Weathering of a Neogene fluviatile fining-upwards sequence at Voervadsbro, Denmark

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By heavy mineral analyses it is shown that a fluviatile fining-upwards sandy sequence from the Neogene of Denmark has been weathered from its upper surface and deep into the sediment. During the weathering amphiboles, epidotes, garnets, kyanite, staurolite and feldspar have been strongly corroded, whereas zircon, rutile and tourmaline were not affected. In the uppermost part of the sequence authigenic anatase and outgrowths on feldspar and quartz occur. The secondary growth of feldspar occurred subsequent to corrosion and the outgrowths are not corroded.

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In Denmark Neogene deposits are found in the southern and western part of Jylland (fig. 1). They constitute a sequence of interfingering marine and non-marine sediments (cf. Rasmussen 1961, fig. 7). During the Miocene a general regression took place, and fluviatile deposits covered the eastern and central parts of Jylland. In these Neogene deposits three heavy mineral associations have been found, an amphibole-epidote association, an epidote association and a metamorphic association dominated by kyanite, sillimanite and staurolite (Friis 1974). The amphibole-epidote association and a metamorphic association deposits whereas the epidote and the metamorphic associations are typically found in fluviatile deposits (Larsen & Friis 1973). Investigations of fluviatile deposits have demonstrated that post-depositional weathering in some cases caused a complete dissolution of epidotes and it was proved that the metamorphic association is a weathering residuum of the epidote association (Friis 1974). Friis & Johannesen (1974) showed that this weathering took place penecontemporaneously with deposition, probably parallelling a cyclicity in deposition. Similarily the epidote association was suggested to be a weathering residuum of the amphibole-epidote association (Friis 1974) as demonstrated from Neogene deposits in northern Germany (Weyl 1953), but it has not been proved that amphiboles were originally abundant in the Neogene fluviatile deposits of Denmark.

Since these previously discussed sections only represent parts of the original profiles as they have been eroded subsequent to the weathering, it was not possible to estimate the

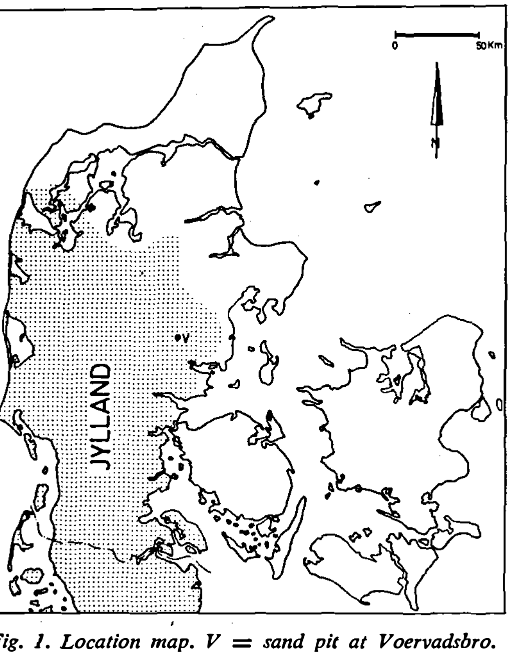

Fig. 1. Location map. V = sand pit at Voervadsbro. Dotted: area of preserved Neogene deposits in Denmark (according to Sorgenfrei 1954).

maximum effects of the weathering processes upon the composition of the heavy mineral associations. Further evidence concerning the environmental conditions and the intensity of the weathering is presented here from heavy mineral analyses of a Neogene sandy sequence at Voervadsbro (fig. 1).

The locality at Voervadsbro has been mentioned previously by Jørgensen (1944), who referred it to the Pliocene, and by Larsen (1963) and Larsen & Friis (1973). At present there is no evidence as to whether the sediments are of Miocene or Pliocene age. They are tentatively referred to the Odderup Formation, defined by Rasmussen (1961) to include Middle Miocene non-marine deposits.

The sandpit exposes a 24 m thick sequence of Neogene deposits, which are mainly cross-bedded coarse sand. Cross-bedding measurements indicate palaeocurrents from the east or southeast (Larsen & Friis 1973). Within the cross-bedded sand an E–W trending gravel-body, which is locally 4 m thick, is found. Erosional features and internal bedding indicate that the gravel was deposited by lateral accretion in a southwards migrating channel. Towards the north the gravel interfingers with cross-bedded sand. Above the gravel 8 m of cross-bedded sand is found. The thickness of individual sets is 30–50 cm.

