Structural Geology of a Limestone Mine at Mønsted, Northern Jutland

by

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Abstract

This paper is a preliminary report on the results of the structural mapping in the Danian limestone exposed in a mine within the area of the Mønsted salt dome (northern Jutland.)

A map of the large scale structure showing the faults and the attitudes of bedding is presented and discussed. It is shown that the dominant tectonic features are normal faults, while folding is of a minor importance and, apparently, produced only as a result of faulting. Through a detailed mapping in selected areas of tectonic joints, here called slip joints, and their lineation (see accompanying stereograms), a genetic relationship between the individual joint sets and the respective faults could be established. In an area where one fault is displaced by another, a rather complex pattern of joints can be resolved into several joint groups whose origins can be traced to the respective faults.

Throughout the entire discussion it is attempted to give an interpretation of the bedding control versus fault control over the orientation of the joints.

Introduction

a) Regional Setting

This paper deals with the geological structure in the Danian limestone as exposed in an underground mine located in the northern part of the Mønsted salt dome. This dome is one of several piercement structures in northern Jutland where Permian (predominantly Zechstein) evaporites have locally elevated the overlying Mesozoic and, at least the oldest, Tertiary formations, while the Quaternary drift discordantly overlies the structures (ANDERSEN, 1944; GREGERSEN and SORGENFREI, 1951; ØDUM, 1960; RASMUSSEN, 1960, 1961; LARSEN, 1964).

The Mønsted structure may be recognized on the map of the pre-Quaternary formations (Fig. 1), since in a Miocene region an isolated area of Danian limestone (of, roughly, 18 km^2) betrays the presence of the dome structure.

ANDERSEN (1944, p. 360) visualized this dome as a N-S trending anticlinal ridge.

On the basis of exposures and a number of shallower water wells, together with three deeper wells drilled by the Danish American Prospecting Co., and, finally, taking into consideration the present topographic

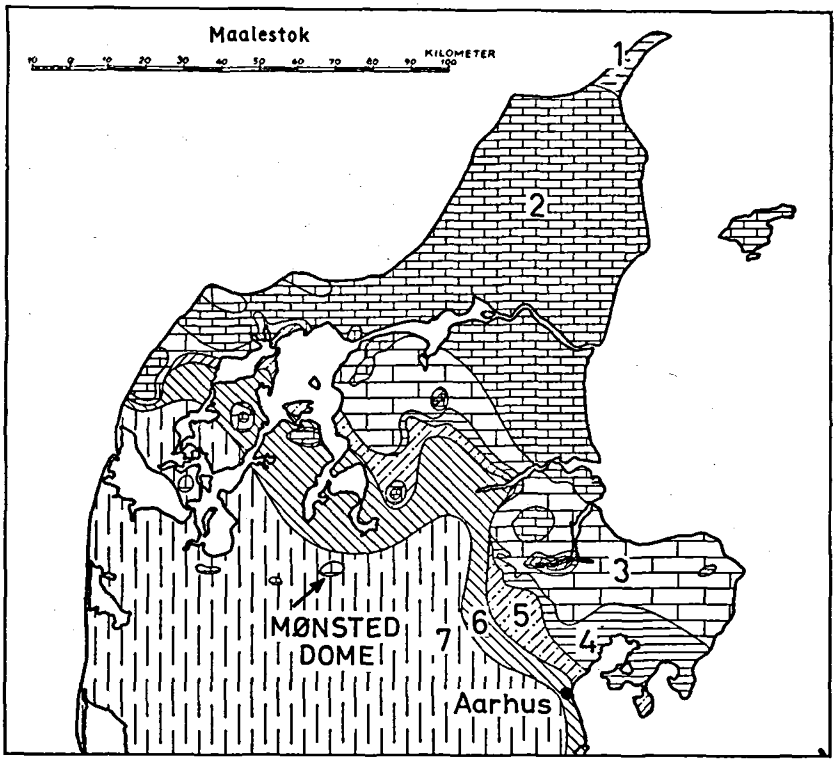


Fig. 1. Geological map of northern Jutland (Denmark) showing formations at the base of Quaternary. 1: Lower Cretaceous, 2: Upper Cretaceous, 3: Danian, 4: Paleocene, 5: Eocene, 6: Oligocene, 7: Micocene. After Th. Sorgenfrei, 1954.

features, a map showing the surface of the Danian limestone in the area of the Mønsted dome (Fig. 2) was prepared (compare Rasmussen, 1960, Fig. 9). The dotted signature indicates areas where the Danian limestone is exposed, or is known to lie practically at the surface, and the solid black indicates smaller areas where Tertiary is exposed.

The only sediments of glacial origin observed in the exposed profiles in the area of the Mønsted dome are glaciofluvial sands, with a thickness which ranges up to 13 m.

Today no morphological high relative to the surrounding areas can be discerned, although such a high, most probably, existed at the onset of the Pleistocene time.

b) *Description of the Mine*

The Danian limestone was quarried, and is exposed, at several localities in the dome area. The largest and the best known of these is a mine owned by Jydske Kalkværker A/S and situated between 1,5 km and 1,8 km north-west of the Mønsted village. At the present time the mine consists

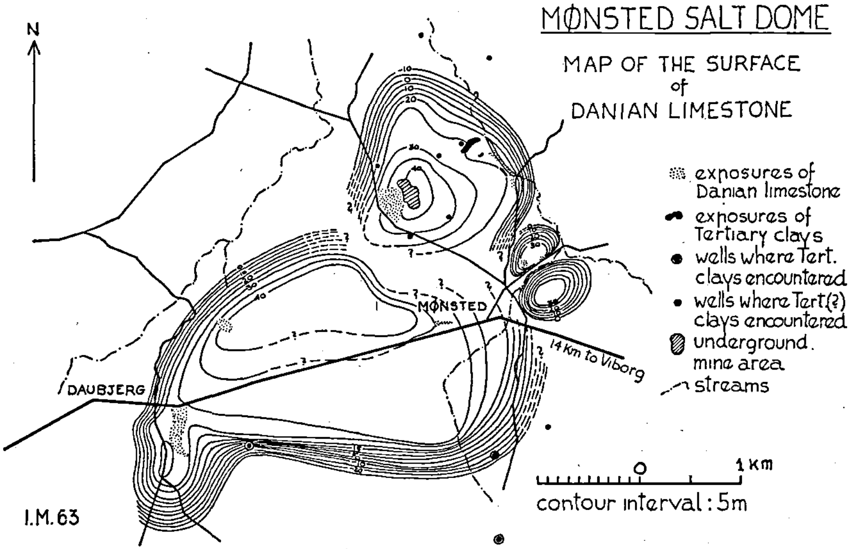


Fig. 2.

of one large and deep pit and of an intricate system of underground corridors.

This underground part of the mine consists, essentially, of three different levels. At the highest, most ancient, level limestone was quarried already in the Middle Ages. The most recent floor is the lowest and, here, the corridors are, in general, very spacious and easily passable reaching in places a height of 10 m or more. However, the passage has been blocked in many places by sand and, locally, clay which were brought down with water through the overlying, older corridors.

Any mining operations were suspended in 1956.

The map of the corridors of the Mønsted Chalk Works prepared in 1933 (see Rasmussen 1960, Fig. 10) has, up to now, been the only one ever made. But since that time new sections have been worked so that, at present, the total area mined is at least two times as large as that would appear from the mentioned map.

c) *Purpose of the Investigation*

The underground part of the Mønsted mine, with its numerous corridors and supporting pillars, offers an excellent and not very common opportunity for direct geological, and particularly structural, study of sedimentary strata topping a salt dome. The author hopes that such a study could contribute to the knowledge and better understanding of the geological structures and particularly of those related to the building of salt domes. With this in view a detailed structural mapping of the underground part of the mine was started in November, 1962.

Apart from the large scale structure, mapping of the small scale structural features was also undertaken and an attempt made to determine their relation to the large scale structure.

For the time being the mapping was limited to the western part (see Plate I) of the most recent and easiest passable floor (which stands, rather evenly, at +19 m and some 25–30 m below the present ground surface).

The first results of this structural study are reported here. The structural study, however, is meant to be a part of a larger research project comprising geophysical, geochemical, as well as other aspects of geology of the Mønsted area, which will be dealt with by other staff members of the Geological Institute, Århus University.

d) *Acknowledgements*

The Direction of Jydske Kalkværker A/S has kindly given the permission for the work in the mine.

The Carlsberg Foundation has placed at the disposal of the Institute the theodolite which the author used in his work in the Mønsted mine.

The Boring Archive of the Danmarks Geologiske Undersøgelse (The Geological Survey of Denmark) has made available to the author the log copies of borings performed by the Danish American Prospecting Co. in the area of the Mønsted salt dome, as well as a number of pertinent water well logs.

The author also wants to express his gratitude to prof. ASGER BERTELSEN, head of the Geological Institute, Århus University. It was thanks to his interest and initiative that this work was started, and his suggestions have been of an invaluable help in the course of this investigation. Prof. BERTHELSEN has also kindly read the manuscript of this paper.

And, finally, the author would like to thank several students of geology, particularly Mr. LEIF CHRISTENSEN (Århus) and Mr. KJELD THAMDRUP (Copenhagen), who have helped him occasionally in his work in the mine.

Previous Work

ØDUM (1926), apparently on the basis of samples from a large pit adjoining the Mønsted underground mine, defined the rock as coccolith limestone of Upper Danian age, belonging to the uppermost (youngest) zone D—the *Tylocidaris vexilifera* zone.

The foraminiferal content of limestone from the underground part of the mine was investigated recently by INGER BANG (see RASMUSSEN, 1960, p. 26).

BRONNIMANN (1953) studied the foraminifera from samples taken at Davbjerg, another locality in the area of the Mønsted dome where limestone was mined (see Fig. 2).

ANDERSEN (1944, p. 358–361) gave a brief account based on direct observations made in open pits and underground mines in the dome area. He distinguished between flint occurring parallel to bedding and flint occurring parallel to fault walls.

