"Unwalled calcispheres"					x					x							
Sponges														x			
Spicules of sparry calcite, monaxons/triaxons	x	x	x	x	x		x	x	x	x							
Mollusc shell-fragments						x			x								x
Pelecypods, *Inoceramus*-like, fragments or prisms					x	x				x							
Valves of planktic (juvenile) pelecypods						x											
Gastropods															x		x
Echinoderm fragments			x	x		x	x		x	x	x				x	x	x
Brachiopod fragments						x								?	x	x	x
Bryozoans																	x
Ostracod carapachs												?		x	x		
Algae, not coated grains														x	x		x
Small plant-like fragments of organic matter	x	x	x	x	x	x	x	x	x	x	x	x					

n.o. = not observed

Table 3: Rock textures and content of fossils, based on the study of thin sections.

Rock sample	$\delta^{18}O$	$\delta^{13}C$	T (°C)
1A-1 C	-13.03	1.37	91
1A-1 M	-9.91	1.65	70
4-2 C	-11.23	1.02	79
4-2 M	-6.56	2.35	50
6A-1 C	-11.99	1.63	84
6A-1 M	-7.88	2.06	58
8-1 C	-10.95	1.59	77
8-1 M	-4.68	2.63	40
11-1 C	-15.12	0.22	106
11-2 C	-12.28	1.34	86
11-2 M	-9.31	2.49	66

Table 4: Oxygen and carbon composition (‰, PDB) of carbonate from matrix samples (M) and sparry cements of younger fractures (C). For the calculation of the oxygen isotopic temperatures a value of 0 ‰ is assumed for $\delta^{18}O_w$.

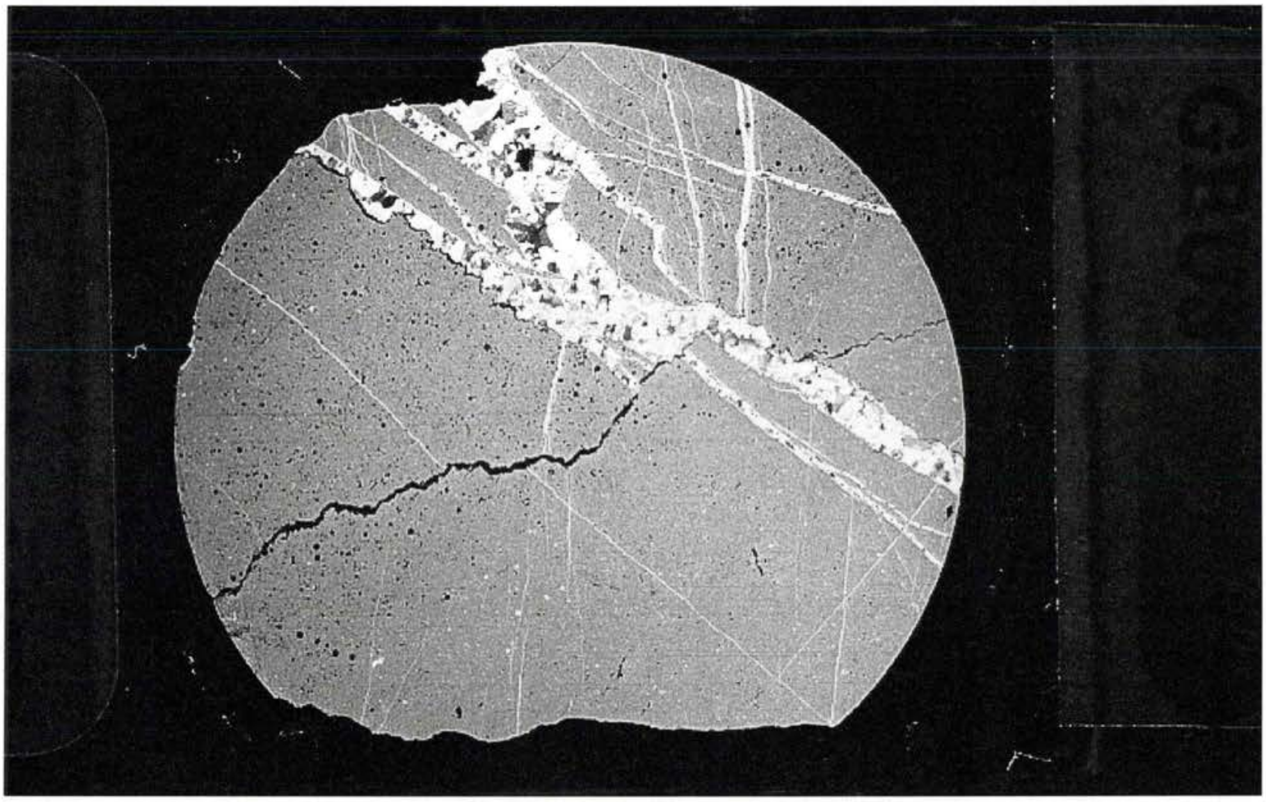


Figure 1: The limestone of thin section 1A-2 is a fossiliferous micrite. The rock, that looks very massive, is cut by multiple, sparfilled fractures and thin hairline-like fractures. With higher magnification of the microscope the latter are observed to be "healed" by sparry calcite too. One of the stylolites is formed in the contact between the sparry calcite of a large fracture and the surrounding micrite; this fracture is approximately orientated in a vertical direction, as deduced from the core piece from which the thin section is manufactured. The many small black dots are framboids. Cross-polarized light. The section is 25 mm in diameter.

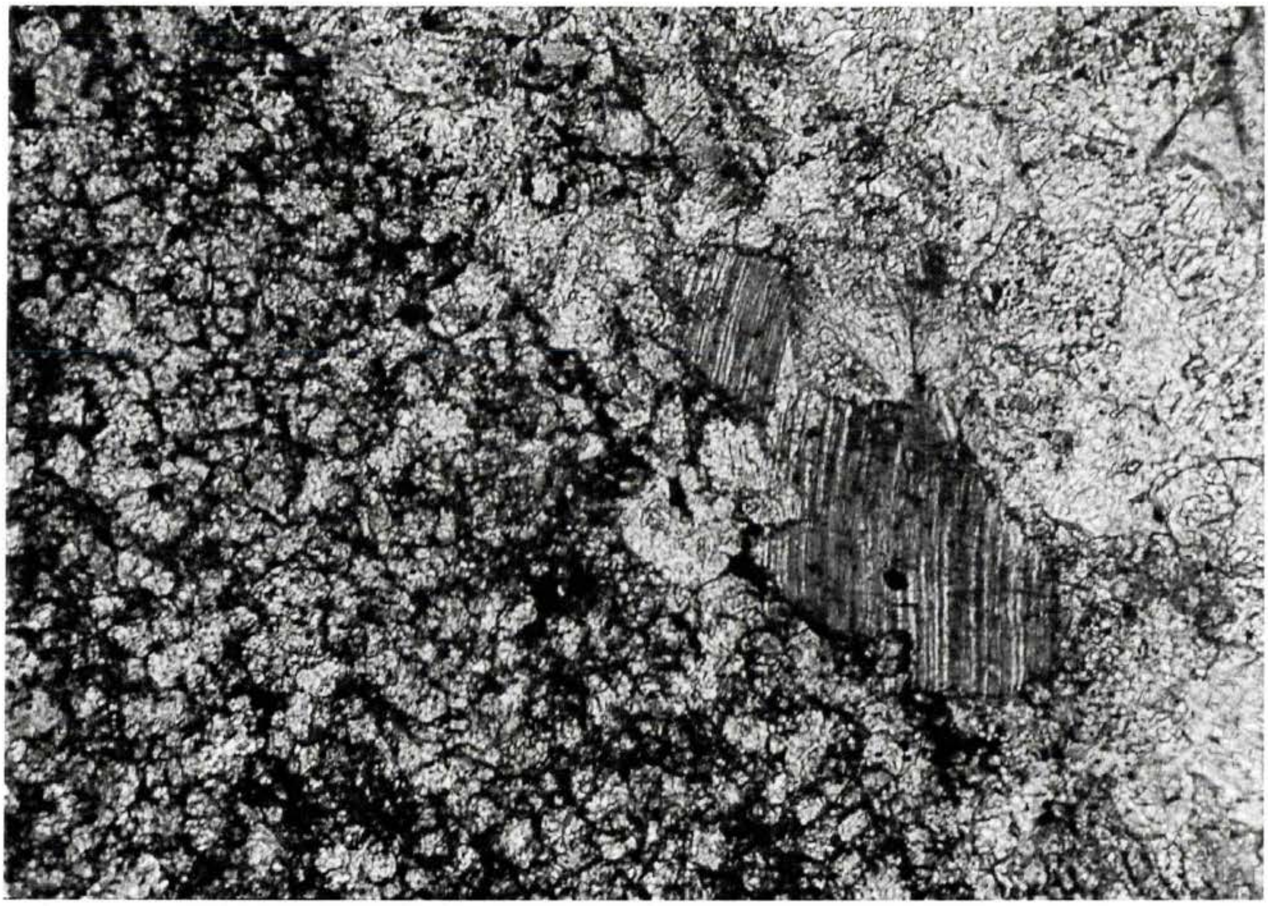


Figure 2. Thin section photomicrograph showing a stylolitic contact between a sparfilled fracture (the coarse-grained crystals to the right) and the surrounding rock matrix. The latter has been exposed to an aggrading neomorphism, perhaps contemporaneously with a similar neomorphism of the coarsely crystalline fracture spar. The presence of residuals of the stylolite seam inside some of the sparry crystals indicate that a phase of recrystallization post-dates the phase of chemical compaction. Width of view is 0.9 mm (Sample 1A-1).

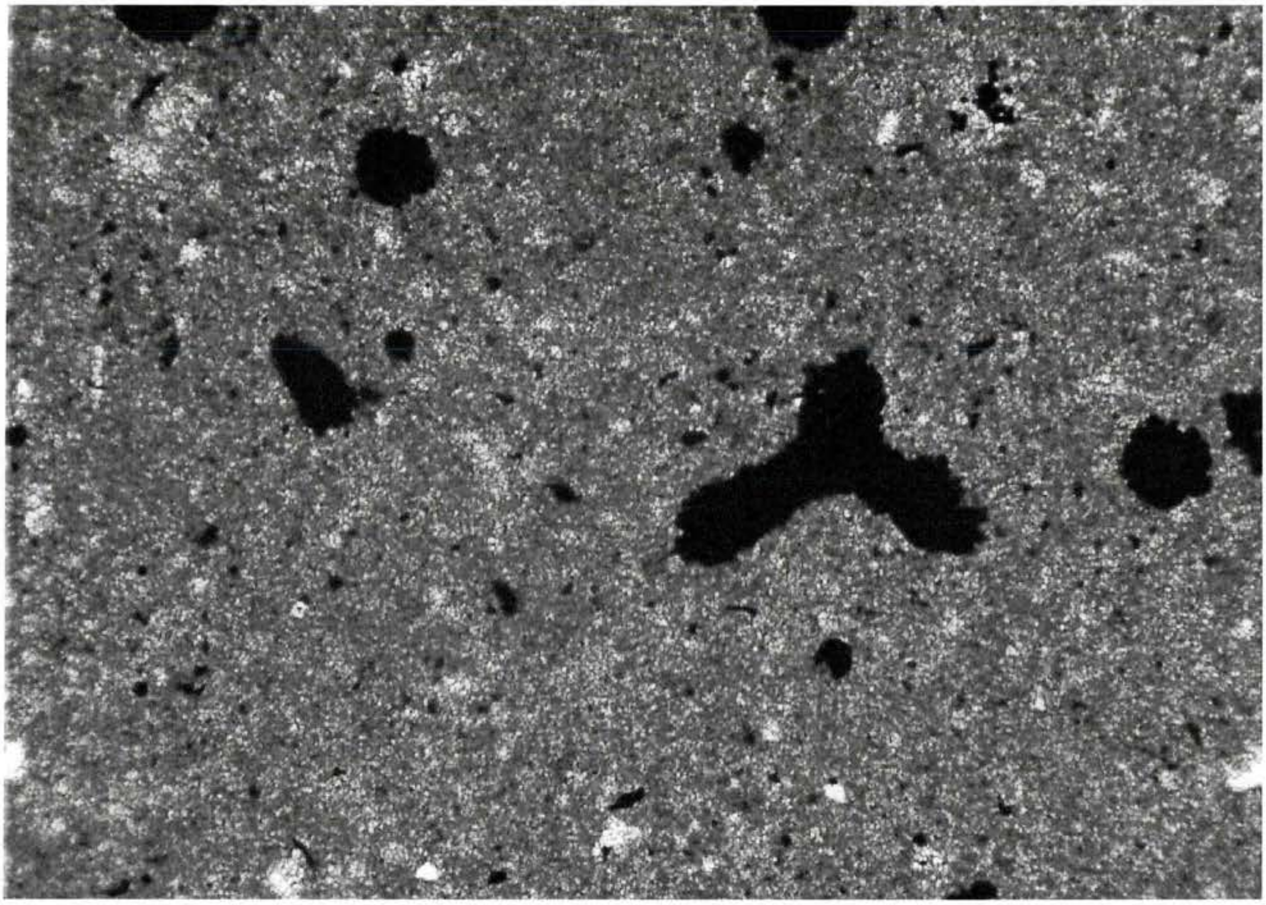


Figure 3. Thin section photomicrograph of fossiliferous micrite with several pyrite grains (framboids). One of them seems to have taken shape of a triaxon spicule. Width of view is 0.9 mm. (Sample 1A-2).

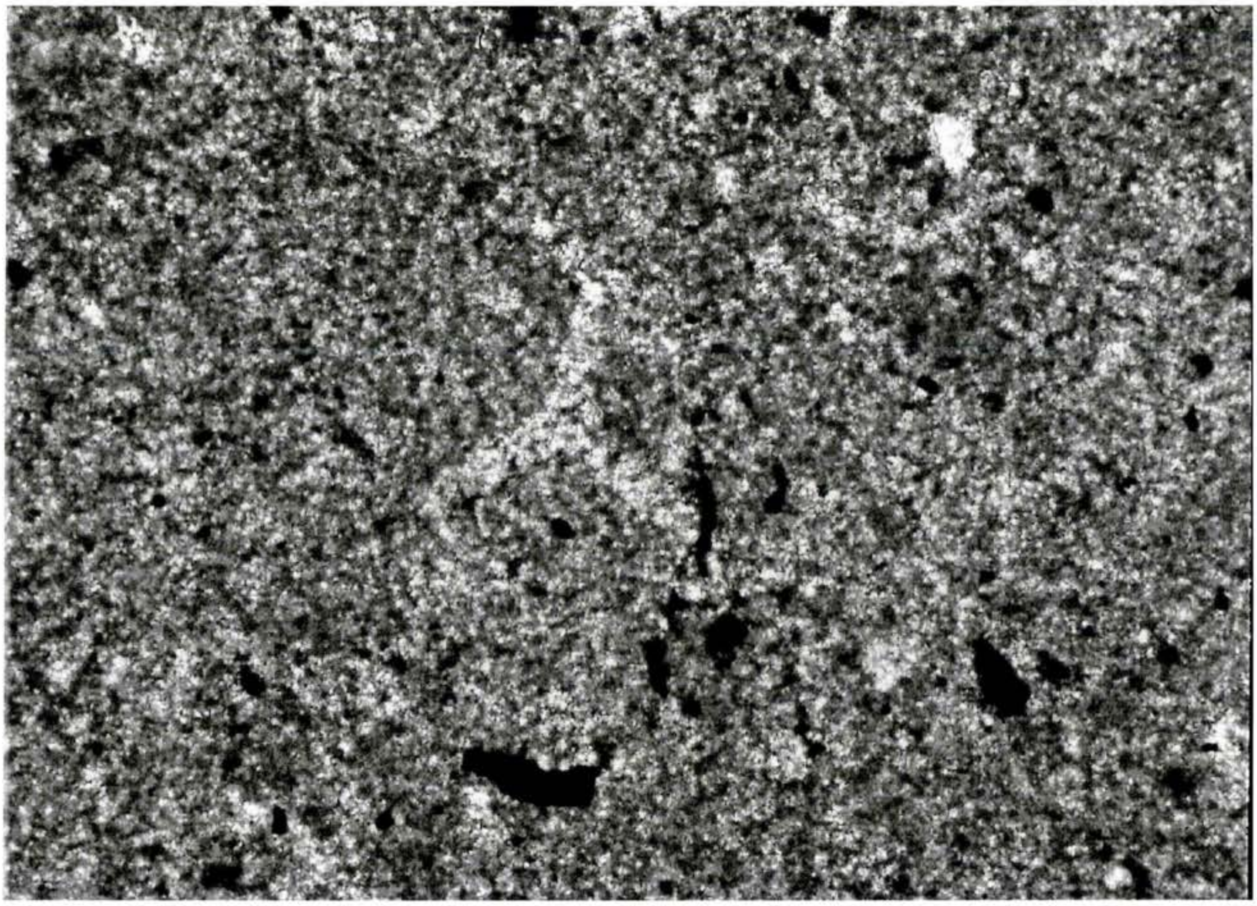


Figure 4. Thin section photomicrograph of fossiliferous micrite with poorly preserved fossils. The triaxon spicule in the middle of the picture shows a ghost-like appearance because of micritization. Width of view is 370 μm. (Sample 1A-3).