The uppermost 4 m of the Neogene sequence is cross-bedded with sets approximately 10 cm in thickness decreasing upwards 2). The lower part of this fine-grained sequence is cross-bedded with sets approximately 10 cm in thickness decreasing upwards to 1–2 cm. The upper part is mainly parallel laminated or massive. In the laminated parts heavy mineral concentrations occur in very thin laminae. Locally lamination has been pressed up to form small cusps and disrupted. Presumably these deformations are water escape structures. Generally the sand is grey, but a secondary brownish staining is seen at a few horizons. The primary sedimentary structures cross these horizons but are partly obliterated at some of them. Upwards the sand grades to silt and clayey silt, and plant remains, presumably roots, become abundant. The clastic sequence is covered by a woody peat of which 30 cm is preserved. The boundary between the Neogene and the Quaternary deposits is erosional.

It is inferred that the Neogene deposits at Voervadsbro represent an alluvial *fining-upwards* sequence (cf. Allen 1964), ranging from coarse-grained point bar deposits of a migrating river to fine-grained and organic top-stratum deposits.

From the uppermost 3.5 m of the fining-upwards sequence samples have been taken at intervals of 15 cm to reflect changes in the distribution of heavy minerals.

Methods

The samples were wet-sieved to separate the 75–250 μm grain-size fraction, which in all samples makes up the major part of the sand fraction. From this grain-size fraction heavy minerals were separated by means of bromoform (S.G. = 2.89) and embedded in Clearax (R.I. = 1.66). The light minerals were embedded in Canada Balsam (R.I. = 1.54). The percentage distribution of the non-opaque heavy minerals was estimated by counting 200 grains while in the light fraction 100 grains were counted. The quartz/feldspar ratio was calculated from a count of 100 grains of quartz and feldspar.

Heavy minerals

The content of heavy minerals in the grain-size fraction 75–250 μm is generally low. In the upper part of the sequence heavy minerals constitute 0.2–0.3 % while in the lowermost metre they make up approximately 0.5–1.0 % (fig. 2). The percentages of opaque grains are high, usually about 80 % of the heavy mineral fraction. Mica, mainly muscovite, is found in small amounts.

The distribution of the non-opaque heavy minerals is shown in fig. 2 and table 1. There are remarkably high percentages of zircon and rutile. In the present material the content of zircon tends to be related to the total amount of heavy minerals in the sediment (fig. 2), but

