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ON THE LITHOLOGY AND PROVENANCE OF THE RUPELIAN BOOM CLAY IN NORTHERN BELGIUM, A VOLCANICLASTIC DEPOSIT

by

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ABSTRACT

The Lower Oligocene Boom Clay (Rupelian) in northern Belgium, 50 to 75 m thick, is composed of a cyclic sequence of clayey silts and silty clays. In the Kruibeke clay pit the upper portion of the Boom Clay (Putte Clay Member) is characterized, according to thin-section analysis, by a crypto-crystalline to microcystalline clayey matrix with an admixture of moderately sorted silt-size to fine-sand size particles: quartz , feldspar, mica, rock fragments, and argillized lithoclasts. The detrital quartz grains are angular, often sharp and rarely rounded. Feldspars, generally as cleavage fragments, are fresh, commonly zoned and rich in minute opaque pigment. The mica content is high; most of the mica consists of muscovite; biotite and thoroughly altered biotite are less common. Sparse siliciclastic rock fragments indicate a sedimentary to low-grade metamorphic source area. Dirty green, argillized lithoclasts rich in leucoxene which represent mainly degraded basalt fragments are a characteristic constituent of the Boom Clay. The presence of these argillized lithoclasts and much degraded biotite , as well as some of the varietal features of the detrital quartz and feldspar point to a volcanic provenance for a considerable portion of the Boom Clay. In this context particular stress is laid on the significance of mineralogically unstable lithoclasts in sediments. The clay matrix contains abundant leucoxene, either as discrete grains or as a diffuse pigment. A considerable portion of the matrix of the Boom Clay, however, consists of primary clay-size particles (< 2 µm), presumably derived from the diagenetic breakdown of altered volcanic ash particles of trachytic and basaltic composition, and of highly altered material derived from extremely unstable minerals and rock fragments of larger grain size which cannot yet be identified with any certainty. Moreover, the mineralogical instability of the unequivocally identified argillized volcaniclasts as well as the textural appearance of the clay matrix (uniform extinction or meshy fabric, ghosts of volcaniclasts) make a volcanogenic derivation of the matrix likely. The Boom Clay is composed of distinct detrital components derived from various rock sources and probably characterized by several transport mechanisms. Resorption diagenesis, however, tends to camouflage the primary lithologies of the various lithoclasts which were presumably brought into the basin and deposited partly in an altered state. The Boom Clay was laid down on a marine shelf some distance from the Siebengebirge and Hocheifel, both active volcanic centers south of the Lower Rhine Embayment (Niederrheinische Bucht), which contributed substantial amounts of volcanic material to the Boom Clay. This study also shows how volcanism played a significant role in shaping the lithostratigraphic record during the Tertiary.

KEY WORDS

Sedimentary petrography, sediment provenance, Boom Clay, Rupelian, northern Belgium, volcaniclastic deposits.

1. INTRODUCTION

In 1989 the Rupelian Stage was made into a worldwide chronostratigraphic unit and a "Rupelian" working group was set up during the RCNPS meeting in Bremen. The aim of the working group is "to prepare proposals for the formal designation of a stratotype and boundary stratotypes". Recently, detailed field sampling of major exposures in Belgium was carried out to obtain suitable samples for various kinds of analysis, particularly paleontological.

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In this context a comprehensive thin-section study of the Rupelian Boom Clay Formation was initiated. Altogether about 150 clay samples will be examined in thin sections in order to supplement existing petrographic data on grain size and lithology. Scanning electron microscope (SEM) and microprobe analyses of selected samples are scheduled to complement the thin-section study. Ten samples of the Boom clay from the base of the Putte Clay Member at the Kruibeke clay pit were examined in thin section. The present contribution reports the tentative results of this thin section study (Part 1). Strictly spoken, the findings presented apply only to this suite of 10 samples.

The Boom Clay sample localities are shown in Figure 1 and a composite section of the Boom Clay made up from exposed sections at Sint Niklaas, Rumst-Terhagen, and Kruibeke is shown in Figure 2.

2. ENVIRONMENT OF DEPOSITION

Recent sediments deposited on open shelves are characterized by Shepard (1963) as being mainly composed of bioturbated silty clays. Locally, discontinuous lenses of sandy sediments occur. Shelf muds commonly contain echinoid fragments and glauconite in the sand fraction. Recent deltafront muds (largely silt), on the other hand, are often laminated and less bioturbated and have a high content of wood fibers and small orange or brown-colored aggregates. Mica is exceptionally abundant in the delta-front muds compared with open-shelf muds. Biogenic remains are far less frequent than in shelf muds. Rapid deposition normally leads to a scarcity of fossils in sediments.

The depositional environment of the Boom Clay was summarized by Vandenberghe (1981, p. 212). The following attributes taken together indicate deposition on an open marine shelf: silty clay, bioturbation, glauconite and echinoid fragments. Main fossils are fishes, molluscs, foraminifera and ostracods. The occasional presence of terrestrial mammal fossil fragments and the abundance of drift wood suggest that the coast was near. The large amount of organic matter and the marked mica content may point to the proximity of a delta. It is inferred that deposition took place in a subtropical climate (warm temperate) on a mud bottom in about 50 m or more of water containing enough oxygen to support a benthic micro- and macrofauna. According to Batjes (1958) the foraminifera are comparable to those on a mud shelf north of Trinidad and the Paria peninsula.

3. PREVIOUS SEDIMENTOLOGICAL WORK

Earlier studies of the Boom Clay concentrated mainly on the bulk clay-mineral composition and the grain-size distribution.

A modern sedimentological study was published by Vandenberghe (1974, 1978). According to Vandenberghe the Boom Clay is composed of clayey silts and silty clays. Glauconite occurs especially in the most silty beds. The Boom Clay is characterized by rather constant chemical and mineralogical properties throughout the whole deposit. Variables are grain-size, carbonate and organic matter content. They vary rhythmically through the clay section. The lignitic organic matter consists largely of land-derived detrital plant remains (phytoclasts). The clay-mineral composition is dominated by illite; it also includes smectite and illite-smectite, mixed-layer clays, kaolinite and some chlorite or degraded chlorite. Feldspar is unusually abundant (up to 25 % of the sand-size grains). Heavy minerals (53-250 µm) comprise zircon, rutile, anatase, sphene, tourmaline, staurolite, kyanite, garnet, epidote, hornblende, and augite. They were most probably derived from the Fennoscandian Shield. As another potential source area, Vandenberghe (1976) inferred for phytoclasts and coal particles found in the Boom Clay derivation from Carboniferous coals outcropping in northern England on the basis of their low vitrinite reflectance.