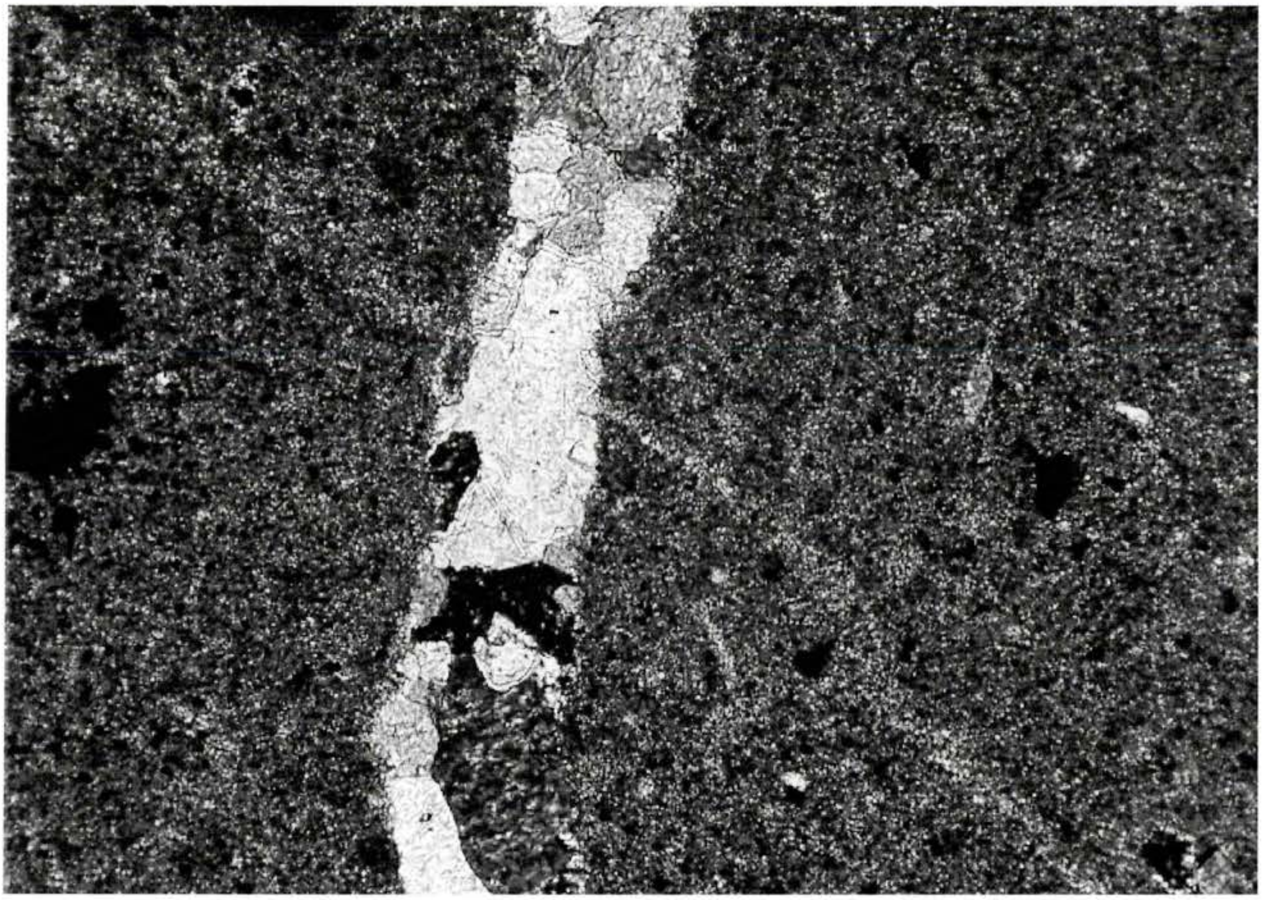


Figure 5. Thin section photomicrograph (crossed nicols) of a younger spar-filled fracture crossing an older indistinct outlined, almost hairline-like fracture. Several pyrite grains are seen scattered in the micritic matrix. Width of view is 0.9 mm. (Sample 1A-4).

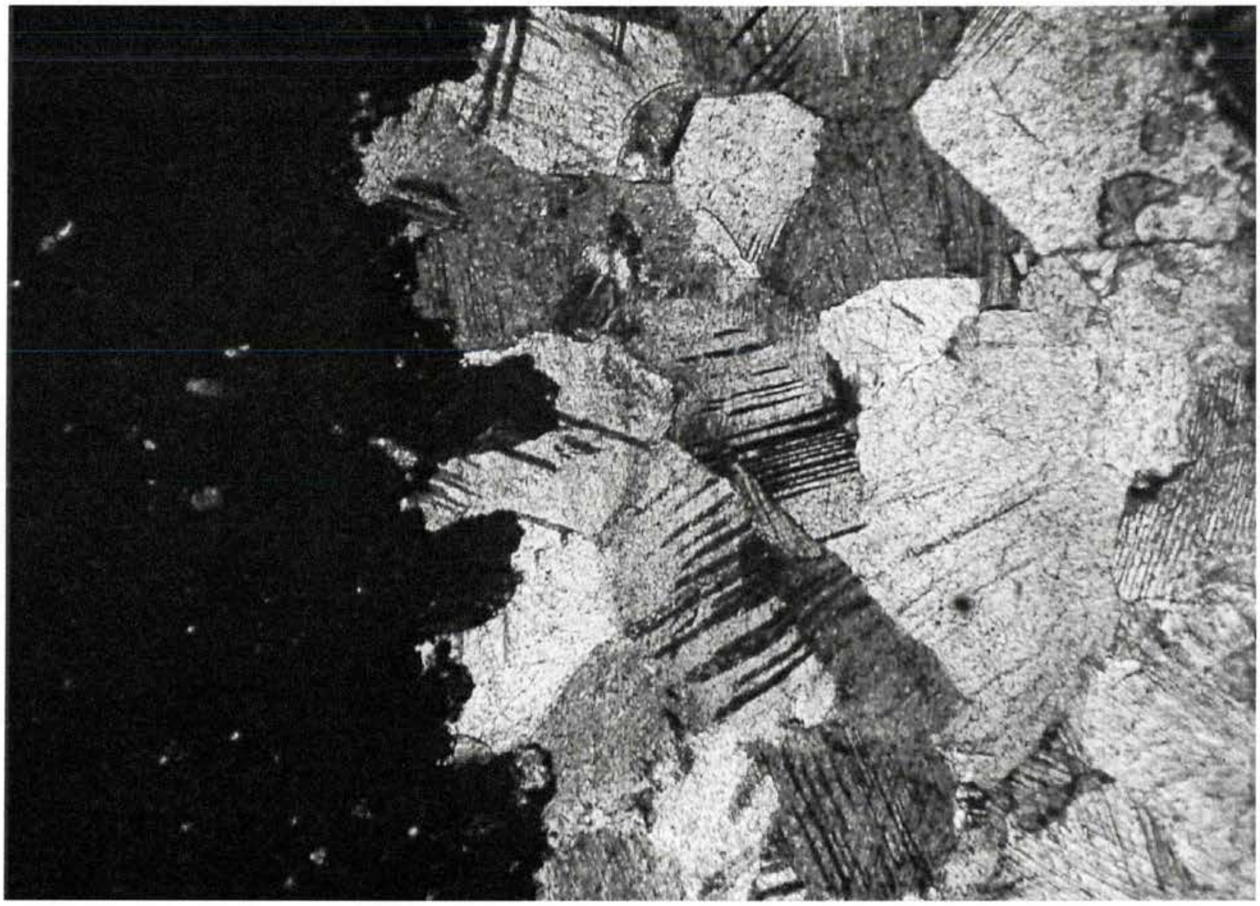


Figure 6. Thin section photomicrograph (crossed nicols) of a fracture with coarse-grained calcite crystals that show twinned stress laminae. The contact between the fracture margin and the surrounding micrite matrix (to the left in the picture) consists of a stylolite. Width of view is 2.2 mm. (Sample 1A-2).

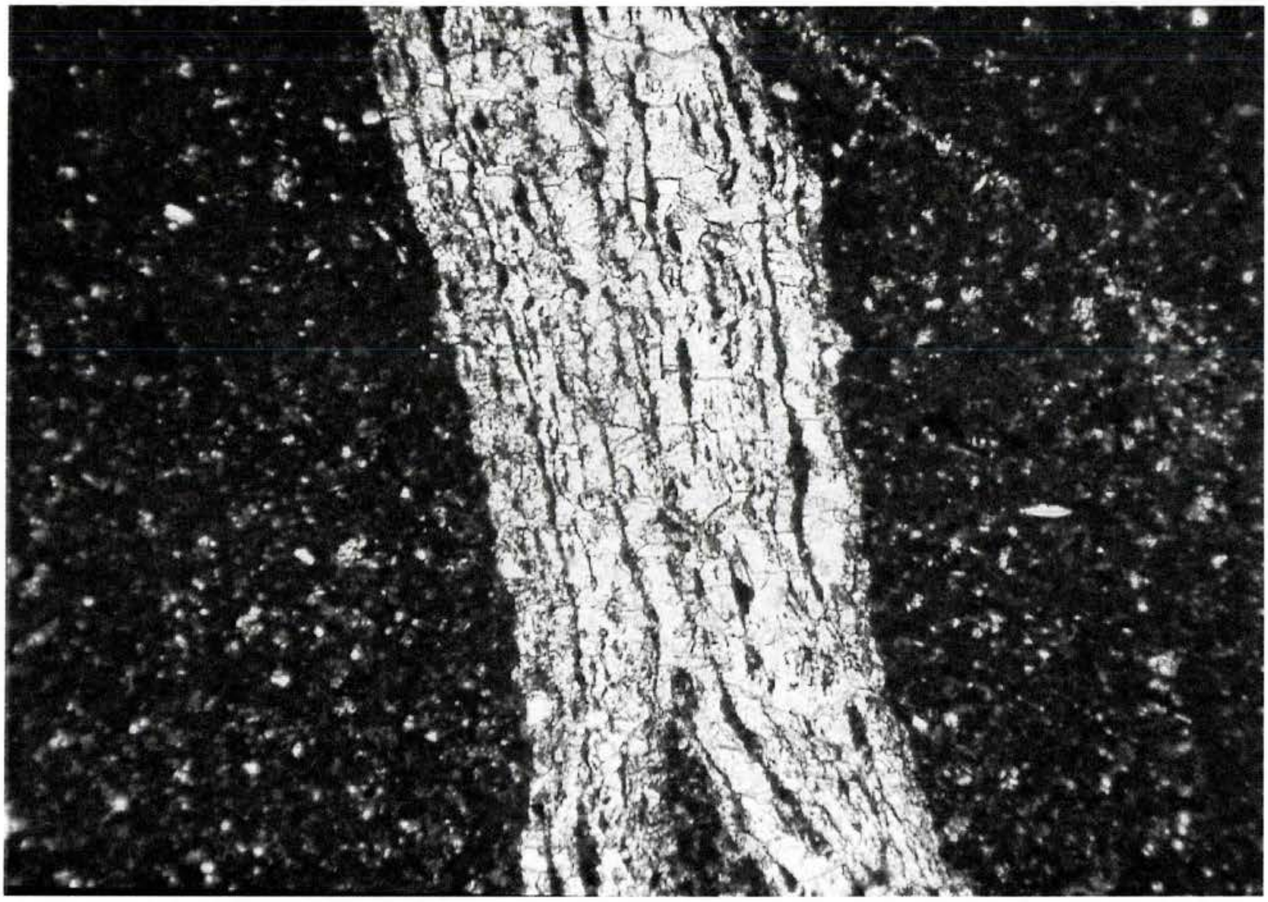


Figure 7a. See the text below figure 7b.

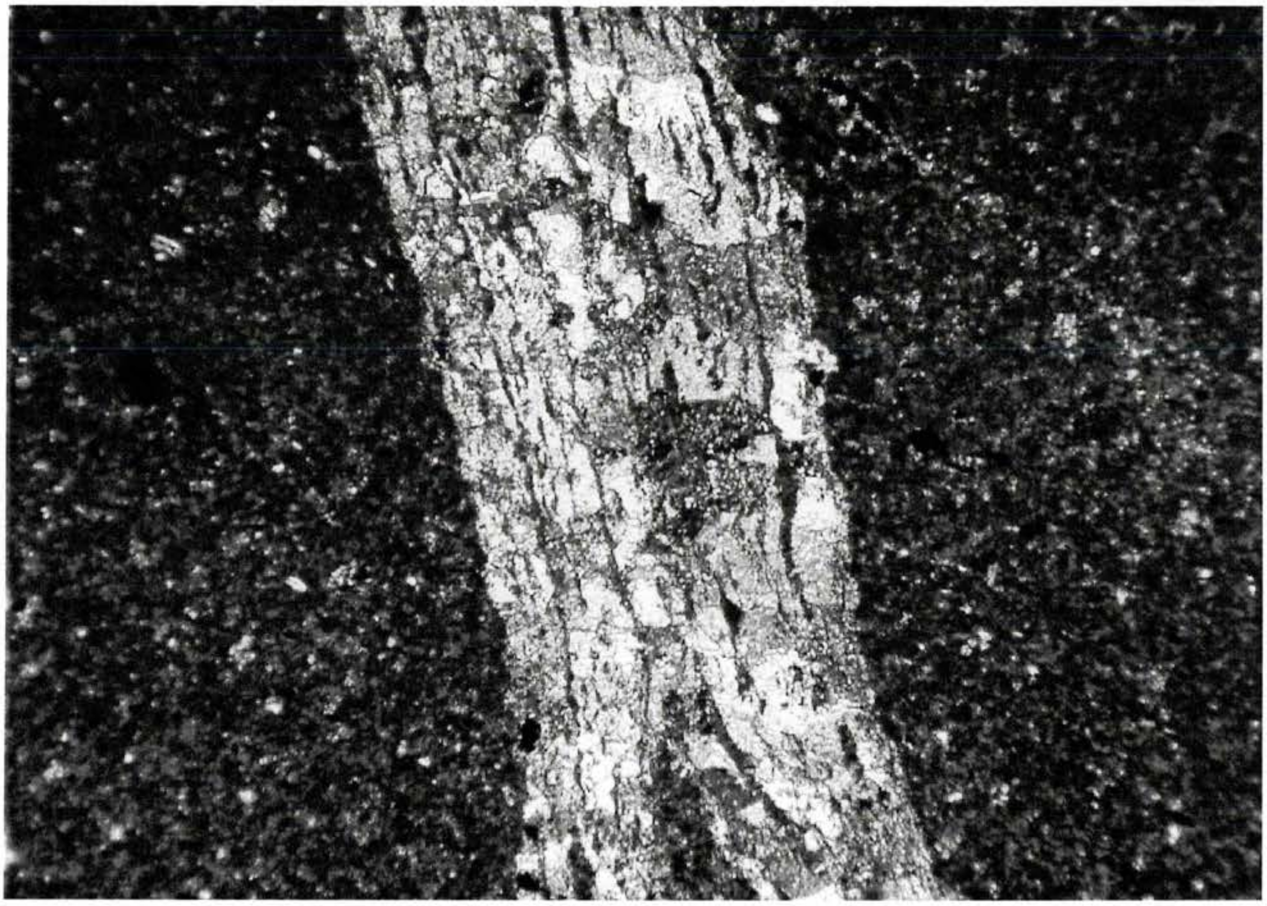


Figure 7b. The thin section photomicrograph of figure 7a is taken with plane polarised light, whereas that of figure 7b is taken with cross-polarised light. The figures show a "younger" fracture rich in rows of fibrous micrite inclusions that run parallel to the fracture margin. When observed under crossed nicols, the sparry cement crystals of the fracture are observed to overlay the micritic fibres. Width of views is 2.2 mm. (Sample 1A-1).

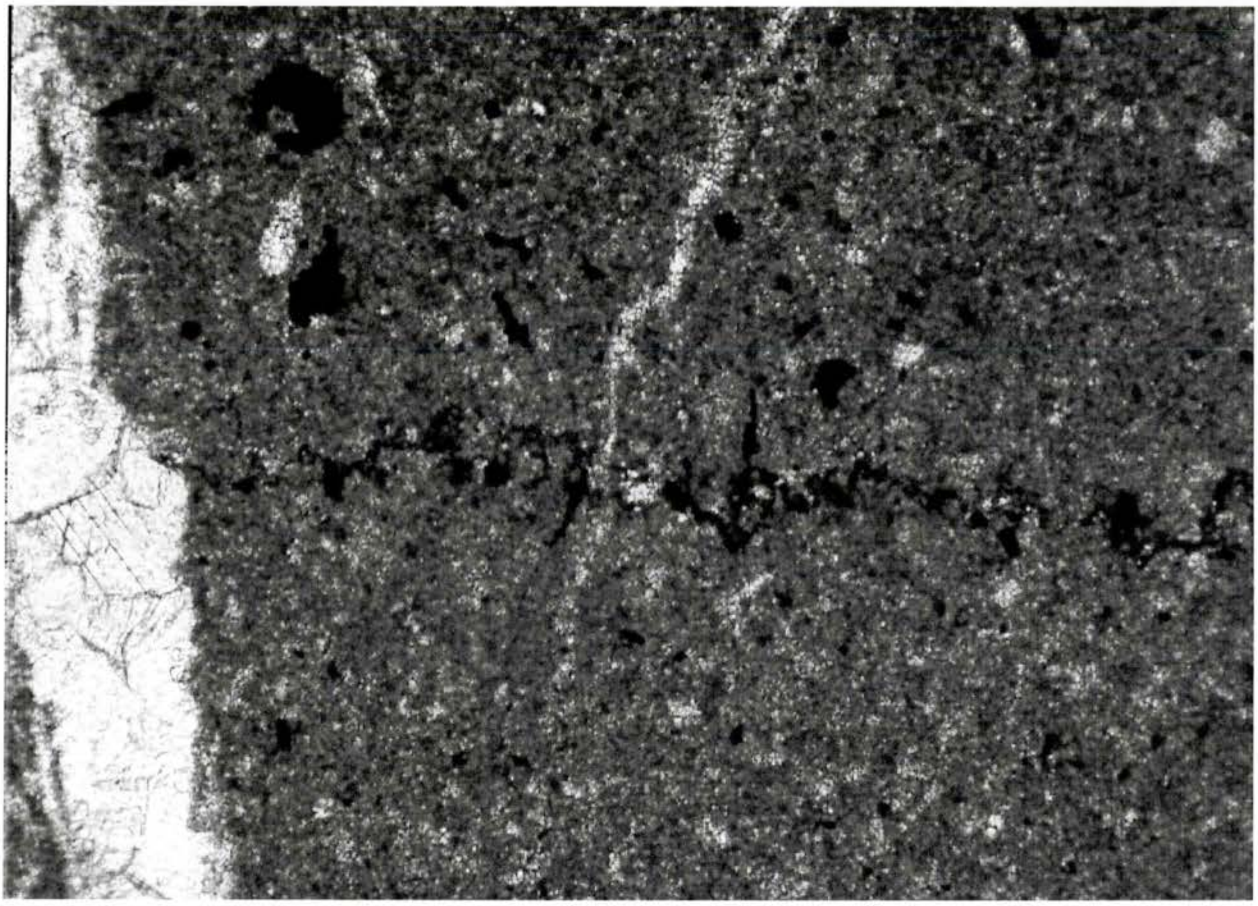


Figure 8. Thin section photomicrograph showing a microstylolite that cut a rather indistinct thin fracture. The stylolite is in turn cut by the coarsely crystalline spar of a younger fracture. Width of view is 0.9 mm. (Sample 1A-2).

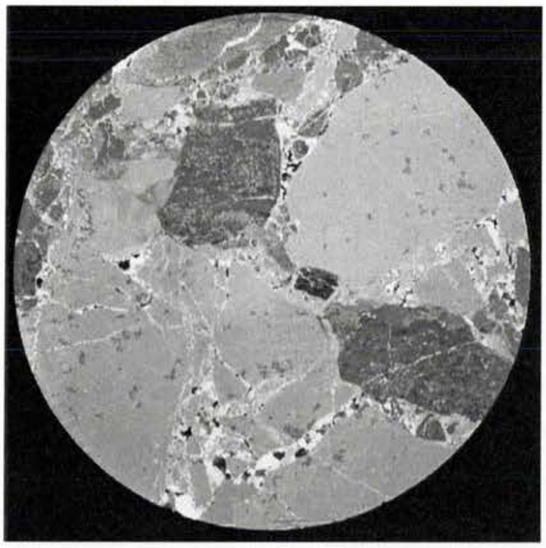


Figure 9: The thin section of sample 4-2 shows a massive limestone that has been brecciated. A coarsely crystalline calcite spar is precipitated in between the angular rock fragments. Some of the fine hairline-like fractures are observed to cross more than one rock fragment without any displacements of the fracture-surface, indicating that a fracturing took place *after* the brecciation. Cross-polarised light. The section is 25 mm in diameter.