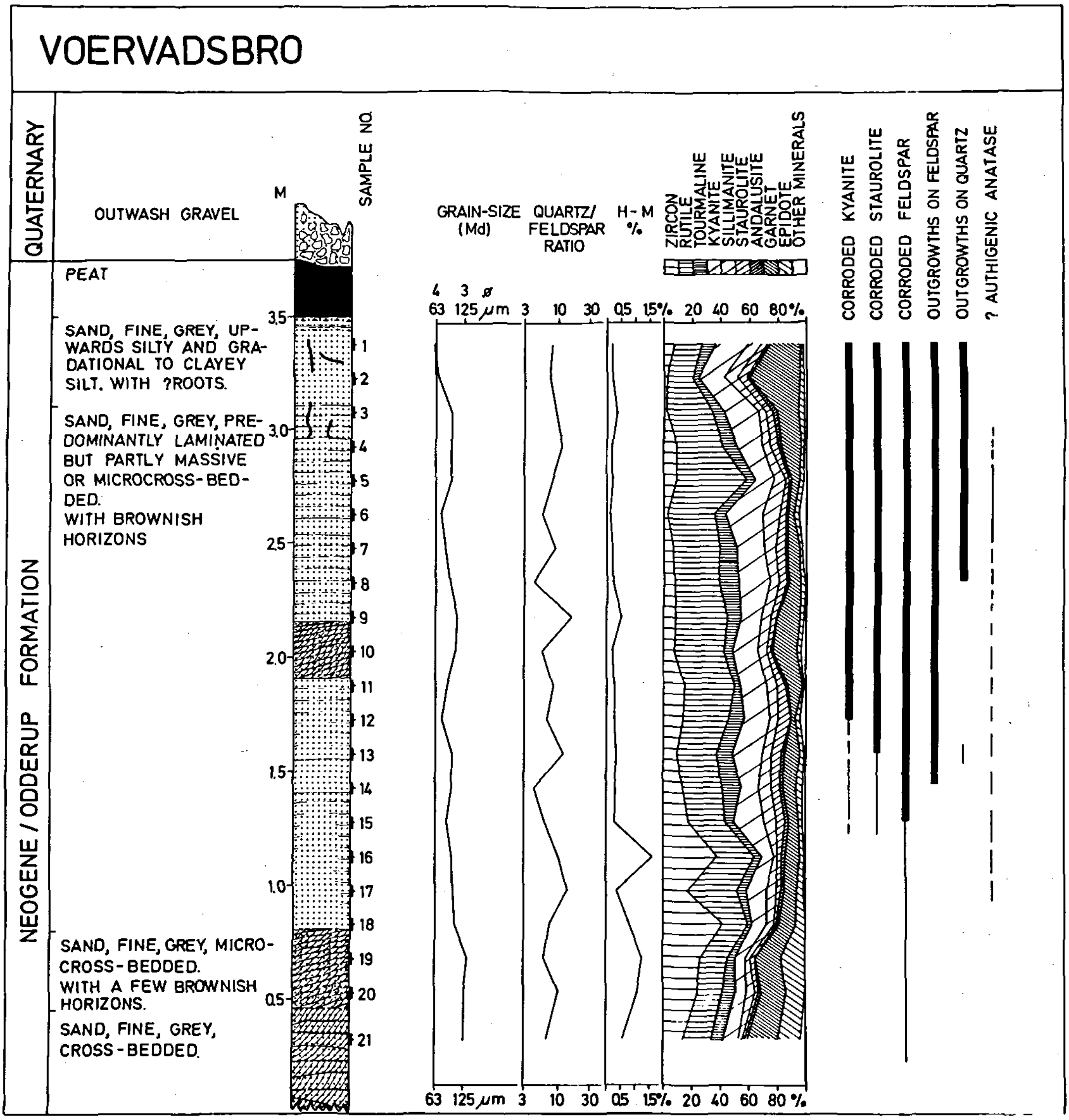

Fig. 2.

this feature is not general within the Neogene deposits of Denmark. It is notable that in the lower part of the section epidotes constitute 10–20 %, decreasing upwards to between 2 and 4 % at 2.5 m below the top. Minor constituents are titanite, anatase and chloritoid (0–1 %). Amphiboles, including hornblende, are found sporadically.

The heavy mineral assemblages from the uppermost part of the section represent the metamorphic association (cf. Friis 1974), gradational in the lowermost part to the epidote association (the coarse-grained sand and the gravel is represented by samples no 22 and 23 in table 1). From other Neogene sections in Denmark this transition has been interpreted as a result of post-depositional weathering (Friis 1974; Friis & Johannesen 1974).

TABLE 1. Composition of non-opaque heavy minerals in the 75–250 μm grain-size fraction. 'Other minerals' includes titanite, chloritoid, amphiboles and aggregates (200 grains were counted, and percentages have been reduced to the nearest whole number). Trace indicated by a cross.

Samples no. 22 and 23 represent coarse sand and gravel from a deeper part of the section.

Sample no.	Zircon	Rutile	Tourmaline	Kyanite	Sillimanite	Staurolite	Andalusite	Garnet	Epidote	Anatase	Other minerals
1	8	20	9	22	9	5	1	22	2	-	+
2	3	17	4	17	9	7	1	36	3	-	+
3	3	31	8	24	5	4	3	15	3	-	1
4	10	32	9	18	5	6	1	14	2	+	1
5	9	48	7	13	8	3	+	6	3	1	+
6	3	33	8	26	11	4	1	5	2	1	3
7	7	33	11	19	8	7	+	9	2	2	1
8	8	31	13	22	6	5	1	8	2	-	1
9	9	36	10	14	7	3	+	16	3	-	+
10	8	35	6	18	6	3	1	16	3	1	1
11	15	34	4	19	7	5	1	10	1	-	1
12	14	31	11	18	6	8	+	3	3	+	3
13	10	27	12	21	6	6	2	11	3	-	1
14	14	28	13	12	9	5	2	9	4	+	2
15	18	25	6	21	9	5	3	6	3	1	1
16	38	27	4	8	3	3	1	10	4	-	+
17	17	34	7	13	7	3	2	9	5	+	+
18	42	18	2	10	5	1	1	12	7	-	+
19	27	18	6	7	3	3	+	18	15	-	+
20	25	17	8	8	6	2	2	16	13	-	+
21	15	20	8	10	3	2	+	21	16	-	2
22	8	9	9	9	5	3	1	6	46	-	-
23	7	9	7	13	7	8	1	4	38	-	3

Weathering phenomena

Throughout the sequence amphiboles, epidotes and garnets are heavily corroded. Many of the grains are clearly reduced in size and some of them only remain as skeletons. This is especially true for amphiboles and for epidotes, which are found in very low percentages in the upper part of the sequence (table 1; fig. 2) but also for garnets, though no reduction in the content of garnets can be registered from bottom to top. However, it appears that the content of garnets is subject to large primary variability.