Description of the Rock

a) Limestone

The rock exposed in the parts of the mine, studied by the author so far, is a soft limestone og greyish to yellowish white color, containing flint layers of varying shades of grey. The limestone has a sandy feel; it is brittle and it fractures easily along more or less regular surfaces. The rock is very poor on macrofossils.

The bedding planes in the limestone can sometimes be clearly seen, and there can be a very slight separation along them. On closer scrutiny thin stratification bands, marking successive stages of deposition, can be seen.

Although the rock has been subjected to faulting, it seems that the limestone remains lithologically very uniform throughout the mine.

b) Flint

From the structural point of view, the following types of flint can be distinguished:

1) Flint, formed parallel to the bedding planes in limestone, which will be referred to here as bedding flint.

Along certain horizons bedding flint forms rather continous layers which can be traced for some distances. The thicknesses of such layers are, most commonly, between 20 cm and 25 cm, sometimes 30 cm, but hardly ever more than that.

Between such continuous layers are often seen thin (10 cm, or less) layers which, usually, do not show continuity nor uniformity in thickness. They are developed only locally along a horizon, and they may, or may not, reappear.

The intervals between the continuous bedding flint layers vary from about 50 cm to a maximum of 2.5–3 m. Most commonly, however, the vertical distances between them do not exceed 1 m.

There are distinctly areas in the mine, as limited by different faults, which differ both in the average thickness and in the frequency of their flint layers.

2) Apart from the bedding flint, we find scattered almost everywhere in limestone pieces of flint of different sizes and shapes. Sometimes these growths have more or less round shape, but, quite frequently, they are triangular, or funnel-shaped, and can attain a size of 1.5 m, or more. They always tend to have their long axes oriented perpendicular to the bedding, but their apexes can point either up or down. The surfaces of such flint bodies often show evidence of slip, particularly if found in the vicinity of some larger structure (Fig. 3 shows an example of this type of flint bodies). They frequently merge with the bedding flint.

3) Flint which has grown parallel to the walls of faults, and, here, will be called fault flint.

Although there are faults along which no flint has formed, or at least the fault plane is free of flint for some distance, along almost all mapped faults flint forming layers parallel to the fault walls was observed.

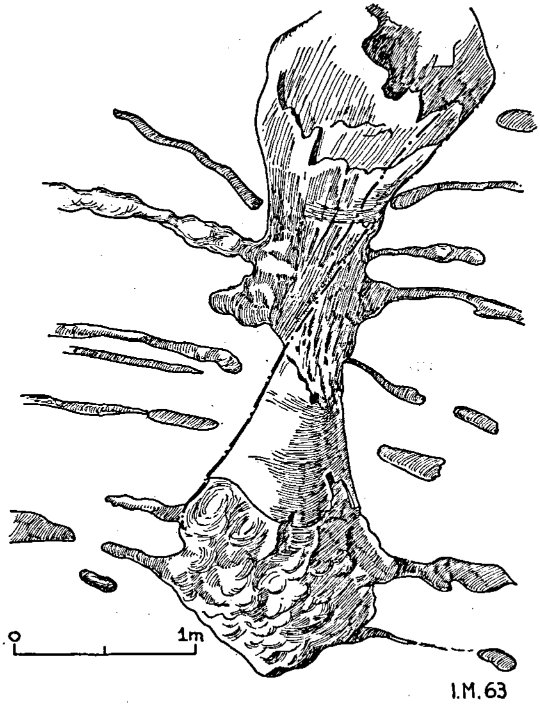


Fig. 3. A sketch of two large flint bodies with their long axes perpendicular to the bedding. Heavy broken lines indicate slip surfaces.

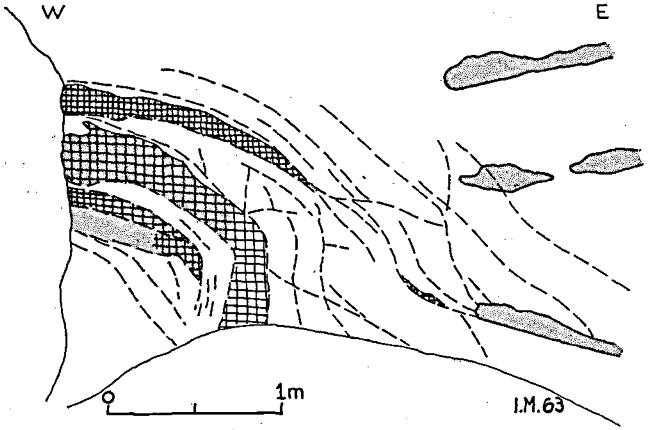


Fig. 4. A locality where the fault N1 consists of three layers of strongly brecciated fault flint. Upper right: layers of bedding flint. Broken lines represent slip joints.

The thickness of the fault flint varies between 10 cm and 30 cm, rarely more. Since, in many instances, the bedding flint is flexed in the vicinity of faults, it must clearly be an older formation than the fault flint.

Consequently, we are dealing with types of flint of two distinctly different ages, and, very likely, they are also different as far as their modes of formation are concerned.

In places, and particularly along the fault N1 (see Fig. 4), fault flint is brecciated and slickensided, thus proving that repeated movements along the same fault occurred.

Methods of Mapping

The original map was prepared on the scale of 1:100. The mapping of the large scale structure was done by means of a theodolite. A retractable stadia 3 m long, with "legs" attached, used. The north line was determined by a compass mounted on the theodolite.

A net, consisting of some 40 stations, was established and some 500 individual points were determined in the preparation of the map of the large scale structure (such as bedding and faults).

Wherever possible points were taken along the exposures of faults, and if these contained flint, the lower boundary of fault flint was measured. On the basis of points determined in this way the structural contours for the individual fault planes were drawn as far as the vertical control permitted. The dip values of the fault planes were solved graphically. The total vertical range of mapping was approximately 10 m. An attempt was made to use triangulation methods for the very high and inaccessible points on faults and thus enlarge the vertical range of mapping. This, unfortunately, proved impossible mainly because of a lack of sufficient light.

The faults were designated arbitrarily by the letters N or E followed by a number. This numbering has no implication whatsoever as to the relative ages of faults.

Strikes and dips of bedding flint were determined by the theodolite using the three points method. These points were measured always along the lower boundary of flint layers. Each area for which the individual strike and dip values are valid is marked by the triangles on the map. In the places where a layer of bedding flint could be traced for some distance, mainly in the N-S direction, structural contours for the layer in question were drawn.

The limits of the corridors and supporting pillars were also accurately mapped.

After the completion of the map of the large scale structure mapping of the small scale structural features was undertaken. Thus, about 600 joint planes were measured with a compass. With the exception of approximately 150 first measurements all other planes were numbered close to where measurements were taken. More than a half of the planes measured contain some type of measurable lineation. In almost all instances the pitch angles were measured directly on the planes. The trends and the plunge angles were then calculated by means of a stereonet.

The diagrams refer to the lower hemisphere of the equal area (Schmidt's) net. The counting was done by means of a circle the area of which is 1 per cent of that of the projection.

The specific areas in which the measurements of joint planes were taken are indicated on the map by the Roman numerals.

Bedding

In the mapped area the bedding in limestone, as expressed by the bedding flint, strikes in a general N-S direction and dips everywhere westwardly. The lowest dip measured is 11° and 33° is the maximum value, but, on the average, the values range between 15° and 25° increasing somewhat from south to north.

In the middle east part of the map the strike and dip measurements reveal a gentle folding of the beds. However, the bedding in the adjoining area on the west side of the fault N1 has a uniform attitude. As will be discussed in detail later, it can be demonstrated that this is a normal fault, so that the east block has moved down relative to the west block. Since the fault plane seems to mark a sharp boundary between the undisturbed beds on the west side and the slightly folded beds on the east side, it is believed that this folding is the result of down-faulting rather than being of an earlier date. However, this subject will be treated again in the discussion on faulting.

In several places the strikes and dips of beds were determined immediately below and above faults to show any possible changes in the attitude of beds due to faulting.

In numerous instances local flexing and brecciation of the bedding flint layers can be seen. Fig. 5 shows an example of such a structure.

On the previously mentioned map of the Mønsted Chalk Works from 1933 many strike and dip measurements were plotted. Unfortunately, Rasmussen (1960) did not state that some of these refer to the bedding and some to the faults so that an impression could easily be gained that the beds in the Mønsted mine are strongly folded. And this, however, is not the case.

The question could be raised if, and to what degree, the structure in the Danian limestone at Mønsted was influenced by the pressure exerted by ice during the Pleistocene time. From the study of the area mapped so far it appears that none of the exposed structural features can be directly related to glacial tectonics. It is conceivable, however, that the movements along faults which were produced either by the upthrust of the salt core, or through later settling due to the solution of the salt, were reactivated after the melting of the ice mass. And, also, Pleistocene movements could be related to a gradual disappearance of the permafrost conditions through which a free circulation of the ground water could again be resumed. Such examples are known from some north-west German salt domes (Gripp, personal information).

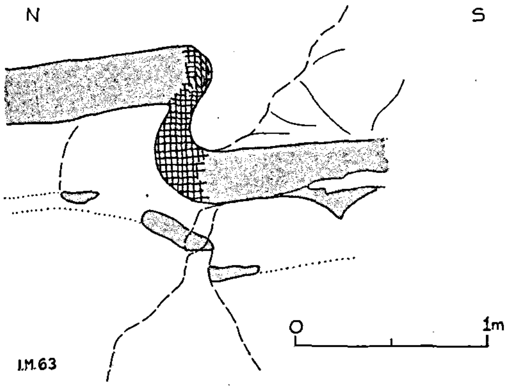


Fig. 5. Flexing and brecciation, indicated by squares, of a bedding flint layer. Dotted lines represent bedding in limestone, and broken lines slip joints.