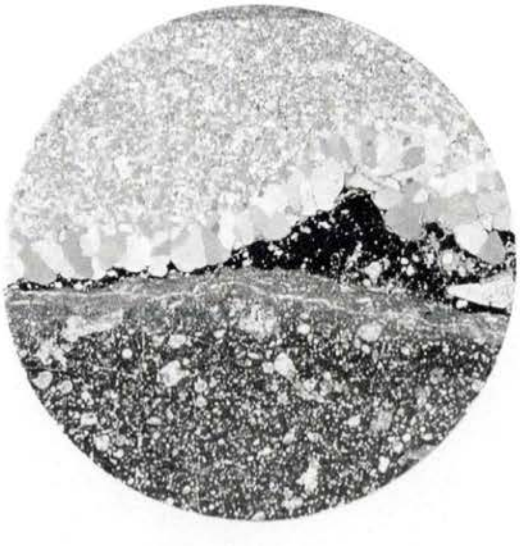


Figure 10: The photo shows the contact between an amygdaloidal basalt (the lower half of the picture) and a massive medium to coarsely crystalline limestone. The thin section measures 25 mm in diameter. (Sample no. 11-1).

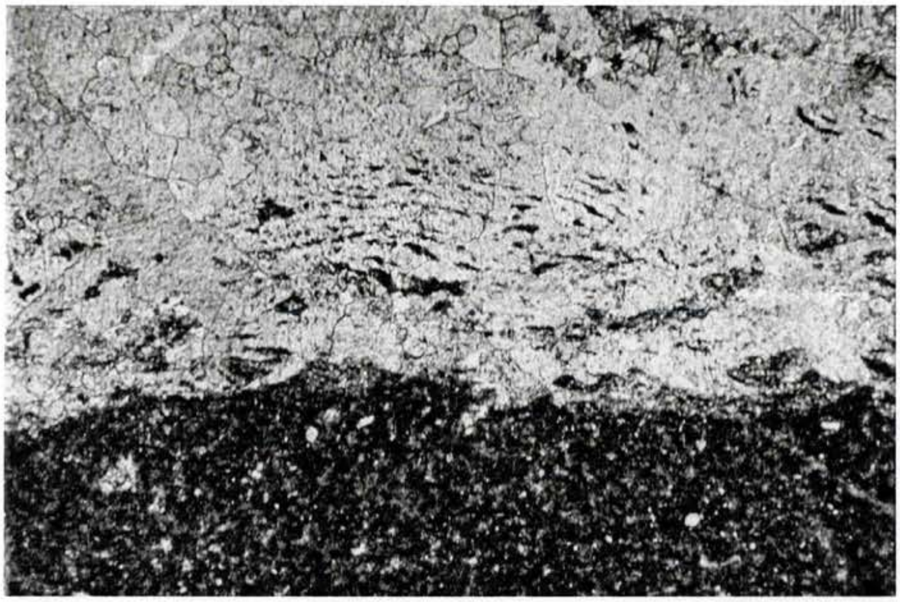


Figure 11: Thin section photomicrograph of a calcite-mineralised fracture (in the upper part of the picture). The coarsely grained spar of the fracture contains rows of fibrous micrite inclusions that run more or less parallel to the fracture margin. Width of view is 2.2 mm. (Sample no. 8-1).

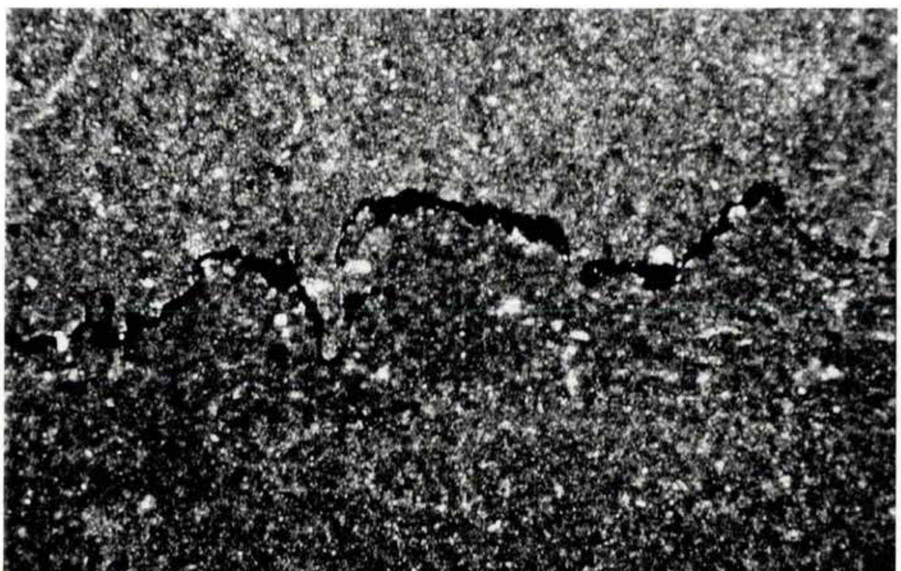


Figure 12a: See the text below Figure 12b.

Figure 12b: The photomicrographs of figures 12a and 12b show a stylolite with an insoluble accumulation of organic matter. In places, the stylolitic joint seems to have been obliterated because of a recrystallisation of the rock matrix. Figure b is a close-up of figure a. Width of view is 2.2 mm for figure a, and 370 μm for figure b. (Sample no. 11-2).

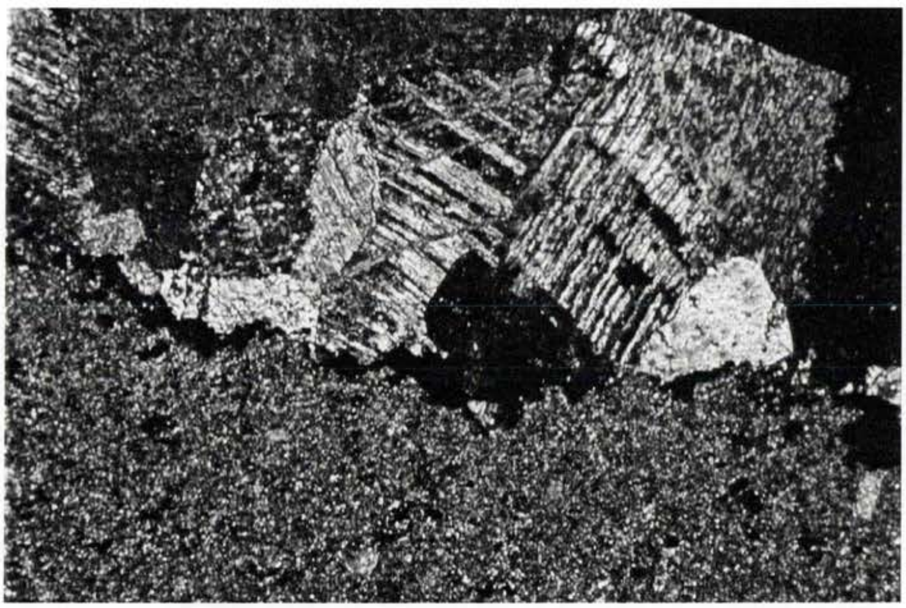


Figure 13: Thin section photomicrograph (crossed nicols) of a stylolite formed in the contact between the coarsely crystalline spar of a vertically orientated fracture and the surrounding micrite matrix. Note the numerous twins in the sparry calcite crystals. Width of view is 0.9 mm. (Sample no. 8-1).

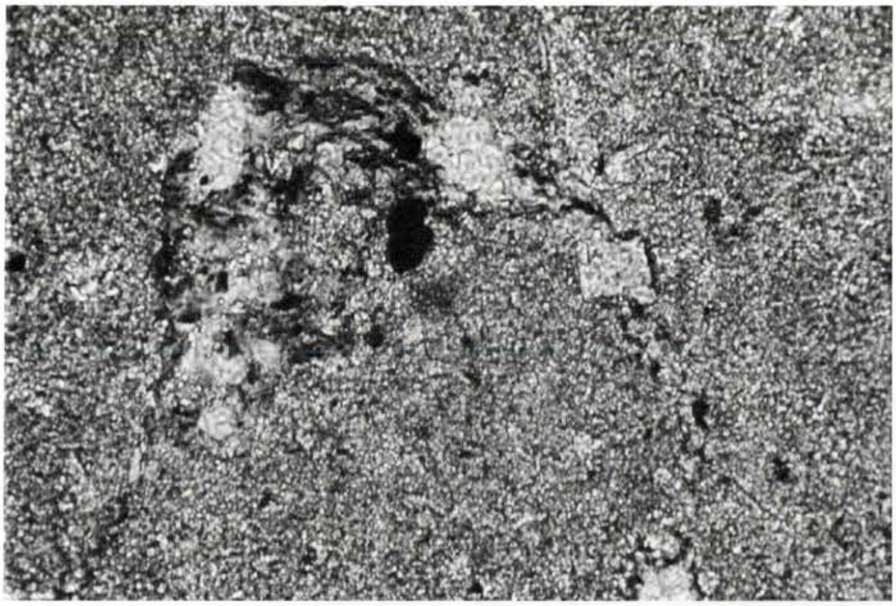


Figure 14: Thin section photomicrograph of a stylolite. Two small silica grains, an opaque pyrite grain, plus a rhombohedral crystal of assumed dolomite can be seen in the stylolitic joint. Width of view is 370 μm. (Sample no. 8-1).

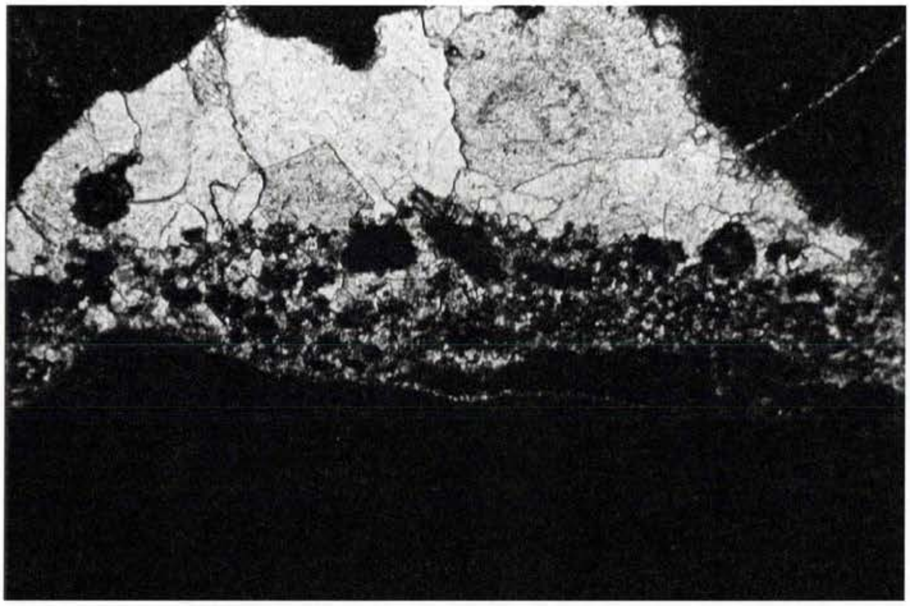


Figure 15: Thin section photomicrograph of a geopetal structure in the brecciated limestone of sample 4-2. The contact between the geopetal sediment and the overlaying sparry calcite indicates an approximate level surface at the time of deposition of the infilling. Width of view is 2.2 mm.

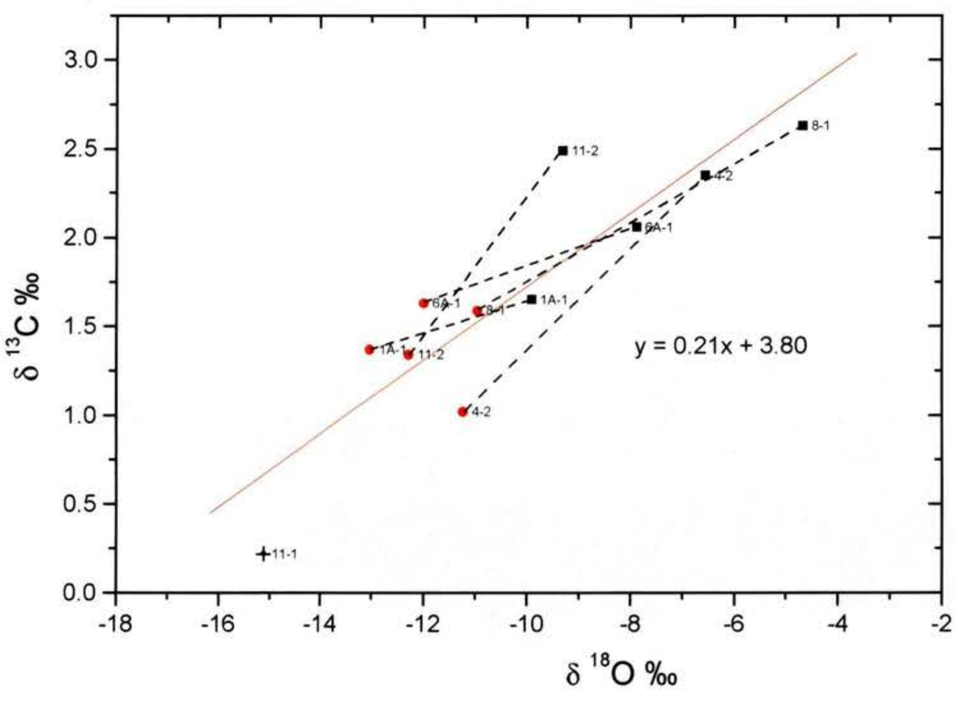


Figure 16: Cross-plot of $\delta^{13}C$ versus $\delta^{18}O$ (‰). ■ and • stand for rock matrix and sparry calcite cement of fractures respectively. Note how the diagenetic trend from matrix to cement roughly parallel the straight line fitted by least squares.

Figure 17: A thin section of the marbled limestone of sample 2-1, being rich in fine almost hairline-like fractures and irregular vein-like patches of sparry calcite. The section is about 25 mm in diameter.

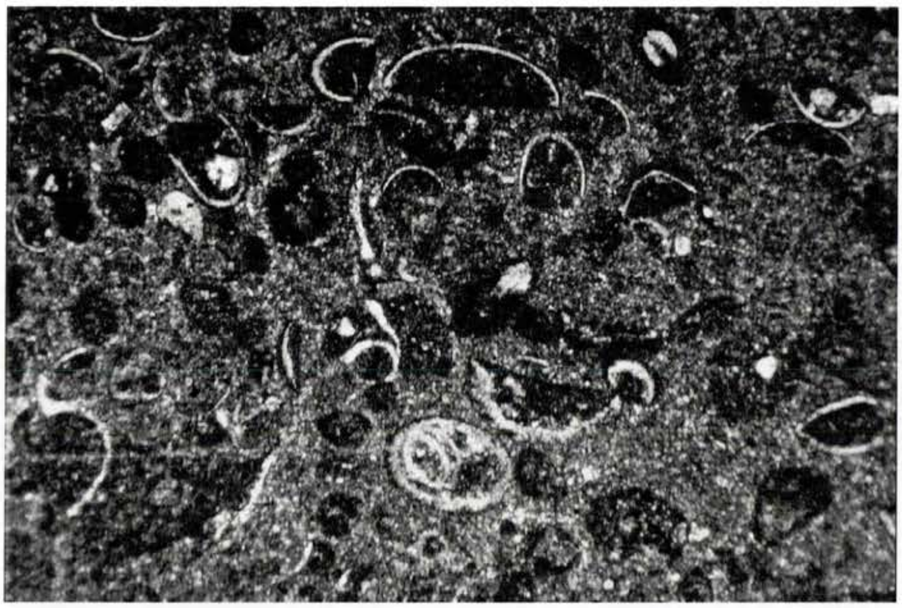


Figure 18: Thin section photomicrograph of a oomicritic limestone. Most of the micritic coats that surround the poorly preserved fossils are very thin. Width of view is 2.2 mm. (Sample 2-2).

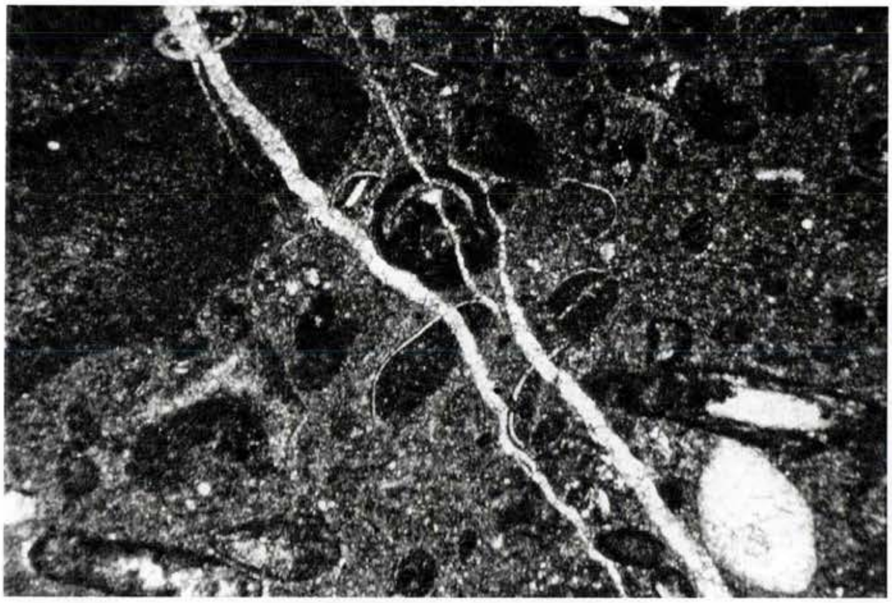


Figure 19a.