Main and trace elements (Cu, Co, Cd, Rb, Zn, Mn, Ga, V, Ni, Cr) of seventeen samples were analyzed by Vandenberghe, too. Noteworthy is the relatively high TiO_2 content of the clay which is also reflected by the results of heavy mineral analysis, i.e. the relative abundance of rutile, anatase and sphene.

The grain-size rhythmicity is a striking feature of the Boom Clay. About every 40 cm a clay-rich bed changes abruptly upwards into a silty bed. The grain-size variations are believed to be the result of intensity changes in bottom turbulence. Black bituminous interbeds also occur. The organic matter distribution is graded with a maximum content at the very bottom of a black bed. Bed-by-bed correlation of this shelf sequence has been carried out in clay pits in northern Belgium over an area of more than 500 km². Grain size and digitized bed-thickness/time series, studied with two forms of power spectral analysis, reveal regular cycles with a wavelength of about one meter. In geological terms this represents approximately one silt-clay cycle. Dating based on planktonic foraminiferal zones suggests that the period of the cycles was less than 120 000 years. The regularity and approximate period of the cycles combined with their great lateral continuity suggest that the most likely control of the

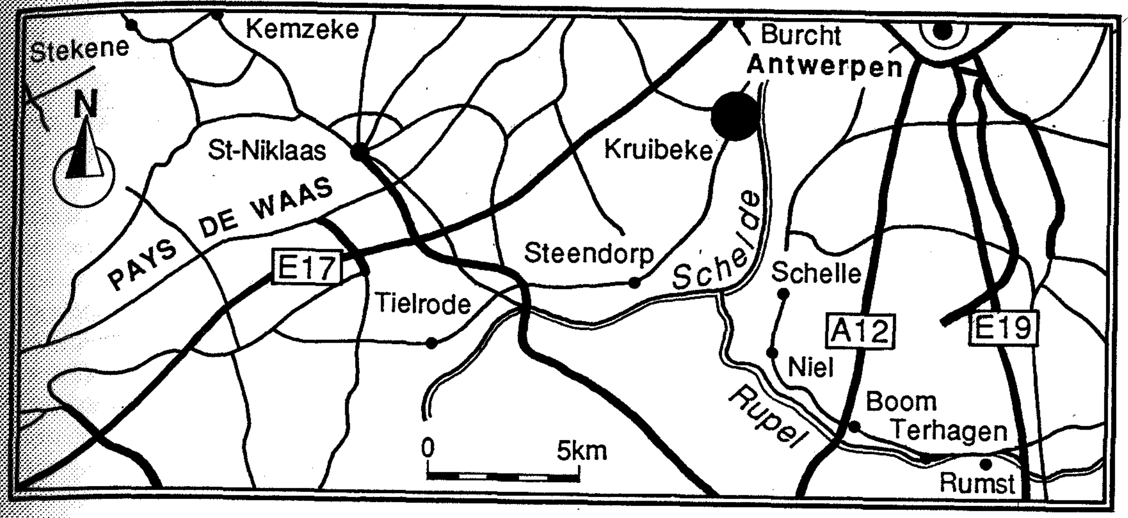

Figure 1. Sample locations in northern Belgium (after Vandenberghe & Van Echelpoel, 1987).

