LOWER EOCENE TUFFS AT MØNSTED, NORTH JUTLAND

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A not earlier known exposure of altered volcanic ash beds of Lower Eocene age occurring in the area of the Mønsted salt dome, north Jutland, is described.

The Mønsted beds are correlated with a section of ash beds from the western Limfjorden (Fur) area, as measured by Bøggild (1918).

Based on the microscopic observations, nineteen chemical analyses, and the X-ray diffraction study (see the part of this paper by *Fregerslev, pp. 311–314), mineral composition of the tuffs, as well* as of the interbedded sediments, is given. Secondary changes which have affected the original mineral compositions of the beds are discussed.

The problem of the source area of ash, particularly in connection with the finding that almost all tuffs at Mønsted are thicker than the corresponding beds in western Limfjorden, is treated and possible reasons for this apparent inconsistency are given.

GEOLOGY OF THE LOWER EOCENE TUFFS AT MØNSTED, NORTH JUTLAND

IVAN MADIRAZZA

Introduction

The Lower Eocene volcanic ash beds of Denmark were described and discussed from different points of view by several authors, *e.g.:* Ussing, 1904, and unpublished notes; Bøggild, 1903, 1918; S. A. Andersen, 1937, 1938; Gry, 1935, 1940; Norin, 1940; J. L. Andersen, 1958; Bonde, 1966; Noe-Nygaard, 1967.

The most comprehensive work was done by Bøggild (1918) who, primarily from the mineralogical point of view, described the ash beds occurring in northern Jutland. In their type area of western Limfjorden these beds alternate with marine beds of diatomaceous earth ("Moler" in Danish, "ler" meaning clay). That author measured sections containing ash beds at a number of localities in that area (see figs. 1, 2), correlated them and gave numbers to the individual ash beds. Bøggild also conveniently divided the ash bed sequence into a lower, "negative" (from ÷ 39 to ÷ 1) part, and an upper, "positive" (from +1 to + 140) part, comprising 179 beds with a

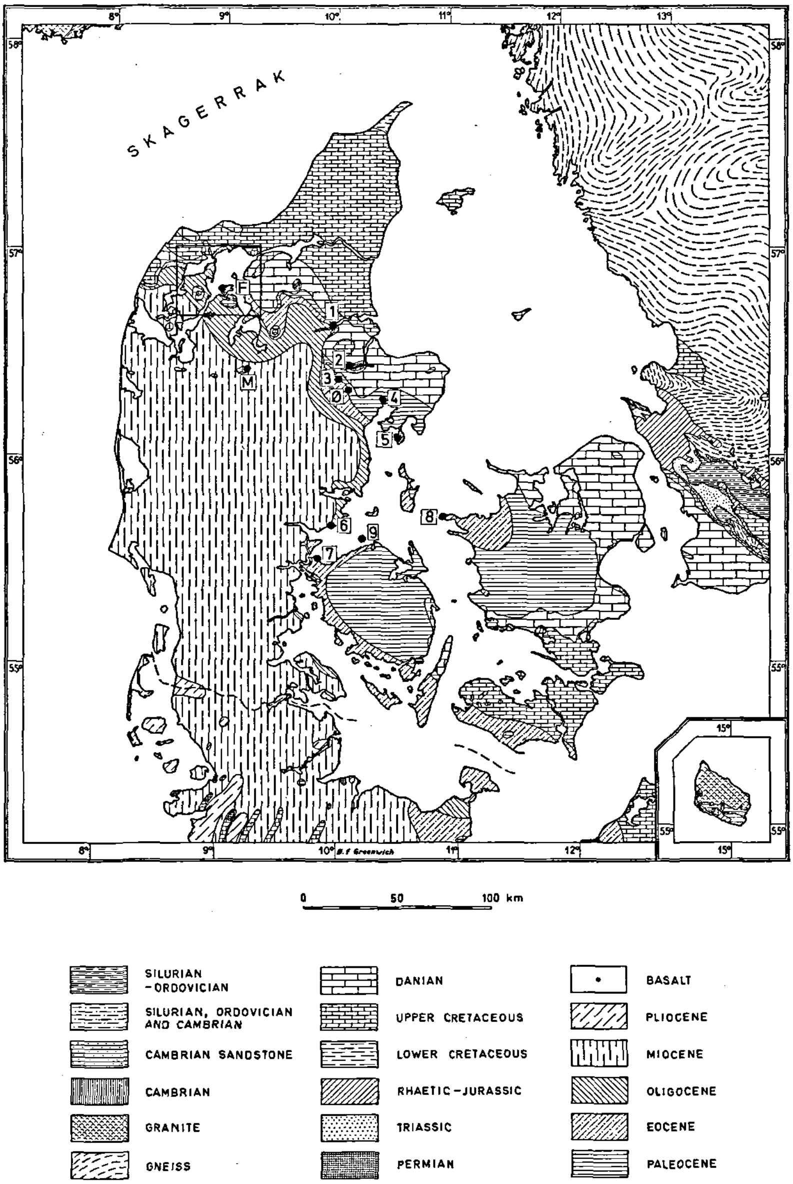

Fig. 1. Geological map of Denmark (below the Quaternary cover), after Th. Sorgenfrei, 1954. Heavy dots indicate exposures of the Lower Eocene tuffs (1. Skovbo, 2. Randers, 3. Haslum, 4. Ugelbølle, 5. Helgenæs, 6. Albækhoved, 7. Røgle Kl., 8. Røsnæs, 9. Æbelø; after S. A. Andersen, 1937, 1938). The tuff section at Mønsted (M) was correlated with a locality on Fur (F) and at Ølst (Ø). For a detailed map of the western Limfjorden localities (limited by the quadrangle) see fig. 2.

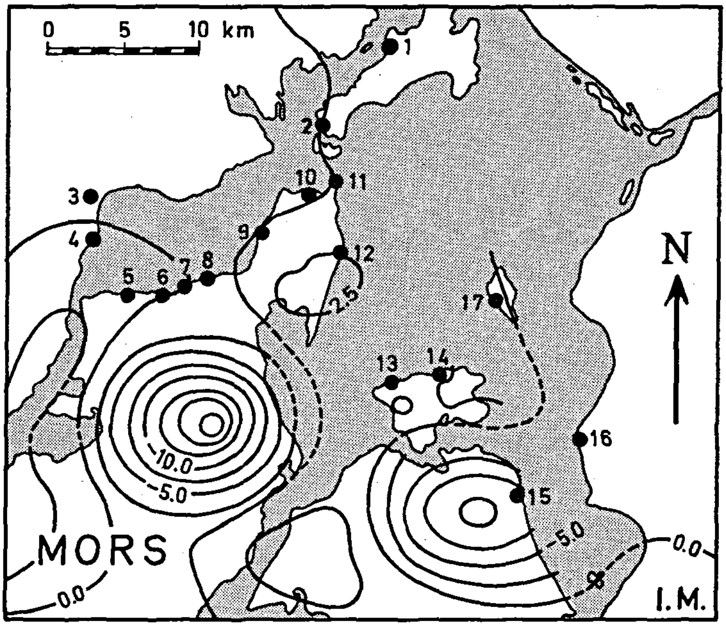

Fig. 2. Map of the western Limfjorden area showing the localities of the Lower Eocene volcanic ash beds, described by Bøggild, 1918 (1. Vesløs, 2. S. Arup, 3. Tilsted, 4. Silstrup, 5. Svalklit, 6. Gullerup, 7. Hanklit, 8. Salgjer Høj, 9. Skjærbæk Klint, 10. Skarrehøj, 11. Feggeklit, 12. Ejerslev, 13. Fur Knudeklint, 14. Fur Stolleklint and Østklint, 15. Junget, 16. Ærtebølle, 17. Livø). Residual gravity minima (after Sorgenfrei & Buch, 1964) indicate two diapiric salt domes: Nykøbing, on the island of Mors, and Batum on the Salling peninsula.

total thickness of about 4.3 metres. Apart from the beds numbered in this way, about 40 beds, usually very thin or only locally observed, were recorded. In the "negative" part the intervals between the volcanic beds were shown to be considerably greater than in the upper part of the sequence.

Already Bøggild (1918) pointed out that the volcanic beds at nearly all localities outside their type area were more or less strongly altered. Accordingly, the term "tuff" was applied to the beds of volcanic origin found outside their type area, and in the present paper this distinction will also be observed. Furthermore, while in western Limfjorden the sequence is dominated by the diatomite facies, in the rest of the Eocene belt the tuffs are interbedded with a clayey rock in which the shells of diatoms are encountered only occasionally. And, in general, these shells have also been attacked, presumably during the time the alteration of the volcanic beds was taking place, so that their original forms cannot be any more recognized.

In some cases the alteration of the ash beds was so intense that it might even be difficult in the field to recognize them as such, or to distinguish them from the interbedded sediments. Moreover, the thicknesses of the tuffs may vary appreciably from one locality to another, and this is also true, only to a much greater extent, of the alternating strata.

These conditions, together with the fact that a great majority of the volcanic beds measured by Bøggild (1918) in their type area, had basaltic or nearly basaltic compositions, made the correlation of the tuffs with the beds of that area difficult.

However, S. A. Andersen (1937) could successfully establish such correlations for a great majority of tuff beds occurring at several localities in eastern Jutland (see fig. 1) by reducing the intervals between the ash beds of western Limfjorden to ⅓. It was thus shown that the rate of sedimentation in that area was considerably faster than in the rest of the country where the equivalent rocks occur.

Field description

Location of the profile

As reported on an earlier occasion (Madirazza, 1966), during the mapping of the Mønsted salt dome area the present writer has encountered an exposure containing tuff beds which were not described earlier. The exposed

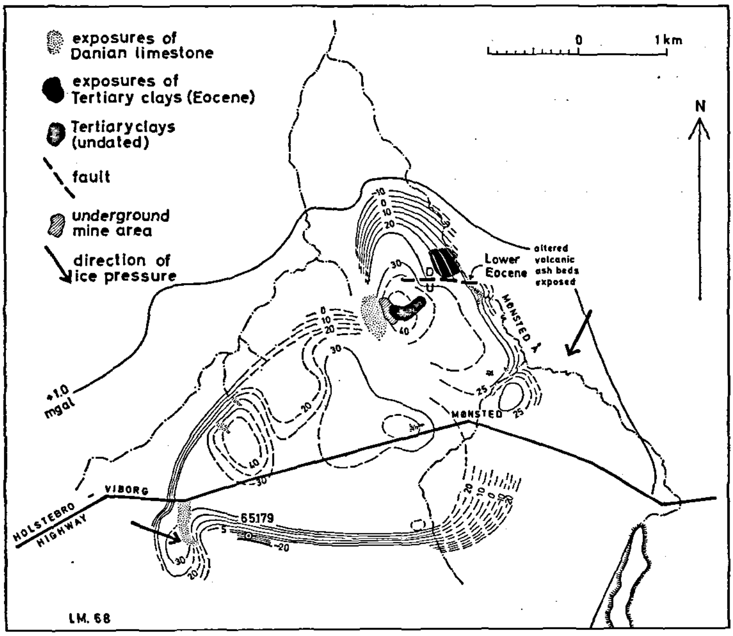

Fig. 3. Map of the Mønsted salt dome showing the surface of Danian limestone. Location of the profile containing the Lower Eocene tuffs is indicated. + 1.0 mgal contour limiting the dome after Bouguer residual anomalies by S. Saxov (personal information, 1967).