Grube (1955) found, on the basis of study of the Breitenburg chalk pit (Holstein), that the master jointing of the Senonian chalk extends into the Pleistocene sediments.

Faulting

The fault planes shown on the map represent the most improtant faults, i. e. those that show some continuity and could be traced and mapped throughout the area. Not all of them contain flint, or else, flint is developed only locally while the rest of the fault is visible only as a more or less clean and regular fracture in limestone with, apparently, no separation between the foot and the hanging wall. The fault N4 is an example of this type of faults (see Fig. 6).

There are fractures exposed in the mine along which the bedding flint shows no noticeable displacement, but, much more commonly, the bedding flint cannot be correlated on both sides of faults when several consecutive layers are considered, which proves that some movement has taken place.

The faults that strike in a general N-S direction dip all eastward, i. e. they are antithetic to the bedding. The E-W striking faults may dip either north or south. In several instances faults strike clearly parallel to the strike of bedding, or their strikes may parallel the strike of bedding for shorter distances to cut again obliquely across the bedding.

The dips of faults differ considerably. Some of them, as, for instance, two faults in the southernmost part of the map, are nearly vertical whilst in the north-east corner a fault (N3) dips only 22° (the lowest dip value for a fault plane recorded in the mapped area). Most commonly, however, the faults dip between 40° and 65°.

Apart from such values which are typical for normal faults, along most of the faults some direct evidence can be found which confirms that we deal with normal faulting. Drag of the bedding flint layers, in the manner that illustrates normal faulting, in the immediate vicinity of

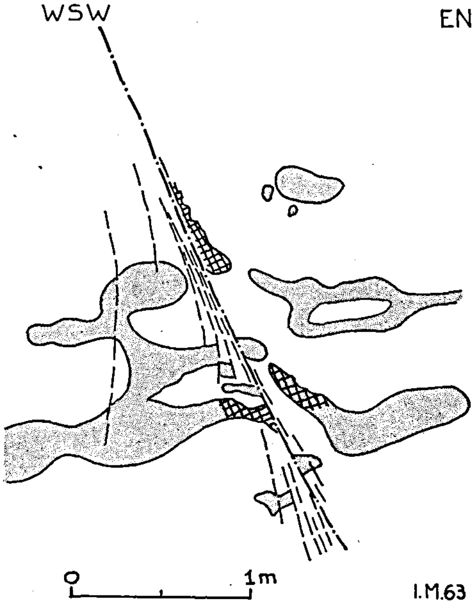


Fig. 6. A locality along the fault N4 where no fault flint developed. The deformation of the bedding flint indicates normal faulting. Thin broken lines represent slip joints.

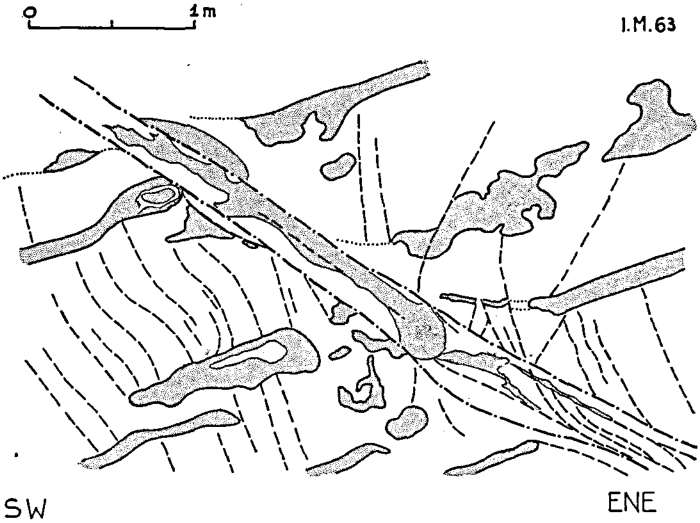


Fig. 7. A locality along the fault N1. The drag of the bedding flint layers indicates normal faulting. Dotted lines represent bedding in limestone, and thin, broken lines, slip joints.

faults (both below and above them) is common. Such deformation of the bedding flint and the bedding planes in limestone can be seen often, especially along the fault N1, where sometimes also smaller secondary faults, synthetic to the bedding, appear (see Fig. 7). Along that same fault flint is locally seen divided into several layers, some of which are strongly brecciated (see Fig. 4). It appears that, in places, the breccia is nearly healed while along some layers it has a relatively fresh appearance. In general, there is more evidence of differential movement along this fault than along other mapped faults.

Along the fault E1 normal faulting can be proved by correlating the bedding flint layers on both sides of the fault. This is the only instance where such correlation can be established with certainty in the area of the mine mapped. On the east wall of a semicircular opening (on the west edge of the map) three consecutive layers of bedding flint are seen off-set by this fault (Fig. 8a and b). The lowest layer A shows an apparent displacement of approximately 50 cm and the middle layer B has an apparent displacement of about 90 cm. Since this exposure is not parallel to the dip direction of the fault, the true displacement would be smaller than what these values indicate. The highest layer C is off-set still by another smaller fault, apparently parallel to the large one, so that this layer was down-faulted by two succesive faults (in the manner of step-faulting) and slightly off-set along each one of them. A part of this flint layer and the trace of the fault coincide. In this opening the strikes and dips of the bedding flint were measured immediately below and above the fault and it was shown that the difference between the two strike values is 11°, while the dips remain virtually the same.

It is of interest to study this exposure a little closer, particularly the down-faulting of the middle flint layer B. This layer was not at all deformed by faulting, but rather it preserves its attitude until the very contact with the fault. However, in the process of faulting the down-thrown segment of the flint layer has moved closer to the up-thrown segment, so that the section of the fault plane between the displaced flint layer becomes more or less vertical and so deviates considerably from the dip of the fault plane as a whole. A similar phenomenon can be observed also along the highest flint layer C.

The above considerations suggest a possibility that the shearing along this fault might have occurred very early, still during an early diagenetic phase of disturbance, in not yet hardened sediments, but after the formation of the bedding flint. The fact that this fault is relatively the oldest, as far as that could be established from the information gathered in the mapped area, would be another argument in favour of such an interpretation.

On the down-faulted (east) side of the prominent fault N1, and about 7.5 m to the north of its presumed contact with the just considered fault E1, we find a segment of a fault that has an almost identical attitude as the fault E1 on the west side. The contact between the fault N1 and the segment on the east side shows that this segment is older than, and that it was down-faulted by, the fault N1.

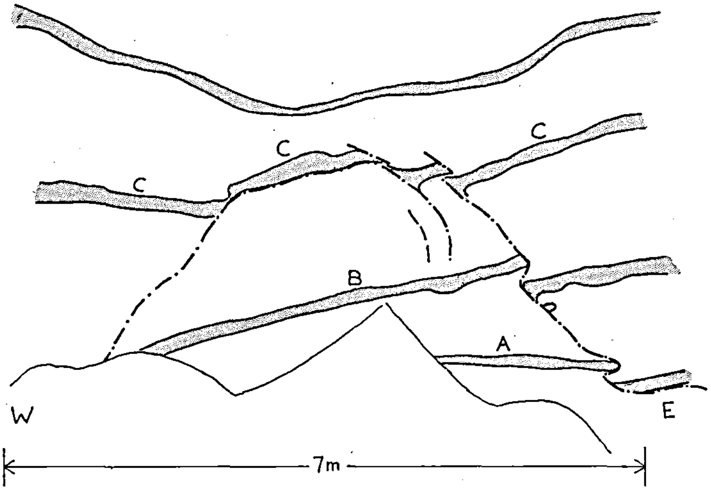


Fig. 8a. A view of the segment of the fault E1 where three consecutive layers of bedding flint can be correlated.

Although no clear evidence of the magnitude of displacement along this (east) segment was found, it may be assumed that it is a continuation of the fault E1 as displaced by the fault N1. On the basis of the strike slip of 7.5 m and the direction of movement along the fault N1, which, as will be discussed later (see p. 536–537), deviates 15° (to the north) from its dip direction, the net slip for the fault N1 was calculated to be about 12 m.

Since the fault N1 is a normal fault, the down-faulted segment of the E-W striking fault ought to be found in the northerly direction. Except the segment mapped, no other E-W striking fault occurs in the hanging wall of the fault N1 for at least a distance of 50 m to the north. Any other E-W striking segment farther than 50 m would presuppose a far greater (> 80 m) net slip for the fault N1. This, however, would be highly improbable, since the borings on the southern flank of the Mønsted dome conducted by the Danish American Prospecting Co. show that the thickness of the Danian (judged, apparently, only on the basis of lithology and the color of flint) is not more than some 80 m, and since the rock on both sides of the fault N1 is of Danian age.

This consideration should be kept in mind when estimating the magnitudes of displacements along any fault in the mine.

Still farther east of the displaced fault E1, a small segment of a fault could, possibly, also be ascribed to that same fault as displaced, again through normal faulting, by the low dipping fault N3.