The surface textures of the corroded grains are comparable to those recorded from weathered Neogene sections in the same area (Friis 1974), and these textures are found to be indicative of post-depositional corrosion.

However, at Voervadsbro kyanite and staurolite have also been severely corroded (fig. 2). Distinct facets have developed on staurolite grains, in some cases determined by inclusions of quartz that have been more resistant to dissolution than the host grain (fig. 3A). The dissolution of staurolite is clearly related to crystallography, and the grains are reduced in the direction of the crystallographic c-axis. The corrosion pattern on kyanite is much more diffuse (fig. 3B), and only in a few cases is corrosion seen to be related to cleavage as also described by Grimm (1973). Jagged grains like those pictured by Edelman & Doeglas (1934) have not been found.

Sillimanite has been stable throughout the sequence, and only a few grains are found in a corroded condition.

Feldspars, which are predominantly alkali feldspar, constitute 10–15 % of the light fraction. All samples contain corroded feldspar in substantial amounts, but only in the upper part are they more frequent than fresh feldspar (fig. 2). Many of the grains are very strongly corroded (fig. 3C).

In the investigated sequence it is found that the intensity of dissolution processes decreased downwards. Amphiboles are hardly present in the sequence and the few grains found are strongly corroded. Epidotes decrease very abruptly in percentages from the bottom to the top and they are strongly corroded in the entire section. Garnets have been rather unstable since they are corroded throughout the section, but evidently they were more stable than the epidotes. Corrosion of kyanite and staurolite was ristricted to the upper part of the sequence and these minerals were definitely more stable than garnets and epidotes. Compared to the results of the experimental work of Nickel (1973) as well as investigations of many workers on natural occurrences (cf. Nickel 1973), the succession of heavy minerals according to stability reflects weathering caused by acidic solutions. The decrease of intensity downwards as well as the grain textures indicate that the weathering occurred subsequent to depositon and was related to the upper surface of the clastic sequence.

Weathering phenomena are known from other areas which were marginal to the Neogene North Sea. To the south, in northern Germany the weathering generally caused