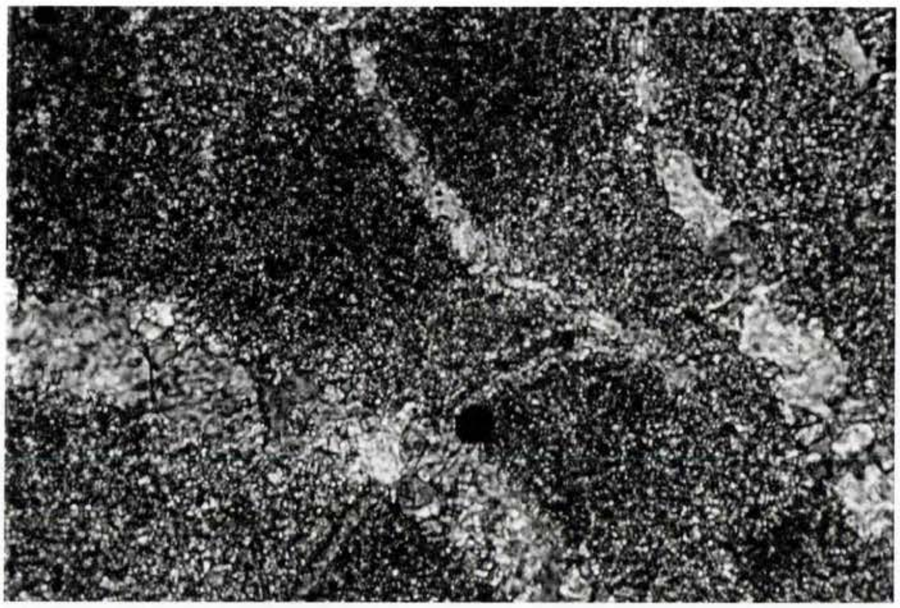


Figure 19b. (a): Thin section photomicrograph of calcite mineralised fractures that cross allochems without any sign of displacement of the rock. (b): With greater magnification the fractures of figure a appear "old" and poorly preserved as if the sparry crystals have suffered from an incipient micritisation. Figure b is taken with ½ cross-polarized light. Width of view is 2.2 mm in figure a, and 370 µm in figure b. (Sample 2-2).

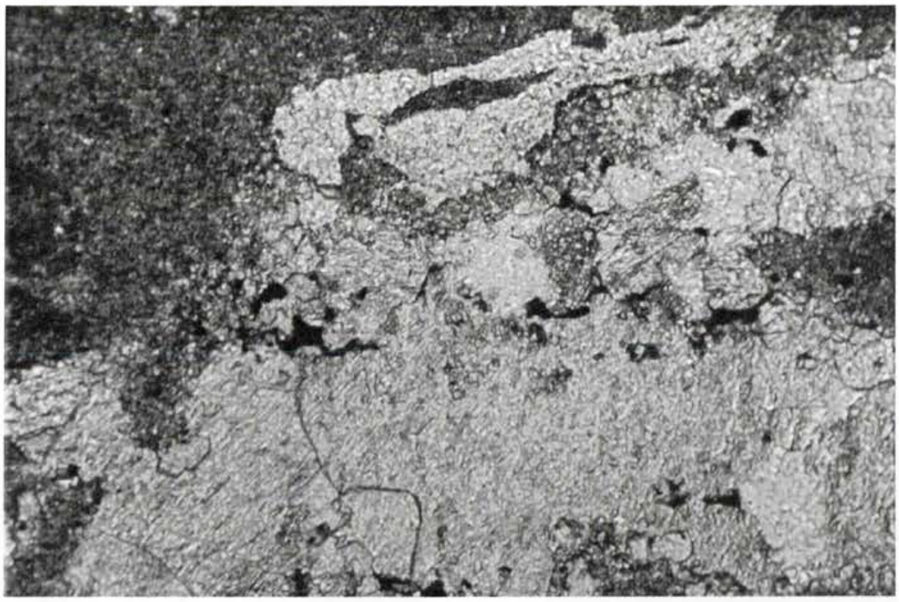


Figure 20: Thin section photomicrograph showing a sparry patch as seen in a dismicrite limestone type. Residuals of a stylolitic joint is seen in the calcite spar. Width of view is 0.9 mm. (Sample 2-2).

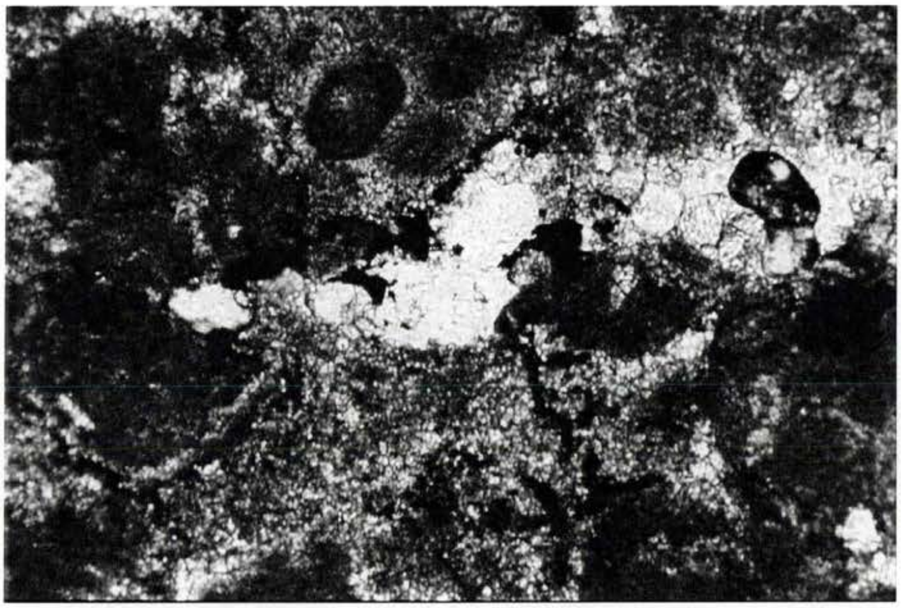


Figure 21: Thin section photomicrograph of pelmicritic limestone with a rather indistinct micro-stylolite. A small solution vug is formed in direct connection to the stylolite. Width of view is about 0.9 mm. (Sample 2-1).

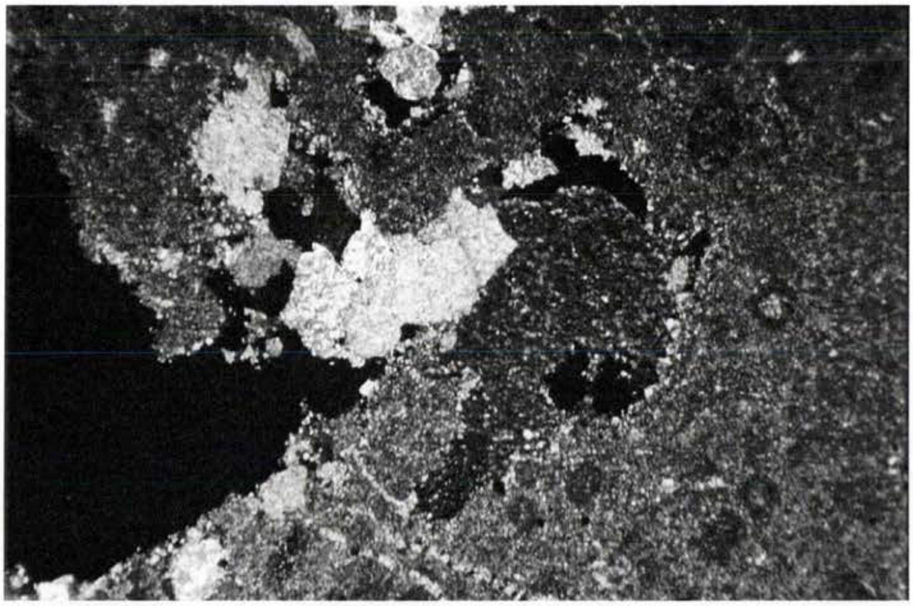


Figure 22: The thin section photomicrograph (crossed nicols) shows a solution vug and a patch of sparry calcite. The corroded appearance of the sparry crystals indicates that dissolution took place after the precipitation of the crystals. Width of view is 2.2 mm. (Sample 2-2).

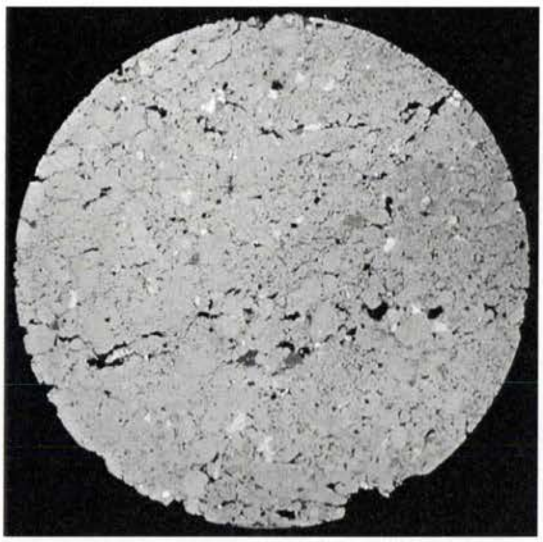


Figure 23: The limestone of sample 2-3 is an oncolitic grainstone. Numerous inter-granular pores are seen, as are a few intra-granular ones. In two levels the inter-granular pores form an interconnected pore system with a wavy to zigzagging course. These pore systems are probably former stylolitic joints that have been solution-enlarged. The diameter of the thin section is 25 mm long. (Crossed nicols).

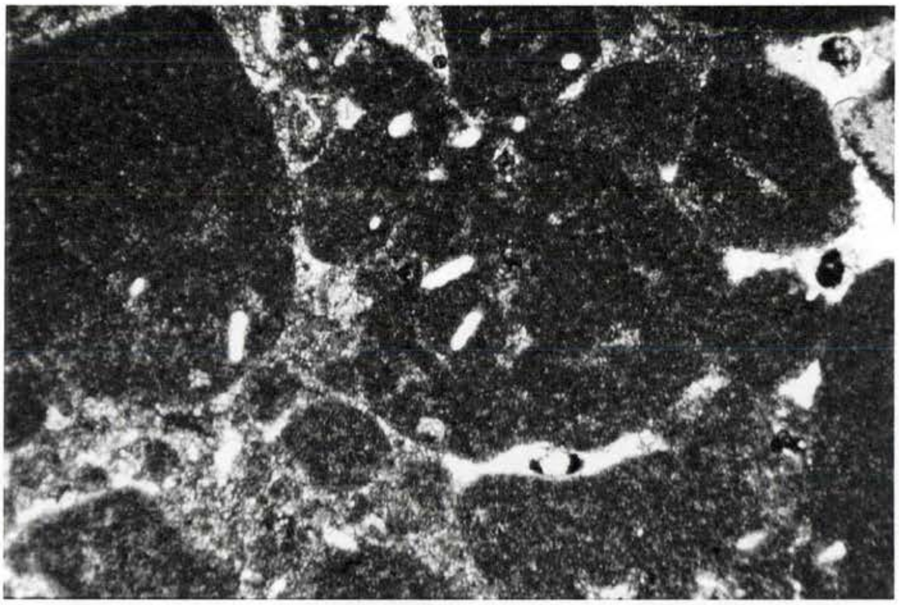


Figure 24: Thin section photomicrograph of an oncolitic grainstone. Tiny little pores are found inside some of the oncoids. These pores are believed to be moulds from former monoclinic gypsum crystals. Width of view is 2.2 mm. (Sample 2-4).

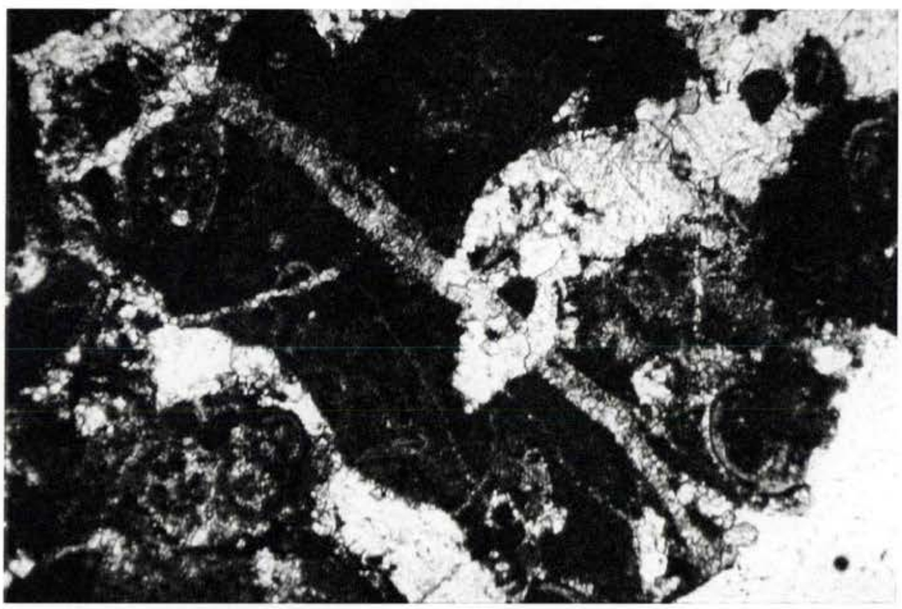


Figure 25: Thin section photomicrograph which shows an older, poorly preserved fracture (running from upper left to lower right corner of the photo) being crossed by irregular patches of younger sparry calcite. Width of view is 2.2 mm. (Sample 2-1).

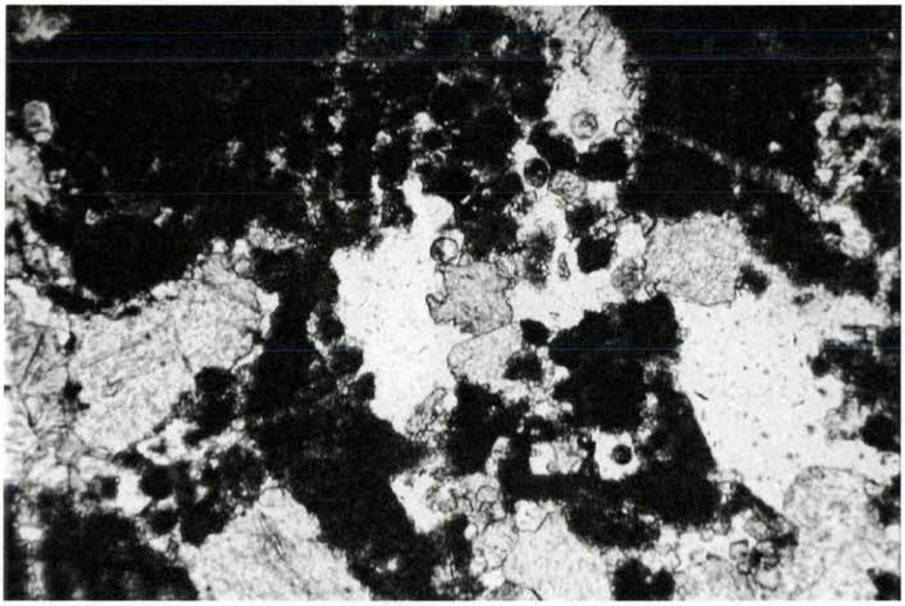


Figure 26: Thin section photomicrograph of limestone rich in pelloids. The rather large dissolution vugs are partly filled in with calcite cement that have subsequently been faintly corroded during a renewed phase of leaching. Width of view is 2.2 mm. (Sample 2-1).

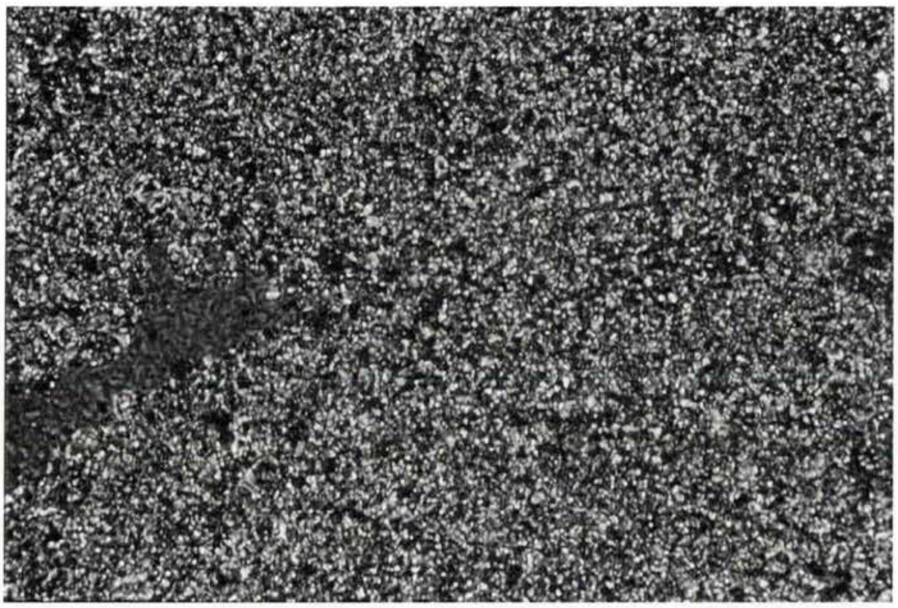


Figure 27: Thin section photomicrograph (½ crossed nicols) which shows the area between two oncoids. It looks as if a micritisation of the oncoids has completely obliterated the grain contact. A small inter-granular pore is seen to the left. The picture is a close-up of the rock shown in figure 28. Width of view is 370 μm. (Sample 2-3).

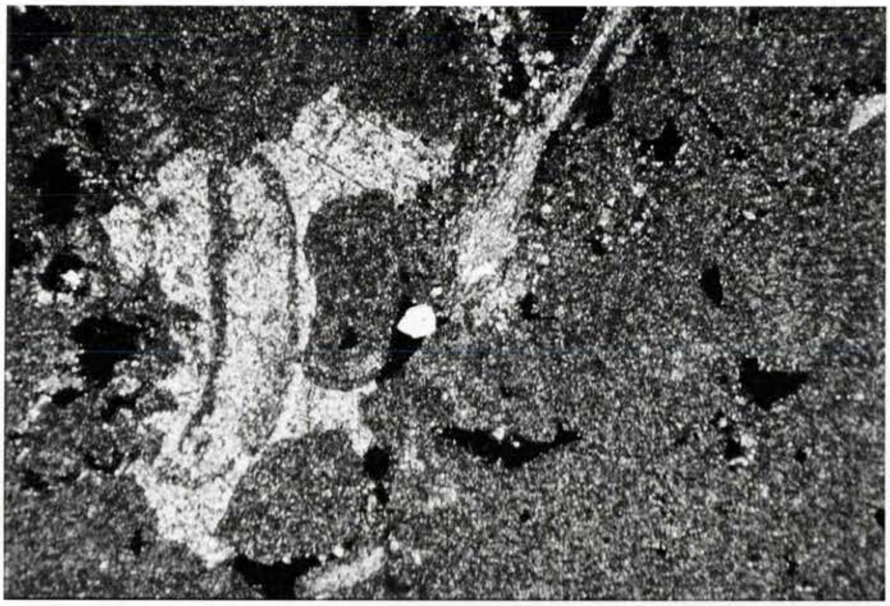


Figure 28: Thin section photomicrograph (crossed nicols) of a densely packed oncolite with inter-granular calcite cement. Note how the oncoids are coalesced. The calcite cement, which appears as one single crystal (being poikilotopic here), seems to have replaced minor parts of the oncoids. Width of view is 2.2 mm (Sample 2-3).