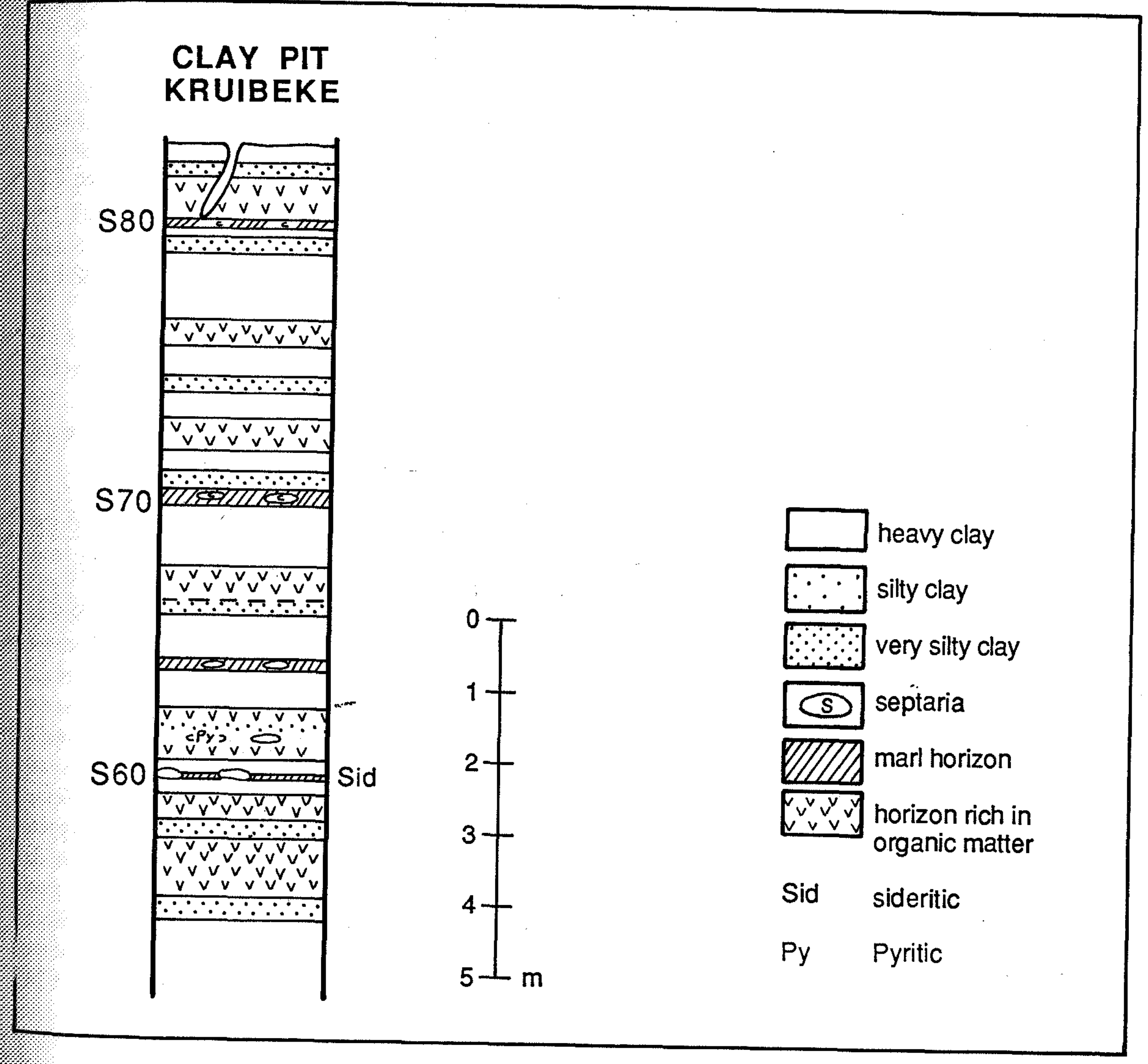

Figure 2. Composite Boom Clay section, northern Belgium (after Vandenberghe & Van Echelpoel, 1987).

cyclicity was a sedimentological process responding, via some climatic mechanism, to orbital variations or Milankovitch cycles (Van Echelpoel & Weedon, 1989, Van Echelpoel, 1991). Variation in grain size may have been linked to variations in relative water depth via changes in bottom-water turbulence. There is no sedimentological or biostratigraphic evidence for major hiatuses in the Boom Clay Formation. Thus, the one meter cyclicity probably reflects a combination of 100 000 and 41 000 year orbital eccentricity.

The probably complex history of the Boom Clay is not simply revealed by bulk rock analysis. The history involves the interaction of the following: primary composition, diagenetic alteration and weathering.

4. THIN-SECTION PETROGRAPHY

Although the mineral and chemical compositions of clays are mostly well known thanks to analytical methods such as X-ray diffraction, X-ray fluorescence and scanning electron microscopy, textural details on a microscopic scale are still unknown. In general, detailed microscope descriptions of shales are surprisingly rare (e.g. Schieber, 1989).

The study of clays in thin section enables us (Zimmerle, 1991) to :

1. reconstruct the primary nature and/or composition of detrital components (i.e. of mineralogically unstable minerals and rock fragments) ;
2. observe the original particle size and particle shape ;
3. trace the course of diagenesis ;
4. obtain a better picture of the depositional environment.

Convential thin sections with a thin cover glass are sufficient for routine analysis. Polished thin sections, however, are the only type of thin section that can be examined effectively by various methods such as transmitted light microscopy, reflected light microscopy, fluorescence microscopy (FL), cathodoluminescence microscopy (CL), scanning electron microscopy (SEM), and X-ray fluorescence spectroscopy (XRF). In this context Nöltner (1988) has demonstrated the successful application of electron-optical methods. The main essential for thin-section petrography of a clay is an absolutely flawless thin section. The fact that this requires a high degree of skill is one of the chief factors delaying the general acceptance and successful application of thin-section microscopy of clays. Conventional thin-sectioning is summarized by Murphy (1986) and Miller (1988). Thin-sectioning of soft clays, however, is still an unsurmountable problem for many.

Plate 1 depicts some of the textural and compositional features of the Boom Clay studied so far in thin section. Textural features are shown in Figs. 1-3. Details of composition and diagenetic alteration are illustrated in Figs. 4-6.

4.1. Texture of the Boom Clay

The texture of an argillaceous sediment comprises the geometric aspects of and the mutual relations among its components, e.g. size, shape and arrangement of the constituents. The term is applied to macroscopic, microscopic and submicroscopic features of a clay.

A major problem in the case of the Boom Clay consists in defining the original grain boundaries and grain sizes of the primary argillaceous sediment, especially those of the soft, ductile and easily deformable components. Siliciclasts show a wide spectrum of angular to rounded grain shapes. Noteworthy is the occurrence of splinter--like quartz grains and elongate cleavage fragments of feldspar. Thin layers of coarse silt or fine sand one grain thick are another characteristic feature. Diagenetic gypsum forms rosettes. Lamination is accentuated by mica flakes, elongated siliciclasts and organic matter. Some sedimentation units, especially highly micaceous layers or single-grain layers, are only about 200 µm thick or even thinner. There is commonly also a cyclic sedimentation on this scale.

Relatively coarse layers of fine sand, composed of foraminifera and biogenic phosphate is shown in Plate 1, Fig. 1. Sand-size, highly altered basalt clasts are a typical feature of Boom Clay texture (Plate 1, Fig. 2); the spectrum of basalt textures is discussed in § 4.2.2.2. The primary poor sorting of a silty Boom Clay sample and the replacement of the coarse-silt-size grains are exemplified in Plate 1, Fig. 3.
Vandenberghe's (1974, p .91) observation that the mica flakes are larger than the quartz grains was corroborated by the present examination of thin sections. This unusual mica:siliciclast size ratio suggests a specific transport or deposition mechanism.

The present thin-section study shows that the primary proportion of > 53 µm particles was definitely much higher than grain-size analyses by sieving would suggest. Wet sieving retains only the compact and hard sediment particles, but not the soft fecal pellets or argillized unstable particles which tend to disaggregate readily. This is also in agreemen with recent observations on modern sediments that the proportion of silt-size particles in an argillaceous sediment is usually much higher than was previously thought (A. Wetzel, personal communication ; Stow, 1981). This interpretation of the Boom Clay possessing a coarser grain size than that determined by previous methods has some bearing on the hydraulic interpretation of the Boom Clay, but certainly does not negate the determination of the cyclic pattern recognised by Vandenberghe (1974), and Vandenberghe & Van Echelpoel (1987).

4.2. Mineral composition

The mineral composition of the argillaceous matrix and of the discrete mineral constituents and rock fragments as seen in thin sections is summarized below (table 1) :

Unspecified clay-size fraction	Silt- to sand-size detrital components					
	Argillized volcani-clasts	Mica	Quartz	Feldspar	Others	Heavy minerals
65 - 95	0 - 10	1 - 5	0 - 9	1 - 16	1 - 4	1 - 4

Table 1. Modal composition (percent) of ten thin-sections of the Boom Clay, Putte Clay Member, Kruibeke clay pit.

