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A review of heavy minerals in clastic sediments with case studies from the alluvial-fan through the nearshore-marine environments

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Abstract

Heavy mineral analysis can play an important part in unraveling the extrabasinal (e.g., source area weathering) and intrabasinal processes (e.g., hydraulic processes) that influence the formation of clastic rocks. Various clastic (conglomerates, wackes, arenites, siltstones) and pyroclastic rocks (tuffs, ignimbrites, lahars) spanning the interval from the Upper Carboniferous through the Early Tertiary SE Germany (Bavaria) and the North German Basin were investigated for their transparent and opaque heavy minerals. The samples have been taken from drill cores, percussion holes and outcrops of various environments of deposition which are representative of a cross-section from the basin edge to the basin center (alluvial fan, braided streams, meandering to anastomosing fluvial drainage patterns, swamps, lakes, estuarine and nearshore-marine deposits). Routine heavy mineral analysis may be applied to heavy mineral separates in the grain size fraction from 0.020 mm to 0.200 mm, using heavy liquids of 2.95 g ml^{-1}. The results furnish evidence that the strong points of this method lie in the fields of provenance analysis, paleoenvironmental analysis, and the study of volcanism and hydrothermal alteration. Routine heavy mineral analysis using the petrographic and ore microscope may successfully be combined with trace element analysis using ICPMS (e.g., REE, Th, U, Zr) and isotope studies (e.g., U, Pb). Radiometric age dating and the determination of the chemical composition of detrital apatite in late Paleozoic arenaceous rocks helped to pinpoint the type of source rocks and constrain the age of intrusion of the granites in the provenance area, from which the apatites were derived. This sedimentological method may be of interest to academicians and geologists working in the various fields of applied research alike (e.g., geoengineering, hydrogeology, exploration for hydrocarbons, uranium, coal and placer deposits).

Keywords: Germany; heavy minerals; sediment geochemistry; provenance analysis; paleoenvironment; hydrothermal alteration

1. Introduction

Heavy minerals (HM) have been widely used, especially by sedimentologists in Europe, to study diagenesis (Morton, 1979, 1986), weathering processes (De Jong and Van der Walls, 1971; Friis et al., 1980), provenance (Schnitzer, 1957; Morton, 1985a; Dill, 1989) of clastic rocks, and to assist stratigraphic correlation of monotonous terrigenous series (Weissbrod and Nachmias, 1986). This group

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of minerals has numerous advantages over light minerals, as HM provide a wider spectrum of silicates, sulfates, sulfides, oxides and phosphates than light minerals in the sand-size fraction, which is dominated by quartz, feldspar and Ca–Mg-bearing calcareous minerals (Milner, 1962; Boenigk, 1983; Mange and Maurer, 1991).

In this paper, the various mineralogical, chemical and geological facets of this method are shown for different sedimentary deposits ranging from conglomerates laid down near the apexes of alluvial fans through fluvial arkoses to fine-grained, well-sorted beach deposits and tidal clastics. The time of formation of the examples under consideration ranges from the Permo-Carboniferous through the early Tertiary. The different processes (e.g., provenance variation, hydrothermal alteration) which control the HM variations are discussed in case histories. The sampling sites selected for this study are located in northern and southeastern Germany (Fig. 1). Their study area covers those parts of (epi)continental basins where HM analysis has proven to work most successfully and may also be of assistance in hydrogeology, geoengineering and economic geology.