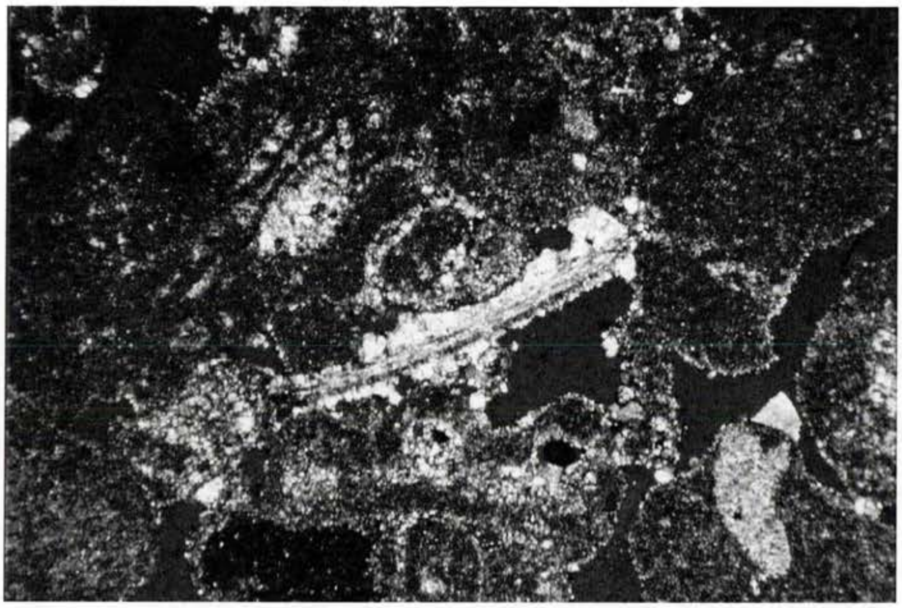


Figure 29: Thin section photomicrograph (½ crossed nicols) of a brachiopod-like shell fragment overgrown by a calcite cement that resembles an early diagenetic, marine cement. The cement crystals have been somewhat corroded during a later phase of leaching. A similar cement is also observed inside zooecia of bryozoan fragments. Width of view is 2.2 mm. (Sample 2-4).

Diagenetic events	Relative time
A. Early, incipient lithification	⇨
B. Fracturing	⇨
C. Recrystallisation	? ? ? ? ? ⇨ ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
D. Chemical compaction I	? ? ? ⇨
E. Chemical compaction II	⇨
F. Leaching phase I	⇨
G. Precipitation of calcite	⇨
H. Leaching phase II	⇨

Figure 30: The diagenetic events arranged in relative time.

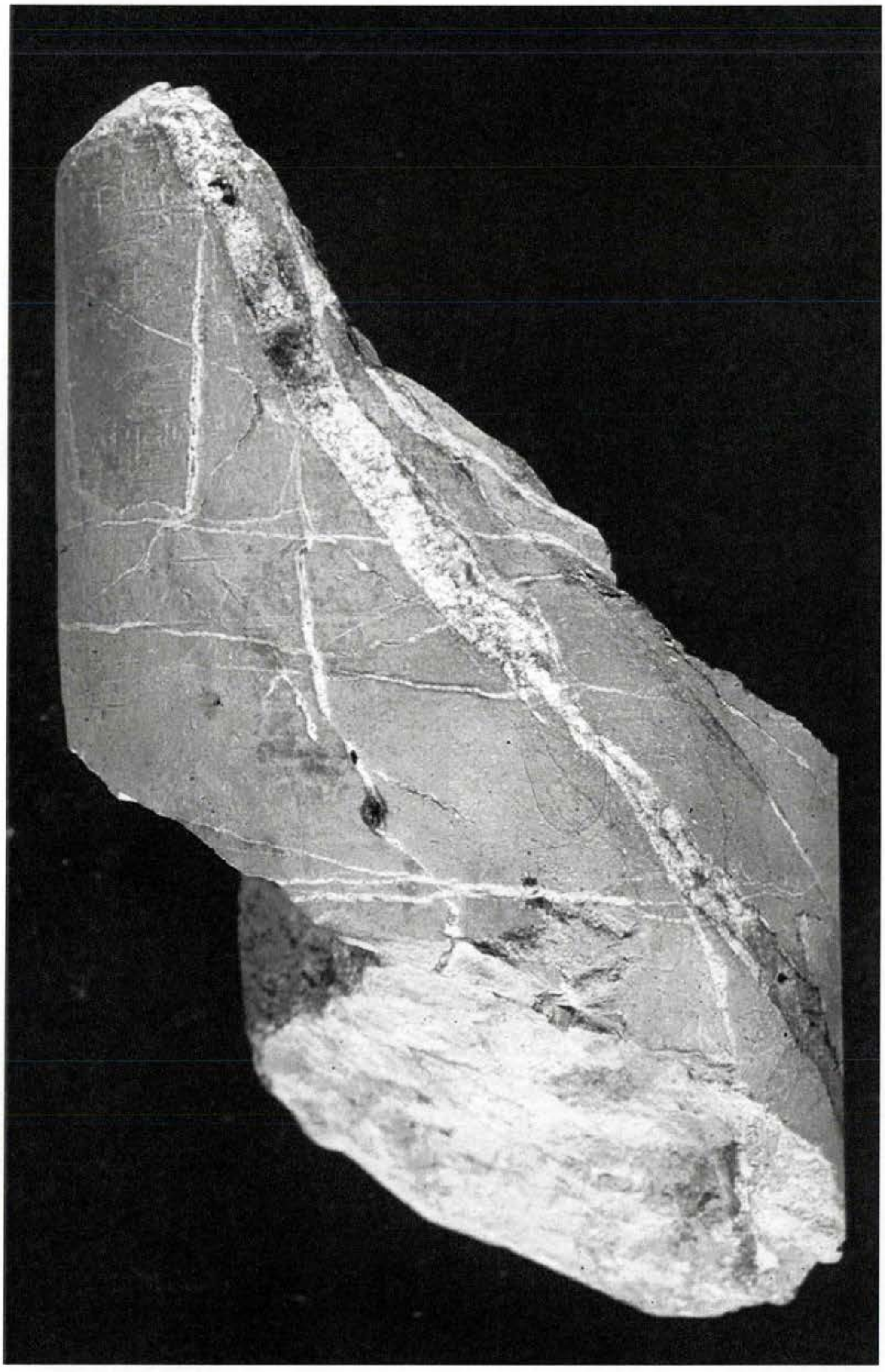
Appendix 1

Macroscopic description
of
core samples

Core sample no. 1A-1

Well: Abadia 1A.
Formation: Montejunto.
Depth: 143.9 metres.

Lithology: Grey-coloured micritic limestone, probably a marly one, hard and massive. Several small, scattered pyrite grains.
Primary structures: Not observed.
Fossils: Not observed.
Fractures: Many fractures, both single fractures and multiple fractures, filled with sparry calcite cut the rock. The surface(s) of some of the fractures show high-angle dips (the angle of inclination of fracture surface from a plane perpendicular to the axis of the core), others are almost horizontal. Indistinct, hairline-like fractures appear as very irregular traces on the rock surface. Even though no displacement of the rock is observed in places where two fractures cross each other, it looks as if the hairline-like fractures were formed prior to the others.
Stylolites: A microstylolite is seen faintly in places along the contact between the spar of a large fracture (showing high-angle dip) and the surrounding micritic matrix.
Porosity: The presence of a few small specks of oil betrays the presence of minor vugs and pores in fractures. Here the latter have either been only partly sealed with calcite cement, or a dissolution of sparry cement crystals have taken place before the oil was introduced.



Sample no. 1A-1.
The core piece is 6.3 cm in diameter.

Core sample no. 1A-2

Well: Abadia 1A.
Formation: Montejunto.
Depth: 158 metres.

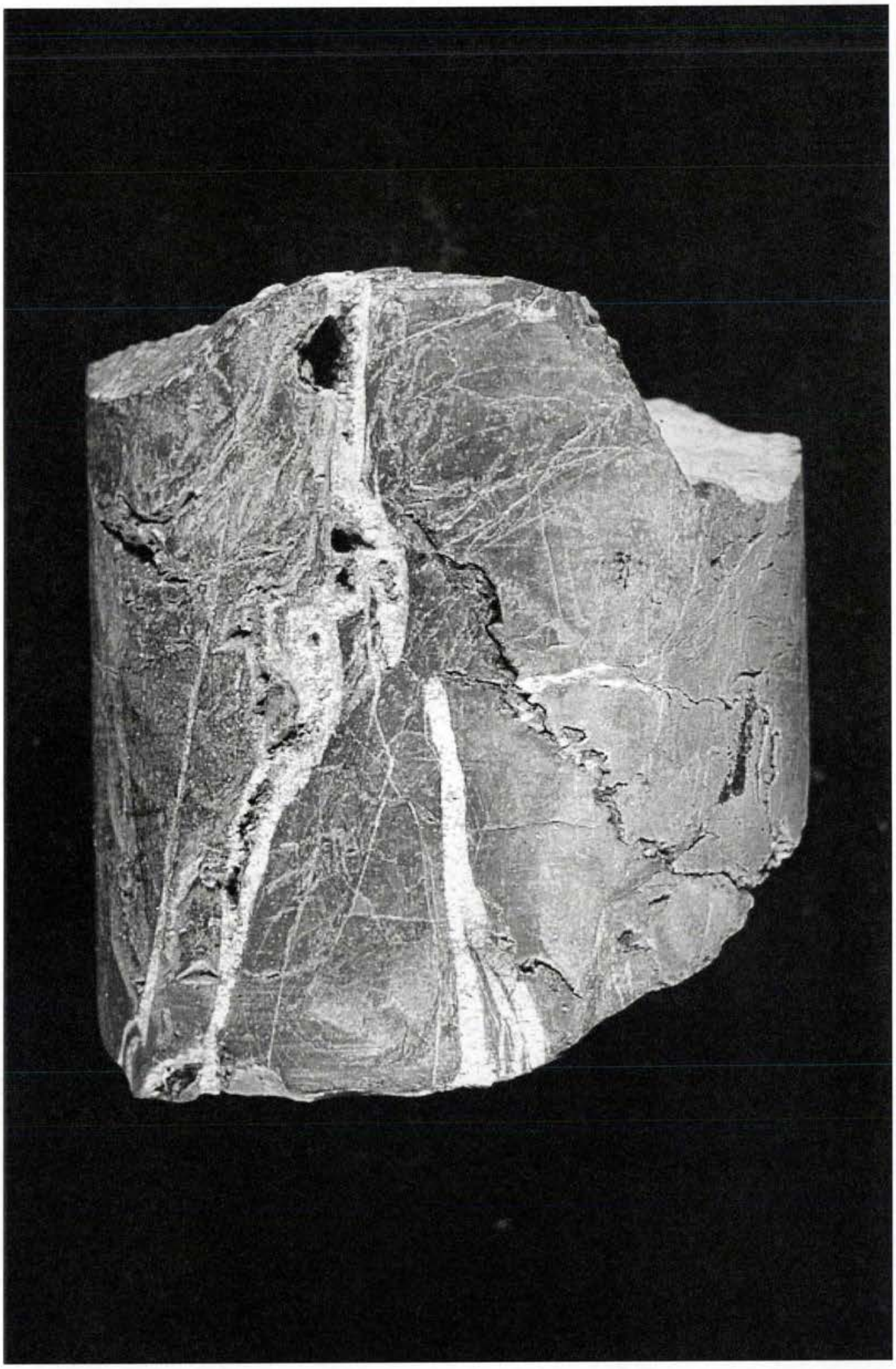
Lithology: Grey to olive-grey coloured micritic limestone. The rock, which looks marly, is hard and massive. Small pyrite grains are seen scattered in the micritic matrix.
Primary structures: Not observed.
Fossils: Not observed.
Fractures: The core piece is crossed and penetrated by numerous calcite-mineralised fractures and multiple fractures, that can be grouped descriptively as follows:

(1) A few distinct ones (showing high-angle dips) being filled with a coarsely crystalline (Cxn) calcite cement. One of them is only partly sealed with cement in places, and remains of oil are seen here. These fracture vugs are lined with a drusy surface.
(2) Numerous visible fractures, i.e.width of fractures is less than ½ mm, but visible .
(3) Several indistinct hairlines, i.e. fractures that appear as hairline traces on the surface of the core piece.

The relative timing of formation of distinct fractures and visible/hairline fractures could not be established macroscopically, they may all have been formed simultaneously.
Stylolites: The rock contains several stylolites that post-date the fractures. Orientations of stylolite teeth (or columns) seem to indicate that we are dealing with two generations of stylolites:

(1) Relatively poorly developed stylolites with ± vertically orientated teeth, and low-angle dips of stylolite surfaces (stylolite joints).
(2) Relatively well-developed stylolites with ± horizontally orientated teeth, and high-angle dips of surfaces.

The latter are formed partly in the micritic matrix, partly in the contacts between sparry cement of larger fractures and surrounding micritic matrix.
Porosity: Fracture pores and vugs containing residuals of oil are seen along a wide fracture, cf. above.

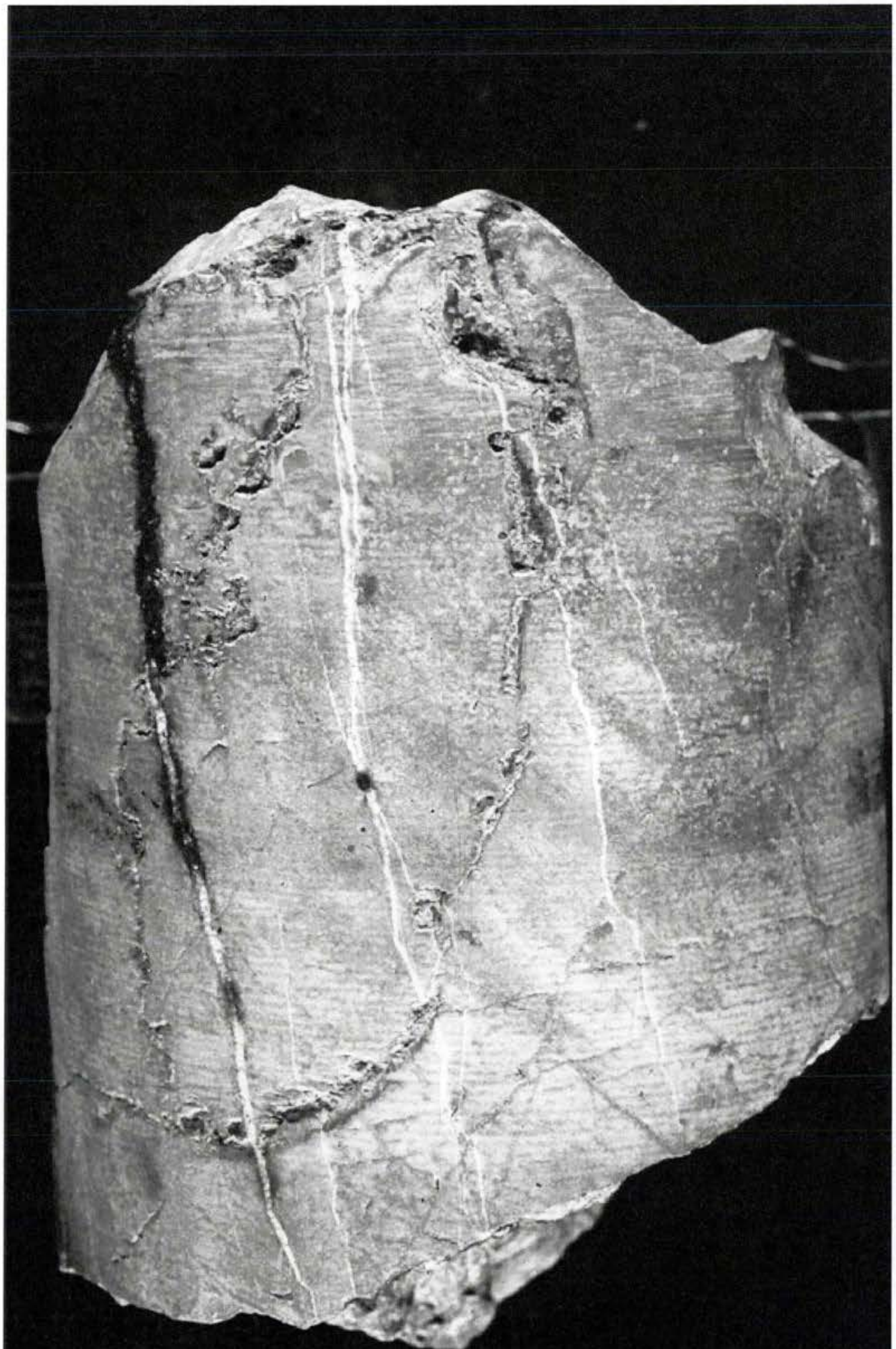


Sample no. 1A-2.
The core is 6.2 cm in diameter.

Core sample no. 1A-3

Well: Abadia 1A.
Formation: Montejunto.
Depth: 161.5 metres.

Lithology: Pale grey to dark grey micritic limestone or marly limestone, hard and massive. Small, scattered pyrite grains are seen in the micritic matrix.
Primary structures: Not observed.
Fossils: Not observed.
Fractures: Several sparfilled fractures and multiple fractures cross and penetrate the core piece. They show high-angle dips and are running more or less parallel to each other. One of the fractured surfaces of the core piece shows a part of a low-angle dipping slickenside that probably represents a sliding surface formed more or less synchronously with the tectonic stylolites.
Stylolites: Many stylolites and microstylolites cross and penetrate the rock. The latter resemble hairline fractures with the naked eye. Two generations of stylolites are found:
(1) An "old" generation of microstylolites with axis of columns orientated ± parallel to core axis.
(2) A "young" generation of more distinct stylolites with column axes orientated almost at right angles to the core axis (tectonic stylolites).
The relative time relation between the two events of chemical compaction is revealed in places where the two types of stylolites cross each other: The surface of the microstylolites, that was formed as a response of a vertically orientated stress (a consequence of "simple" overburden), is here displaced a little along the surface of the "tectonic stylolite".
Porosity: Specks and streaks of oil are connected with fractures and stylolites. Minor dissolutions of calcite may have taken place here prior to the introduction of oil.