It is difficult to obtain a reliable estimate of the proportion of truly volcanic material in the Boom Clay. The estimates of argillized volcaniclasts are minimum values. A considerable proportion of the feldspar cleavage fragments are also derived from volcanic rocks, on account of the abundant microlithic inclusions, in particular rutile prisms, and narrow zoning, partly accentuated by dark pigment.

4.2.1 Clay-size fraction

The clay-size fraction commonly makes up over 50 % of the Boom Clay. It mostly consists either of primary clay particles (< 2 µm), floccules or of highly altered material derived from originally coarser, extremely unstable minerals and rock fragments, most of which cannot be identified with any certainty. However, the original mineralogical instability postulated for the argillized clasts and the textural features of the present clay matrix strongly suggest volcanogenic origin. For instance, the finest particles in a modern volcanic ash are normally 0.1 - 1 µm in size. In the case of clays and argillaceous rocks, X-ray diffraction analysis alone rarely allows reliable determination of volcanic components and provenance.

About 50-70 % of the clay consists of greenish to brownish argillacoeus matrix which shows uniform extinction under crossed nicols. Organic pigment, leucoxene, minute rutile prisms (Tonschiefernädelchen), and pyrite are finely dispersed throughout the cryptoto microcrystalline matrix. Occasionally, domains of cloudy leucoxene are observed, presumably marking the site of completely resorbed primary grains. No fecal pellets were identified. The major clay minerals as identified by X-ray diffraction are illite, kaolinite, smectite, and mixed-layer minerals, as well as minor chlorite.

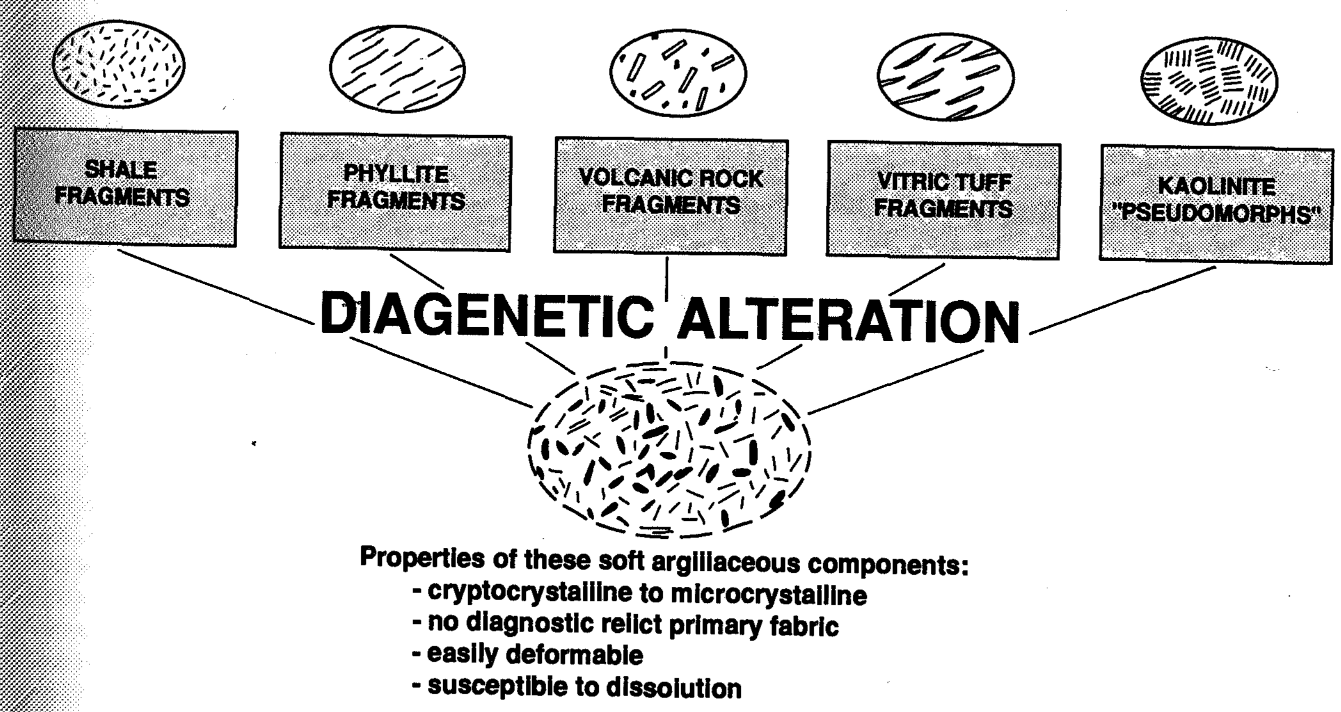

Figure 3. Mineralogically unstable clasts in clays, shales and sandstones, an often-neglected, but important component of sedimentary rocks.

4.2.2. Discrete constituents

The discrete constituents of the Boom Clay comprise silt-size and fine sand-size grains, either rigid and hard siliciclastic components or soft deformable clay and mineralogically unstable rock fragments. Soft deformable clay and mineralogically unstable rock fragments are in general widespread and common, also in other clays and shales, even in sandstones. But little attention has been paid to them so far. This lack of knowledge is one of the substantial barriers to further research on the provenance of sediments and sedimentary rocks.

4.2.2.1. Detrital minerals

Detrital minerals present comprise quartz, feldspar, micas, and transparent heavy minerals.

Quartz is mostly equidimensional and angular; well rounded grains (eolian) or sharp splinters of quartz (volcanic derivation) are less frequent (Plate 1, Fig. 3). Noteworthy are irregular or amoeboid shapes of some quartz grains and occasionally corroded quartz. Magmatic embayments, however, are sparse. Undulose extinction is common. No secondary overgrowths of quartz were observed. Some quartz grains contain long apatite prisms, others rutile twins and prisms. Unusually large gas and liquid bubbles characterize quartz grains of hydrothermal origin. Club-shaped quartz grains or undulose extinction of unusual dimension are sparse. Solitary quartz grains with rounded secondary overgrowths indicate a sedimentary source for a few of the detrital quartz grains, i.e. eroded sandstones.