Fig. 4. Photograph showing the greater part of the section containing the Lower Eocene tuffs at Mønsted. The tip of the spade handle rests on the thick tuff bed No. 29 (+ 79). Length of handle: 0.5 m.

profile of the Lower Eocene rocks is located in the marginal, north-eastern part of the salt dome (see fig. 3). The profile, measuring about 2.3 metres, is found at the base of the eastern wall of the valley of Mønsted Å (Å = stream). This valley parallels closely the front of a Würm terminal moraine which borders the salt dome on that side.

In fig. 4 a photograph of the section taken in the southern part of the exposure is shown.

Of all the other known localities where tuffs occur, this locality is the closest to the type area of western Limfjorden (see fig. 1).

Types of beds

According to the lithology, color, type of bedding, and other field characteristics, the following types of beds can be distinguished in the profile:

a) Beds consisting of brittle, hard "clay", whose lower limits are nearly always very sharp and regular. Within their lower, or basal, parts they are usually somewhat coarser ("sandy") and they grade upwards into finer, clay-size particles.

These beds are generally strongly fractured, the fragments having uneven, curved surfaces and sharp edges. When cut with a knife, the material leaves a characteristically smooth and shiny surface. A number of beds of this type possesses also fractures which are oriented, and, as will be discussed in more detail later (see pp. 296–300), are joints whose origin may be traced to the tectonics of the salt structure itself.

The material making up these beds is always magnetic, as can be easily detected already by means of an ordinary field magnet. Magnetism is not evenly distributed, and some parts of the same bed can be more magnetic than others. It seems that, in general, the intensity of this property decreases upwards within a bed.

In the profile these beds are readily distinguished by their strong colors, mainly red, brown, and orange, or a blend of shades of these colors. The coloration, however, is only surficial, being due to a very thin coating of iron hydroxides along the fractures. The material itself is always of same shade of green, the most descriptive, perhaps, being the olive green shade.

On the basis of their field properties, especially the type of bedding, the nature of their boundaries, and relatively strong magnetism, these beds were classified as tuffs.

b) Alternating with the tuffs are clayey beds which are not hardened as the tuffs, and, in contrast to these, are usually finely laminated. This quality, especially when the material is dry, gives them a characteristic "shaly" appearance. The fine laminae can be either light yellow or light grey, the two colors frequently alternating. The overall color, however, is predominantly a greyish white.

The lower boundaries of this type of beds are less sharp than those of the tuffs, and may be gradational.

Also these beds are magnetic, although, in general, markedly less than the tuffs (in a few beds of this type this property was so weak that it could not be confirmed without the use of the magnetic separator).

c) Beds which according to their lithology and their colors are very similar to the tuffs, and always occur between two beds of that type. Any one of them is only about 1.0 centimeter thick. The materials is not so hard and compact as that making up the tuffs, and it crumbles easily into subspherical fragments which give the impression of being small concretions.

No lamination can be detected in this type of beds.

Although very thin, these beds are usually persistent and their thicknesses fairly constant within the exposure, but because of their small thicknesses and their similarity with the enclosing tuffs, they can easily be overlooked.

Also the beds of this type are magnetic. The intensity of this property is not so great as for the tuff material, although it is greater than for the beds described under b).

d) Several thin layers of compact, soft, greasy, green clay are also present in the exposed profile, nearly all of them occurring in its uppermost part. These clays are mainly associated with the beds described under b).

One or two layers in the exposure could not be assigned to either of the described types.

None of the beds in the profile are calcareous, and no macrofossils were encountered in them. No foraminifera were observed in any of the types of beds described. In the b) type, however, forms of mainly round, triangular or oval, clearly tridimensional shapes are occasionally found. It can hardly be doubted that these forms have an organic origin, and that they most likely represent shells of diatoms which have been coated with siliceous material.

Measured section

Based on the above division, the profile measured at Mønsted is shown in fig. 5, middle column. As indicated along the left side of the column, the beds were numbered consecutively starting with No. 1 from the bottom. The lowermost bed, which is a tuff, was dug out at a later date and carries no number. In some instances (*e.g.* No. 44) the measured units consist of several layers, but the field differences were not deemed sufficiently great to consider each layer as a separate unit.

In those cases where the thicknesses of beds vary appreciably the maximum values were consistently plotted in the column of fig. 5.

In the following the thicknesses of the beds, their types, and possible other distinguishing features, are given:

Lowermost bed: ca. 12.0 cm; tuff
1) 4.5–5.0 cm; b) type; very clearly laminated; within the basal part oval inclusions (about 1.0 cm long) of greenish clay, arranged parallel to the bedding (possibly material from the underlying tuff?), can be found
2) 4.0 cm; tuff; lowermost few mm very distinctly coarser, darker, and more magnetic than the rest of the bed
3) 2.0–2.5 cm; b) type
4) 3.5–4.0 cm; tuff
5) 3.0–3.5 cm; b) type; relatively strongly magnetic for this type of bed
6) 2.0 cm; tuff; thin but distinct bed; very distinctly coarser within the lower half, which is orange colored, while the rest of the bed is of the more usual reddish brown color
7) ca. 3.0 cm; b) type; slightly greenish in the upper part; both boundaries, especially the lower one, poorly defined
8) 6.5–7.0 cm; approximately the lower half of this unit is of the tuff type material, the rest mainly of the b) type material; the boundary between the two types is irregular, and tuff material reaches in places to the top of the unit
9) 1.5 cm; tuff
10) 3.5 cm; predominantly of the b) type, but tuff material may also be present
11) 3.0 cm; tuff
12) ca. 1.5 cm; b) type
13) 4.5 cm; tuff; very regular and uniformly thick bed; lowermost 7 to 8 mm very distinctly coarser
14) 1.5 cm; b) type; lamination not well developed (as in other beds of this type)

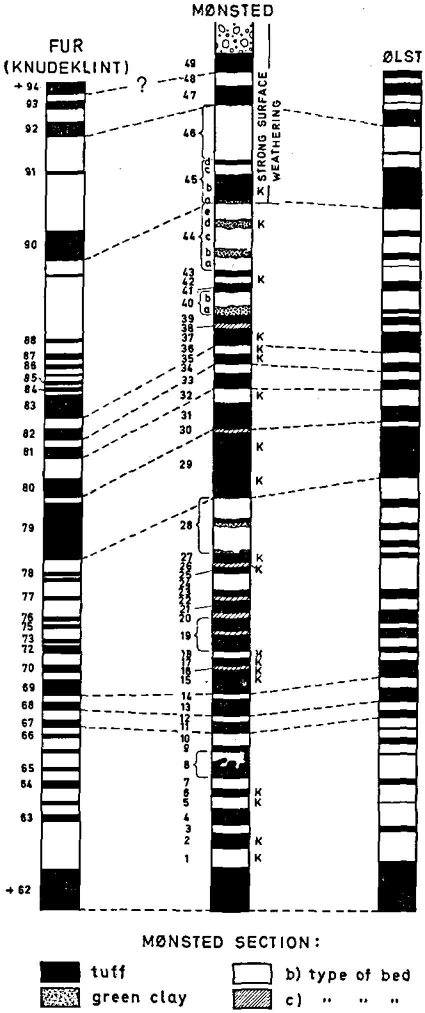

Fig. 5. Section of the Lower Eocene rocks measured at Mønsted shown with the relevant parts of the sections from Knudeklint (Fur), measured by Bøggild (1918), and from Ølst, measured by S. A. Andersen (1937). Scale 1 : 10, with the exception of the intervals between the ash beds from Fur, which are here reduced to ⅓. Letter »K« denotes beds on which chemical analyses were made.
For location of the three sections see fig. 1.

15) 6.5 cm; tuff; very strongly iron-stained; healed fractures
16) 1.0 cm; c) type
17) 2.0 cm; tuff; although thin, very regular and uniformly thick bed; very clearly coarser at base
18) 1.8–2.0 cm; b) type; very well developed lamination
19) 8.0–9.0 cm; unit consists of 3 beds: lower 4.5 cm is a tuff, then ca.

1.0 cm a c) type of bed, and again a tuff 3.0–3.5 cm thick. The c) type of bed not uniformly thick and may be discontinuous

20) 1.3–1.5 cm; c) type; well defined bed
21) 3.0 cm; tuff
22) ca. 1.0 cm; c) type; irregularly thick
23) ca. 1.5 cm; tuff; lowermost 1 to 2 mm distinctly coarser
24) 4.5–5.0 cm; b) type; very well developed lamination; relatively strongly magnetic for this type of beds
25) 1.6 cm; tuff; very distinctly coarser in the lower part
26) 1.2 cm; c) type
27) 2.5–3.0 cm; tuff
28) unit consists of:
lower about 8.0 cm of impure clay of grey to black color which contains 1.0 to 1.5 cm thick, irregular band of green clay at top and also ca. 1.0 cm thick discontinuous green clay at base
upper about 6.5 cm of clay, yellow to light brown, not laminated, which at base contains about 1.5 cm thick black band whose lower limit to green clay is very sharp
This entire unit is inhomogeneous and of variable thickness
29) average thickness 17.5 cm, but varies from 17.0 to 18.0 cm; tuff; lower part of the bed generally coarser, but no distinctly coarser layer at bottom (as in most beds of this type); lower part more magnetic than the upper; numerous irregular fractures and joints; healed fractures
30) ca. 1.0 cm, max. 1.5 cm; c) type; inhomogeneous, contains some soft clay and also some white material of the b) type; both boundaries fairly good
31) ca. 7.0 cm; tuff; very clearly coarser at base; healed fractures
32) ca. 4.0 cm; b) type; lamination very distinct ("shaly"); some greenish laminae between light yellow ones; unit relatively strongly magnetic for this type of beds
33) 4.0 cm; tuff; very thin coarser band at bottom; healed fractures
34) 2.5 cm; b) type; similar to No. 32
35) ca. 2.5 cm; tuff; healed fractures, seemingly displaced along others
36) ca. 2.5 cm; b) type; similar to No. 32
37) 4.5 cm; tuff; very uniform bed; very sharp lower boundary; very distinctly coarser at base (of all tuff beds in the section this feature is best developed in this bed); numerous joints
38) 1.2 cm; c) type
39) 2.0 cm; tuff; jointed
40) unit, 6.0–6.5 cm thick, consists of:
a) light green, compact, greasy, soft clay, in angular fragments mainly 2.0 to 3.0 cm large; lower boundary gradational, upper one sharp but uneven
b) upper part of the unit is of the b) type material; irregular, very thin, black line through about the middle of this part.
The entire unit, especially the upper part, is inhomogeneous; relatively strongly magnetic
41) ca. 2.0 cm (max. 2.5 cm); tuff; usually directly below it a very thin (1 to 2 mm) band of green clay whose upper boundary to the tuff is very sharp; a very thin band of similar green clay in places also tops the tuff bed. This bed is softer and of a lighter green color than tuffs in general, and may laterally grade into green clay similar to 40 a)
42) ca. 2.0 cm; b) type; distinctly and very regularly laminated (a "clean" bed); quite weakly magnetic
43) 1.5 cm; tuff
44) unit, ca. 18.0 cm (max. 20.0 cm) thick, consists of:
a) 3.5–4.0 cm; b) type; not pure, contains lumps of green clay as the overlying

b) 2.0–2.5 cm; green clay, greasy, compact, not hardened
c) ca. 5.5 cm; b) type
d) 2.0–2.5 cm; as 44 b)
e) ca. 4.0 cm; b) type
45) unit, ca. 10.5 cm thick, consists of:
a) ca. 1.0 cm; dark green clay, very sharp upper limit; strongly magnetic
b) 6.0–7.0 cm; tuff; very distinctly coarser at bottom
c) max. 2.0 cm; reddish clay, laminated
d) ca. 1.0 cm; reddish clay, nodular. This layer is most probably a strongly weathered tuff
46) ca. 15.0 cm; b) type; well developed lamination, especially in the lower third of the bed
47) ca. 5.0 cm; tuff
48) 3.0–3.5 cm; b) type
49) ca. 5.0 cm; tuff

The profile of the Lower Eocene beds is topped by the Quaternary material which is maximum 1.0 m thick at the southern end of the exposure. This material is made up of sand and gravel (with cobbles of up to 10 cm in size), and is generally poorly sorted and oriented. It is thought that, at least in part, this cover is solifluction material.