2. Sampling techniques and methods of investigation

Disintegrated samples of clastic and volcaniclastic rocks taken from several boreholes sunk into late Paleozoic and Mesozoic basin fills and from quarries were passed through 0.065 mm and 0.200 mm sieves. During some of these case studies volcanic rocks from the Permo-Carboniferous basin fill as well as Paleozoic and Precambrian crystalline rocks from the nearby basement were included in the HM investigations in order to get an overview of the potential source rocks. HM from silty marine sediments of early Tertiary age were extracted from the 0.020 mm to 0.125 mm size fraction, due to the small grain size of host rocks, which would not yield a reasonable

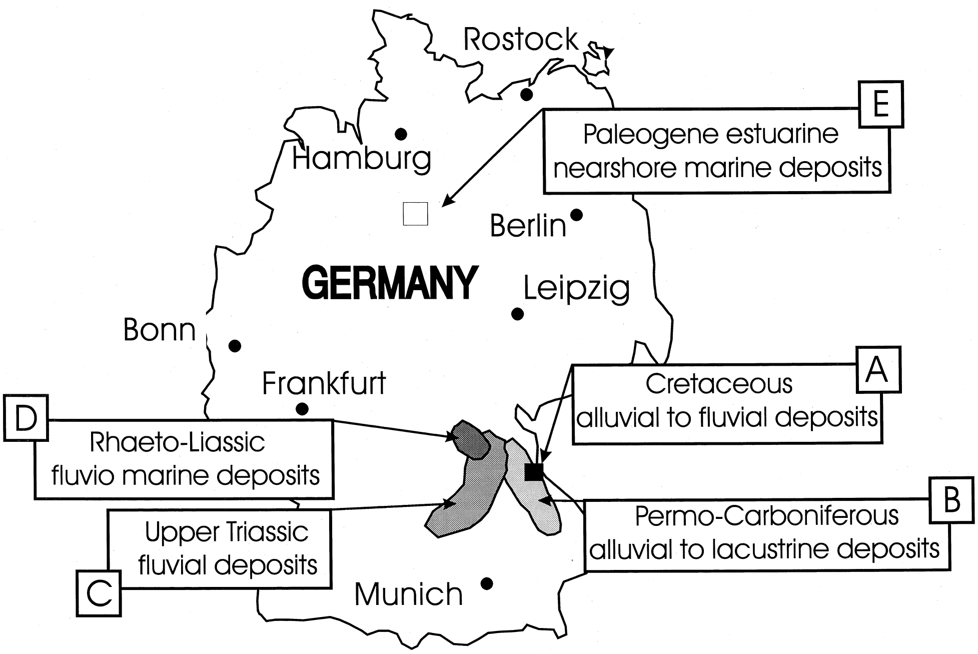


Fig. 1. Sketch map to show the position of the study areas in Germany: (A) The Cretaceous Parkstein Fan Complex, (B) Permo-Carboniferous Basins along the western edge of the Bohemian Massif, (C) Upper Triassic platform sediments in southern Germany, (D) Rhaeto-Liassic platform sediments in southern Germany, (E) Paleogene in northern Germany (Gorleben area).

quantity of HM in the 0.065 mm and 0.200 mm size fraction. Subsequently, mineral separations using heavy liquids in a settling tube (tetrabromethane: 2.95 g ml^{-1}) were performed. After removal of iron oxide coatings with Na dithionite, translucent HM were mounted on glass disks using Canada basalm, and opaque minerals were mounted on particulate polished sections.

The resulting HM separates were identified under the petrographic microscope or ore microscope counting between 200 to 300 grains per sample. Biotite (and green chlorite originating from biotite), commonly excluded from HM analyses (Mange and Maurer, 1991), were included in the grain counts in the present study. Experimental analyses prior to this investigation reveal that flakes of biotite and chlorite in these clastic rocks do not disintegrate into several daughter flakes when ‘softly’ preparing these samples. The numerical results are, therefore, not disturbed by the unique flaky structure of the biotite and chlorite.