The content of feldspar is unusually high (11 - 28 % in 19 samples). Feldspar is characterized as follows: colorless, also yellowish, some grains slightly turbid, mostly angular cleavage fragments; rarely wellrounded grains with secondary overgrowths. Untwinned potassium feldspar is more abundant than finely twinned plagioclase. Many feldspars are characterized by inclusions of minute rutile prisms or by zonal growth outlined by opaque pigment (Plate 1, Fig. 4). Some feldspar grains also contain droplet-shaped inclusions, others are corroded by reaction with the clay matrix. In the thoroughly altered volcaniclasts, feldspars are either pseudomorphed or concealed amongst the cryptocrystalline to microcrystalline alteration products.

The mica flakes are exceptionally large, they reach a length of up to 300 µm. Colorless muscovite - commonly turbid, pigmented and/or with inclusions - is generally more prominent than biotite and its alteration products. The important question, however, still remains unanswered, i.e. whether or not most of the presumed muscovite flakes formed diagenetically from original biotite. Biotite is greenish, greenish brown or dark olive gray. It is rarely fresh, but mostly degraded to microcrystalline aggregates of clay minerals, limonite, leucoxene/rutile and carbonate minerals. Some biotite flakes are also partly altered to granular siderite. Biotite and its alteration products occur occasionally in thin layers ; it is often associated with splinters of quartz.

Heavy minerals as observed in thin sections comprise aggregates of diffuse leucoxene of varying size, zircon (subrounded, forming halos in the enclosing clay), rutile (twins and larger prisms), colorless garnet, tourmaline (euhedral, exceptionally as inclusions in siliciclasts, with polar corrosion), pistacite, angular green hornblende (commonly corroded), sphene (40 µm), and brookite. Also solitary grains of angular, dark or reddish brown spinel occur. Rarely, heavy minerals such as zircon form loose one-grain-thick layers.

Diagenetically formed minerals comprise pyrite, glauconite, siderite and gypsum. Pyrite occurs as minute framboids ; it also occasionally replaces calcitic tests or forms geopetal precipitates in fossil chambers. Round glauconite grains, normally about 80 µm in size, rarely 100-200 µm, are dirty green or green. The larger grains appear to be more turbid. They are often rimmed or penetrated by cryptocrystalline leucoxene. Some glauconite grains are reminiscent of amygdules, i.e. the infillings of vesicles and some enclose minute angular mineral fragments. Clusters of granular siderite are sparsely disseminated in the Boom Clay. Gypsum occurs as rosettes or along fractures. Biogenic constituents are echinoid fragments, calcareous or arenaceous foraminifera, biogenic phosphate and carbonaceous particles, some of which show relicts of plant tissue. The biogenic components are enriched in certain layers.

Fragments of beige or violet grayish, biogenic chalcedony - called silex by Vandenberghe (1974, p. 92) - are common. Due to their particle-shape-related, symmetrical extinction the chalcedony fragments are interpreted as siliceous sponge fragments deposited in a shallow marine environment.

4.2.2.2. Detrital rock fragments

The most spectacular components are soft, but equidimensional, mainly coarse-silt to fine-sand-sized, dirty green clasts (50-200 µm) of completely argillized volcanic rock showing a variety of relict textures (Plate 1, Fig. 5). The dominant texture is a basaltic type and consists of ghosts of feldspar in a groundmass rich in ore minerals. Some fragments also contain round vesicles and globules. Other textures include groundmass rich in cryptocrystalline leucoxene, groundmass with minute "ghosts" of phenocrysts or argillized trachytic groundmass with small elongate feldspar laths. The recognisable solitary volcanic rock

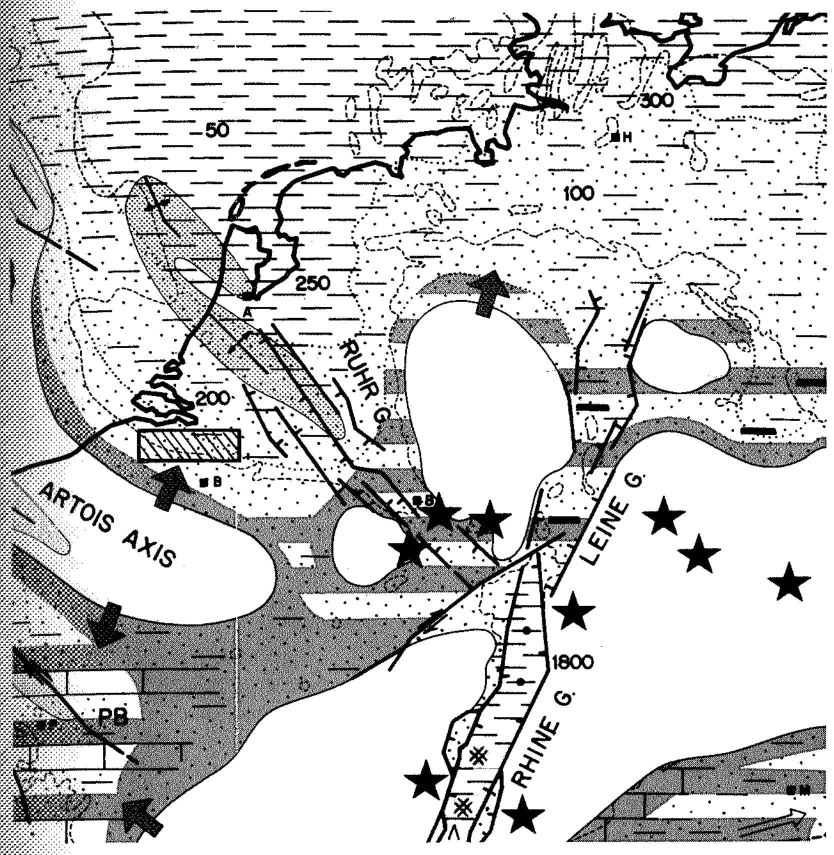

Figure 4. Oligocene paleogeography of northwestern Europe (detail) (according to P.A. Ziegler, 1990). Insert shows the area with outcropping Rupelian Boom Clay in northern Belgium. Stars indicate volcanic eruption centers, arrows direction of main sediment transport, and white areas continental areas. In the area shown in the insert mainly deltaic, coastal and shallow-marine clastics (sands) and shales are exposed. For lithological symbols see legend by Ziegler (1990, encl. 55).