As mentioned previously, the bedding flint cannot be correlated with certainty along the segment of the fault E1 on the east side of the fault N1. It appears, therefore, that in the process of down-faulting along the fault N1 the movement along this segment of E1 was reactivated. This

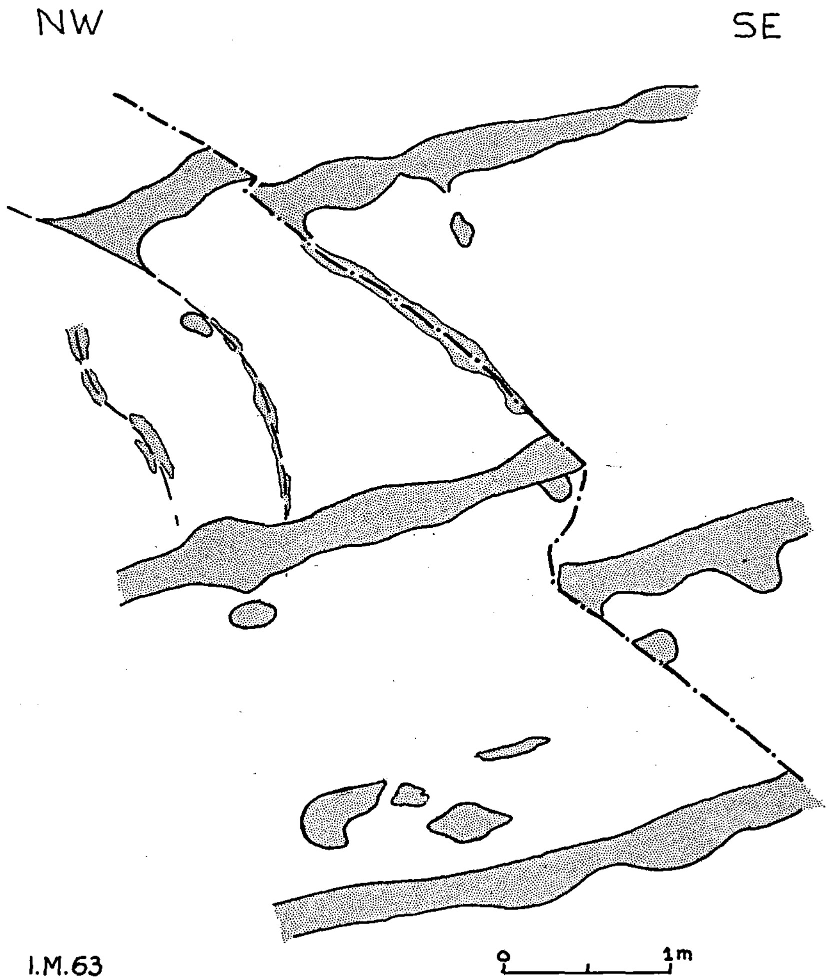


Fig. 8*b*. A detail of the same exposure showing down-faulting of the bedding flint layers *B* and *C*.

would result in the slight folding of the beds, which was mentioned before, around an E-W axis. Such an explanation is supported by the study of the small scale structure. Along and on the surface of the fault N1 we find, apart from the most prominent, eastward plunging lineation (at angles similar to the dip angle of the fault plane), also southward plunging lineation at very low angles. Along the fault N2, whose plane shows considerable curvature, and which is, apparently, of the same age, or slightly younger than the fault N1, normal faulting can be demonstrated by the manner of flexing of the bedding flint in several places (see Fig. 9).

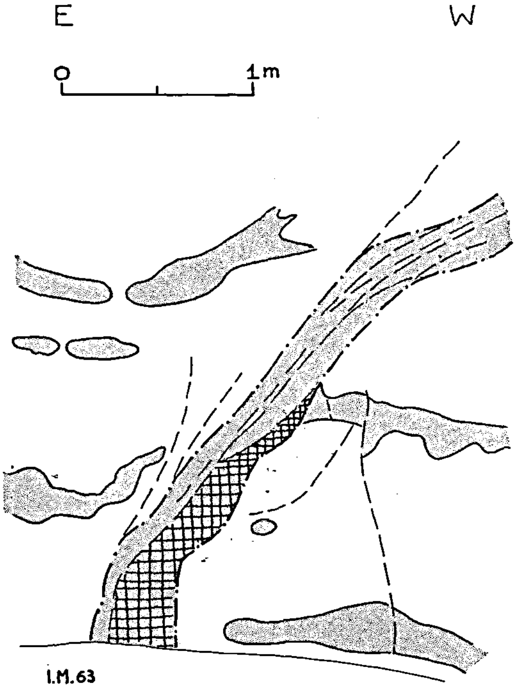


Fig. 9. A locality alont the fault N2. A part of the fault flint is strongly brecciated (indicated by squares). The drag of the bedding flint layers illustrates normal faulting. Thin broken lines represent slip joints.

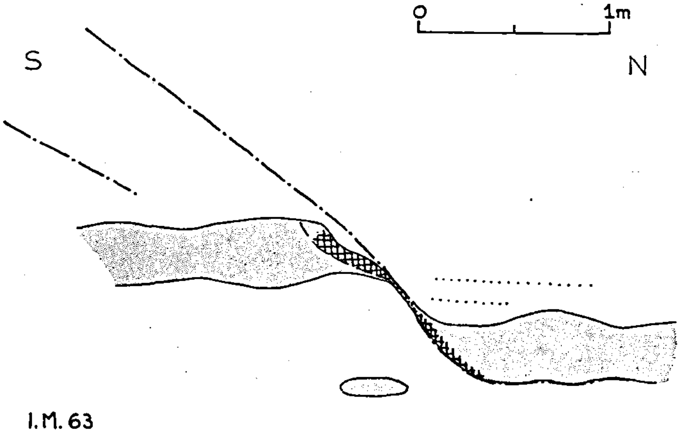


Fig. 10. A small fault with an apparent displacement of about 50 cm. The bedding flint layer affected is brecciated (shown by squares) close to the fault. Dotted lines indicate bedding in limestone.

However, in one place, practically on the upper limit of this fault, very clear lineation was measured which has plunge of 20° at a trend of 175°. And, finally, the fault E2, which is younger than the fault N1, has seemingly not been affected by the folding.

The area where the fault N1 and the E-W striking fault E2 come in contact is, unfortunately, largely concealed by a sand pile and a lot of limestone debris. Therefore, it was not possible to determine here more fully the attitude of the fault N1. It appears certain, however, that this fault just in this area changes its strike tending to adjust itself to the N-S strike of the bedding. In one place (on the west wall) the contact between the two faults was dug out and it was shown that the fault E2 is younger and that it off-sets the fault N1 through normal faulting. The direction of movement along the younger fault E2, as deduced from the study of the small scale structure, deviates 12° (to the west) from the dip direction of the fault plane (see p. 540).

In this same area a smaller fault (Fig. 10) is exposed along which an apparent displacement of approximately 50 cm was measured. The flint layer affected, whose true thickness is about 30 cm, was stretched in the process of faulting and it is only about 5 cm thick along the fault itself. The bedding flint is brecciated only quite close to the fracture.

In this area, but on the south side of the fault E2, a small segment of a fault could be mapped, which, because of its attitude and the character of the breccia, is believed to be a segment of the fault N1.

The faults E2 and E3 actually limit a narrow graben. The rock between these two faults is severely broken up and the bedding is disturbed so that here it was not possible to determine its attitude.

In the southernmost part of the map the bedding attitude could again be determined and it proved to be quite comparable to the values obtained in other parts of the mapped area.

In order to summarize briefly the discussion on faults, it can be stated that for nearly all faults mapped some direct evidence is found which proves that, in this part of the Mønsted mine, we are dealing with normal faulting. The faults proved to be of (at least) three different ages. Along one fault, whose origin could conceivably be traced to an early diagenetic disturbance, the movement was, apparently, reactivated in the process of later faulting. The directions of movements along the faults studied deviate only little from their dip directions.

Jointing

a) General Considerations

Without going into a detailed classification of joints or their modes of formation, the author would like to cite a definition of a joint from a paper by SWANSON (1927), which is thought to be very clear and useful. SWANSON says: "A joint is a fracture in a rock due either to a small slip of one protion of the mass past the other along the break or to a tearing apart of one portion from the other, the movement being normal to the break". The first class are commonly known as "shear joints" and the second as "tension joints". And, in the same paper, SWANSON proposes the term "slip joints" for all joints of the first class and "rip joints" for all joints of the second class, thus avoiding any reference to stresses in the nomenclature of joints.

In such a strongly faulted rock as the limestone exposed in the Mønsted mine it is difficult to ascertain whether any joints exist that are not related to the faulting. In other words, whether we have fractures that are clearly older than the faults, and which could be designated as primary joints.

Although there are some areas in the mine, as for instance just north of the entrance, where the rock is almost free of any visible jointing, there exists a definite tendency in the limestone to fracture along surfaces perpendicular to the bedding. These surfaces are, in general, irregular and unevenly spaced, their strikes changing within short distances, so that they could not be considered as planes. Therefore, it would be difficult to accomplish a systematic and statistically reliable measuring of these joints.

In most cases such joints could be considered as closed, their walls showing no noticeable separation, but sometimes, a slight separation exists (which, however, could have been caused by weathering). Usually, these joints do not cut the bedding flint, but are limited to the sections of limestone between two more or less massive layers of flint.

The type of fractures just described could be regarded as primary joints.

Apart from this type of joints, we encounter, in extremely large amounts, joints whose surfaces are much more regular, often almost perfect planes. The rock is very easily separated along them, and sometimes it takes only a small effort by hand to accomplish that. These joints, or rather their exposed surfaces, are found in large numbers along the walls of the mine where the pieces of rock, either above or below them, have fallen off. Therefore, the measurements of these surfaces can be done relatively easy and with a high degree of accuracy. A systematic study of such joints was undertaken, and nearly 600 of them were measured, most of them in a few selected areas along the fault N1.

While it seems that, usually, such joints cut the neighbouring layers of bedding flint, in many instances this is not the case.

The surfaces of these joints, which are nearly always slickensided, can be extremely smooth, often highly polished, with no other record of slip along them. Or, they may also contain striae which can be very clearly defined, sometimes as very coarse, but more often as dense, sharp, little grooves. Many times, however, the grooves are much less pronounced, so that they cannot be so readily seen.

In not a few instances the surfaces of these joints show also some sign of relative movement along them, either in the form of small "steps", or just in the degree of smoothness as detected by passing a hand over them in one or the other direction. Many times an exposed surface of a joint was found to be cut by one or more joints belonging to a different set, or sets. A study of their intersections has shown that, in a great majority of cases, no measurable displacement has taken place along any of the planes. Occasionally, however, the displacements are more easily noticed and they may amount to several millimetres and, in a few extreme cases, 2–3 centimetres. In this way the relative ages of movements along some sets could be established.