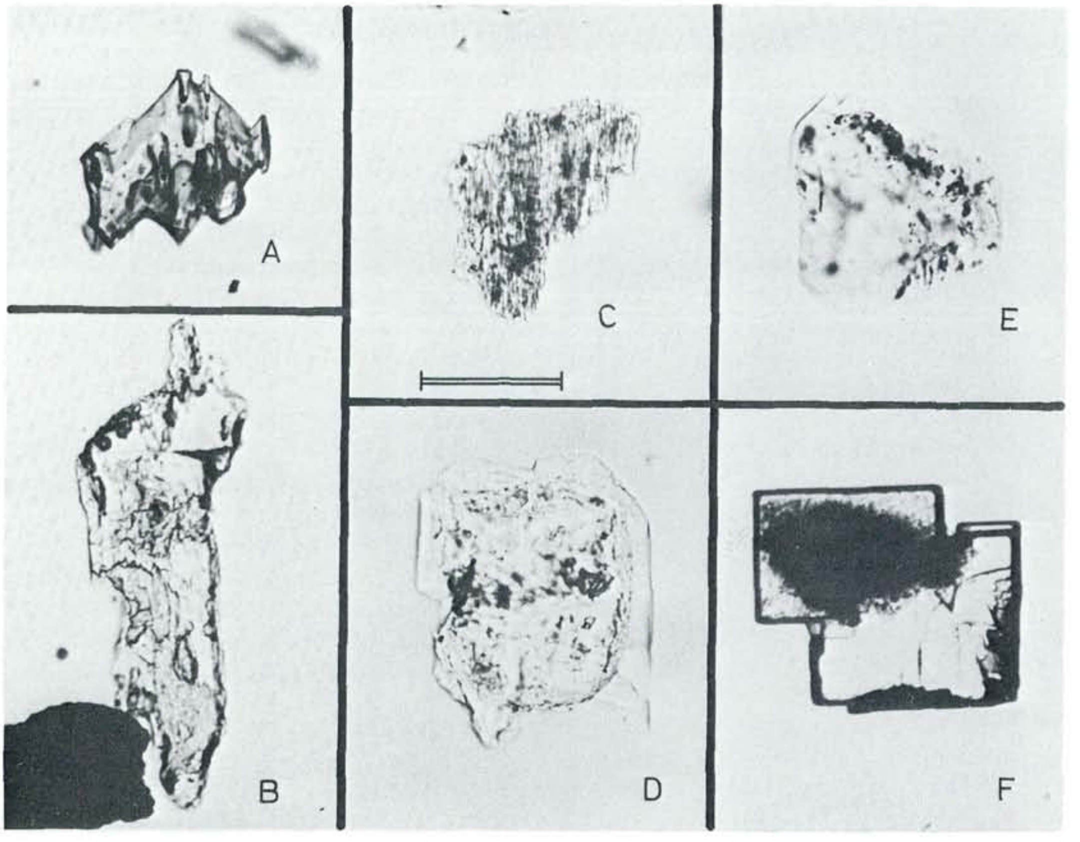

Fig. 3. A: Corroded staurolite grain with inclusions of quartz. B: Corroded kyanite grain. C: Corroded feldspar grain. D: Authigenic outgrowth on slightly corroded feldspar grain. E: Authigenic outgrowth on quartz grain. F: Authigenic anatase. Scale = 100 μm.

dissolution of amphiboles, epidotes and garnets (Weyl 1952) whereas in southern Limburg (The Netherlands) it is a general feature that staurolite and to some extent tourmaline are also corroded (van Loon 1973).

According to the experimental works by Dietz (1968) staurolite is very resistant to abrasion during transportation so it is unlikely that the characteristic appearance of staurolite (cf. fig. 3 A) should be changed substantially by local reworking. Since weathered staurolite grains have not been registered from other Neogene deposits in Denmark it is inferred that the weathering only rarely was intensive enough to cause corrosion on staurolite.

As mentioned by van Loon (1973) corrosion of staurolite is a common feature within the Neogene of southern Limburg where presumably the weathering was in general more intense than in the Danish area. This is probably a reflection of climatic differences, but the time available for weathering processes to effect the sediment is also an important factor.

Authigenic minerals

In the upper part of the sequence grains of alkali feldspar and quartz commonly bear secondary outgrowths (fig. 2). In the uppermost part distinct outgrowths are forund on about 10 % of the feldspar grains. These outgrowths are neither corroded nor worn and are found upon both strongly corroded grains and quite fresh, well-rounded grains (fig. 3D). It is therefore assumed that the secondary growth occurred in situ subsequent to the corrosion of the feldspar. The outgrowths on quartz grains are generally on a very small scale (fig. 3E) and occur on approximately 5 % of the grains. They do not appear to be worn and it is supposed that they formed in situ.

There is a small but significant content of anatase in samples from Voervadsbro (fig. 2) whereas this mineral is extremely scarce in other Neogene deposits in Denmark. The grains are tabular and clearly not worn (fig. 3F), so in situ growth of this mineral is inferred.

The occurence of outgrowhts clearly coincides with the zone of the most intense corrosion of feldspar as well as other minerals, but it is assumed that the authigenic growth occurred subsequent to the weathering. However the present material is considered to be insufficient for discussion of the conditions responsible for the authigenic growth of feldspar, quartz and anatase.

Conclusions

During some periods of the Neogene, alluvial plains were situated between the North Sea and the Fennoscandian Shield, which supplied clastic material to the North Sea Basin. The deposits at Voervadsbro represent a completely developed fluviatile fining-upwards sequence laid down within such an alluvial plain. Locally the plain was covered by vegetation as evidenced by the occurrence of roots in the upper part of the sequence. The brownish horizons within the sequence may represent fluctuations in ground water level, but there is no evidence of temporary vegetation during deposition of the sequence. From Miocene deposits in central Jylland, Larsen & Kuyp (1971) described traces of local fluctuations in ground water level. Partly as a consequence of the biological processes connected to the vegetational cover, the sediments of the alluvial plain were strongly weathered and, in a few cases, as at Voervadsbro, conditions were so aggressive that staurolite and kyanite were corroded. However conditions in general were less aggressive in the Danish area than in the southernmost parts of the North Sea area.

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Dansk sammendrag

Fra en sandgrav ved Voervadsbro (fig. 1) beskrives en fluviatil 'fining-upwards' serie, hvis øverste dele (fig. 2) har været udsat for en meget kraftig forvitring, hvorunder amfiboler, epidoter, granater, kyanit, staurolit og alkalifeldspat er blevet kraftigt korroderet. Forvitringen har en tydelig relation til selve flodslettens overflade, hvor der lokalt må have været en kraftig vegetation. I profilets øverste del forekommer der yderligere nydannelser af mineralerne kvarts, feldspat og anatas, for kvarts og feldspats vedkommende som sekundære udvoksninger. Udvoksningerne på feldspat er tydeligvis dannet efter korrosionspåvirkningen.

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