fragments, now soft due to post-deposition alteration and argillization, could have been derived either from erosion of older volcanic rocks or from contemporaneous volcanic activity. The second alternative is favoured (1) by the composition of the Boom Clay, (2) the fact that the volcanic rock fragments are mostly indistinguishable from the cryptocrystalline clay matrix, and (3) depositional features such as monomineralic layering of degraded micas and angular and elongate quartz and feldspar fragments. All these clasts contrast strongly with the enclosing clay matrix by remaining black under crossed nicols and not displaying any birefringence or other interference effect. Under plane polarized light they contrast only occasionally by showing a more greenish hue. When deposited the clasts were discrete, hard, and undeformed grains. Thus, alteration to thoroughly argillized clasts occurred essentially during diagenesis. These grains frequently appear to be concealed in the clay matrix. Similar fragments of thoroughly argillized volcanic rocks were observed in the Eocene Messel Oil Shale (Kubanek *et al.*, 1988, Plate 1, Fig. 2 + 3) and in fossiliferous basalt tuffs from Enspel, Westerwald.

Cryptocrystalline to microcrystalline lithoclasts of undefinable fabric and provenance signature, many of which are presumably concealed in the Boom Clay, are widespread in sedimentary rocks of various ages. The fact that their lithological identification is difficult and often impossible without additional microprobe work represents a considerable barrier in sediment-petrographic work. A wide range of rock types and compositions produce similar clasts when argillized (Fig. 3.). The convergence involved makes interpretation difficult, but not impossible. It is a new challenge for sedimentary petrography.

Nontransparent cryptocrystalline leucoxene grains and dark-colored grains of microcrystalline clay - occasionally surrounded by a lighter-colored clay crust - are also dispersed throughout. Solitary reddish brown or brick red shale grains are derived from eroded soil. There are clasts composed of various minerals (about 10 µm in size), locally with disseminated rutile prisms, which cannot yet be attributed to any source rock.

These clasts occasionally form elongate splinters similar to quartz. The presence of such elongate composite grains may be a further evidence that some or all components were shattered by a violent volcanic explosion.

Fragments of phyllite, myrmekite, and sericitic polyquartz are rare ; they indicate derivation from an old sedimentary "basement". Cryptocrystalline calcite pellets, similar to the purely coccolithic fecal pellets found in the Toarcian, and small rounded carbonate particles are rare.

With respect to the distribution of volcanic rock fragments the following working hypothesis is put forward : Basalt fragments are found mainly in the fine-sand fraction; trachyte and trachytic tuff particles, on the other hand, are concealed in the fine silt and clay fractions of the Boom Clay due to their small particle size and to progressive alteration.

4.3. Diagenesis of the Boom Clay

According to Vandenberghe (1974, p. 181-183) the diagenetic evolution of the Boom Clay on a macroscopic scale started with the neoformation of pyrite via mackinawite by bacterial sulfate reduction. Pyrite forms layers ; it occurs as replaced fossil shells etc. Sulfate reduction was associated with the transformation of organic matter and re-precipitation of carbonate as well as formation of septaria. Neoformation of siderite followed the formation of calcareous concretions, and gypsum was generated from the breakdown of pyrite. The detrital clay minerals reacted early with the sea water and mixed-layer minerals formed diagenetically. The clay lost about 50 % of its original interstitial porewater by compaction. Vitrinite reflectance measurements show that the diagenetic rank of the Boom Clay is low; it falls in the range of methane generation. The above changes follow the conventional concept of early diagenesis.

Replacement and resorption of primary minerals and mineralogically unstable rock fragments are the dominant microfeatures of the Boom Clay, and in fact of many other clays and shales. Resorption diagenesis, a term minted by the author and here defined as the sum of diagenetic processes resorbing unstable detrital components such as argillaceous and/or calcareous silt- to sand-grade particles (i.e. detrital minerals and rock fragments) and unstable pore fillings and/or cement minerals. The previous mineral composition and texture can be partially or completely extinguished.

Examples of resorption diagenesis are shown in Plate 1. Figure 5 depicts the progressive resorption of a highly altered detrital basalt clast. Figure 6 illustrates the incipient resorption of an angular feldspar fragment.

5. ON THE PROVENANCE AND LITHOGENESIS OF THE BOOM CLAY

The provenance and lithogenesis of the Boom Clay is essentially reflected by the history of the clay-size fraction and the clay minerals. The clay size fraction is the main component, but its derivation is difficult to decipher. It is often less of a problem to attribute the coarse-silt and fine-sand constituents such as quartz, feldspar and mica minerals to certain types of source rock.

The paleogeographic setting of the Oligocene in northwestern Europe is shown in Figure 4.

On the basis of both X-ray diffraction analysis and thin-section evaluation the mineral and especially the clay-mineral composition is tentatively interpreted as follows. Quartz is of complex heterogeneous provenance; it is mainly detrital and to a minor extent volcanogenic (e.g. the splintery grains). Feldspar, mostly angular cleavage fragments, is volcanogenic to a large extent (presumably > 50 % of the total feldspar content). Pyrite, mostly framboids, is of very early diagenetic origin ; gypsum is derived from the alteration of pyrite. The prevailing clay-mineral association has a complex history and is likewise of heterogeneous derivation. Vandenberghe's (1974, p. 116-121) interpretation of his X-ray diffraction data has to be modified and extended in the light of thin-section analysis. His discussion of the genetic aspects of the clay mineral formation is rather inconclusive. Kaolinite does not provide an unambiguous indication of its origin; it may be of detrital or diagenetic origin, likewise illite. Montmorillonite/smectite and illite/montmorillonite mixed-layer minerals are in the present case most probably alteration products of acid and basic volcanic glass and crystalline volcanic clasts, being derived directly from volcanic source areas or indirectly from volcanic soils. The common traces of chlorite might indicate derivation from altered basic volcanics.

In the second part of the study, fractionation of clay minerals according to size is envisaged in order to improve distinc- tion between primary components and secondary alteration products among the clay minerals.