HM separates rich in apatite were submitted to chemical analyses after having been concentrated by magnetic separation and checked under the optical microscope. Rare earth (REE) measurements were accomplished using inductively coupled plasma mass spectrometry (ICPMS). The U and Pb isotope analyses for age determinations were performed on a MAT R 261 mass spectrometer (thermal ionization with samples placed on a heating filament using silica gel [Carl and Dill, 1985]). To show the range of REE contents in each sampling site, the data arrays were plotted according to the procedure of Grauch (1989). The main reason for using bulk samples for geochemical analysis was that the contents of elements of interest in this study were below detection limits of electron microprobe analysis (EMP). Single grain measurements as done by

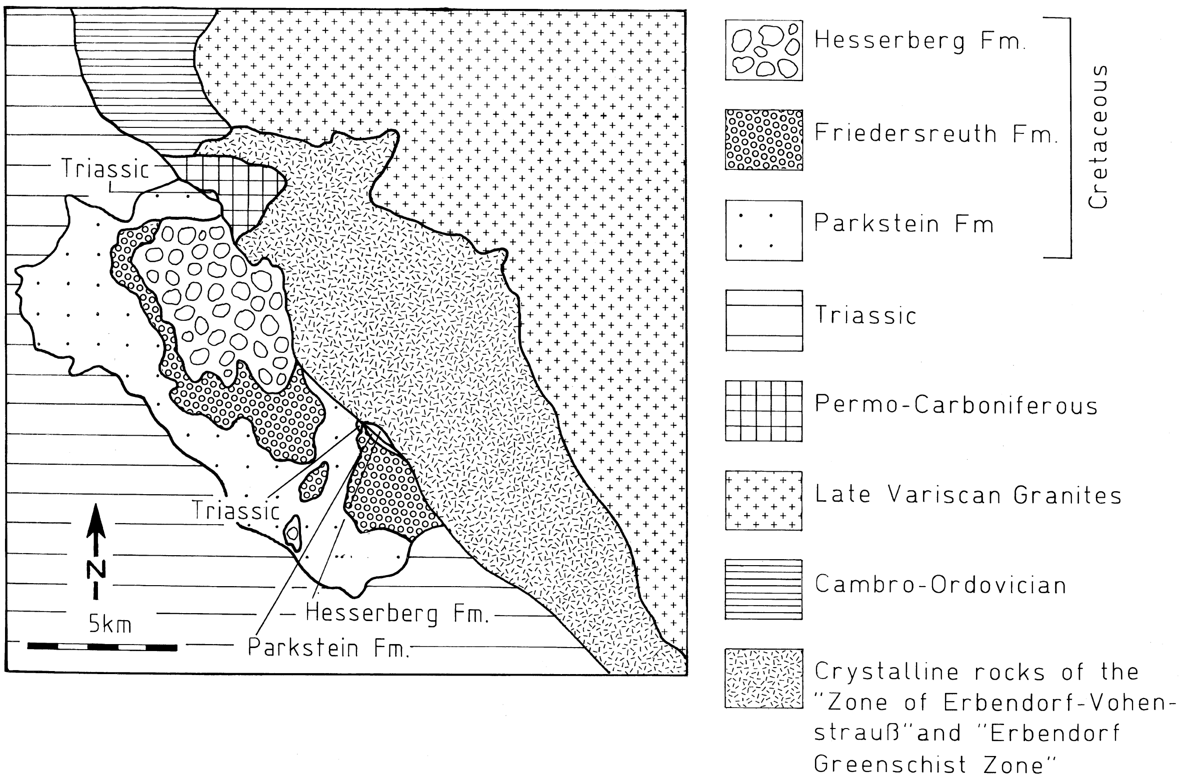


Fig. 2. Geological setting of the Parkstein fan complex.

Grigsby (1991) on detrital ilmenite, Nöltner and Zimmerle (1991) on allanite, or Morton (1985b) on garnet, can only yield valuable information if the contents of the elements of interest are in the range of X.0 to 0.X percent. This is, however, not the case for the REE, U and Th contents in these apatites. To corroborate zircon counts in HM separates measurements of whole-rock Zr contents were carried out by X-ray fluorescence (XRF).