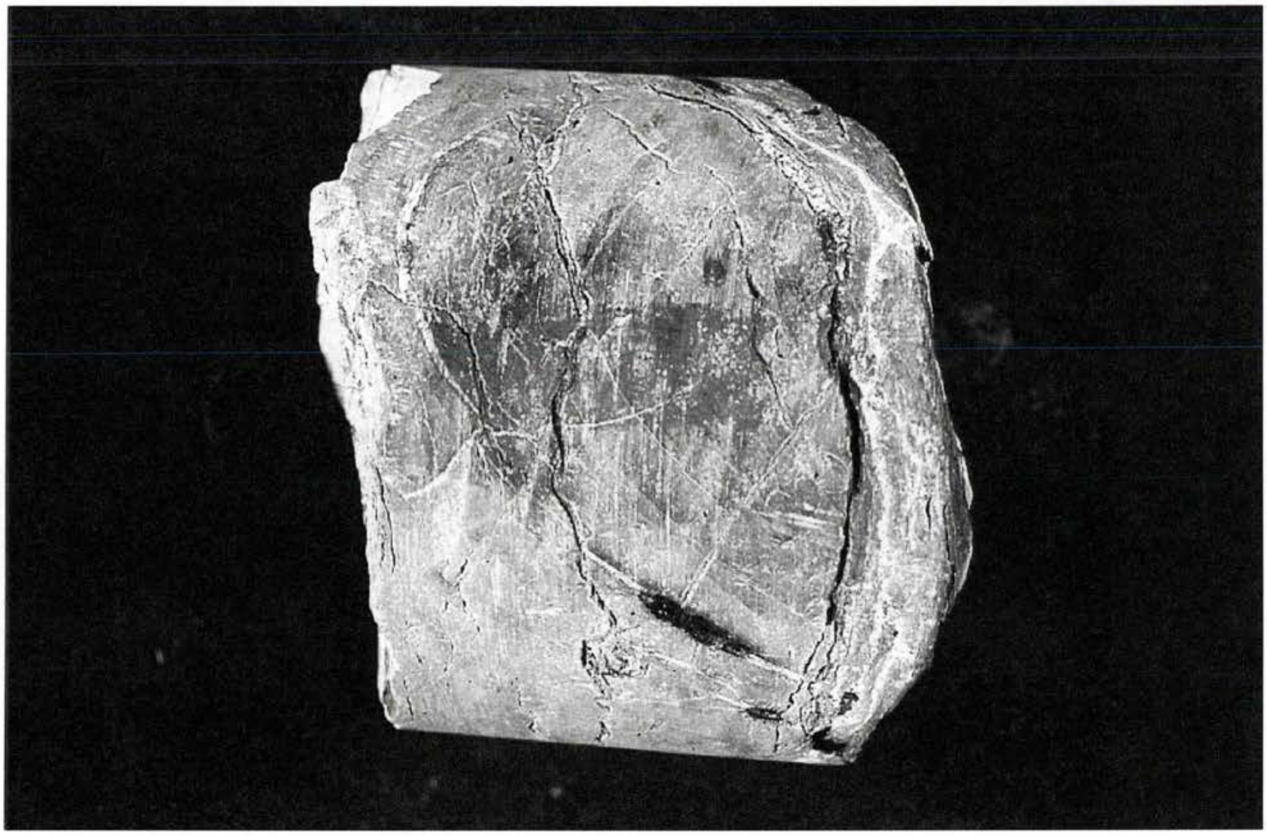


Sample no. 1A-3.
The core piece is 6.2 cm in diameter.

Core sample no. 1A-4

Well: Abadia 1A.
Formation: Montejunto.
Depth: 182.5 metres.

Lithology: Grey coloured micritic, marly limestone, hard and massive. Scattered pyrite grains are commonly seen.
Primary structures: Not observed.
Fossils: Not observed.
Fractures: Many calcite-mineralised fractures cross and penetrate the core piece. The fractures form a rather complex network in the rock, and dips of fracture vary a lot (low- to high-angle). At least one low-angle dipping slickenside is seen at one of the fractured terminal surfaces of the core piece. A small (short) calcite filled vein is developed on the sliding surface (cf. the "enduits de calcite" described by Arthaud & Mattauer, 1969).
Stylolites: Less developed to well-developed stylolites and solution seams are common; many are almost invisible to the naked eye. The stylolite surfaces are irregular, and interconnected networks are formed in places. The surfaces show low-angle dips, mostly less than 15°. Some of the stylolites are formed in the contact between calcite cement of fractures and surrounding micritic matrix. Displacements of fractures along stylolites also indicate that chemical compaction took place after fracturing.
Porosity: In several places, tiny little pores are found in the sparry calcite of fractures. Specks or streaks of oil reveal their presence. Oil remains are also seen in the surface of a few stylolites, which have probably been solution-enlarged prior to the introduction of oil.

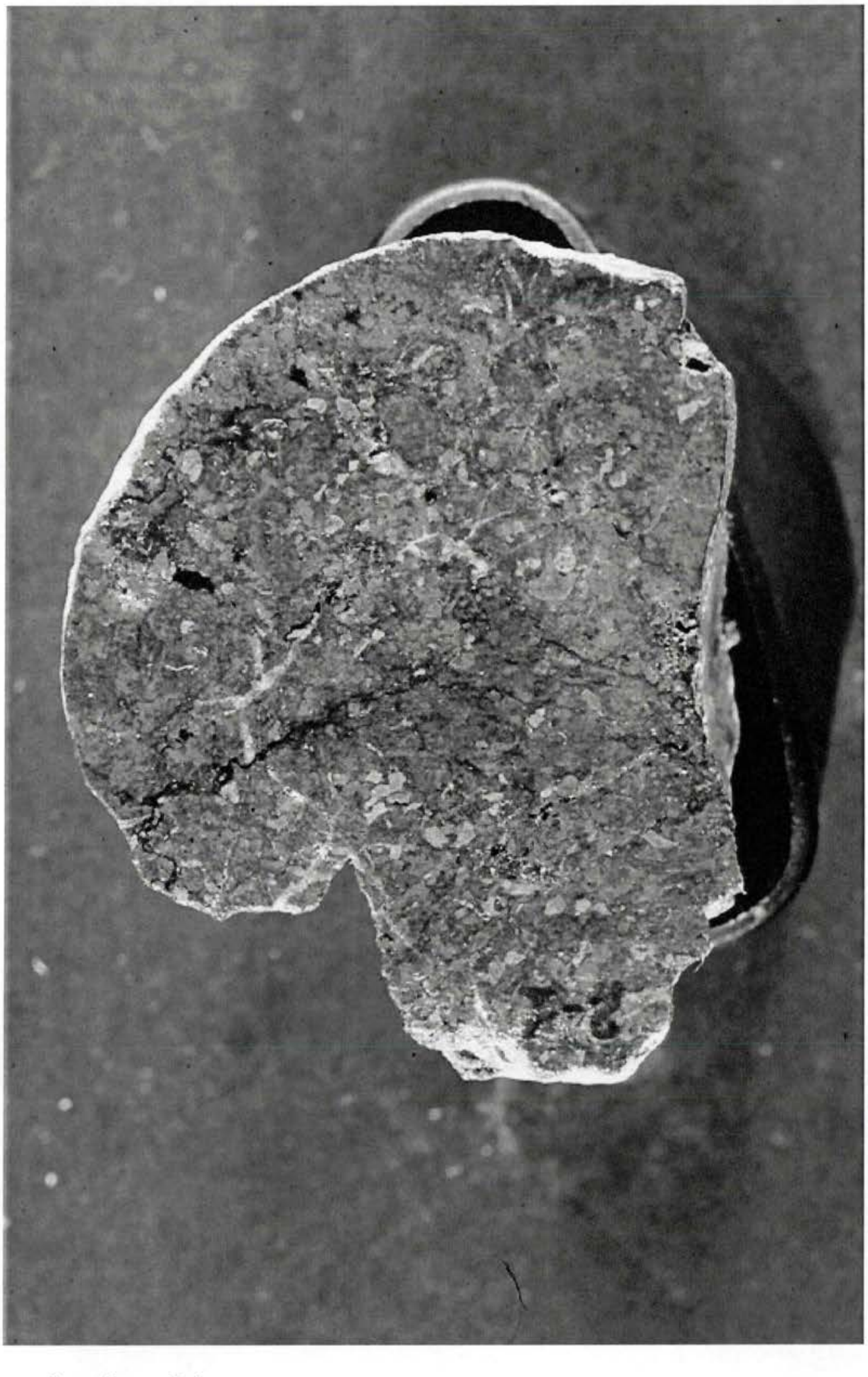


Sample no. 1A-4.
The core piece is 6.3 cm in diameter.

Core sample no. 2-1

Well: Abadia 2.
Formation: Cabaços.
Depth: 255 metres.

Lithology: Pale grey limestone with a faint marbled appearance. It is hard and massive, except for a rather few scattered solution vugs and pores. The rock resembles an oncoidal/ooidal packstone. (The brownish appearance of the core piece in the figure is due to the fact that the sample has been moistened with water prior to photographing).
Primary structures: Coated grains.
Fossils: Algae (not the coated grains).
Fractures: Several small, irregular fractures, both penetrating and enclosed. They are mineralised with sparry calcite and vary in width from visible to hairline. The fractures are generally poorly preserved; some are ghost-like as if a neomorphic alteration of fracture and surrounding matrix has taken place simultaneously.
Stylolites: Stylolites and microstylolites are commonly seen. They are rendered more visible by oil. In many places, the rock shows a fitted fabric as contacts between many allochems (oncoids/ooids) consist of microstylolites. The chemical compaction post-dates formation and cementation of fractures.
Porosity: Scattered vugs and tiny pores are connected with stylolites, which seem to be solution-enlarged.

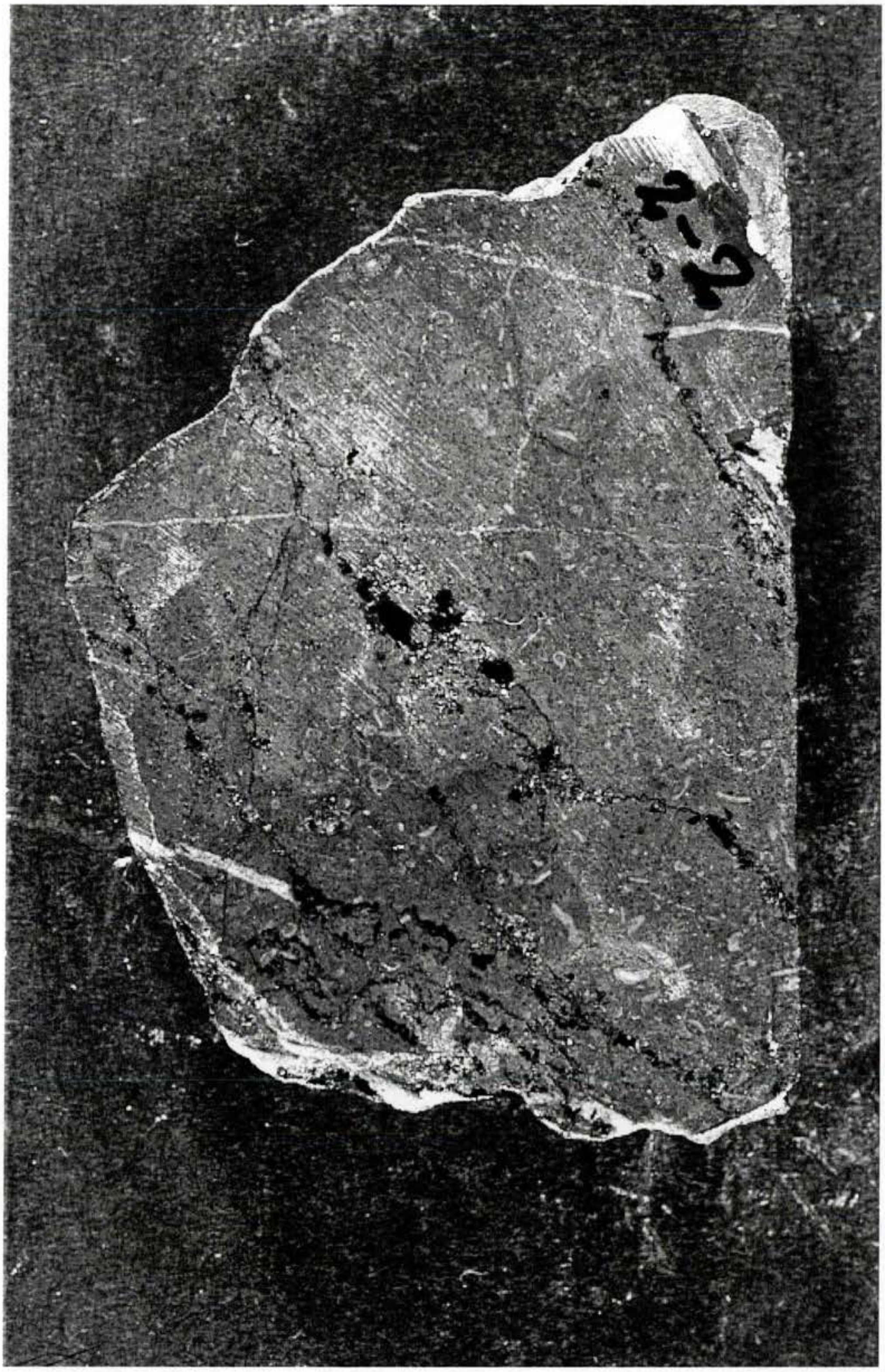


Sample no. 2-1.
The slabbed core piece is about 6 cm across.

Core sample no. 2-2

Well: Abadia 2.
Formation: Cabaços.
Depth: 275 metres.

Lithology: Pale grey limestone, hard and massive except for small vugs and pores connected with stylolites (cf. sample 2-1). The rock resembles a sparse to packed biomicrite with allochems of small indeterminable shell fragments and coated grains.
Primary structures: Coated grains.
Fossils: Shell fragments and algae.
Fractures: Several fractures of varying width (hairline to visible) that are filled with sparry calcite. A few of them are very indistinct, almost invisible to the naked eye.
Stylolites: Both well-developed ones, rendered more visible by oil, and indistinct microstylolites occur. Stylolite planes are irregular, and interconnected networks are seen in places. The chemical compaction post-dates the fracturing, but is in turn followed by a phase of leaching, as indicated by the presence of many small vugs and pores that are formed along the stylolite surfaces.
Porosity: All small vugs and pores in the rock are connected with stylolites. Aggressive fluids seem to have percolated the rock via the insoluble residue accumulations of stylolites. Oil was subsequently introduced here.

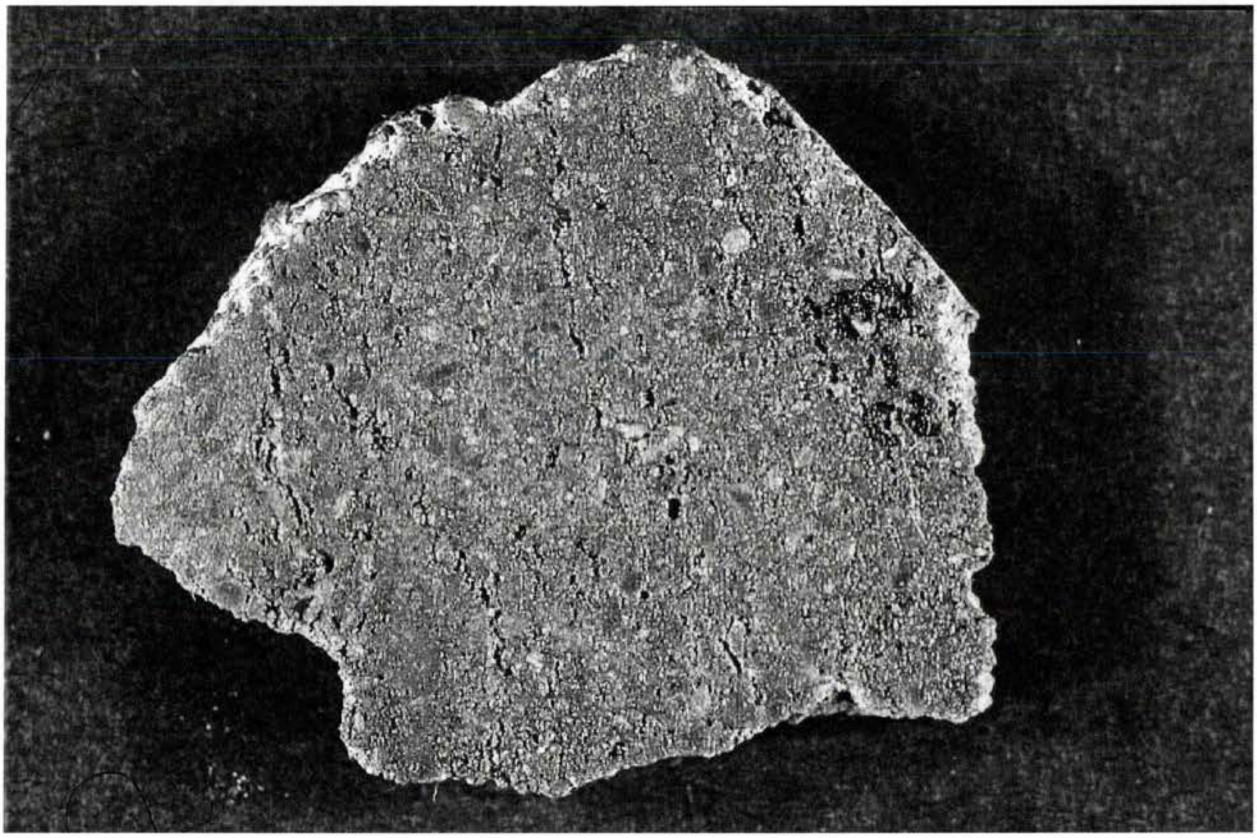


Sample no. 2-2.
The slabbed core piece is about 5 cm in length.

Core sample no. 2-3

Well: Abadia 2.
Formation: Cabaços (?).
Depth: About 334 metres.

Lithology: Grey coloured, hard, but rather porous limestone, an oncolithic pack- to grainstone.
Primary structures: Coated grains.
Fossils: Algae (?).
Fractures: Not observed.
Stylolites: Microstylolitic grain contacts are seen in many places between the tightly packed oncoids (a condensed fabric). The more well-developed microstylolites, that run across the rock piece more or less parallel to each other, have been solution-enlarged during a rather late diagenetic phase of leaching.
Porosity: The rock contains many small intergranular pores and porous streaks along microstylolites, that seem to have acted as conduits for aggressive fluids. These streaks form interconnected pore systems in the rock.



Sample no. 2-3.
The core piece is about 4 cm across.

Core sample no. 2-4

Well: Abadia.
Formation: Bathonian Stage?
Depth: About 393 metres.