The minute particle size and the high degree of alteration of clays and argillaceous rocks in general and of the Boom Clay in particular, as well as the lack of published data on the problem of modal analysis of clays make a quantitative thin-section evaluation of these argillaceous rocks extremely difficult. Consequently, the detrital composition of the Boom Clay, i.e. the mode, can only be approximated (Table 1) in this initial stage of the study. The difficulties involved have been discussed by Zimmerle *et al.* (1990) for clays of similar age from northwestern Germany. At least 50 vol. % of the Boom Clay is estimated to be derived from fresh and weathered volcanic rocks. Volcanic components are :
(1) much of the smectitic clay-size fraction, (2) biotite and its various alteration products, (3) cleavage fragments of feldspar, (4) splintery quartz and (5) heavy minerals much as brown spinel, green hornblende and sphene. The remaining vol. 50 % of the Boom Clay

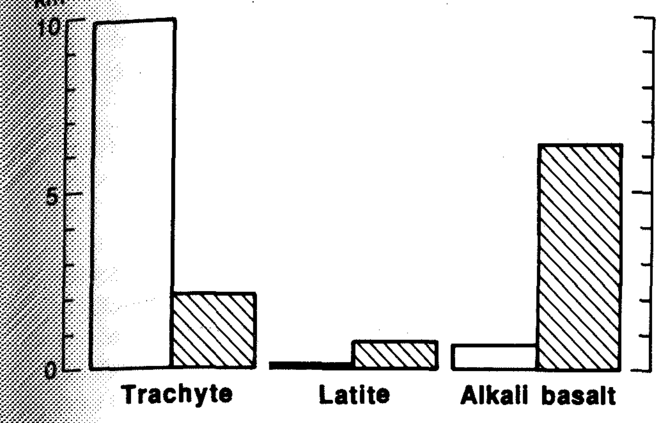

Figure 5. Areal distribution of the various types of volcanic rocks in the Siebengebirge. Tuffs = white ; Solid volcanic rock = hatched (modified from Vieten *et al.*, 1988).

come either from older sediments to the south, from the tectonized Paleozoic "basement" or Fennoscandian igneous rocks.

According to the current, most simple conception, which necessarily must not be the final one, the volcanic minerals and rock fragments and their alteration products were derived from volcanic areas known to have been active at that time. These areas are the Siebengebirge and the Hocheifel (High Eifel), about 200 km to the east. The volcanic rocks found in the Siebengebirge are trachytic tuffs, trachytes, latites, and alkali basalts (Fig. 5). The volcanoes were active from the Eocene to the Miocene as documented by radiometric age determinations (Fig. 6). The volcanic debris consisted mainly of ash composed of volcanic glass, crystals and/or lithic clasts of trachytic to basaltic composition. Brown spinel and sphene are considered to be key heavy minerals diagnostic of volcanic provenance in the present case. Direct ash fall or erosion of deeply weathered volcanic soils on the land as well as longshore drift are the main modes of transport. Airborne ashes can travel over considerable distances (several hundred kilometers) as shown in a modern example from central America (Fig. 7).

In the context of the volcanic activity documented in Oligocene sediments of central Europe, it might be mentioned that in the stratigraphic equivalent of the Boom Clay in NW Germany, the Septarian Clay (Rupelian 4 according to F. Gramann), a highly argillized, smectitic dust tuff with minute mineral fragments, was described from the Teufelsmoor well, near Bremen (Zimmerle *et al.* 1990, p. 124-125 ; Zimmerle, 1991, p. 168, Plate 2, Fig. 6). The extremely fine particle size makes identification of this sediment as volcanogenic troublesome. Similar lithology (composition, structure and particle size) - as those characteristic fragments in the Boom Clay - were observed in altered, lacustrine fossiliferous basalt tuffs of approximately the same age (Oligocene) close to one of the inferred source area (Enspel, Westerwald). Oligocene sediments in the Neuwied Embayment (Neuwieder Bucht), north of Koblenz, also contain volcaniclastic admixtures.

The highly fossiliferous, coarse-silty to fine-sandy Boom Clay, characterized by a marked organic matter and mica content, was deposited on an open marine shelf, possibly under the influence of a delta in a subtropical climate. The sedimentary setting was that of sedimentation of volcanic material in modern oceans as described by Lisitzin (1972, p. 179-193). Indirect effects of volcanism on the biogenic sedimentation may be mass deaths of plankton and occasional plankton blooms subsequent to powerful volcanic eruptions. Many of the liquid and gaseous volcanic products, however, that entered the chemical reservoir of the ocean, lost their volcanogenic identity rather quickly by mixing with terrestrial debris. Evidence of seismic phenomena such as slides and turbidity current transport are to be expected in these sediments, if sufficient slope was present. The areal distribution of ash and its properties are largely determined by three factors: the volume ejected, the height of ejection, and the particle size of debris. Usually more than 90 % of an ash is composed of volcanic glass.

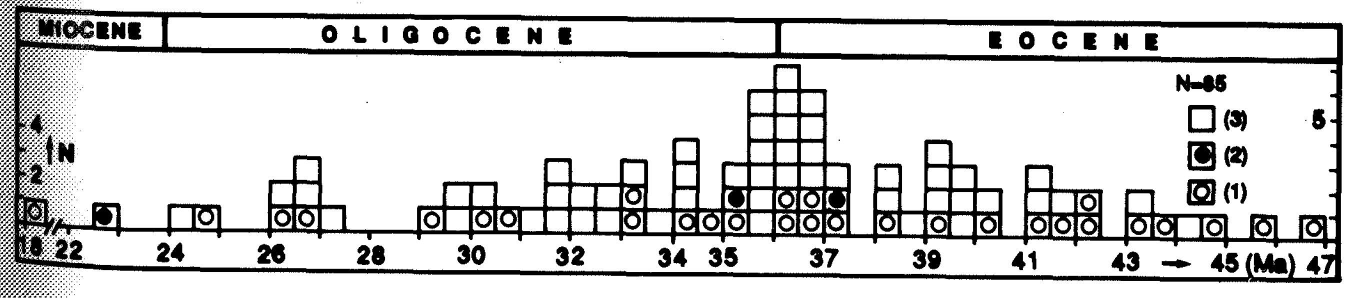

Figure 6. Distribution of isotopic K-Ar ages or volcanic rocks from the Hocheifel. (1) after Cantarel & Lippolt, 1977 ; Lippolt & Fuhrmann, 1983 ; Lippolt 1983. (2) after Schmincke & Mertes, 1979. (3) after Horn, Müller-Sohnius & Huckenholz 1985 and unpubl. data (after Huckenholz & Büchel, 1988).