3. Case histories from the alluvial fan through the nearshore-marine environments

3.1. HM response to fan progradation and unroofing of source area

3.1.1. Geological setting of the Upper Cretaceous Parkstein fan

From the late Paleozoic to the Recent, the Northeast Bavarian basement has been continuously uplifted. Detritus eroded during this period has been accumulated in various terrigenous depositional systems of the south German Basin (Helmkampf and Waeber, 1983; Klare, 1989; Dill, 1990a,b) (Fig. 1A to D). During the Late Cretaceous, a fan sequence was deposited in the adjacent lowlands near Parkstein (Figs. 1A and 2). The coarsening-upward succession of this fan sequence has been subdivided into three different units (Figs. 2 and 3) (Dill, 1990a, 1995). Upper Triassic arkoses are unconformably overlain by an arenaceous series, named the Parkstein Formation, which contains coal lenses in its lowermost part and contains abundant ferruginous crusts in its upper parts (Fig. 3, Table 1). The series represents a meandering to anastomosing fluvial system (Dill, 1990a). The succeeding Friedersreuth Formation was deposited in an alluvial fan system and contains debris flow deposits. Alluvial fan progradation ended with the deposition of boulder conglomerates of the Hesserberg Formation (Table 1).

The ‘dirty’, high-ash coal of the Parkstein Formation has a rather low vitrinite reflectance (R_V = 0.51%). This *R*-value of coalified matter in the paludal member of Parkstein Formation corresponds to a burial depth of about 500 m (Teichmüller et al., 1984).

A moderate diagenetic alteration may also be judged by the presence of vermiculite and smectite among the phyllosilicates (Ferreiro Mählmann, 1994; Krumm et al., 1995) (Table 1). The redox conditions fluctuated throughout deposition of the Upper Cretaceous fan sediments. Pyrite and marcasite are indicative of reducing conditions and goethite attests to oxidizing conditions (Table 1).

3.1.2. HM analysis of the Upper Cretaceous fan complex

3.1.2.1. Results. Minerals of high chemical and mechanical stability such as tourmaline, rutile and zircon prevail among the HM of the lowermost unit, whereas minerals of intermediate or low stability (sensu Morton, 1984) are present only in subordinate amounts. These include staurolite, epidote-group minerals, monazite, sphene, garnet, amphibole and biotite (Fig. 3). Kyanite is present throughout the entire fan sequence whereas apatite, which is widespread in the underlying Triassic arkoses, is missing (Salger, 1985; Dill, 1990a). Pyrite is replaced by goethite towards younger deposits. The central formation, named Friedersreuth Formation of the fan sequence is enriched in biotite and the topmost Hesserberg Formation is rich in amphibole, epidote-group minerals and garnet. HM analyses of samples from outcrops of the adjacent basement and of rock fragments contained in the various coarse-grained fan sediments yielded the same variegated spectrum of HM as it was encountered in the arenaceous and silty fan sediments. Apatite (in granitoids and porphyritic volcanic rocks), clinopyroxene and orthopyroxene (in pyroxene–garnet fels and metabasic igneous rocks), however, are exclusively encountered in rock fragments. The samples were taken from the nearby basement as well as Permo-Carboniferous rocks (for geological setting of Permo-Carboniferous rocks, see succeeding chapter).

3.1.2.2. Interpretation. In principle, HM mixing and variations in the paleorelief are responsible for the coexistence of HMs with different stabilities. Two processes, tectonic uplift and unroofing controlled the variation of HM. During deposition of the Parkstein Formation, the relief was low and the rate of