Mineral compositions of the different types of beds

On the basis of their field properties, such as very sharp lower boundaries, graded bedding, and relatively strong magnetism it could be concluded already in the early stages of this investigation that the beds described under a) were more or less strongly altered beds of volcanic ash.

Four thin sections of the tuff material were prepared. Only in one of these the grain sizes showed to be sufficiently large for a suitable microscopic investigation. The components of the section can be divided into:

1) Clearly crystalline grains. These make up less than 1 % of the section. Only plagioclase could be identified with certainty. While a part of plagioclase grains is fresh, they can also be found in different stages of alteration. Some of them are only partly altered, others may be completely "sericitized", so that only relict grains can be discerned. Nearly all plagioclase crystals show well developed albite twins. In composition they vary from about An_{45} to An_{63} (andesine to labradorite).

2) Vitric material, and material found in different stages of devitrification. Isotropic or only very faintly birefringent material consists predominantly of clear, colorless fragments. Light brown to reddish brown fragments usually show cryptocrystalline structure and appear to be the original vitric material which can be encountered in all stages of devitrification. It seems that the intensity of the coloration of a grain increases in step with the degree of devitrification.

Many fragments have lighter, thin rims along their original boundaries and, similarly, very fine lighter lines can be seen inside the individual grains.

The shape of the fragments can be very different: angular, circular, elongate, and a large number of them have irregular shapes ("shards").

3) Opaque material. This material is of dark brown to black color (it is possible, however, that the dark brown grains are only an extreme case of alteration of the vitric material in which the color masks other optical properties). The black opaque material is found as individual grains, very finely divided, or in patches among other grains.

Furthermore, spherulitic grains can be seen in the thin section. They can be of two types: spherulites consisting of radiating, very finely divided material of high birefringence, which have very sharp boundaries. This type sometimes occurs inside a larger, irregular grain which is seemingly made up of the same type of material. This type of spherulites are possibly feldspars (plagioclase?) altered to micaceous material.

Another type of spherulites consists of low to moderately birefringent material with clear extinction crosses. Their boundaries are more diffuse than in the first type. This type of spherulites is probably made up of zeolitic material.

No lamination or orientation of the grains can be detected in the thin section.

At this point it should be mentioned that the coarsest fractions of the tuff material in nearly all beds have yielded, apart from plagioclase, a few light green augite grains. These very often show signs of strong intrastratal solution (see Pettijohn, 1957, p. 675). Plagioclase is always found in considerably larger quantities than augite. But, with the exceptions of two beds in which plagioclase reflexes appear, neither of these two minerals is in the bulk samples found in large enough proportions to be registered by the X-ray diffractometer (see the part of this paper by Fregerslev, pp. 311–314). No amphiboles were observed either microscopically or by means of the X-ray diffractometer in the tuff beds.

Frequently (*e.g.* in the beds Nos 4, 6, 17) plagioclase grains contain one or several clear, long, rod-like inclusions, which are "broken up" into several segments. Their refraction is somewhat higher than that of the plagioclase. These inclusions are most likely apatite, segmented parallel to {0001} cleavage (according to the chemical analyses, see pp. 301–306, very small amounts of apatite are theoretically possible in all types of Mønsted beds).

Occasionally quartz was also identified microscopically in some tuff beds. The quartz grains may be of different shapes: rounded to subrounded, oval, angular, but also quite irregularly shaped. In no tuff bed is enough quartz found to be identified by the X-ray diffractometer.

As for the beds described under b), the nature of their boundaries, the type of bedding, an their general appearance indicate that they were water-laid and that their mode of deposition was "normal" as compared to the wind transported and quickly sedimented volcanic ash material. Since their thicknesses are relatively small (in the majority of cases smaller than those of the tuff beds with which they are in contact), it can be expected that they were contaminated by smaller or greater amounts of the volcanic material originating from the enclosing tuffs. Probably, the thinner a bed of this type is, the proportionally greater amount of the volcanic material admixed it might contain.

The coarsest fractions of this type of beds are more monotonous under the microscope, and, apart from a few quartz grains, plagioclase crystals are occasionally present.

Both in the tuffs and the beds described under b) a zeolitic mineral was identified microscopically. In the latter type the zeolite heulandite could be registered in nearly all beds by the X-ray diffractometer method, while only in a few tuffs heulandite was detected by this method. Characteristically, in all beds of the b) type also quartz was registered by the X-ray diffractometer.

The very thin beds described under c) presented the greatest difficulty in deciding on their origin, and, consequently, also in establishing a correlation of the Mønsted section with the previously known sections of volcanic beds. While, as mentioned, the c) type of beds in several aspects closely resemble the tuffs which enclose them, they are not so hard as the tuffs, and they seemingly lack graded bedding exhibited by the wind-borne material. On the other hand they also lack some important features, such as lamination, found in the b) type of beds, and, consistently, they are all very thin.

The fact that in the exposed section these beds are always found enclosed between two thicker beds which can unquestionably be classified as tuffs, permits us to consider them, just as the b) type of beds, equivalent to the much thicker beds of the diatomite facies of the Limfjorden area. The results of the chemical analyses made on all types of beds in the profile, together with the X-ray diffractometer study, indicate that this is the correct interpretation. Because of their very small thicknesses, it can be expected that they, just as the b) type of beds only to a much larger extent, contain volcanic material admixed.

The clay mineral present in all types of beds is montmorillonite. Furthermore, anatase, TiO_2, and maghemite, γ Fe_2O_3 (also called magnetic hematite), are the two minerals registered by the X-ray diffractometer in all types of beds and in nearly all samples examined by that method.

The coarsest grain size in both the tuffs and the b) type of beds is somewhat less than ca. 0.6 mm. The fraction between ca. 0.6 and 0.2 mm constitutes only a small part of 1 %. In the b) type about 80 %, or more, is made up of particles smaller than ca. 0.04 mm, while in the tuffs the grain size seems to be in general somewhat coarser, and the fractions between ca. 0.06 and 0.04 mm, and less than ca. 0.04 mm, together make up about 80 %.

Correlation

In trying to establish a correlation based on the thicknesses of beds of this type, thick beds and their relative positions within the section are of primary importance. In the case of the Mønsted profile this would, in the first place, be the bed No. 29 which is the thickest tuff having an average thickness of 17.5 cm.

Of all the known Lower Eocene ash beds only three are comparable in thickness to that tuff bed at Mønsted. The thickest ash bed in western Limfjorden is + 19 measuring from 15.0 cm to a maximum of 19.0 cm at one locality. Another bed, + 118, attains the same maximum thickness at one locality, but generally it is considerably thinner, that is between 13.0 and 16.0 cm. And, finally, the bed + 79 which at one Limfjorden locality has a thickness of 16.0 cm, but, most commonly, it measures 15.0 cm.

Of these three possibilites the Mønsted section compares favorably only with the relevant part of the section containing the bed + 79. As for + 19, it can also be pointed out that this bed was by Bøggild (1918), on the basis of a mineralogical investigation and of a chemical analysis, classified as one of the few beds in the entire sequence having an acid (andesitic) composition. Thus + 19 can be eliminated also for this reason, since, according to the present study which includes two chemical analyses of the tuff No. 29 at Mønsted, this bed must be regarded as having been originally basaltic in composition.

In western Limfjorden a short distance below the bed + 118 another relatively thick bed, *i.e.* + 114, which on the average is only slightly thinner than + 118, occurs. In the Mønsted profile, however, no other tuff has a thickness comparable to that of No. 29. This would again eliminate the bed + 118 (and, at the same time, + 114).

In fig. 5 the section measured at Mønsted is shown compared to the relevant part of the section of ash beds containing the bed + 79, as measured by Bøggild (1918) at Knudeklint on the island of Fur, some 45 km NNW of the Mønsted locality. To make the comparison easier the intervals between the ash beds on Fur were here reduced to ⅓.

The rythmograms of the shown sections from Fur and from Mønsted were prepared (see fig. 6). In them the volcanic beds are represented by the heavy solid lines and the intervals between them by the stippled lines. In the Mønsted section both b) and c) types of beds are represented by the stippled line. The units No. 28, No. 40, and the unit No. 44 which includes b) type of beds and two layers of green clay, were all plotted as units. It should be pointed out that, contrary to the Fur section of fig. 5, in the rythmogram from Fur also the true thicknesses of the beds alternating with the ash beds are shown, so that a direct comparison of the volcanic beds as well as the alternating beds becomes possible.

There is a great similarity between the two diagrams, and all the major peaks in the line representing the volcanic beds from Fur are clearly recognizable in the Mønsted diagram. In nearly all cases, however, the tuffs at Mønsted are thicker than the corresponding beds on Fur.

The sediments which alternate with the volcanic beds can also be equated, except that these, as already stated, are considerably thicker on Fur than at Mønsted.

In fig. 5 the Mønsted section is also compared to the relevant part of the sequence containing the bed + 79 from a locality at Ølst, as correlated with the Limfjorden localities by S. A. Andersen (1937). That locality is one of the closest to the Mønsted exposure where tuffs are encountered

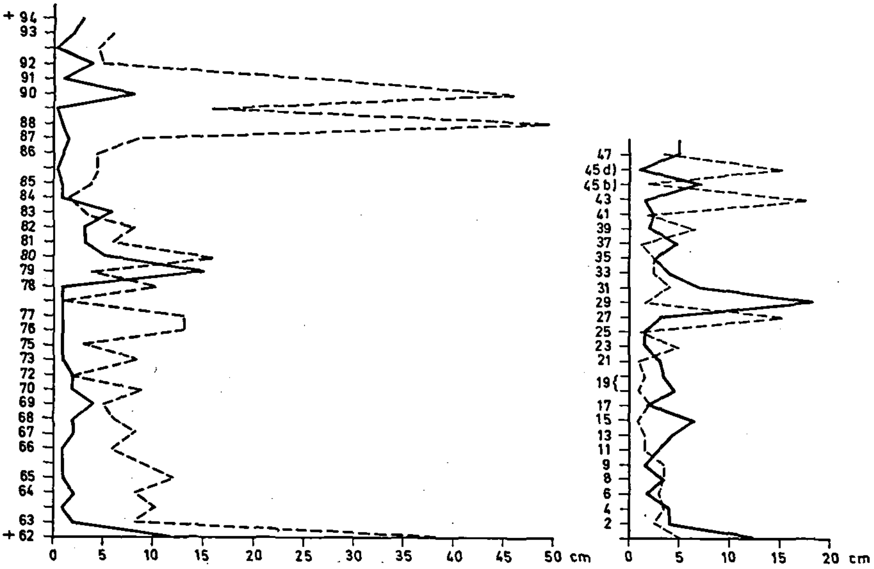

Fig. 6. Rythmograms of the sections from Knudeklint (Fur) and from Mønsted, shown in fig. 5.