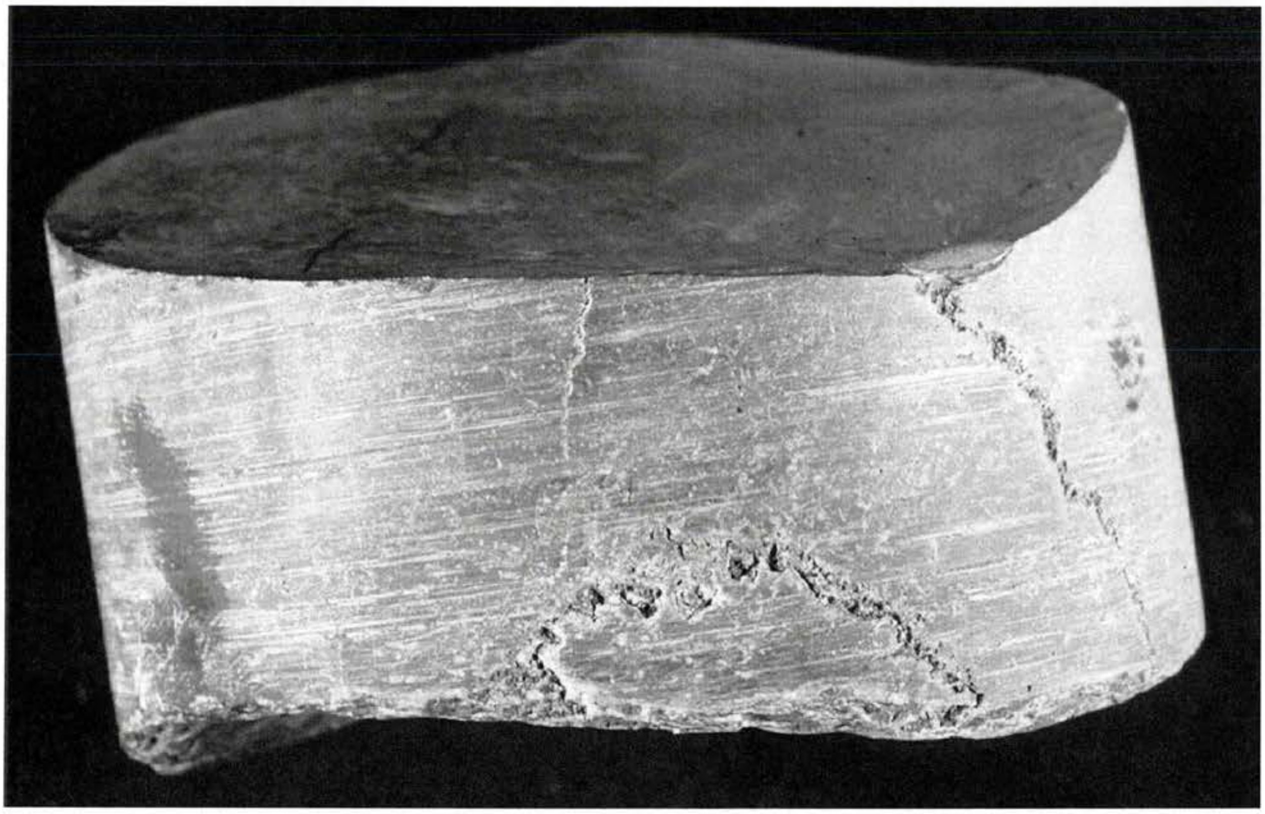
Lithology: A grey coloured, hard and porous limestone. It is an oncolithic grain- to packstone, which has a close resemblance to the rock of sample 2-3.
Primary structures: Coated grains.
Fossils: Algae (?) and a few shell fragments from macrofossils.
Fractures: Not observed.
Stylolites: The rock has a condensed to fitted fabric as many grain contacts are observed to consist of microstylolites.
Porosity: The rock is rich in intergranular pores. A phase of leaching seems to post-date a phase of chemical compaction.

Sample no. 2-4.
The small core sample, that has been sawed out and polished, is about 3½ cm long.

Sample no. 4-1

Well: Abadia 4.
Formation: Montejunto. (?)
Depth: 161.5 metres.

Lithology: Pale grey to bluish grey micritic limestone, hard and massive.
Primary structures: Not observed.
Fossils: A few small, scattered shell fragments, indeterminable.
Fractures: A few indistinct ± vertically orientated hairlines cross the sample. Through a magnifying glass the hairlines are observed to be filled of a sparry, finely crystalline calcite.
Stylolites: The sample is cut by two stylolites. Their surfaces show high-angle dips, being almost vertically orientated.
Porosity: No pores or vugs are observed.

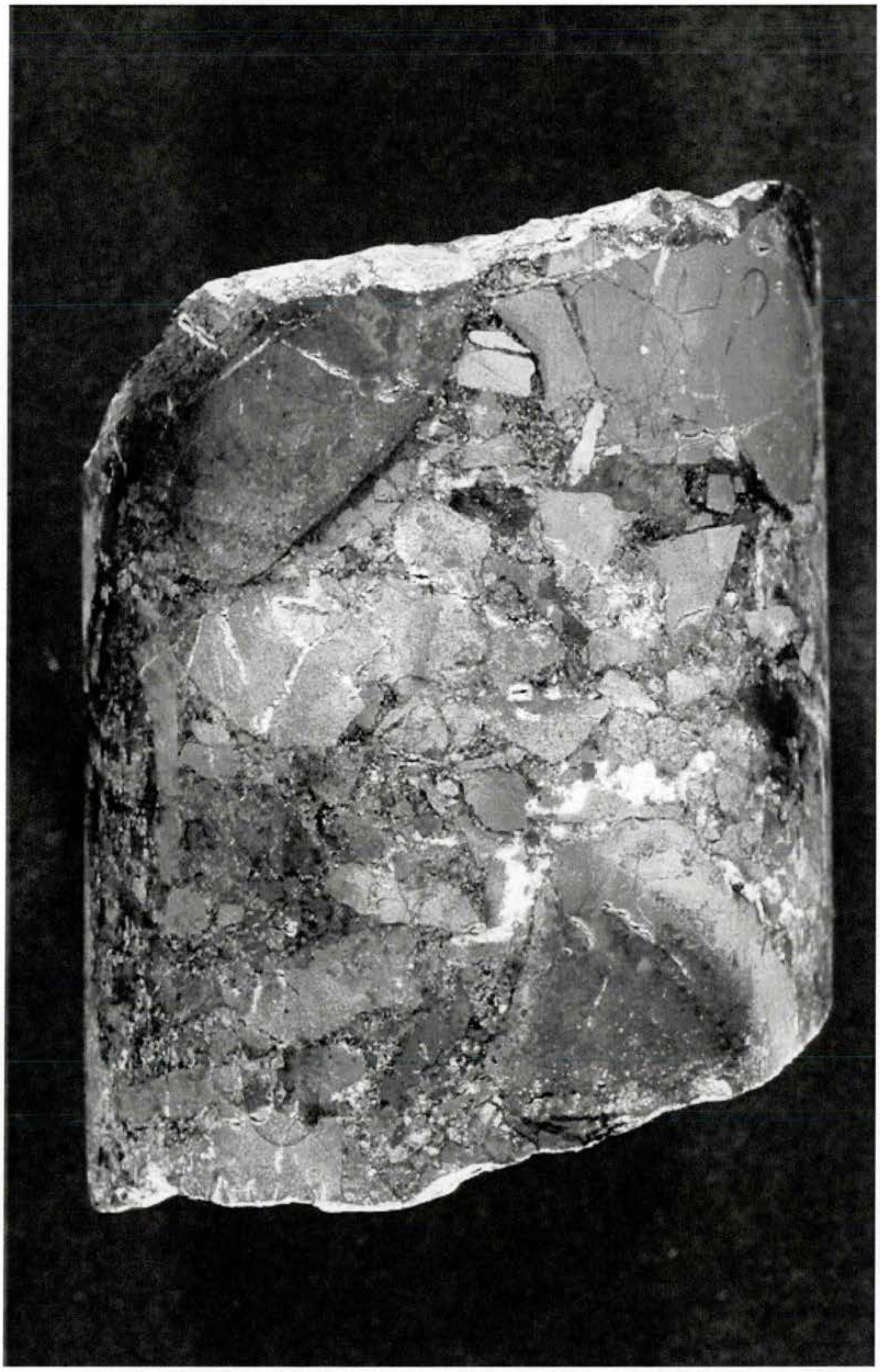


Sample no. 4-1.
The core piece is 8.5 cm in diameter.

Core sample no. 4-2

Well: Abadia 4.
Formation: Montejunto.
Depth: 285 metres.

Lithology: A varicoloured (pale grey, pale bluish grey, and olive-grey shades are seen) massive and hard limestone. We are probably dealing with a tectonic breccia with carbonate veins. The latter are sparfilled, irregular fractures of which many are observed to be multiple. The brecciation may be the result of crushing or grinding along a fault zone.
Primary structures: No primary structures are seen in the more or less angular rock fragments that make up the core piece.
Fossils: Not observed.
Fractures: The many small calcite-mineralised fractures of the rock fragments themselves may have been formed prior to, or contemporaneous with, the chemical compaction (see below). A few larger fractures can be followed without any displacements across two or more rock fragments, indicating that they were formed after the brecciation.
Stylolites: The contacts between many of the ± angular limestone fragments consist of microstylolites. A few scattered specks of oil are connected with some of these intergranular stylolites.
Porosity: No pores or vugs were observed, not even in the small specks of oil.



Sample no. 4-2.
The core piece is 7.3 cm in diameter.

Core sample no. 4-3

Well: Abadia 4.
Formation: Montejunto.
Depth: 298.9 metres.

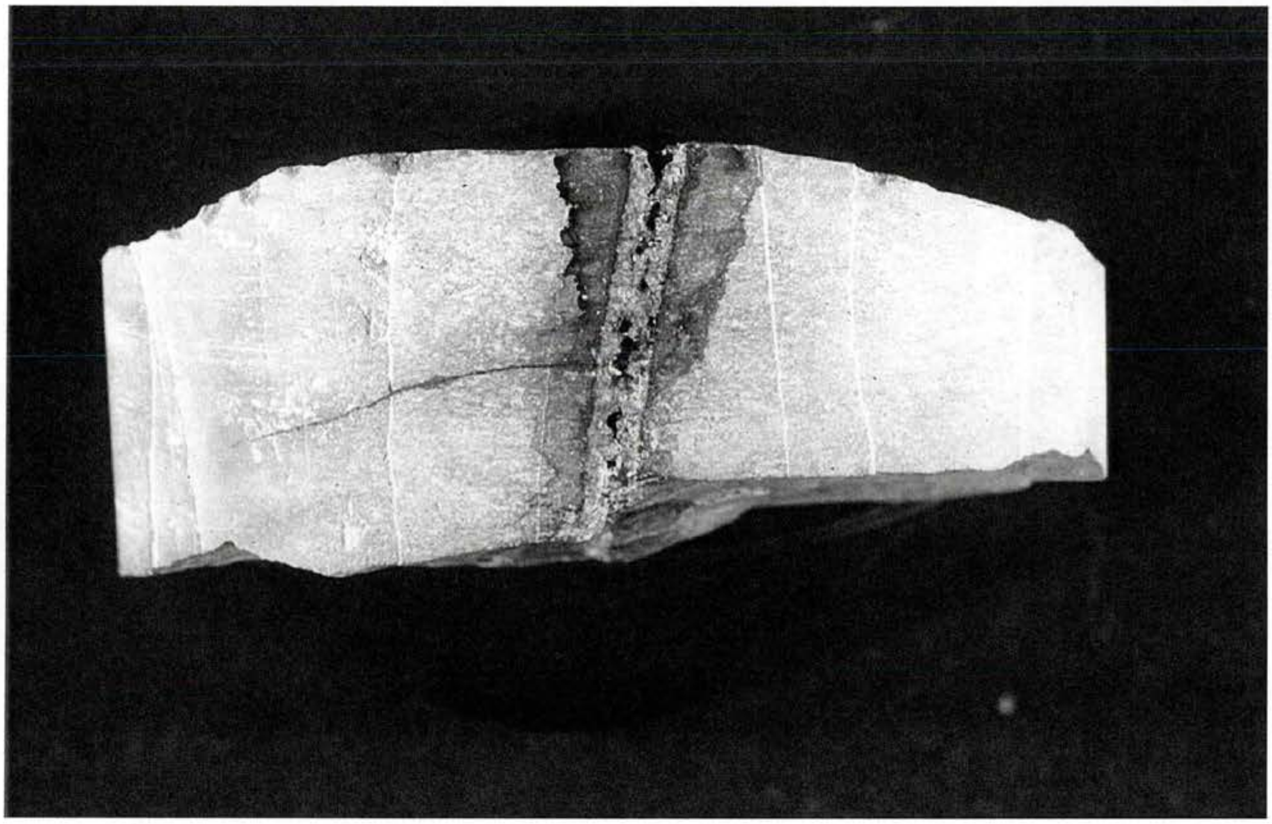
Lithology: Pale grey to greyish blue micritic limestone, a fossiliferous micrite, hard and massive.
Primary structures: Not observed.
Fossils: A few scattered shell fragments of unknown origin.
Fractures: The rock contains many fractures, sealed with calcite cement. In a few places the fractures are only partly filled with spar, otherwise oil-filled. Multiple fractures occur in places. Most fractures are less than ½ mm in width. The dipping of the fractures vary a lot, from almost vertical to almost horizontal. The presence of small displacements indicates that we are dealing with at least two generations, or events, of fracturing. A brecciation of the rock is seen locally along a high-angle dipping fracture. A grinding may have taken place along a fault during the tectonic phase(s) that also resulted in formation of second generation of fractures and tectonic stylolites.
Stylolites: Poorly developed stylolites and microstylolites are rather common. Two generations are seen: one having the teeth orientated almost parallel with the core axis, and another generation having their teeth orientated almost at right angles to this axis. Some of the stylolites of the latter generation are developed along sparfilled fractures. The second generation of stylolites post-dates fracturings, whereas the first generation of stylolites post-dates the first phase of fracturing, but predates the second phase of fracturing.
Porosity: Scattered oil-filled vugs and pores are observed both in stylolite surfaces and in larger fractures, the latter being intercrystalline pores in sparry cement of fractures.

Sample no. 4-3.
The core piece is 7.3 cm in diameter.

Core sample no. 6A-1

Well: Abadia 6A.
Formation: Montejunto.
Depth: 239.8 metres.

Lithology: Pale grey to bluish grey micritic limestone, hard and massive.
Primary structures: Not observed.
Fossils: A few small, indeterminable shell fragments.
Fractures: An up to several mm wide calcitemineralised fracture and several thin fractures, also being sealed with calcite cement, cross the rock sample. All fractures are ± vertically orientated. The large fracture is not completely filled in with sparry cement, as several intercrystalline vugs and pores occur in the cement. Residuals of oil are now found in these cavities.
Stylolites: Three microstylolites penetrate the core sample. The stylolite surfaces are horizontally orientated. Residuals of oil are found in the surfaces. The chemical compaction post-dates the formation of the hairline-like fractures. The contacts between the spar of the well-developed fracture and the surrounding micritic matrix show some resemblance to microstylolites.
Porosity: Fracture-pores, now occupied by oil, cf. above.

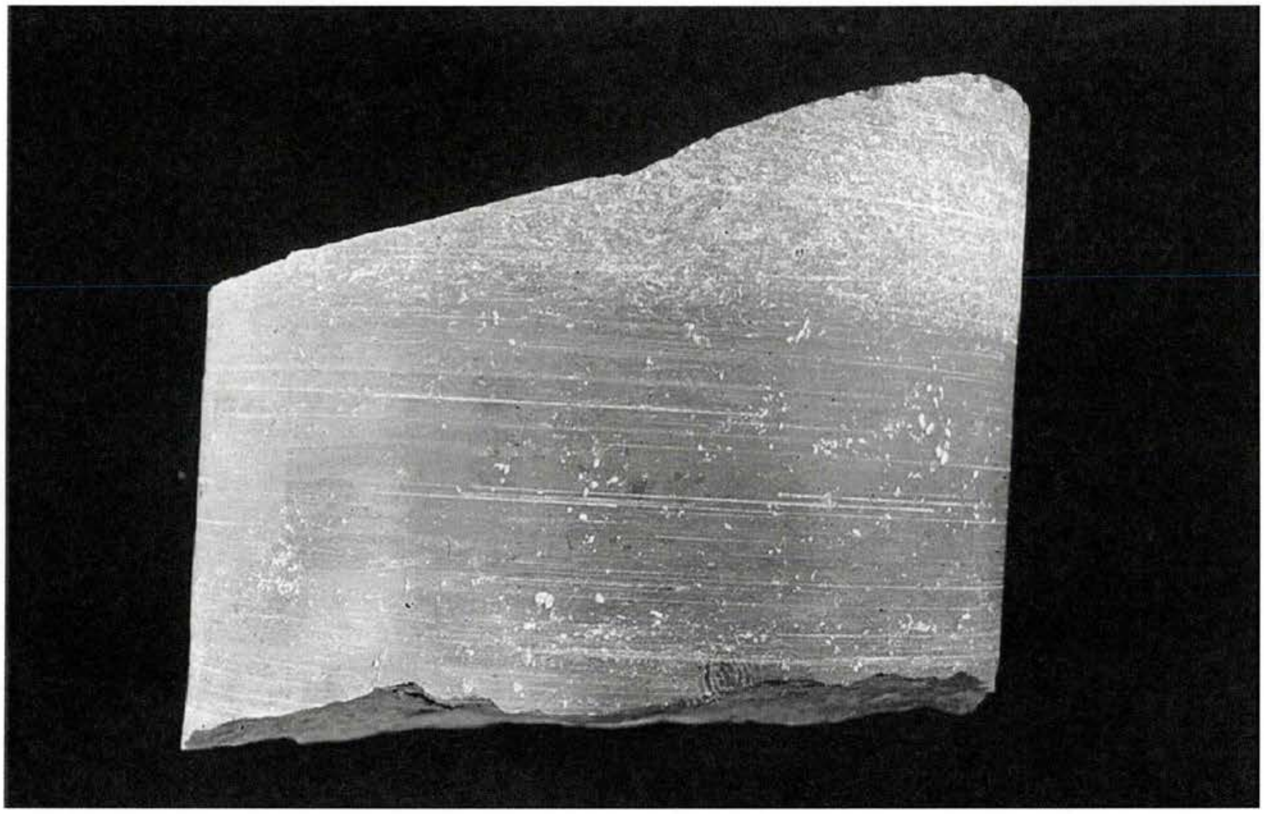


Sample no. 6A-1.
The core piece is 7.2 cm in diameter.

Core sample no. 6A-2

Well: Abadia 6a.
Formation: Montejunto.
Depth: About 223 metres.

Lithology: Grey to bluish grey micritic limestone, hard and massive. A few rather large crystal-aggregates of pyrite are seen, as are several tiny, scattered pyrite crystals.
Primary structures: Several small traces that resemble *Chondrites.*
Fossils: A few scattered small shell fragments of unknown origin.
Fractures: A few hairlines, that penetrate or are embedded in the core piece, are rendered visible when the rock is moistened with water. The fractures show high-angle dips.
Stylolites: A microstylolite penetrate the rock; its surface is horizontal. Chemical compaction post-dates formation of hairlines.
Porosity: No pores are observed.