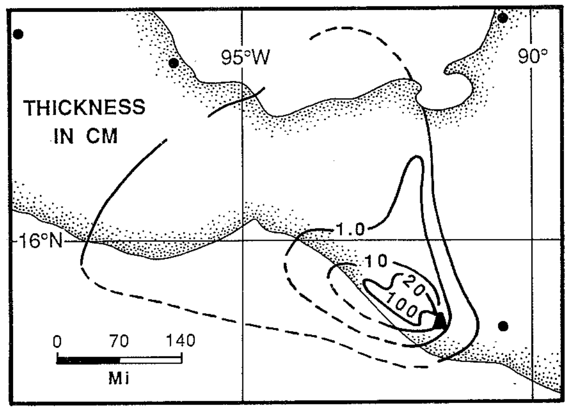

Figure 7. Example of tropospheric ash fall, Santa Maria volcano, Guatemala (after Lisitzin, 1972, fig. 173, B (2)). The volcanic cloud was transported northwestward by the winds over a distance of 450 miles.

The Boom Clay turns out to be composed of distinct detrital components derived from various rock sources and characterized by several transport mechanisms: eolian, fluviatile and marine. Long transport and polycyclic reworking, however, of the presumably soft and mineralogically unstable, argillaceous grains composing the Boom Clay seem to be less likely than short-distance first-cycle sedimentation. Only a minor amount of detrital grains are definitely of polycyclic origin.

Synsedimentary alteration and early diagenesis had a marked effect on the composition of the heterogeneous argillaceous sediments. Taking into consideration the dominance of volcanogenic debris, halmyrolysis and palagonitization were the important post-depositional processes in the forming of the Boom Clay. Halmyrolysis or submarine weathering is the geochemical reaction of sea water and sediment in a seabottom area. Palagonitization is a post-eruptive process which follows vitrification and granulation of basic magmas, i.e the alteration of basaltic glass by sea water (Honnorez, 1972).

Primary mafic minerals such as olivine, pyroxene and/or hornblende and other unstable volcanic components were presumably quickly transformed into a highly reactive, catalytically effective clay after deposition.

Additional interference by hydrothermal exhalations cannot be ruled out at this stage of early diagenesis.

During diagenesis, alteration of mica minerals, especially of biotite, continued and resorption of the mineralogically unstable and, to a lesser extent, of siliciclastic debris progressed.

6. CONCLUSIONS

The present thin-section examination of the Boom Clay - combined with previous observations and conclusions - lead to the following conclusions :

- The clayey silts and silty clays are composed of a soft argillaceous material (60-80 %) and siliciclastic silt and fine sand (20-40 %). The soft argillaceous material includes the clay-size fraction (< 2 µm) and thoroughly argillized larger particles of silt and sand size. The siliciclastic silt and fine sand consist of feldspar, quartz, micas and rock fragments.
- Fine-sand-size particles (100-300 µm) composed of secondary clays are key components for the genetic interpretation of the Boom Clay. They are interpreted to be thoroughly altered round lithoclasts of basalt and tuff. Also some fragments of more silicic trachyte occur. Similar altered lithoclasts are commonly observed in other clays and sandstones of varying age in which the degree of argillization increases with decreasing sediment grain size and increasing age.
- The mineralogically unstable clasts and other unstable minerals in the Boom Clay are seen in various stages of progressive resorption and replacement.
- A major problem of the Boom Clay fabric is that the grain contacts between the silt- and sand-size, argillized lithic grains and the microcrystalline clay matrix are "hazy". Thus, the original grain sizes and grain shapes are difficult to determine.
- In spite of the fact that the present particle-size distribution of the Boom Clay shows 60-80 % clay fraction, it is likely that the original sediment contained a considerably higher silt-size fraction.
- The Boom Clay is a marine shelf sediment containing a considerable amount of direct and/or indirect volcanogenic input from contemporaneous volcanoes in the Rhenish Massif (Siebengebirge and Hocheifel).
- The various components of the Boom Clay indicate a heterogeneous provenance: phytoclasts - heavy minerals - terrigenous siliciclastic material, some showing an oriented fabric - volcanic feldspars - argillized clasts of pyroclastic material.
- The complex sediment composition and heterogeneous provenance point to a variety of transport mechanism : eolian - fluviatile - marine.
- Thin-section analysis of argillaceous rocks provides valuable data on their original grain size and mineralogy, present mineral composition, sedimentary and tectonic fabrics and diagenetic alteration.
- Additional methodological efforts seem to be promising. Further thin-section study of the Boom Clay is planned to include possible refinements of the method. In addition, supplementary analyses are envisaged of: varietal features of light and heavy minerals, shape and surface features of the silt and sand grains using the scanning electron microscope, cathodoluminescence of selected samples and total rock composition (ICP-MS).

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PLATE 1

All microphotographs are taken in plane polarized light

Figure 1 - Layer of sand-size calcareous and agglutinated foraminifera filled with geopetal pyrite in sandy Boom Clay - TS 35.

Figure 2 - Silty Boom Clay with two almost completely masked, intensely weathered basalt grains of fine-sand size (dashed lines) - S 34b.

Figure 3 - Silty Boom Clay with coarser laminae containing coarse-silt-sized oval eolian quartz (Q), glauconite (G) with leucoxene, completely degraded biotite and a single minute quartz splinter - TS 32b.

Figure 4 - Elongate cleavage fragment of feldspar with zoning enhanced by opaque pigment (arrow) and well rounded, presumably eolian quartz (Q) in sandy Boom Clay - TS 33.

Figure 5 - Ore-pigmented volcanic rock fragment (dashed line and arrow) in an advanced stage of resorption by the argillaceous matrix in sandy Boom Clay. "Ghosts" of almost completely resorbed, mineralogically unstable grains can just be made out. Note cluster of three equidimensional angular or rounded quartz grains in the bedding plane which display corrosion and/or fracturing, and smaller elongate quartz splinters - TS 31.

Figure 6 - Angular fragment of relict feldspar partially resorbed by the pigmented clay matrix - TS 35.