And here it is thought to be more appropriate to speak about the ages of movements, rather than the ages of joint sets as such. Along the same set several movements could have occurred and so a false impression as to the relative ages of different joint sets could be gained from the study of their intersections. Thus an older (first formed) set might displace a younger set (or sets).

The kind of joints under consideration can be found in many areas of the mine, but, undoubtedly, they are heavily concentrated in the immediate vicinity of faults, both below and above the limits of fault zones, as well as within fault zones themselves.

Since almost all such joint planes measured in the Mønsted mine show some evidence of slip, either by being smoothed and polished—with or without some form of lineation on them—or else, their intersections show that some sets were displaced by others, it is evident that they represent planes along which the shearing of limestone took place during the process of faulting. This type of joints, which the author prefers to call by the term of slip joints, were formed either slightly before or during the faulting. The faulting, of course, could have happened in several stages, as the brecciation of the fault flint and the striae on the fault flint indicate.

As will be shown, the movements along the slip joints were predominantly parallel to the directions of movements along faults. Also, it appears sure that, under certain conditions, the bedding has exercised a decisive control over the distribution of these joints. On the other hand, there are situations when joints formed symmetrically to the fault planes, and, sometimes, a compromise between the faults and the bedding for the control over the joints is achieved.

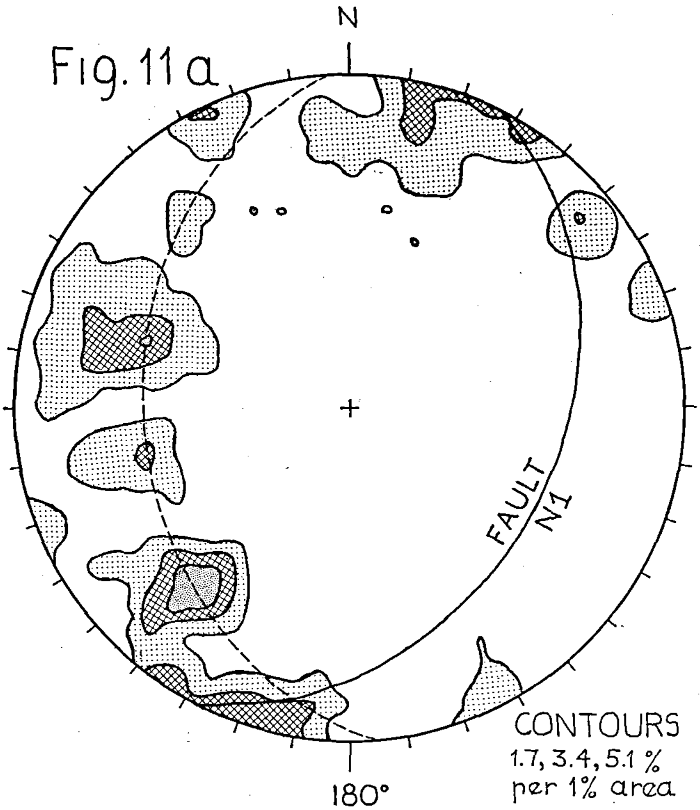
As mentioned, along the fault N1 several areas (see Plate 1) were chosen within which a number of slip joints and, where possible, their lineation was measured. These areas were restricted to the vicinities of faults, usually not more than a few metres away from them, so that very local pictures can be obtained, and possible slight variations in the attitude of bedding and respective faults be taken into consideration. Where possible, measurements were also taken either on the upper or the lower limits of faults proper (which usually means on fault flint).

b) *Joints in Areas I, II, III*

In the areas I, II, and III 117 slip joints were measured and, also, 12 measurements were taken directly on the surface of the fault N1, most of them on the upper fault limit. The diagram representing these measurements is shown in Fig. 11a.

In the area I (where about a half of all the measurements was taken) the planes were measured almost exclusively below the lower limit of the fault in question.

Fig. 11 a



Contoured poles to 117 slip joints from the areas I, II and III (see Plate I).

On 81 planes also lineation could be determined, including 5 values on the fault itself (Fig. 11b).

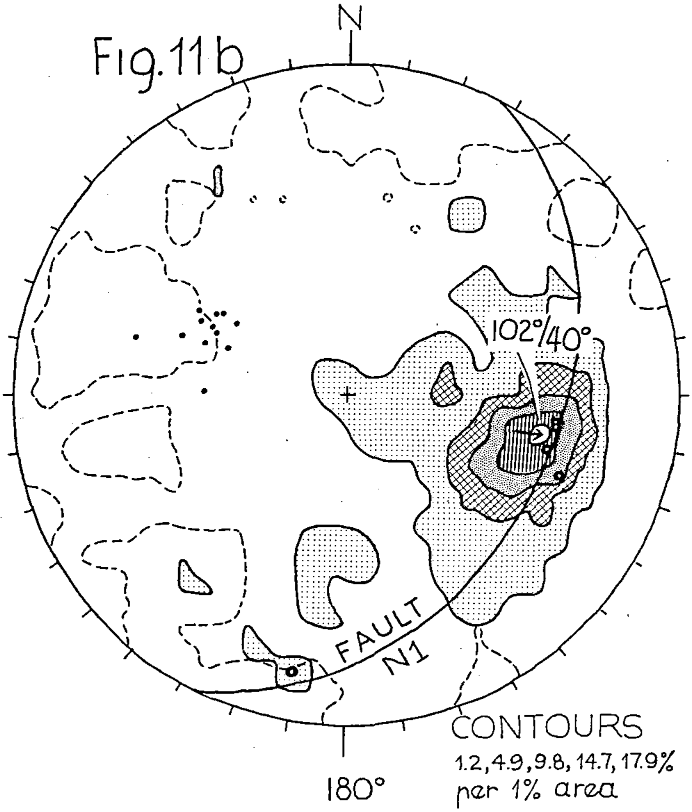
On the diagram of the joint planes a great circle connecting four areas can be drawn. A majority of the planes represented by these areas, particularly the one whose average plane has an attitude of 130°/62° E, stands at right angles to the bedding. The great circle strikes nearly N-S, thus reflecting the strike of the bedding.

Apart from these joints, a set of ESE-striking joints is clearly defined. They dip steeply either north or south, and quite a few of them are vertical.

On the basis of 12 values obtained directly on the fault, the average attitude of the fault plane here is 27°/37° E. This is in close agreement with the values as read off the map of the large scale structure: 24°/33° E (for the area I) and 31°/40° E (for the areas II and III). (The fault plane just here becomes somewhat irregular).

The diagram of the lineation shows a very strong maximum at the

Fig.11b



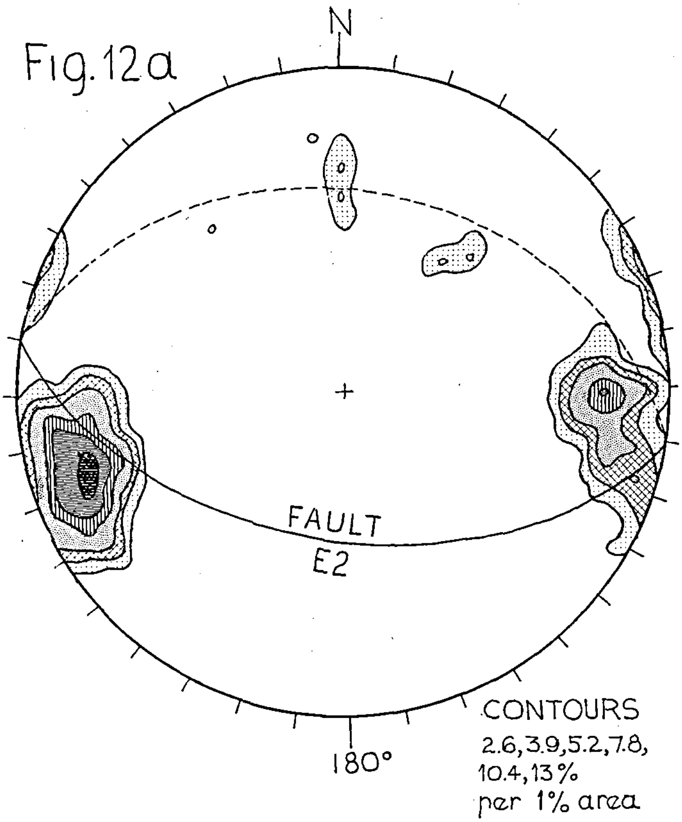
Contours for 81 lineation poles from areas I, II and III. 76 were measured on slip joints, and 5 (indicated by circles) on the N1 fault proper. Heavy dots are poles to surfaces of N1 fault. Dashed line shows joint pattern. For discussion of both diagrams, see p. 535-539.

trend of 102°. The lineation measured on the fault itself (and falling within this field) also has an average trend of 102°.

Apart from the dominant eastward plunging lineation, a few values plunging southward at low angles were also recorded. In a place where the contact between the faults N1 and E1 is exposed, marked striae having a trend of 191° were measured on the upper surface of the fault N1 itself.