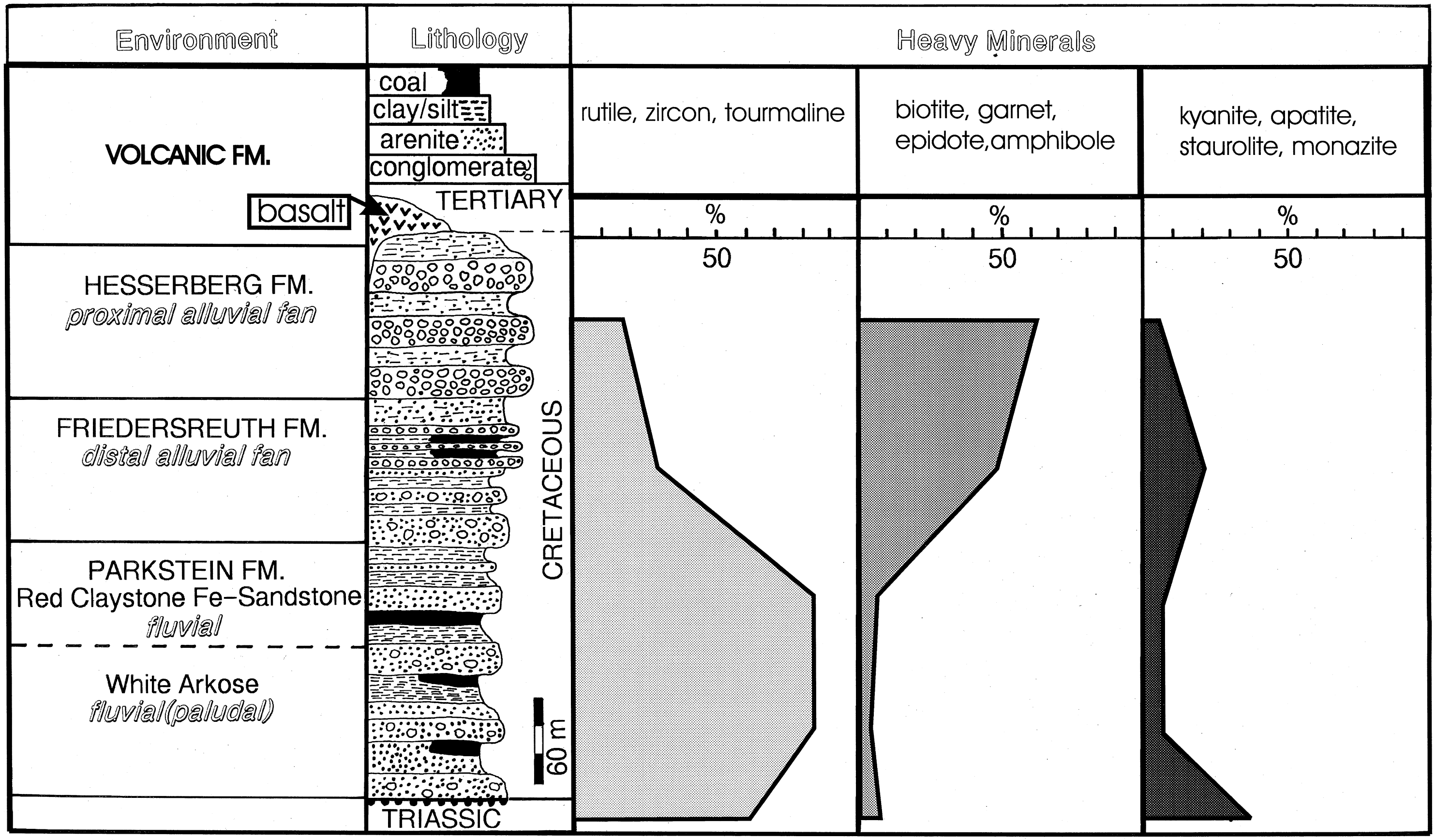


Fig. 3. Heavy mineral response to the variation in lithology of the prograding Parkstein fan complex. A total of 320 samples weighing 2 to 4 kg were taken from bore holes and surface exposures across the entire fan complex for HM study.