(see fig. 1). Also this part resembles closely the Mønsted section, especially from, and including, the bed + 79 upwards.

Furthermore, it can be mentioned that the bed + 90 is one of the few so-called "double layers", *i.e.* it consists of two distinct ash beds directly overlying each other. Its basal layer is always very thin having on Fur a maximum thickness of 1.5 cm. The bed No. 45 b at Mønsted, which corresponds to + 90 from Fur, also rests on a layer of clay (No. 45 a) about 1.0 cm thick, which can thus very well represent the basal layer of + 90.

On the basis of the above considerations it may be concluded that the tuffs at Mønsted correspond to the volcanic ash beds from + 62 to + 93 (or possibly + 94) and thus belong to the upper part of the "positive" part of the sequence of Lower Eocene ash beds. In fig. 5 only in the most obvious cases the lines joining the corresponding beds at the three localities were drawn.

Structural considerations

Structural setting

As previously mentioned, a terminal moraine follows closely the north-eastern margin of the Mønsted salt dome. The exposure of the Lower Eocene beds is encountered at the very base of the eastern wall of the valley of Mønsted Å, and on the downthrown (north) side of a major E-W trending fault – or a fault zone (see fig. 3). The existence of this fault was deduced from the map of the limestone surface and the relationship between the Lower Eocene and the Upper Cretaceous rocks, which are here found exposed at the same level and only maximum some 30 m apart. The results of a magnetic survey performed in this area showed to be compatible with this conclusion based on geological information (Madirazza, 1968).

Boring

A boring was drilled at the foot of the exposure of the Lower Eocene beds. The drilling was done with a mobile rig and the samples were recovered from the drilling fluid. The main objective of the boring was to supply the information on the depth to the limestone surface at this point.

The first, approximately two, metres of the strata penetrated in the boring are a continuation of the same type of volcanic beds as in the exposed section, most likely in alternation with the type of beds described under b) (see p. 288). At about that depth bluish to light green, non-calcareous, mainly magnetic clays appear, which, essentially, make up the rest of the strata above the limestone. The limestone surface was reached at a depth of 9.5 m. The age of the limestone was determined as Danian by E. Stenestad on the basis of the foraminiferal fauna (personal information).

Faults and joints

The exposure of the Lower Eocene beds, which is about 50 m long, is more or less parallel to the strike of the beds, so that most beds can be traced throughout the length of the exposure. The strike of the beds varies little, the average value being about 160°, and they have moderate, most commonly 18°–20°, eastwardly dips. At several places, however, more northerly strikes (up to 0°) were measured.

There are no indications that these rocks form part of a larger, more complex fold(s) of the type exhibited by the ash beds in western Limfjorden, which were there produced by the ice pressure during the Pleistocene. No major faults within the exposure limits were observed, although minor, steep normal faults, along which the displacements are on the order of a few centimetres, cut the beds at several places. The strikes of such faults are quite constant vertically, but the dip of a same fault may vary considerably, depending on the type and the thickness of the bed it dissects at a particular level. For instance, at a place where a number of joints was measured (see below), a normal fault having a displacement of maximum 10 cm occurs. Its attitude within some beds is as follows:

No. 35 – 77°/52° NW
No. 29 – 67°/64° NW
No. 26 – 77°/35° NW
No. 19 – 72°/53° NW

The individual beds show well developed jointing. Particularly the tuffs, due to the quality of the material itself, exhibit a large number of easily measurable joints.

The joint pattern in the profile is very similar both in the horizontal and in the vertical sense. Essentially, two sets of joints striking more or less at right angles are present: a stronger set striking from NNE to NE which shows several maxima, and a set striking from ESE to SE which is usually more restricted (see figs. 7, 8, 9). A great majority of the joint planes are approximately perpendicular to the bedding.

At a place where 100 joints were measured (within a horizontal distance of about 1 m) in the thickest tuff bed No. 29 (+ 79), another set striking N-S and dipping east, that is in the same sense as the bedding, is developed

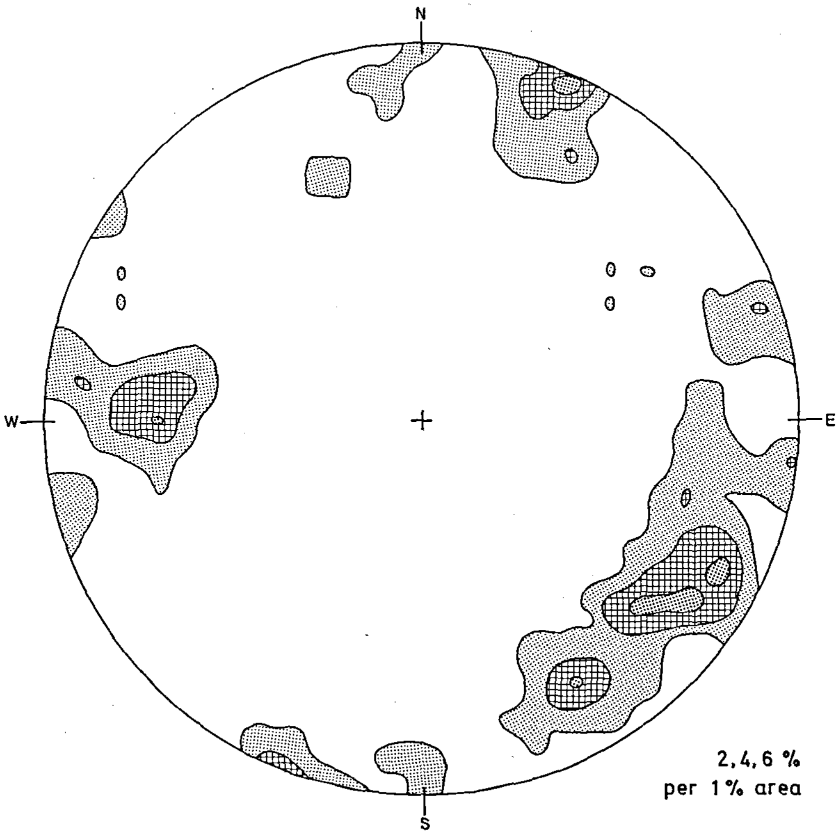

Fig. 7. Contoured poles to 100 joints (lower hemisphere) in the tuff bed No. 29 (+ 79) measured within a horizontal distance of ca. 1 m. Attitude of the bed: 165°/18° E.

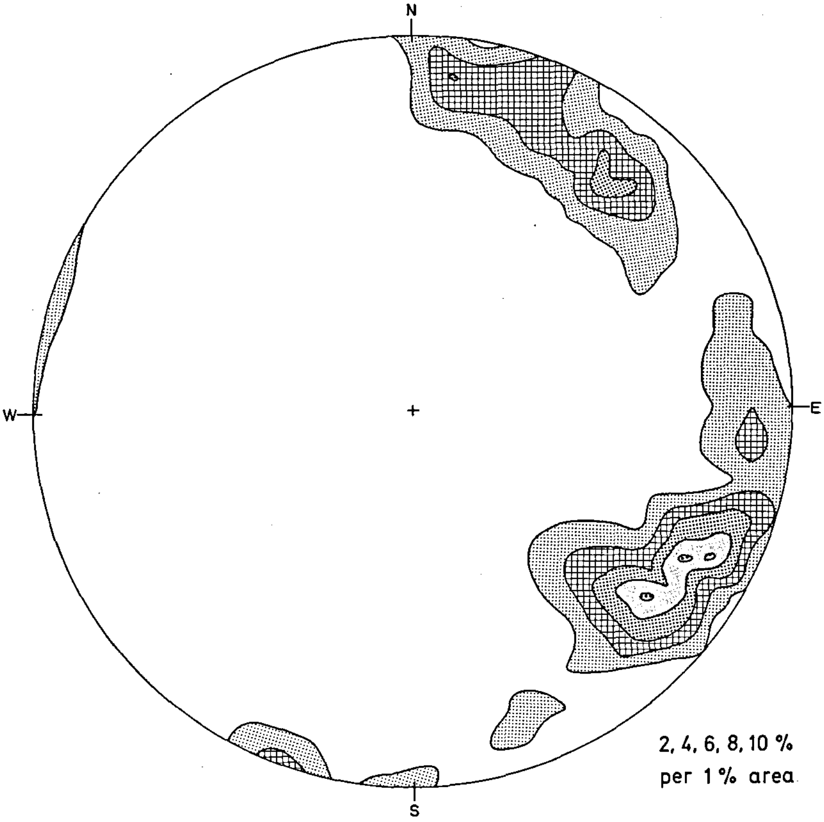

Fig. 8. Contoured poles to 100 joints (lower hemisphere) in the tuff bed No. 37 (+ 83) measured above the place where measurements shown in fig. 7 were taken. Attitude of the bed: 157°/18° E.

(fig. 7). This set is not generally present. For instance, in the bed No. 37 (+ 83), which is only some 25 cm above No. 29, directly above that same place this set was not encountered (fig. 8). And some 10 m north of that place this set is also lacking in the very same bed No. 29 (fig. 9). Some purely local conditions, then, must have produced this N-S striking and east dipping set.

From the joint pattern it appears unlikely that the jointing was produced by the ice pressure which in this area of the salt dome originated from a northeasterly direction (fig. 3). Similarly, from the attitudes of the beds it does not appear that the ice pressure was responsible for the tilting of the beds. And, finally, the discussed type of minor faults cannot normally be ascribed to glacial tectonics.

It is more probable that the causes of disturbance ought to be looked for in the tectonics of the salt structure itself, particularly since it appears certain that the strata penetrated in the mentioned boring represent a sequence of Lower Tertiary rocks occurring *in situ*. Moderate dips of the exposed beds away from the salt structure and their position on its flank, together with their proximity to a major fault, lend support to this view. There can be no doubt that the Lower Eocene strata, just as the Upper Cretaceous limestone, which form an inlier within a region of Miocene rocks (see fig. 1), are found in their present position due to the uplift of the underlying salt body.

Further investigation, combined with one or two additional borings with "undisturbed" sampling in the area of the exposure, would enable us to reconstruct more fully the tectonic events in this part of the salt structure.