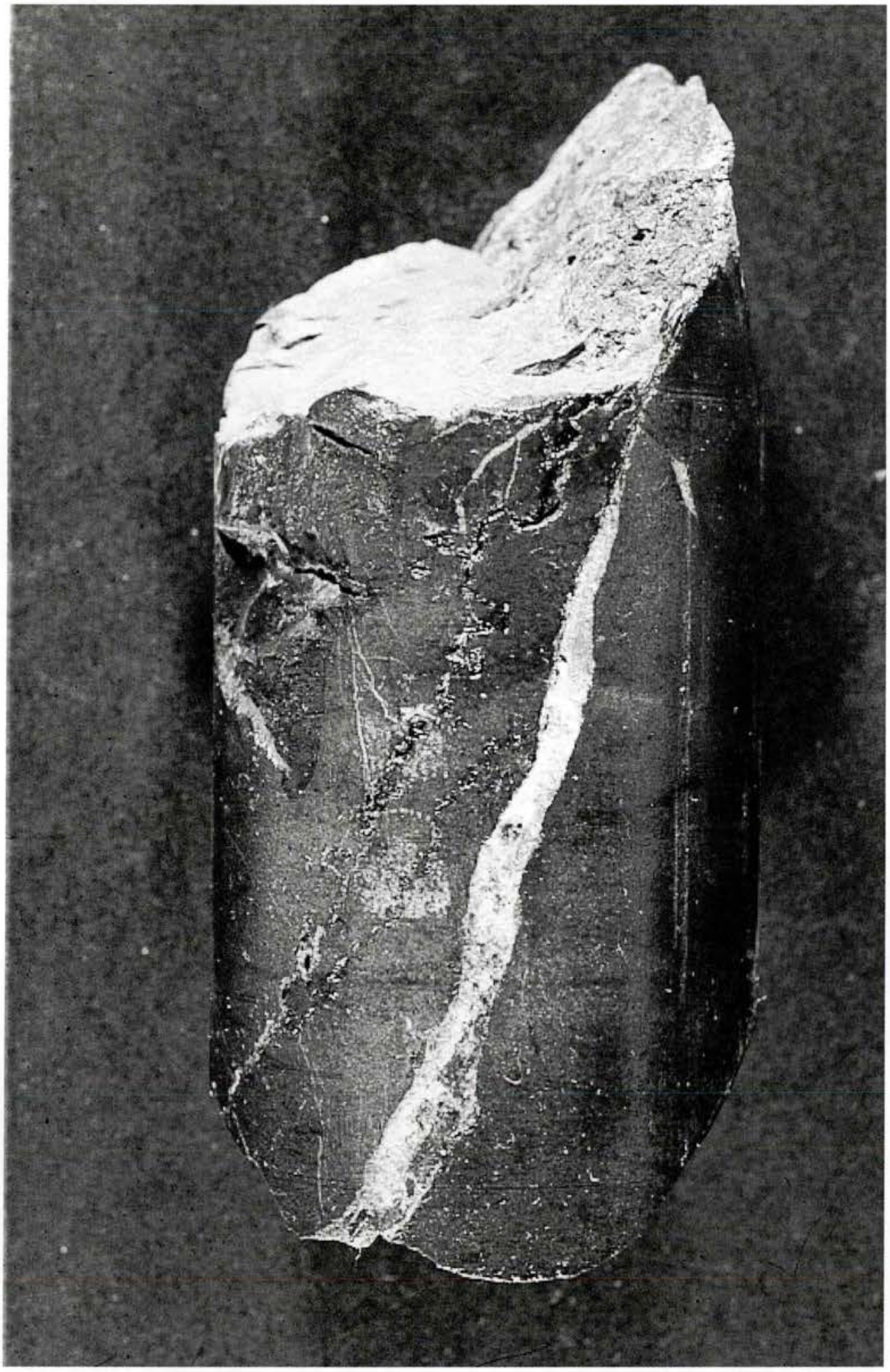


Sample no. 6A-2.
The core piece is 7.2 cm in diameter.

Core sample no. 8-1

Well: Abadia 8.
Formation: Montejunto.
Depth: 476.5 metres.

Lithology: Grey to bluish grey micritic limestone, hard and massive.
Primary structures: Not observed.
Fossils: Not observed.
Fractures: An up to several mm wide, calcite-mineralised fracture is seen (high-angle dip), as are several fine, almost hairline-like fractures, that are also sealed with calcite cement.
Stylolites: Several stylolites cross or penetrate the sample. A few are rather distinct with long axes of columns (the teeth) orientated almost in a horizontal direction; the remaining are microstylolites that are formed in the contact between fracture cements and surrounding micritic matrix. Chemical compaction post-dates formation of fractures. It looks as if the direction of stress has almost changed from the vertical (with formation of fractures) to the horizontal (with formation of high-angle dipping stylolite surfaces) during the diagenetic history.
Porosity: No pores are observed.

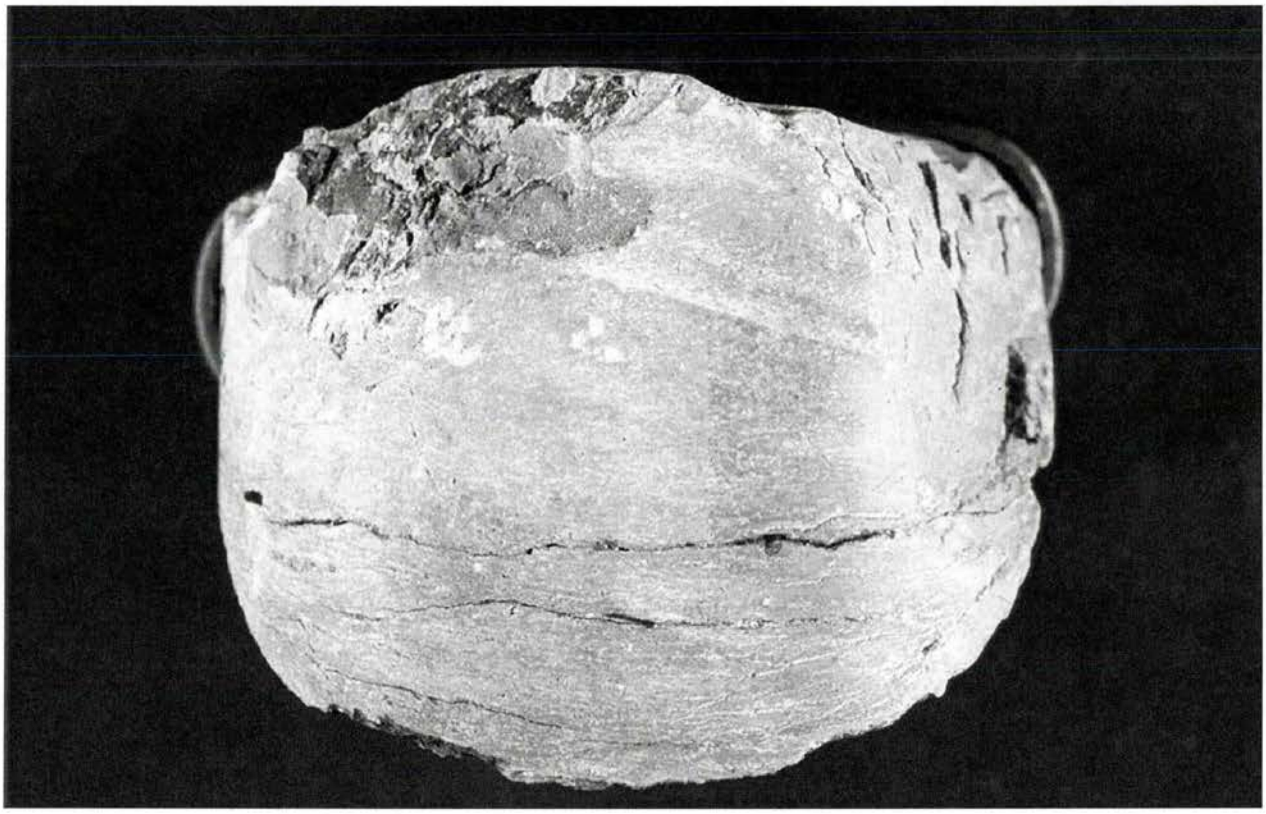


Sample no. 8-1.
The core piece is 6.4 cm in diameter.

Core sample no. 8-2

Well: Abadia 8.
Formation: Montejunto.
Depth: 493.8 metres.

Lithology: Grey to bluish grey micritic limestone, hard and massive. The sample is artificially broken along fracture-slickensides and stylolite surfaces that dip 35° - 45° (angle of inclination from a plane perpendicular to the axis of the core).
Primary structures: Not observed.
Fossils: Not observed.
Fractures: A few embedded hairline-like (indistinct) fractures with high-angle dips, and one distinct, sparfilled fracture dipping about 45°, and bound by slickensides. The latter is probably a calcite filled fracture-like cavity formed along a sliding surface (cf. the "enduits de calcite" described by Arthaud & Mattauer, 1969).
Stylolites: Several poorly developed stylolites cross the sample, they dip 35° - 45°, but form in places interconnected network stylolites. The stylolites seem to post-date the hairline-like fractures, but are in turn crossed by sliding surfaces with slickensides
Porosity: No pores were observed.

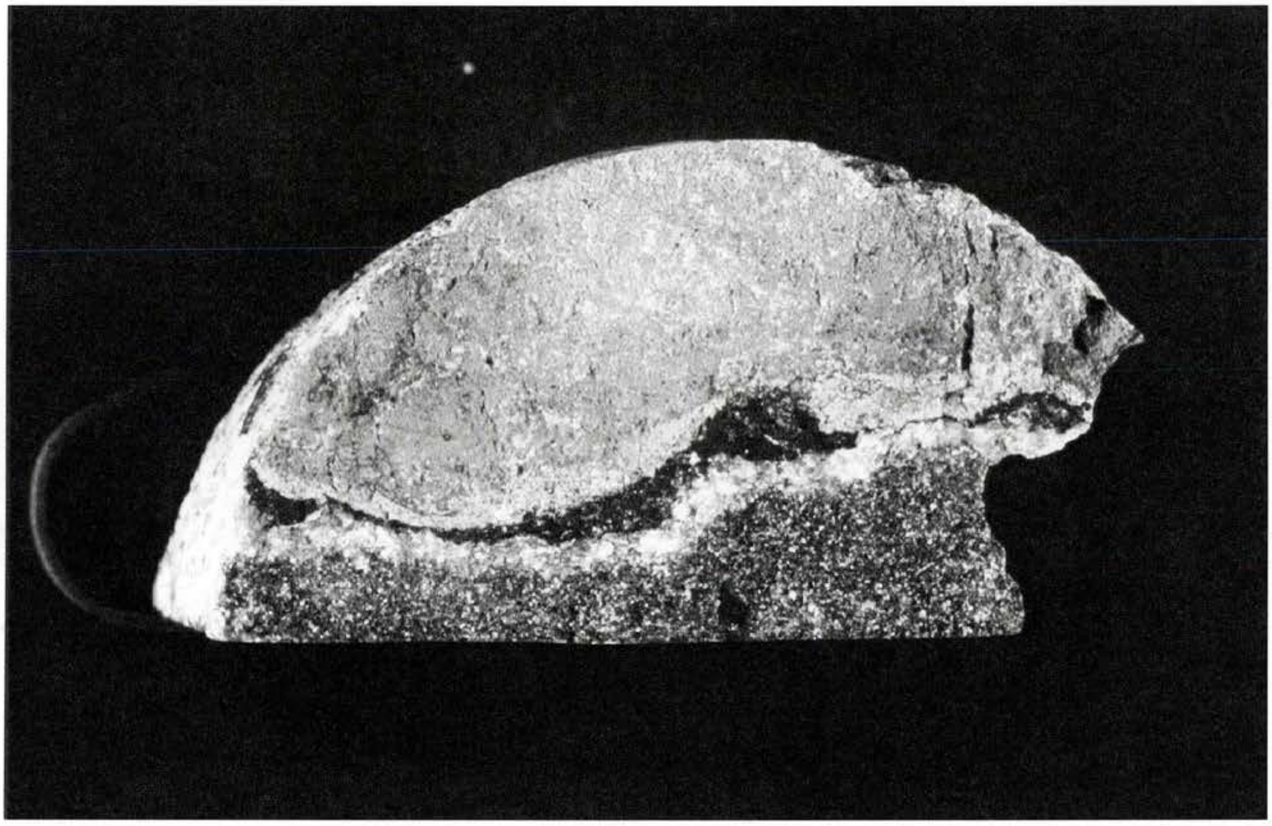


Sample no. 8-2.
The core piece is 6.2 cm in diameter.

Core sample no. 11-1

Well: Abadia 11.
Formation: Montejunto.
Depth: 266.4 metres.

Lithology: The rock shows the contact between basalt and limestone. The basalt is grey to pale ochre-yellow in colour. Under a dissection microscope the basalt is observed to contain numerous small amygdales filled with calcite(?). The limestone is dark grey-coloured, massive and medium to coarsely crystalline. The crystals grow in size in direction towards the basalt. Close to the basalt they form a vein-like structure of coarse crystals. A dark, sulphide-like mineral is precipitated along the contact between limestone and basalt, where it forms a stylolite-like, irregular structure on the rock surface. The surface of this stylolite-like structure shows a dip of about 60°.
Primary structures: No primary structures are seen in the carbonate rock.
Fossils: Not observed.
Fractures: Not observed.
Stylolites: Not observed in the limestone. However, the contact between basalt and limestone resembles a stylolitic joint (cf. above).
Porosity: Not observed.

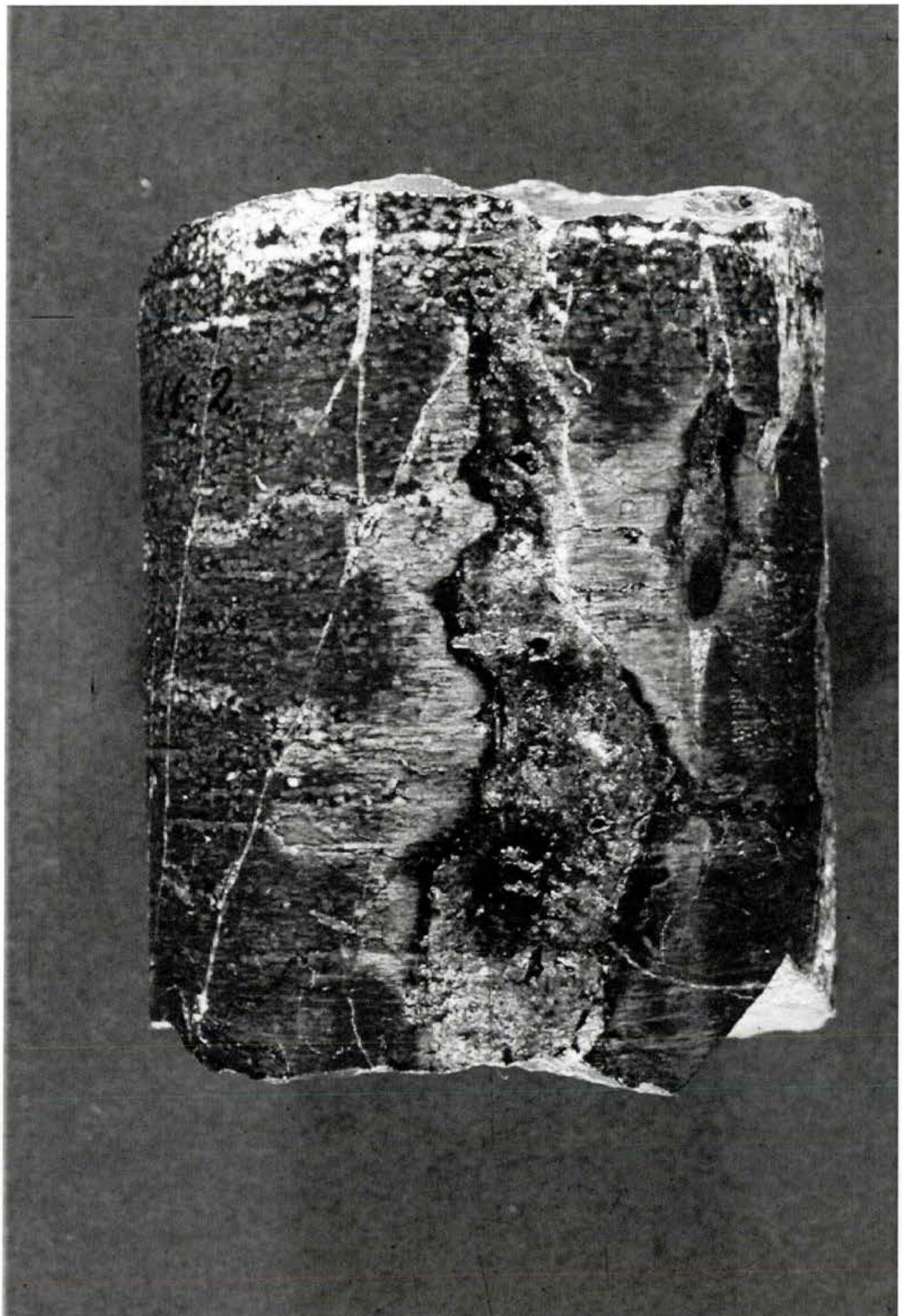


Sample no. 11-1.
The shown rock surface is orientated almost at right angles to the core axis.
The core piece is about 7 cm in length.

Core sample no. 11-2

Well: Abadia.
Formation: Montejunto.
Depth: 297 metres.

Lithology: Grey to bluish grey micritic limestone, seemingly a fossiliferous micrite. The rock is hard and massive, except for the presence of many oil-filled solution vugs connected with the sparfilled fractures, and fewer small pores in stylolitic surfaces.
Fossils: A few scattered fossil fragments are dimly seen.
Fractures: The sample is crossed by many sparfilled fractures that vary in widths from hairline to several mm. On the photograph below one of the fractures seems to be up to 2 cm in width, but it is due to the fact that the surface of the core cuts the fracture in an oblique angle. The fractures show high-angle dips, being ± vertically orientated.
Stylolites: Stylolites are commonly seen. Two generations seem to exist: An older generation having their surfaces orientated ± at right angles to the core axis, and in places forming interconnected network stylolites, and a younger generation orientated almost parallel to this axis. The stylolites of the latter generation are formed in the contact between cement spar of larger fractures and surrounding rock matrix. The chemical compactions seem to post-date the fracturing.
Porosity: Fracture porosity is seen, represented by scattered, in places interconnected, vugs and pores in the sparry cement of larger fractures. However, several tiny little pores are also seen in places along stylolite surfaces, that have all been more or less oil-stained.



Sample no. 11-2.
The core piece is 7.6 cm in diameter.