The two diagrams show that the movements along a great majority of slip joints can be directly related to the main movement along the fault N1. The direction of this movement (102°) deviated 15° (to the north) from the dip direction of the fault plane. (On the basis of this angle the net slip along the fault N1 was later calculated). Hovewer, we see that the joint pattern is not symmetrical to the plane of the fault, with the exception of the set striking ESE, that is approximately at right angles to the strike of the fault. Therefore, we can say that in this case,

Fig.12a



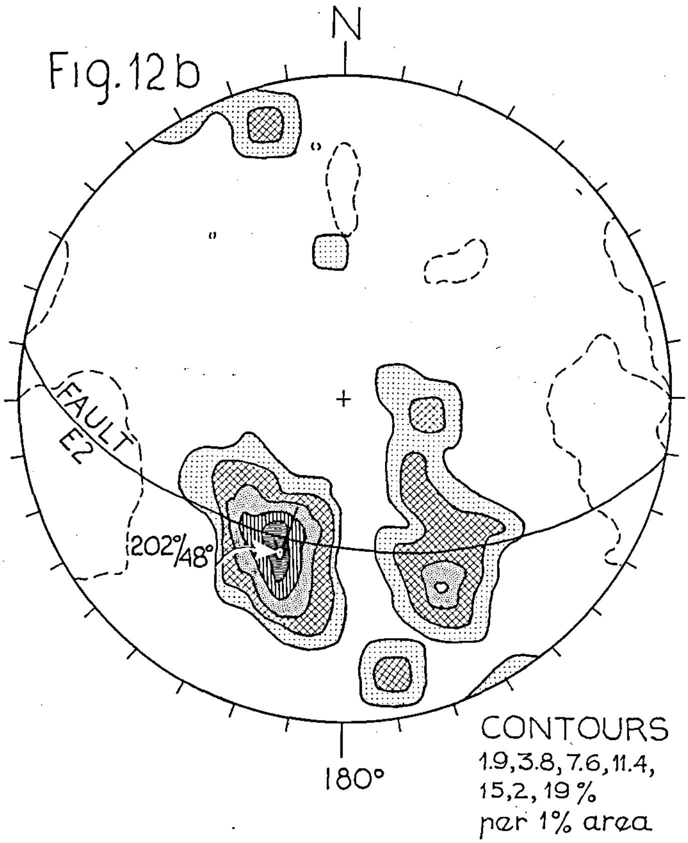
Contoured poles to 77 slip joints from area IV.

although the joints were formed in the process of faulting, the bedding has exercised a decisive control over their distribution.

Furthermore, we see that, apart from the very intense movement in the easterly direction, a much less accentuated movement in the southerly direction along the fault N1 has taken place also.

In the discussion on faulting (see p. 530-533) it has been assumed that in the process of faulting along the fault N1 the movement along the downfaulted segment of the fault E1, which just in this area comes in contact with the fault N1, was reactivated. The fact that we find southward plunging lineation on the upper surface of the fault N1 (and above the contact with the fault E1) confirms this assumption. Furthermore, below the fault E1, but farther away (east) from its contact with the fault N1, some lineation could be measured which also had sub-horizontal or very low, southward plunges. The slip joints, however, are not nearly as abundant here as they are in the immediate vicinity of the fault N1. Also, the joints have rough surfaces which, in general, are not striated.

Fig. 12b



Contours for 53 lineations on slip joints of Fig. 12a. Dashed line shows joint pattern. For discussion of both diagrams see p. 539-541.

The eastward plunging lineation, so characteristic for the fault N1, could not be detected here.

c) *Joints in Area IV*

In the area IV 77 slip joints were measured and on 53 of these also lineation could be determined (see Fig. 12a and b). All the planes were measured above the E-W striking fault E2 (having an attitude of 100°/52° S in this area), that is, they are all within the hanging wall of this fault. Consequently, they are also above the older fault N1, a great majority of them being considerably higher, so that the influence of that fault on the jointing in this area must be negligible.

On the joint diagram (Fig. 12a) we see two well defined sets: one, very well defined and strongly concentrated set which dips steeply east, and whose average plane has an attitude of 162°/71° E, and another, more diffuse set which dips, also steeply, west. Both of these sets are new, i. e. they were not represented in the previous diagram (Fig. 11 a).

The W-dipping set strikes more or less at right angles to the plane of the fault E2 and, on the basis of the previous experience, we can assume that the joints of this set were formed in the process of faulting along this fault. This is supported by the fact that four planes measured immediately (within a few centimetres) above the upper fault limit strike nearly at right angles to the fault. All these planes show very good, strong striae. On two of them normal movement could be proved.

The E-dipping set shows no symmetrical arrangement with respect to the fault plane.

Apart from these two sets, a few joints, more or less parallel to the fault plane, are present.

On the diagram of Fig. 12b the most concentrated and best defined group of lineation has a maximum, which lies almost on the fault plane, at a trend of 202°. The lineation trends on the four mentioned planes (immediately above the fault) are very close (209°, 203°, 210°, 217°) to that value, and on one plane (not represented in this diagram) just below the fault and striking parallel to it, lineation has again a similar trend (204°).

Nearly all lineation of this group was measured on the joints striking more or less at right angles to the fault and dipping steeply west. The exceptions are only four poles, and they belong to the planes parallel to the fault.

The lineation poles whose maximum has a trend of about 152° belong, almost entirely, to the set of steeply E-dipping joints. And, again, the only exceptions are two poles which belong to the joints parallel to the fault plane.

A few lineation poles show trends of about 100°. These could be related to the movement along the fault N1.

Finally, in a few cases, we see very low, or nearly horizontal, lineation plunges. All of these were measured on planes of the steeply E-dipping set, particularly on a group striking about 145°.

Since the lineation whose maximum has a trend of about 202° was almost exclusively measured on joints arranged symmetrically with respect to the fault plane, we can safely assume that this trend coincides with the direction of movement along this fault. Thus, although no lineation could be measured on the surface of the fault itself, we can deduce that the direction of movement along this E-W striking fault deviates about 12° (towards west) from the direction of its dip. The fact that we are dealing with structures contained within the hanging wall of the fault shows that this block was active during the faulting.

While in the first case considered (Fig. 11 a and b) the strike of the fault N1 and the strike of the bedding made an angle of about 30°, in this area the fault E2 strikes approximately at right angles to the strike of the bedding. In this case we see that, apparently, the only joints formed in the process of faulting (within the hanging wall) are those that strike at right angles to the fault plane. But, at the same time, they are also symmetrical to the bedding, i. e. they strike parallel to it.

The joints associated with this fault and whose planes would make 90° with the bedding planes are missing in such a situation.

d) Joints in Area V

In the area V 74 slip joints were measured, three of them within the fault zone. One measurement was taken on the fault surface. On 33 of the joint planes the directions of movements could also be established. All the measured planes lie above the fault N1, a considerable number of them quite close to, or immediately above, the upper limit of the fault zone. The area is far, both horizontally and vertically, from the fault E2 so that, here, its influence on the jointing is eliminated as much as possible.

On the joint diagram (Fig. 13a) we observe several, more or less connected, areas of rather low concentrations representing joints striking N-S to E-W and dipping east or south. Such a picture is quite similar to the one of the first diagram (Fig. 11a) representing measurements taken also along the fault N1. Here, however, such a symmetrical arrangement with respect to both the bedding and the fault plane does not exist probably because this is an area of repeated later disturbances.

The joints striking approximately N-S and steeply W-dipping seen on the previous diagram (Fig. 12a) are completely missing here. This confirms that that set of joints is genetically related to the fault E2. But the joints dipping steeply east and having similar strong concentration, are present also here, where they show two, possibly three, maxima. Two well defined maxima are: 158°/66° E and 158/88° E, while a third group strikes from about 140° to 150°.

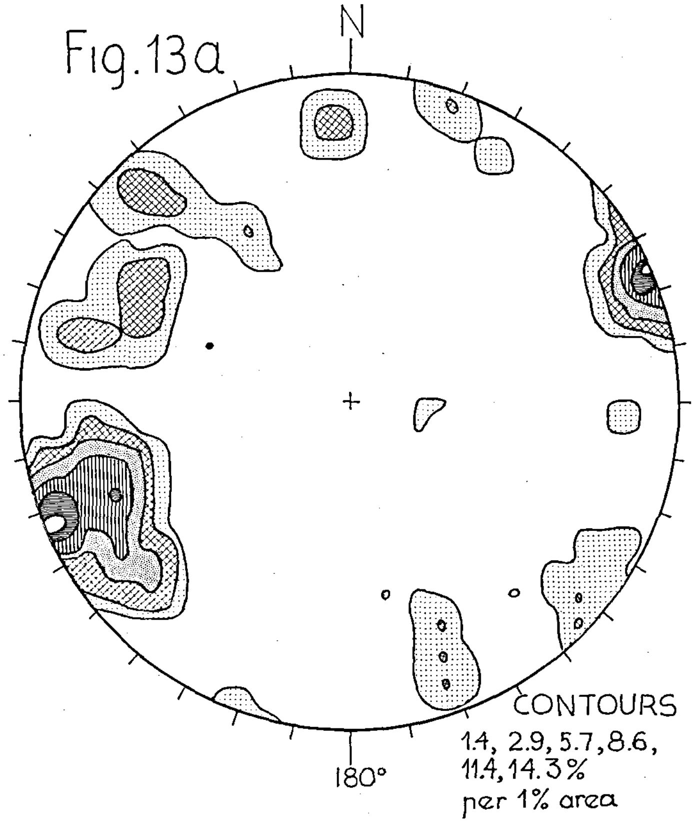
This entire group of E-dipping joints is seemingly unrelated also to this (N1) fault, and the intersections of several of these joints with the joints associated with the fault show that this group of joints is unquestionably younger than the fault.

On the lineation diagram (Fig. 13b) the group whose maximum had a trend of about 202° is, of course, missing (compare with Fig. 12b). We do have a few values with trends between 180° and 200° and very low plunge angles. These, however, belong to the joints associated with this (N1) fault. (On the diagram of Fig. 11b, also representing lineation along the fault N1, we have seen a few values nearly identical in their trends and plunges). This confirms again that, apart from the near down-dip movement along this fault, there must have occurred (within the hanging wall) another, nearly horizontal, movement in the southerly direction.

In the present diagram there is also the familiar trend represented, namely between 100° and 110°. One of these values was determined directly on the fault surface.

The highly concentrated lineation poles (having a maximum between 155° and 165°) have mainly low plunge angles, a few of them are horizontal, or even slightly N-plunging. All the lineation of this group corresponds to the steeply E-dipping joints. While most of these joints, par-

Fig. 13a



Contoured poles to 74 slip joints from area V. Heavy dot is a pole to surface of N1 fault.