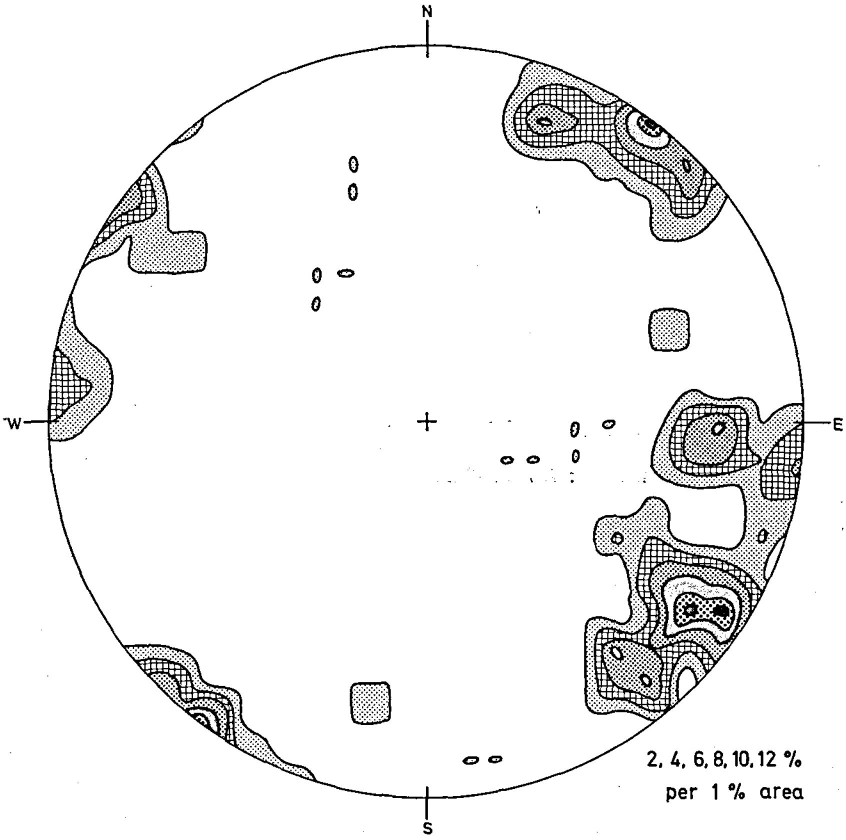

Fig. 9. Contoured poles to 50 joints (lower hemisphere) in the tuff bed No. 29 (+ 79) measured within a horizontal distance of 1 m, ca. 10 m north of the place of figs. 7 and 8. Attitude of the bed: 0°/15° E.

Chemical analyses

Earlier data

Chemical compositions of only a few volcanic ash beds from Denmark were known earlier. Complete chemical analyses of three beds (÷ 17, ÷ 12, + 19) were published by Bøggild (1918). They were all done on samples from western Limfjorden, that is on the unaltered or relatively little altered volcanic ash material. Later, Norin (1940) presented several chemical analyses of the bed + 101, together with a few additional analyses of the beds ÷ 12 and + 19 from the Limfjorden area, and also of the samples of the altered volcanic ash material from several localities in eastern Jutland where these same beds occur.

Choice of beds for analyses

In the selection of beds for the chemical analyses an attempt was made to cover the entire section as good as reasonably possible and, at the same time, to secure the analyses of several beds of each type represented in the section, but including also the most characteristic beds. Thus, ten tuffs were chosen, including the thickest bed No. 29 (+ 79) and the bed No. 37 (+ 83), six beds of the b) type, and two beds of the c) type. Also, one layer of greasy, green clay was analysed. Furthermore, in one instance, the analyses were made on four consecutive beds (from No. 15 to No. 18) representing the tuffs and the beds of the b) and c) types (consult fig. 5).

Due to the unusually great thickness of the bed No. 29 (+ 79) chemical analyses on two samples from this bed were made: one from its lower part (No. 29_1), and one from its upper part (No. 29_2). The differences in the chemical compositions of the two parts of this bed were shown to be only slight (similarly, the X-ray diffractometer study did not detect any difference in the mineral composition of the two parts of this bed).

A total of nineteen chemical analyses was made. They were made under the supervision of Sveinung Bergstøl, Geological Museum, University of Oslo. The determination of SiO_2, Al_2O_3, TiO_2, Fe_2O_3 (total), CaO and P_2O_5 was done by the X-ray fluorescence method (PW 1540 spectrometer), of MgO by the atomic absorption method (Beckmann spectrometer), of Na_2O and K_2O by the flame photometer, and FeO was determined titrimetrically. The results are presented in table 1, and in table 2 these are shown recalculated on the waterfree basis (see pp. 302–303).

Discussion

A fleeting inspection of the results of the analyses of the Mønsted beds seems to justify fully the distinction made in the field as to the different types of beds being present in the exposed section. The compositions of the different types, particularly of the tuffs and the c) type of beds, remain quite constant.

As recalculated on the waterfree basis, the SiO_2 content of the tuffs

Table 1.

weight %	No. 1 b)	No. 2 tuff	No. 5 b)	No. 6 tuff	No. 15 tuff	No. 16 c)	No. 17 tuff	No. 18 b)	No. 26 c)	No. 27 tuff	No. 29$_1$ tuff	No. 29$_2$	No. 32 b)	No. 35 tuff	No. 36 b)	No. 37 tuff	No. 42 b)	No. 44d green clay	No. 45b tuff
SiO_2	51.33	43.28	50.08	44.13	44.10	46.70	43.15	53.10	46.68	44.10	46.18	46.40	50.70	45.05	48.90	43.68	50.50	52.40	45.55
TiO_2	3.59	4.03	3.45	4.44	3.62	2.46	4.19	2.26	2.53	3.64	3.55	3.26	3.27	3.89	3.52	4.06	3.15	2.63	4.08
Al_2O_3	15.38	12.07	14.98	12.03	11.74	11.25	11.95	14.63	12.25	12.29	13.05	11.98	15.18	12.78	15.79	13.40	15.83	13.88	13.20
Fe_2O_3	10.75	18.04	12.63	17.08	16.81	15.75	16.79	9.97	15.49	15.99	16.30	16.61	11.61	17.70	12.21	17.37	11.43	14.28	16.56
FeO	0.32	0.35	0.36	0.20	0.47	0.45	0.53	0.21	0.27	0.31	0.34	0.30	0.32	0.34	0.34	0.44	0.40	0.38	0.34
MgO	3.55	6.75	5.33	7.12	6.23	7.32	6.73	4.11	6.72	6.39	6.42	6.30	6.58	4.02	4.35	6.38	4.05	3.71	6.08
CaO	1.28	1.50	1.34	1.47	1.50	1.41	1.44	1.31	1.26	1.37	1.40	1.46	0.83	1.05	0.82	0.95	0.72	0.49	0.69
Na_2O	0.24	0.11	0.16	0.11	0.11	0.13	0.09	0.24	0.08	0.07	0.07	0.07	0.13	0.06	0.12	0.06	0.14	0.09	0.06
K_2O	1.64	0.16	1.05	0.21	0.20	0.49	0.14	1.65	0.66	0.15	0.11	0.27	1.77	0.15	1.11	0.12	1.39	2.94	0.21
P_2O_5	0.14	0.15	0.12	0.12	0.20	0.13	0.13	0.11	0.11	0.14	0.13	0.19	0.11	0.11	0.12	0.13	0.09	0.07	0.08
H_2O^+	7.26	6.37	7.38	6.96	6.10	6.50	6.46	7.09	6.87	6.61	6.53	6.47	7.17	6.47	8.03	7.57	7.71	6.88	6.23
H_2O^-	5.29	9.13	4.07	7.04	10.17	8.80	9.24	5.25	8.48	7.55	6.07	6.70	3.79	6.24	5.60	5.07	4.60	2.91	5.33
	100.77	101.94	100.95	100.91	101.25	101.39	100.84	99.93	101.40	98.61	100.15	100.01	101.46	97.86	100.91	99.23	100.01	100.66	98.41

Analyst: S. Bergstøl.

Chemical analyses of ten tuff beds, six beds of the b) type, two beds of the c) type, and one bed of green clay from the Mønsted profile (consult fig. 5). In table 2 the analyses are shown recalculated on waterfree basis to 100 per cent.

Table 2.

	No. 1 b)	No. 2 tuff	No. 5 b)	No. 6 tuff	No. 15 tuff	No. 16 c)	No. 17 tuff	No. 18 b)	No. 26 c)	No. 27 tuff	No. 29_1 tuff	No. 29_2	No. 32 b)	No. 35 tuff	No. 36 b)	No. 37 tuff	No. 42 b)	No. 44d green clay	No. 45b tuff
SiO_2	58.20	50.07	55.96	50.78	51.89	54.24	50.68	60.62	54.25	52.22	52.75	53.43	56.02	52.90	56.03	50.44	57.58	57.67	52.44
TiO_2	4.07	4.66	3.85	5.11	4.26	2.86	4.93	2.58	2.94	4.31	4.05	3.75	3.61	4.57	4.03	4.69	3.59	2.89	4.70
Al_2O_3	17.43	13.96	16.74	13.84	13.81	13.07	14.04	16.70	14.24	14.55	14.90	13.80	16.78	15.01	18.09	15.47	18.05	15.27	15.20
Fe_2O_3	12.18	20.87	14.11	19.65	19.78	18.30	19.72	11.39	18.00	18.93	18.62	19.13	12.83	20.79	13.99	20.06	13.03	15.71	19.07
FeO	0.36	0.41	0.40	0.23	0.55	0.52	0.62	0.24	0.31	0.37	0.39	0.35	0.35	0.40	0.39	0.51	0.46	0.42	0.39
MgO	4.02	7.81	5.96	8.19	7.33	8.50	7.90	4.69	7.81	7.57	7.33	7.25	7.27	4.72	4.98	7.37	4.62	4.08	7.00
CaO	1.45	1.74	1.50	1.69	1.77	1.64	1.69	1.50	1.46	1.62	1.60	1.68	0.92	1.23	0.94	1.10	0.82	0.54	0.80
Na_2O	0.27	0.13	0.18	0.13	0.13	0.15	0.11	0.27	0.09	0.08	0.08	0.08	0.14	0.07	0.14	0.07	0.16	0.10	0.07
K_2O	1.86	0.18	1.17	0.24	0.24	0.57	0.16	1.88	0.77	0.18	0.13	0.31	1.96	0.18	1.27	0.14	1.59	3.24	0.24
P_2O_5	0.16	0.17	0.13	0.14	0.24	0.15	0.15	0.13	0.13	0.17	0.15	0.22	0.12	0.13	0.14	0.15	0.10	0.08	0.09

analysed varies from about 50 % to a maximum of about 53.4 %. The b) type of beds have consistently higher SiO_2 content, ranging from about 56 % to a maximum of about 60.6 %. In this respect the c) type of beds are closer to the tuffs than to the b) type of beds.

By way of comparison the chemical analysis of the basaltic volcanic ash bed ÷ 12 from Limfjorden, published by Bøggild (1918, p. 23), is shown in table 3.

From the abnormally low and the abnormally high values of some components it is clear that all types of beds from the Mønsted profile underwent some kind of strong alteration, one of the results being a loss of alkalies and, most likely, also of CaO. The Fe_2O_3 values are extremely high in all tuffs, while they are less high in the b) type of beds. Again, as far as this component it concerned, the c) type of beds are much closer to the tuffs. A characteristic feature for all types of beds is a high content of TiO_2, which tends to be highest in the tuffs. The MgO content is very high in both the tuffs and the c) type of beds, while it tends to be appreciably lower in the b) type. All these values point to secondary changes which must have affected the original mineral compositions.

In table 4 the cation percentages calculated for two beds are shown: one for the tuff No. 17, and one for the b) type of bed No. 18 which has the highest SiO_2 content of all the beds analysed.

Concerning the Fe_2O_3 component, according to the X-ray diffraction pattern either magnetite, $FeO.Fe_2O_3$, or maghemite, γ Fe_2O_3, can be present in all samples. The quantity of magnetite, being governed by the extremely low values of FeO, could be only negligible even if all of FeO available were assigned to this mineral. Furthermore, as previously stated,

Table 3.

	weight %	recalculated on waterfree basis
SiO_2	50.42	52.12
TiO_2	6.26	6.47
Al_2O_3	14.09	14.57
Fe_2O_3	2.72	2.81
FeO	6.40	6.61
MnO	tr.	–
MgO	2.80	2.90
CaO	7.62	7.88
Na_2O	5.01	5.18
K_2O	1.10	1.14
P_2O_5	0.31	0.32
H_2O^+	3.57	–
H_2O^-	1.52	–
	101.82	100.00

Analyst: Chr. Winther.