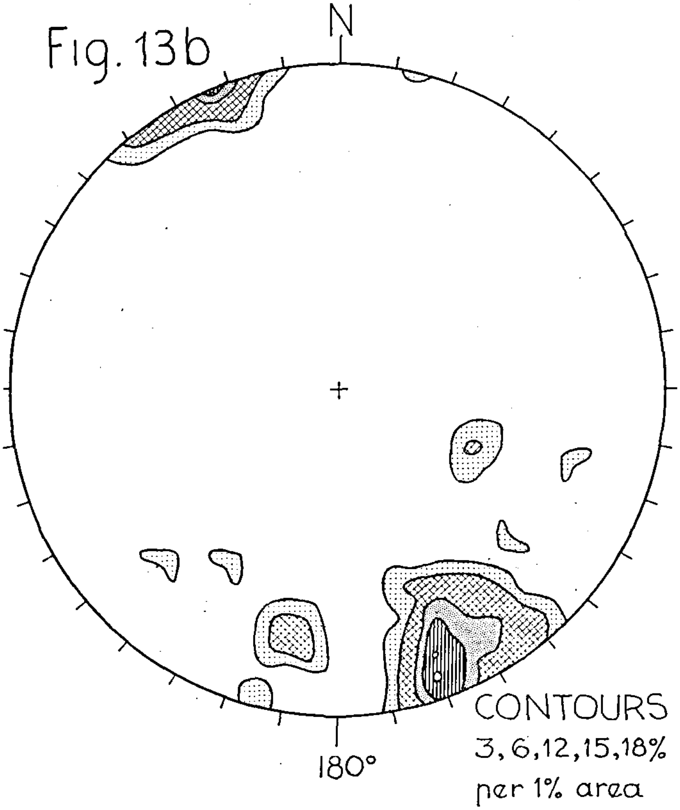
ticularly those striking about 158°, show excellent, coarse striae, on most of the planes striking between 140° and 150° the directions are difficult to read and at least two sets of striae can sometimes be discerned. Both of these sets, however, have very low, or sub-horizontal, plunge angles.

It is significant that in this area we see only a few values, as compared with those of Fig. 11b, that record the main, eastward movement along this fault. This would again confirm the assumption that that movement was the earlier one, and that in this area subsequent movements in different directions have utilized also the earlier formed slip joints erasing partially, or totally, the record of the older movement.

e) Joints in Area VI

The diagram of Fig. 14 represents 150 slip joints measured in the area VI. Thus, all the planes measured lie below the fault E2 and, also, above the fault N1. A good number of them are quite close to the fault E2. As

Fig. 13b



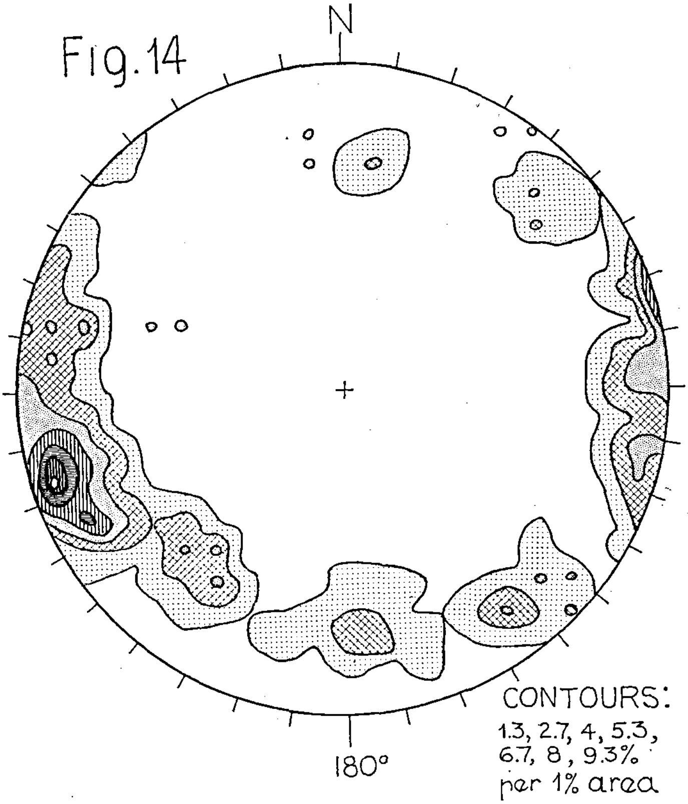
Contours for 33 lineations on slip joints of Fig. 13a. For discussion of both diagrams see p. 541-542.

mentioned before, the exact attitude of the plane of the fault N1 is here, unfortunately, uncertain, but it is believed that only a small part of the measured planes lies closer than 1 m above that fault. As could be expected, in this area we find a more complex pattern of slip joints produced by both faults.

We encounter again the N-S striking and steeply W-dipping joints (missing in the previous diagram, Fig. 13a) which strike at right angles to the fault E2. A set striking parallel to that fault and dipping in the same direction, only slightly steeper than the fault plane, is present as well. However, here, we see also another set developed which strikes parallel to the fault, but dips in the opposite direction, i. e. north, with angles between 60° and 70°. This set, which thus makes angles of 60° and 70° with the plane of the fault, was, apparently, not present in the hanging wall.

We can clearly distinguish joints associated with the fault N1 displaying again similar pattern as on previous diagrams and having similar concen-

Fig. 14



Contoured poles to 150 slip joints from area VI. For discussion see p. 542-545.

trations. The set whose average plane has an attitude of about 130°/60° E is here again well developed, just as in the first case considered (Fig. 11 a). The set striking at right angles to the fault N1 is, apparently, missing. It is possible that this set appears only in the immediate vicinity of fault zones. And another, quite likely more important, reason may be that just in this area the (N1) fault changes its strike to accommodate itself to the N-S strike of the bedding so that the slip joints might have developed in relation to the bedding whose strike here must be very similar, or possibly identical, to the strike of the fault itself.

Two other sets are present: one, whose average plane has an attitude of 55°/74° NW, and another, not so well defined, set whose planes strike between 130° and 145° and dip steeply south-west. The strikes of these two sets make angles of more or less 90°.

In the area represented by the first diagram (Fig. 11 a) we have seen two similar sets which, necessarily, had to be produced by the fault N1. And on the just considered diagram (Fig. 13 a) some planes with attitudes similar to the NW-dipping set of the present diagram were also seen.

The study of the intersections of the joints belonging to these two sets shows that they are always the oldest, which would tend to confirm that they are associated with the fault N1.

And, finally, we see again the most concentrated group of steeply E-dipping joints, having here the strongest maximum at 162°/83° E with another, weaker maximum at 154°/78° E. This group of joints appears, then, with quite constant attitudes over a large area both in the horizontal as well as in the vertical sense. In light of the information gathered so far it can be concluded that this group of joints, having always the relatively strongest concentrations, is not related to either of the two faults. The movement along their planes was not "down-dip" as along the two faults, but at low angles, or even horizontal. Furthermore, from the study of the surfaces of these joints, as well as their intersections with joints of other sets, both in this area and elsewhere, it appears that these movements were in the sinistral sense. For these reasons it is believed that this group of joints should be considered as a separate entity and that, in reality, it represents another fault in its embryonic stage.

It is hoped that the above discussion has, to a degree, illustrated the interdependence between the large and the small scale structure and emphasized the importance which the small scale structure has for the interpretation of the large scale structural features. It was also attempted to elucidate the role played by bedding in specific situations and to point out that a fine balance, apparently, exists between the control over the jointing as exercised separately by the bedding and separately by the faults.

Furthermore, it becomes obvious that without a very detailed mapping of the small scale structure in specific and very limited areas, it would have been impossible to interpret satisfactorily the relationship between the large and the small scale structure.

SUMMARY AND CONCLUSIONS

A map showing the surface of the Danian limestone in the area of the Mønsted salt dome is presented.

A map of the large scale structure in the Danian limestone, as exposed in an underground mine at Mønsted, was prepared on an original scale of 1:100.

From the structural point of view, the flint layers in the limestone can be grouped into:

1) bedding flint, i. e. flint that has grown parallel to the bedding planes in limestone.

2) flint bodies of different sizes and shapes developed irregularly between layers of bedding flint.

3) fault flint, i. e. flint which has grown parallel to the walls of faults and is clearly younger than the bedding flint. The fault flint is frequently brecciated and slickensided proving that repeated movements along the same faults took place.

The attitude of the beds remains fairly uniform throughout the mapped area. They strike N-S and dip everywhere westwardly. On the average, the dips range between 15° and 25°, increasing somewhat in the northerly direction.

In an area limited by several faults slight folding around an E-W axis could be proved. It is thought that this folding was caused by lateral compression resulting from the down-faulting along one of the limiting faults.

No intense folding was detected in the mapped area.

It appears that none of the exposed structural features can be directly related to glacial tectonics.

The faults that strike in the general N-S direction are all antithetic to the bedding, i. e. they all dip eastward. Their dips range from very low (22°) to nearly vertical, but, in general, they are between 40° and 65°.

Nearly all faults show some direct evidence of normal faulting. Along one fault bedding flint could be correlated with certainty, and an apparent displacement of a maximum of 90 cm was measured. It is thought that this fault originated already during an early diagenetic phase of disturbance. Apparently, the movement along the same fault was reactivated due to the down-faulting along a younger fault for which the net slip was tentatively calculated to amount to about 12 m.

On the basis of the study of small scale structure the directions of movements along fault planes could be determined in two cases and they deviate 15° and 12° from the dip directions of the respective fault planes.

The faults studies proved to be of at least 3 different ages.

There exists a tendency in the limestone to fracture along more or less irregular surfaces perpendicular to the bedding. These fractures appear to be unrelated to the faulting and could be considered as *primary joints*.

Apart from this type of joints, there are found in large numbers, usually only in immediate vicinities of faults, joints which have very regular, often highly polished, surfaces. In the majority of cases they also contain some type of lineation. They are referred to as slip joints.