Chemical analysis of the basaltic volcanic ash bed ÷12 from Limfjorden (Bøggild, 1918).

Table 4.

	No. 17 tuff		No. 18 b)	
	weight %	cation %	weight %	cation %
SiO_2	50.68	50.48	60.62	59.08
TiO_2	4.93	3.68	2.58	1.89
Al_2O_3	14.04	16.46	16.70	19.15
Fe_2O_3	19.72	14.73	11.39	8.32
FeO	0.62	0.51	0.24	0.19
MgO	7.90	11.80	4.69	6.86
CaO	1.69	1.80	1.50	1.55
Na_2O	0.11	0.21	0.27	0.51
K_2O	0.16	0.20	1.88	2.34
P_2O_5	0.15	0.13	0.13	0.11

Cation percentages calculated for one tuff (No. 17) and one b) type of bed (No. 18) from the Mønsted profile.

the material making up all types of beds, and the tuffs in particular, is relatively strongly magnetic. Consequently, the possibility that the mineral magnetite is responsible for this property is only very remote. It is therefore considered that here we are dealing practically only with the strongly magnetic mineral maghemite, although magnetite might be present in extremely small amounts.

Since the X-ray diffractometer investigation has indentified the mineral anatase, TiO_2, in all samples and in all types of beds, it would seem that this mineral is present in fairly large proportions. Only a very minor part of TiO_2 can be combined with FeO to form ilmenite $FeO.TiO_2$ (sphene was not identified in any of the beds either microscopically or by the X-ray diffractometer method). It can therefore be concluded that by far the greatest part of TiO_2 constitutes the mineral anatase. Theoretically, even if all of FeO were allotted to ilmenite, this mineral could be present in only very small quantities, generally less in the b) type of beds than in the tuffs.

As for the very large amount of SiO_2, it appears from the microscopical observations and the X-ray diffraction that only a minor part of this component forms quartz. The diffraction pattern tends to indicate that there is more quartz in the b) than in the c) type of beds. In the tuffs quartz could not be detected at all by that method, although it was identified microscopically. Consequently, this mineral must be considered as being present only in very minor amounts in the tuffs. In this respect, the c) type of beds seem to occupy a middle position between the tuffs and the b) type of beds.

The largest part of SiO_2, combined with a part of Al_2O_3 and a part of H_2O+, whose content was very high in all samples, undoubtedly forms clay minerals, of which montmorillonite was identified in all types of beds and in all samples examined by the X-ray diffractometer.

A minor part of SiO_2, Al_2O_3, and a proportionally much smaller part of CaO, combined with a part of H_2O+, is constituted as the mineral heulandite. This mineral was identified by the X-ray diffractometer in nearly all beds of the b) type, while only in a few tuffs and in one bed of the c) type reflexes for heulandite appear.

As for MgO, it is considered that only a very minor part of this component is bound in the pyroxenes which were identified microscopically (augite) in nearly all tuffs, but could not be detected by the X-ray diffractometer. Thus, by far the largest part of MgO most probably forms part of the montmorillonite lattice.

Due to the very low CaO content and the abnormally low alkalies, especially in the tuffs, only very minor quantities of feldspars are possible. Of these only plagioclase could be identified microscopically, but the amounts present are too small to be detected by the X-ray diffractometer (we know that a part of CaO is also bound in heulandite, and in apatite, if present).

In the process of decomposition of the more complex silicates, in the first place feldspars, nearly all alkalies must be assumed to have been lost (it was mentioned earlier that the pyroxene grains very often show signs of strong intrastratal solution). The persistently higher K_2O content in the b) type of beds probably indicates an originally higher amount of this component in these beds. Also as far as this component is concerned, the c) type of beds occupy a position between the tuffs and the b) type of beds. Contrary to that, and probably for the same reason, the amounts of CaO always tend to be higher in the tuffs than in the b) type of beds.

Of the earlier known chemical analyses only two, those of the acid bed + 19 published by Norin (1940, p. 42, 43), are, generally speaking, comparable to the analyses from the Mønsted beds. The common characteristics are the very high values of H_2O+ and Fe_2O_3, while the alkalies, FeO and CaO are abnormally low.

In light of the foregoing discussion, the question can be raised whether in the mentioned case it was justifiable to solve the problem of the very high amounts of Fe_2O_3 and H_2O+ simply by omitting a quantity of Fe_2O_3 equivalent to the amount of H_2O+. This was done on the assumption that these two components form amorphous limonite, and in that proportion.

By doing this the amount of SiO_2 of the bulk analyses increased from about 50 % to about 70 % and thus corresponded to the two analyses done on the bed + 19 from Limfjorden, which, as mentioned earlier, was by Bøggild (1918) classified as andesitic in composition. Without doing this the SiO_2 content for both analyses would have been only about 60 %, or slightly higher, that is considerably less than in the analyses from Limfjorden. By performing a similar operation, all of the eighteen beds from Mønsted for which the chemical analyses are here available would become considerably more acid, and practically all the b) type of beds, which have higher SiO_2 content, could be interpreted as having been originally granitic ash beds. And this is an untenable supposition.

The origin of the different types of beds

Based on the information gathered in the field, the results of the chemical analyses, combined with the X-ray diffractometer study and the microscopic observations, the following conclusions concerning the origin of the different types of beds in the Mønsted profile may be drawn:

1) As for the tuff beds, their low SiO_2 content, the very high Fe_2O_3 and TiO_2 contents, together with the presence of augite and plagioclase, indicate that, originally, these volcanic beds were basaltic in composition.

By far the largest part of TiO_2 is constituted as the mineral anatase, while practically all of Fe_2O_3 forms maghemite. The latter, which is a strongly magnetic mineral, is responsible for the magnetism of the tuff material. The most probable source of derivation for maghemite is magnetite, of which maghemite is an oxidation product believed to form at low temperature and, according to some authors (Eyles et al., 1952), is an indication of tropical weathering conditions.

The mineral anatase, especially when relatively abundant, is considered most likely to be derived *in situ* from the decomposition of other titaniferous species, in the first place ilmenite (Brammall & Harwood, 1923).

Magnetite and ilmenite again indicate basic composition of the original ash material.

2) Two kinds of sediments which alternate with the tuffs, and which correspond to the much thicker diatomite facies of Limfjorden, can be distinguished:

beds described under b) in the measured profile. These are generally clearly laminated. Their SiO_2 content is relatively high (up to 60 %). The high Fe_2O_3, TiO_2, and MgO contents of these beds, together with plagioclase observed microscopically, indicate that they also contain certain amounts of the volcanic material admixed. At least a part of this material could have come already from the source area of the clay sediments. Furthermore, the volcanic material could have originated from the underlying ash layers due to the wave action, or it could have been dispersed as very fine ash particles throughout these beds. Also, this material could be derived from very thin ash beds contained in this b) type of beds, but which cannot be recognized in the profile.

beds described under c) in the measured profile. Lamination cannot be discerned in this type of beds. Although stratigraphically correlative with the diatomites of Limfjorden, they are according to their appearance and their chemical compositions closer to the tuffs than to the just discussed type of beds. This is due primarily to their small (about 1.0 cm) thicknesses. They were laid down during a relatively very short interval of time between the end of one major eruption and the start of the next one. The volcanic material, which could have been introduced by any of the above mentioned processes, most likely constitutes a proportionally greater part of an entire bed of this type. Hence the similarity of these beds with the enclosing tuffs.

3) Beds which were in the measure profile described under d), *i.e.* the few beds of compact, greasy, green clays. Their positions in the section,

where at least in two cases they occur enclosed by the laminated sediments (unit No. 44), suggest that, originally, they might also have been beds of volcanic ash. In the section from Ølst two tuff layers occur in the similar positions as the green clays of that unit, and they have thicknesses similar to those of the clays of that unit.

The green clay No. 40 a), apart from montmorillonite, contains maghemite and anatase, just as all the other beds examined by the X-ray diffractometer. Neither quartz nor heulandite were detected, while these two minerals are characteristic for the beds of the b) type. This, again, suggests that these clays might have a volcanic origin.

On the other hand, in the section from Fur with which the Mønsted profile was correlated, no such thick volcanic beds are present in the positions of the green clays of the unit No. 44. In the rythmogram of fig. 6 the green clays, and this concerns in the first place this same unit, were not considered representing the tuffs, but were plotted as a unit together with the laminated b) type of beds. The great resemblance with the Fur rythmogram in this particular place might be taken as an indication that the green clays from Mønsted cannot be interpreted as being altered volcanic ash beds. Moreover, the chemical analyses of the green clay 44 d) shows an SiO_2 content best comparable with the laminated type of beds. And the same can be said about its CaO and MgO contents. The K_2O is unusually high and is the highest value obtained for any sample analysed chemically.

It is possible that the clays in question represent a type of sediments essentially different from both the tuffs and the b) and c) types of beds. Further investigation might clarify the problem of their origin.

As stated, the zeolite heulandite and quartz are the two minerals characteristically found in the beds of the b) type, while montmorillonite is present in all types of beds. According to Coombs *et al.* (1959), the assemblage heulandite-montmorillonoid-quartz designates the lowest step in the mineral alteration taking place after the deposition of sediments.

The palaeontological evidence from the diatomite beds in western Limfjorden shows that the climate was tropic to subtropic during the time of deposition of the Lower Eocene volcanic beds (Bonde, 1966). The climate was gradually worsening during the rest of the Tertiary time. As mentioned, mineral maghemite is most commonly interpreted as being a low temperature oxidation product of magnetite, and an indication of tropical weathering conditions. This, in itself, is suggestive of a relatively early alteration of the Mønsted sediments.

The western Limfjorden area is small compared to the Eocene belt of Denmark. While in that area volcanic beds alternate with thick beds of diatomites, in the rest of the country the same beds are strongly altered and alternate with considerably thinner clayey rock, similar to that at Mønsted. This difference in thickness is in the first place due to the originally greater quantities of diatoms living in that area. These peculiarities reflect the differences in the depositional environment of Limfjorden, some of the important features being the richness of waters in silica and the existence of conditions favorable to the life of diatoms. It seems reasonable to suppose that the environmental conditions were also determinative for the subsequent strong alteration of the volcanic beds which has taken place outside Limfjorden, but not inside that area.

There are thus several indications that the alteration of the volcanic beds and the interbedded clayey sediments was an early diagenetic process and that it took place at a very shallow depth of burial and corresponding low temperatures. The red staining, due to the iron hydroxides, seen along the fractures and joints in the tuff material at Mønsted, is clearly a younger phenomenon and it could very well have taken place during the Pleistocene due to the work of the ground water.

On the source area of ash

The bed + 79 is markedly thicker at Mønsted than either on Fur or at Ølst. Likewise, a majority of tuff beds at Mønsted, especially those below + 79, are thicker than the corresponding beds at either of the two localities. This is surprising, since the Mønsted locality is found some 45 km SSE of Knudeklint, a locality on Fur with which the Mønsted section was correlated. According to the now generally accepted view, the center (or centers?) of the volcanic activity which produced volcanic beds in Jutland during the Lower Eocene was located somewhere in Skagerrak, that is in the northerly, or northwesterly, direction from western Limfjorden (see fig. 1). Thus, a thinning of the beds towards the south, and at Mønsted, is to be expected.

Already Ussing (1904), and then Bøggild (1918), have suggested the area of Skagerrak as the most probable source of ash. Bøggild's measurements in western Limfjorden tended to show a thinning of beds in a southerly direction. However, that author himself refrained from reaching a conclusion as to the location of the volcanic eruption, based on relative thicknesses of individual beds at different localities. Bøggild (1918, p. 35), as translated by the present writer, says: "It would be of greatest interest if some relationship between the thicknesses of the ash beds and the distances between the different localities [where these beds occur] could be established, and thus arrive at a conclusion as to the location of eruption; or, in any case, in which direction from the Moler area [western Limfjorden] the place of eruption was located. But, unfortunately, this can hardly be done. One should keep in mind that the thicknesses of a same layer do not depend on the size of eruption and the distance from the place of eruption alone, but that also the wind direction is extremely important, and this factor, which is beyond any control, can produce essential variations in the thickness of one and the same bed at different places. Similarly, currents and other accidental factors can influence the thicknesses. The conclusion must be that one cannot count on the variations [in thickness] of the individual layers and that, consequently, it is impossible to decide with some degree of certainty whether all ash originated from one and the same center of eruption."

The implications of this statement are that the drawing of the isopachs for the individual ash beds, as that was done later (S. A. Andersen, 1937), and in this way trying to "pinpoint" the location of the source of ash throughout the period of the time involved, is not a procedure devoid of pitfalls. The "abnormally" thick tuffs at Mønsted serve to illustrate this view.

In this connection the present writer again wants to underline that only in their type area, that is in western Limfjorden, we are dealing with relatively unaltered ash beds, while at all the other localities in eastern Jutland the same beds have been more or less strongly altered. As we have seen, these alterations have produced changes in the original mineral compositions, decomposition of some minerals and reconstitution of new ones. These processes could have also easily affected the original total volumes of the ash beds.

Furthermore, it is well known (see *e. g.* Gry, 1940) that the ash beds in western Limfjorden were subjected to strong folding as a result of pressure exerted by the ice in the Pleistocene. Such folding would produce general thinning of the beds but, locally, thickening can also be expected (*e. g.* in the hinges of the folds). Thus further inconsistencies in the thickness of the same bed can be introduced, depending on where in the fold measurements were taken.

Mønsted tuffs are found on the flank of a salt dome and, at the same time, on the downthrown side of a major fault. Consequently, purely local conditions, dependent on the tectonics, could have affected the thicknesses of both the volcanic beds and those of the terrigenous origin. Tertiary sediments could conceivably be abnormally thin in this part of the salt structure. And in case of penecontemporaneous faulting, relatively thicker sediments would accumulate on the downthrown side.

Moreover, the area of western Limfjorden where Bøggild measured his sections is characterised by intense salt tectonics dominated by diapirism and, there, several shallow diapiric domes occur. The structure Nykøbing (Mors) exhibits the strongest gravimetric anomalies in Jutland (see fig. 2). Therefore the thicknesses of the rocks in question in that area do not have to be representative.

In summarising, the writer wants to emphasize that the conclusions as to the place of eruption, in this case the area of Skagerrak to the north or northwest of western Limfjorden, based only on relative thicknesses of volcanic beds at different Jutland localities, should be treated with caution.

AN X-RAY POWDER DIFFRACTION STUDY OF THE LOWER EOCENE TUFF SEQUENCE FROM MØNSTED, NORTH JUTLAND

SIDSEL FREGERSLEV

Technique

The identification of the various minerals was based on X-ray powder methods, using a "Philips" X-ray diffractometer with Cu Kα-radiation. The diffractometer has a proportional counter and a pulse height analyser. The slit sizes used were: divergence slit 1°, receiving slit 0.2° and anti-scatter slit 1°. The runs were made from 2° to about 60°, 2θ, at a rate of 1° 2θ per minute per 10 mm of chart. The samples were made by pressing the powder into the sample holder.

The diffractometer diagrams of samples from one b) type of bed (No. 7) and from one tuff (No. 17) are shown in fig. 10.

Mineral identification

The minerals identified in the bulk samples from the Mønsted profile, represented in fig. 5, are listed in table 5. The identification of the minerals is in some cases based only on the strongest reflection. In table 5 this is indicated with +. In a few cases samples from both basal, or lower, part (*e. g.* No. 29_1) and from upper part (*e. g.* No. 29_2) of the same bed were examined.

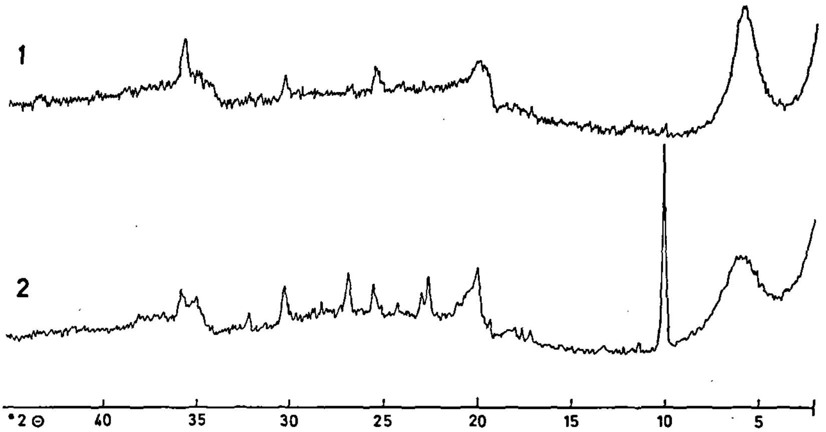

Fig. 10. Diffractometer diagrams of: 1. a tuff (No. 17) and 2. a b) type of bed (No. 7).

Table 5. Minerals identified in the Mønsted profile

No.	type of bed	montmorillonite	anatase	maghemite	quartz	heulandite	plagioclase	pyrite
46	b).........	++	+		++			
45b	tuff........	++	+	+				
44d	green clay..	++	+		+			
43	tuff........	++	+	++				
42	b).........	++	+	++	+			
41	tuff........	++	+	+				
40b	b).........	++	++	++	+	+		
40a	green clay..	++	++	++				
39	tuff........	++	+	++				
38	c).........	++	+	++				
37_2	tuff........	++	+	++				
37_1	tuff........	++	+	++		+		
36	b).........	++	+	++	++	+		
35_2	tuff........	++	+	+				
35_1	tuff........	++	+	++				
34	b).........	++	+	++	++	+		
33	tuff........	++	+	++				
32	b).........	++	+	++	++	+		
31_2	tuff........	++	+	++				
31_1	tuff........	++	+	++				
30	c).........	++	+	+	+			
29_2	tuff........	++	+	++				
29_1	tuff........	++	+	++				
28_2	b).........	++	+	++	+	++		
28_1	b).........	++	+	++	+	++		
27	tuff........	++	+	++				
26	c).........	++	+	++	+			
25	tuff........	++	+	++		+		
24	b).........	++	+	++	++	++		
23	tuff........	++	+	++				
22	c).........	++	+	+				
21	tuff........	++	+	++				
20	c).........	++	+	++	+	+		
19	tuff........	++	+	++				
18	b).........	++	+	+	++	++		
17	tuff........	++	+	++				
16	c).........	++	+	+	+			
15	tuff........	++	+	++				
14	b).........	++	+	++	+	++		
13_2	tuff........	++	+	++				
13_1	tuff........	++	+	++			+	
12	b).........	++	+	+	+	++		
11	tuff........	++	+	+				
10	b).........	++	+	++	+	++		
9	tuff........	++	+	++		++		
7	b).........	++	++	++	++	++		
6	tuff........	++	+	++		++		
5	b).........	++	++	++	+	++		
4	tuff........	++	+	++			+	
3	b).........	++	++	++	+	+		
2	tuff........	++	+	++				++
1	b).........	++	++	++	+	+		

A clay mineral with spacings at about 14.7 Å, 4.48 Å, 2.56 Å and 1.50 Å is present in all samples. The reflections mentioned occurred in unoriented air-dried samples, and are nearly the same as the reflections for montmorillonite in the ASTM Index card No. 2–0037. The identification of such a clay mineral should indeed also be based on the reflections from the basal spacings of oriented samples. Such samples of the Mønsted material were very difficult to make, but in a few cases we succeeded. The spacings for the samples No. 17 and No. 18 untreated were 14.7 Å (broad peak), and 17.1 Å to 17.4 Å treated with ethylene glycol. After heating the samples at 600° C for one hour, the peak moved to 10.2 Å.

These observations show that the mineral belongs to one of the swelling clay-mineral types, either the montmorillonite or the vermiculite. The two types can be distinguished by saturating the samples with magnesium ions before addition of glycerol (Brown, 1961, p. 315). Unfortunately we did not succeed in preparing such samples. The position of the 0 2 11 peak is, however, not the same for the two minerals. In the case of montmorillonite it should be at about 4.5 Å, and in the case of vermiculite at about 4.6 Å and not very strong. The peak in our unoriented samples always occurred at about 4.48 Å. It is therefore concluded that the mineral in question is montmorillonite.

Reflections indicating mixed layer minerals were not observed.

Anatase is characterised by peaks due to spacings at 3.51 Å, 1.89 Å, 2.38 Å, and 1.699 Å (ASTM Index card No. 4–0477). Peaks at 3.51 Å, and sometimes also at 1.89 Å, 2.38 Å and 1.70 Å, were observed in the diffractograms. The peak height of the second line of anatase should theoretically be ⅓ of the height of the first one. Due to the very small quantities of the crystalline material, we can hardly expect to get the second line in every case. Therefore we tried to concentrate one sample by boiling it in concentrated hydrochloric acid for one hour. After this treatment the sample showed reflections at 3.51 Å, 1.89 Å, 2.38 Å, 1.699 Å, 1.665 Å and 1.480 Å, which indicate, without a doubt, that the mineral in question is anatase. It is therefore assumed that all samples having the 3.51 Å spacing contain anatase.

Magnetite and maghemite have spacings at 2.53 Å, 1.485 Å, 2.97 Å, 1.617 Å and at 2.51 Å, 1.474 Å, 2.95 Å, 1.604 Å, respectively (Brown, 1961, p. 386–387). Peaks due to spacings from 2.51 Å to 2.53 Å, from 2.95 Å to 2.97 Å and 1.48 Å were observed in all diffractograms. It is difficult to decide only from these data, whether the mineral is magnetite or maghemite. However, the chemical analyses (see tables 1 and 2, pp. 302–303) showed that the content of FeO is maximum about 0.5 %, and thus magnetite could be present only in extremely small amounts. It is therefore assumed that the mentioned spacings are due to the mineral maghemite.

Quartz was detected only in some of the samples analysed. It is characterised by peaks due to spacings at 3.34 Å, 4.26 Å, and 1.82 Å (ASTM Index card No. 5–0490). For quartz, just as in the case of anatase, only the strongest reflection is present in a number of samples.

In most of the samples where quartz is present, the zeolite mineral heulandite is recognized by its peaks close to the spacings at 8.93 Å, 2.96 Å, 3.97 Å, 3.88 Å, 7.96 Å, 5.06 Å, 4.62 Å, 4.44 Å, 2.80 Å and 2.71 Å (ASTM Index card No. 14–248).

The presence of plagioclase is indicated only in two samples by a sharp peak at 3.20 Å (ASTM Index card No. 9–465). High intensity only from 040 (the 3.20 Å peak) suggests that preferred orientation enhances the reflection.

Pyrite is recognized only in the bed No. 2 by its reflections at 1.63 Å and 2.71 Å (ASTM Index card No. 6–0710).