Almost 600 slip joints were measured. It was shown that the movements along them occurred predominantly parallel to the movements along faults. Depending on the attitude of the faults relative to the bedding, some slip joints develop symmetrically to the planes of the faults, while others form symmetrically to the bedding. Although the lsip joints are related to faulting and they represent structural planes along which the shearing in limestone took place during the process of faulting, the bedding has, to a greater or lesser degree, controlled their dictribution.

DANSK RESUMÉ

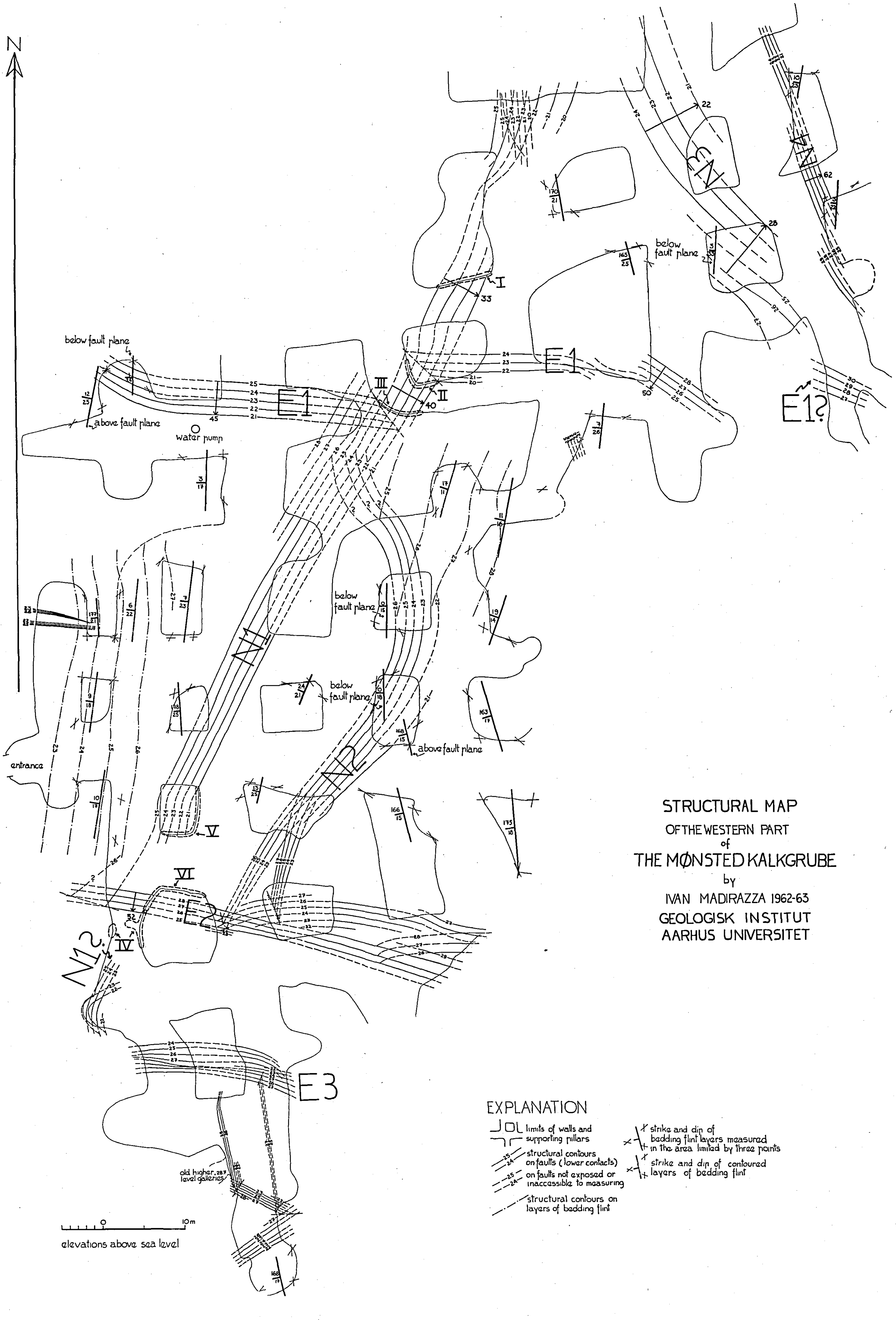
Fra november 1962 til december 1963 udførte forfatteren en strukturel kortlægning af den vestlige del af Mønsted Kalkgruber (tilhørende De Jyske Kalkværker A/S), som ligger i den nordlige del af en større saltdome-struktur (se fig. 1 og 2). Mineområdet, som opmåltes i 1:100, er vist på kortet i tavle 1, hvor danskekalkens lagstilling (strike and dip) er angivet, og hvor forkastningerne (E1, N1 o. s. v.) er indtegnet med deres strygningslinier (structural contours).

Fra et strukturelt synspunkt kan flinten i kalkstenen grupperes som følger:

1) *lagflint*, d. v. s. flint dannet parallelt med kalkstenens lagdeling.

2) flintlegemer, af forskellig størrelse og form, udviklet uregelmæssigt mellem lag af lagflint.

3) *forkastningsflint*, d. v. s. flint dannet i forkastningsplaner. Forkastningsflinten



STRUCTURAL MAP
OF THE WESTERN PART
of
THE MØNSTED KALKGRUBE
by
IVAN MADIRAZZA 1962-63
GEOLOGISK INSTITUT
AARHUS UNIVERSITET

EXPLANATION

limits of walls and supporting pillars

structural contours on faults (lower contacts)

on faults not exposed or inaccessible to measuring

structural contours on layers of bedding flint

strike and dip of bedding flint layers measured in the area limited by three points

strike and dip of contoured layers of bedding flint er klart yngre end lagflinten, og den er hyppigt breccieret og har udviklet harniskflader, hvilket viser, at gentagne bevægelser har fundet sted langs den samme forkastning.

Lagstillingen i det karterede område er ret ensartet, idet strygningen er ca. N-S, og hældningen overvejende varierer mellem 15° og 25° mod vest — tiltagende noget i den nordlige del af kortet.

Ingen intens foldning er konstateret i det karterede område; men i et område *begrænset af flere forkastninger er der påvist en svag foldning med en* V-dykkende akse. Denne lokale foldning forklares ved sideværts sammenpresning frembragt ved nedsænkning langs begrænsende forkastninger.

Ingen af de blottede strukturer synes at kunne sættes i direkte relation til glacial tektonik.

Forkastninger, der stryger N-S, er alle antithetiske, d. v. s. de hælder mod øst — modsat lagdelingen. Forkastningerne hælder fra 22° til næsten vertikalt, dog normalt mellem 40° og 65°.

Næsten alle forkastninger kan vises at være normale. Langs E1 forkastningen kan lagflinten korreleres og en maximal forskydning på 90 cm påvises. Denne forkastning tænkes opstået syndiagenetisk; men den blev senere genoplivet i forbindelse med dannelsen af en yngre forkastning (N1), som viser en total forskydning på ca. 12 m.

Baseret på studiet af detailstrukturer kan forskydningerne langs N1 og E2 vises at afvige henholdsvis 15° og 12° fra forkastningens hældningsretninger.

De kortlagte forkastninger er af mindst tre forskellige aldre.

I kalkstenen ses en tendens til brud langs mere eller mindre uregelmæssige planer vinkelret på lagdelingen. Disse brud synes at være uden relation til forkastningerne og kan muligvis betragtes som primære sprækker.

Bortset fra denne type sprækker findes der, som regel kun i umiddelbar nærhed af forkastningerne, meget regelmæssige sprækker, oftest velpolerede og i de fleste tilfælde med lineation. Disse sprækker kaldes her glidesprækker (slip joints).

Næsten 600 glidesprækker er blevet målt. Bevægelserne langs med disse var hovedsageligt parallelle med bevægelserne langs forkastningerne.

Glidesprækkerne står derfor i forbindelse med bevægelser langs forkastningerne og er dannet ved samtidig delbevægelse af kalkstenen; men kalkstenens lagdeling har dog i større eller mindre grad været bestemmende for glidesprækkernes fordeling og orientering.

REFERENCES

D.G.U.: Danmarks Geologiske Undersøgelse (Geological Survey of Denmark).

D.G.F.: Meddelelser fra Dansk Geologisk Forening (Bulletin of the Geological Society of Denmark).

ANDERSEN, S. A., 1944: Det danske Landskabs Historie, 2. Udgave, I Bind, p. 358–361.

BANKE RASMUSSEN, LEIF, 1960: Geology of North-Eastern Denmark (International Geological Congress, XXI Session, Guide-book II), p. 22–26.

— 1961: De Miocæne Formationer i Danmark, D.G.U., IV rk., Bd. 4, Nr. 5, 45 s.

BRONNIMANN, P., 1953: Note on planktonic Foraminifera from Danian localities of Jutland, Denmark, Eclog. Geol. Helvetiae, vol. 45 (1952), No. 2, p. 339–341.

GREGERSEN, ALBERT og SORGENFREI, THEODOR, 1951: Efterforskningsarbejdet i Danmarks dybere undergrund (Exploration of the subsurface geology of Denmark), D.G.F., bd. 12, hft. 1, s. 141–151.

GRUBE, F., 1955: Tektonische Untersuchungen in der Oberkreide von Lägerdorf (Holstein), Mitt. Geol. Staatsinst. Hamburg, Heft 24, S. 5–32.

LARSEN, GUNNAR, 1964: Saltaflejringer og salthorste i Danmark, specielt med henblik på Suldrup, D.G.F., Bd. 15, s. 420–425.

SORGENFREI, THEODOR og BERTHELSEN, OLE, 1954: Geologi og vandboring, D.G.U., III rk., Nr. 31, 106 s.

SWANSON, C. O., 1927: Notes on Stress, Strain and Joints, The Journal of Geology, vol. XXXV, No. 3, p. 193–223.

ØDUM, H., 1926: Studier over Daniet i Jylland og på Fyn, D.G.U., II rk., Nr. 45, 306 s.

— 1960: Saltefterforskninger i Danmark, D.G.U., III rk., Nr. 34, 43 s.