Pyroxene (augite) and plagioclase, although identified microscopically, were not (except for plagioclase in the two samples mentioned) detected by the X-ray diffraction method.

From table 5 it can be seen that in the samples from the b) type of beds quartz always occurs while this mineral was not registered in any of the tuff samples.

Heulandite is present in almost all beds of the b) type.

The contents of quartz and heulandite in the c) type of beds and in the green clays apparently do not follow any definite pattern.

Summary and conclusions

As earlier reported (Madirazza, 1966), an exposure containing tuff beds of Lower Eocene age was encountered in the north-eastern, marginal part of the Mønsted salt dome.

In the profile, which measures ca. 2.3 m, the tuffs alternate with two types of beds: b) type, which consists of generally clearly laminated, clayey beds of a greyish white color, and c) type, which are very similar in appearance to the tuffs, always very thin (ca. 1.0 cm), and apparently not laminated. Several layers of greasy, green clay also occur in the profile.

The tuff material is relatively strongly magnetic, but also the beds which alternate with the tuffs are magnetic, the c) type more so than the b) type.

Both b) and c) types of beds correspond to the much thicker beds of the diatomite facies of western Limfjorden.

The strike of the beds is, most commonly, ca. 160° and the dip 18°–20°E. The beds, especially the tuffs, are cut by numerous joints. Essentially, two sets of joints, striking more or less at right angles, are present. A great majority of the joint planes are approximately perpendicular to the bedding (see the accompanying stereograms). Only minor, normal faults, with displacements of a few centimetres, were observed in the exposed profile.

It is considered that the above mentioned structures cannot be satisfactorily explained by the glacial tectonics, but that their origins should be sought in the tectonics of the salt structure itself.

A boring drilled at the foot of the exposure reached the limestone of Danian age (E. Stenestad, personal information) at a depth of 9.5 m. From the information supplied by the boring it appears certain that the Lower Eocene tuff sequence is encountered *in situ*.

With the help of a rhytmogram of the Mønsted section, the tuffs can be correlated with the volcanic ash beds from + 62 to + 93 (or possibly

+ 94), as measured by Bøggild (1918) at Knudeklint on the island of Fur, and they include the very thick bed + 79. Nearly all tuffs at Mønsted are thicker than the corresponding beds in western Limfjorden.

Microscopic investigation (including a study of a thin section) of the tuff material showed that the clearly crystalline components are found in very small amounts (less than 1 %). They consist of plagioclase (andesine to labradorite) and augite, and occasional quartz grains. The bulk of the material is vitric, or encountered in different stages of devitrification, and opaque.

Also the b) and c) types of beds contain volcanic material admixed. In the c) type, due to their unusually small thicknesses, this material probably constitutes a proportionally greater part of an entire bed.

The X-ray diffraction study has identified the minerals montmorillonite and anatase in all types of beds. Furthermore, strongly magnetic mineral maghemite, most commonly interpreted as a low temperature oxidation product of magnetite (Eyles *et al.*, 1952), is thought to be present in considerable quantities in all types of beds (most in the tuffs). This mineral is responsible for the magnetism of the Mønsted beds.

Quartz and the zeolite heulandite are the two minerals identified by the X-ray diffractometer in almost all beds of the b) type.

The results of chemical analyses (a total of nineteen) made on all types of beds, including ten tuffs, are interpreted in light of the microscopic observations and the X-ray diffraction study.

The common characteristics for all types of beds are very high Fe_2O_3 values (highest in the tuffs), while the alkalies, FeO and CaO are abnormally low. Furthermore, all beds have a very high H_2O+ content. The chemical composition of the c) type is, in general, closer to that of the tuffs than to the b) type of beds.

The SiO_2 content of the tuffs (from ca. 50 % to a maximum ca. 53.4 %, as recalculated on waterfree basis), their very high Fe_2O_3 and TiO_2 contents, together with their mineral content, show that these volcanic beds were originally basaltic in composition.

There are several indications, among others the mineral assemblage heulandite-montmorillonite-quartz (see Coombs *et al.*, 1959), that the alteration of the volcanic beds and the interbedded clayey sediments at Mønsted was a relatively early diagenetic process having taken place at a shallow depth of burial and corresponding low temperatures.

According to the generally accepted view the source area of ash in the Lower Eocene was somewhere in Skagerrak, *i. e.* to the north or northwest of western Limfjorden. It might therefore be expected that the tuffs at Mønsted would be thinner than the corresponding beds in western Limfjorden (see fig. 1), but the opposite is true. In order to explain this apparent inconsistency several reasons can be given.

It is emphasized that only in western Limfjorden unaltered, or relatively little altered, ash beds occur, while at all the other localities in eastern Jutland the same beds have been more or less strongly altered (*e. g.* at Mønsted). The changes in the original mineral compositions, decomposition of some minerals and reconstitution of new ones, have most likely also affected the original volumes of the ash beds.

Furthermore, the ash beds in western Limfjorden were subjected to strong folding due to the ice pressure during the Pleistocene and thus variations in the thickness of a same bed can easily occur within short distances. Therefore the comparison of the thicknesses of the ash beds found inside the Limfjorden area, and then also those of that area with the corresponding beds in other parts of Jutland, can only have a limited value as far as the determination of the place of eruption is concerned.

Salt tectonics could have also influenced the thicknesses of the volcanic sequence in western Limfjorden. But, similarly, at other localities, as *e. g.* at Mønsted, purely local conditions dependent on the tectonics could have affected the thicknesses of beds.

Dansk sammendrag

Som tidligere meddelt (Madirazza, 1966) blev en forekomst med Nedre Eocæne tuflag fundet i den nordøstlige, marginale del af Mønsted saltstrukturen.

I profilet, som måler ca. 2,3 m, veksler tuflagene med to andre typer lag: type b) som er hvide til grå, tydeligt laminerede, lerede lag, og type c) der meget ligner tuflagene, altid meget tynde (ca. 1,0 cm) og tilsyneladende ikke laminerede. Desuden forekommer flere lag af grønt ler i profilet.

Tufmaterialet er relativt stærk magnetisk, men også de lag, som veksler med tuflagene er magnetiske, type c) mere end type b). Type b) og c) lagene er stratigrafisk ækvivalente til de betydeligt mægtigere diatomé-facies lag, som findes i den vestlige Limfjorden.

Lagenes strygning er i gennemsnit ca. 160° og hældning 18°–20° Ø. Hele profilet, især tuflagene, er gennemsat af et stort antal joints. Hovedsagelig findes to sæt joints vinkelret på hinanden. Langt de fleste af disse er samtidig næsten vinkelret på lagdelingen. Kun normale forkastninger, med forsætninger på nogle få centimeter, kan iagttages i profilet. Det anses, at de her omtalte strukturer ikke var dannede af isens tryk i Pleistocæn, men at deres oprindelse må søges i saltstrukturens tektonik.

I en boring lige under profilet blev kalksten nået i en dybde af 9,5 m. Ifølge E. Stenestad (personlig meddelelse) er denne kalksten af Danien alder. På grundlag af oplysningerne fra denne boring anses det for mest sandsynligt, at forekomsten af de Nedre Eocæne lag findes *in situ*.

Ved hjælp af et rhytmogram fra Mønsted profilet kan tuflagene korreleres med de vulkanske askelag fra +62 til +93 (eller muligvis +94) fra Fur (lokalitet Knudeklint) som beskrevet af Bøggild (1918). Mønsted profilet indeholder således det mægtige lag +79. Næsten alle tuflagene ved Mønsted er mægtigere end de tilsvarende lag i den vestlige del af Limfjorden.

Undersøgelser af tyndslib såvel som løst tufmateriale viser, at de tydeligt krystallinske komponenter kun forekommer i meget små mængder (mindre end 1 %). Disse udgøres af plagioklas (andesin til labradorit) og augit samt enkelte kvartskorn. Hovedparten af tufmaterialet findes som glas eller på forskellige trin af devitrifikation, og som opakt materiale.

Lag af type b) og c) indeholder også indblandet vulkansk materiale, hvilket i lagene af type c) sandsynligvis udgør den største del af lagene på grund af disses meget ringe tykkelse.

Ved røntgen diffraktometriske undersøgelser er mineralerne montmorillonit og anatas identificerede i alle typer lag. Endvidere synes det stærkt magnetiske mineral maghemit, sædvanligvis betragtet som et lavtemperatur oxidationsprodukt af magnetit, at være tilstede i betydelige mængder i alle typer af lag (dog mest i tuflagene). Dette mineral er ansvarlig for Mønsted lagenes magnetiske egenskaber.

Kvarts og heulandit er identificerede ved hjælp af røntgen diffraktometeret i næsten alle lag af type b).

Resultaterne af nitten kemiske analyser af alle typer af lag, deraf ti analyser på tuflag, diskuteres og tolkes udfra de mikroskopiske observationer og røntgen diffraktion undersøgelserne.

Fælles træk for alle typer af lag er et meget stort indhold af Fe_2O_3 (størst i tuflagene) og et abnormt lille indhold af K_2O, Na_2O, FeO og CaO. Endvidere har alle lag et stort indhold af H_2O+. Den kemiske sammensætning af type c) lagene viser i almindelighed større ligheder med tuflagene end med type b) lagene.

Tuflagenes SiO_2 indhold (fra ca. 50 % til maximalt ca. 53,4 %, beregnet på vandfri basis), deres meget store Fe_2O_3 og TiO_2-indhold, sammen med deres mineralindhold viser, at disse vulkanske lag oprindeligt havde basaltisk sammensætning.

Der er flere indikationer på, blandt andet mineralselskabet heulandit-montmorillonit-kvarts (se Coombs *et al.*, 1959), at omdannelsen af de vulkanske lag og de mellemliggende sedimenter ved Mønsted, er en relativ tidlig diagenetisk proces, som er foregået under et tyndt sedimentdække og tilsvarende lave temperaturer.

I overensstemmelse med almindeligt accepterede synspunkter stammer den Nedre Eocæne aske fra et udbrudsområde et sted i Skagerrak, nord eller nordvest for den vestlige del af Limfjorden. Det skulle derfor forventes, at tuflagene ved Mønsted skulle være tyndere end tilsvarende lag i den vestlige Limfjorden (se fig. 1). Forskellige grunde kan gives for at forklare, at Mønsted tuflagene er mægtigere.

Det understreges, at uomdannede eller relativt lidt omdannede askelag, kun forefindes i den vestlige del af Limfjorden, medens de samme lag ved alle lokaliteter i Østjylland er mere eller mindre stærkt omdannede. Forandringer i de oprindelige mineralers sammensætning, nedbrydning af nogle mineraler og dannelsen af nye, har sandsynligvis ændret askelagenes oprindelige totale volumen.

Tektoniken kunne også have influeret på mægtigheden af den vulkanske sekvens. De fleste forekomster af askelag i den vestlige del af Limfjorden findes i nærheden af saltdiapire (Mors, Batum). Endvidere har askelagene i det samme område været udsat for kraftig foldning på grund af isens tryk, således at et enkelt lags mægtighed kan variere indenfor korte afstande. På samme måde ved andre lokaliteter, som f. eks. Mønsted, kunne helt lokale tektoniske forhold have influeret på lagenes mægtighed.

En sammenligning mellem askelagenes mægtigheder i Limfjordsområdet og tilsvarende lags mægtigheder andre steder i Jylland menes derfor kun at have en begrænset værdi med hensyn til bestemmelse af eruptionsområdets beliggenhed.

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