erosion was slow as suggested by high sinuosity channel patterns. Weathering could attack minerals for a long period and reduce labile constituents such as apatite from the underlying Triassic arkoses, which were dragged along the boundary fault (Tillmann, 1964; Dill, 1990a). Off the fan apex in the crystalline basement, medium-grade metamorphic rocks with kyanite and sillimanite were intermittently exposed during the initial stages of fan progradation. During deposition of the younger Friedersreuth Formation, the Mesozoic cover of the basement was almost completely stripped off, resulting in a considerable increase in the abundance of staurolite, epidote, garnet and biotite, derived from the medium-grade metamorphic rocks (Fig. 3). In the uppermost section of the fan, labile HM prevail over stable HM which originated from granitic and metamorphic rocks. The conglomerates of this host formation attest to a rugged relief and a very steep fan gradient, which allowed unstable minerals such as epidote and amphibole to persist even under extreme conditions of chemical weathering. The HM assemblage in this prograding fan in the Parkstein area mirror the reverse order of the lithology of the neighboring source areas.

Diagenetic alteration induced by deep burial was too low to promote significant replacement of detrital minerals. No skeletal minerals, no etch pits or precipitation of new minerals others than those related to weathering were observed. Cementation with quartz, calcite or barite as found in the underlying Permo-Triassic bedrocks is absent from the Upper Cretaceous rocks (Borg, 1986; Dill, 1990b).

Paleogeographic time slices and provenance analysis applied in a way similar to the approach taken in the case study of the Parkstein fan complex play a significant part in routine HM analysis (Allen and Mange-Rajetzky, 1992; Larue, 1997; Etienne and Le Griel, 1997). These sedimentological investigations are not only worth to be considered by basin analysts as they deal with the polycyclic evolution of the basin proper, but their results may also deserve attention beyond the edge of the basin under study by petrographers who try to reconstruct the geodynamic evolution of the source area and mostly have nothing but the detrital components in the clastic apron around the basement to shed some light on the youngest stages of basement uplift.

3.1.3. Economic geology

The study area is densely vegetated. Quarries and natural outcrops are rare. The limited human impact on this environment through industrial plants and agriculture, high rainfall, the geodynamic position close to an uplifting hinterland and the excellent hydraulic properties of the upper Cretaceous clastic

Table 1
Lithological characteristics of the Upper Cretaceous formations of the Parkstein fan complex

Formation	Rock color	Lithology and grain size	Bedding type	Rock-forming minerals	Environment
Hesserberg Fm.	gray to brown	claystones, siltstones, boulder conglomerates	massive to crudely bedded	quartz, feldspar, kaolinite, illite, chlorite	proximal alluvial fan
Friedersreuth Fm.	white to yellow brown	siltstones, matrix to clast-supported conglomerates (up to 2 m thick), plant debris	massive to planar cross bedding	quartz, feldspar, kaolinite, illite, chlorite, smectite	distal alluvial fan
Parkstein Fm.	white to yellow brown	claystones, siltstones, subarkoses, conglomerates, dirty high-ash coal, ferricretes	planar cross bedding $\gg$ trough cross bedding, fining-upward sequence	quartz, kaolinite, illite, vermiculite, goethite, marcasite, pyrite	fluvial, paludal

Stratigraphical order: youngest formation at the top.

rocks make this fan complex an excellent water reservoir for the neighboring towns. A couple of densely spaced wells drilled for water are a good coverage for sedimentologic investigations. HM analysis proved to be a valuable tool for paleo-environmental analysis and the only means for lithostratigraphic correlation of these water wells, because of lack of any paleontological data and to delineate the various aquifers. Mining subsidences and dumps lined up alongside the small gorges that cut into the Parkstein fan deposits are convincing evidence that ancient mining activities were targeted towards fluvial placer gold. Dispersal of mineralized bedrock and concentrates of precious metals are found in the uppermost proximal fan deposits where the boulder conglomerates of Hesserberg formation attest to a proximal alluvial fan environment and a rugged relief with a very steep fan gradient. These conditions were favorable and allowed unstable transparent and opaque HM minerals alike to be accumulated near the source area. While these alluvial–fluvial environments in mid-Europe have since long been abandoned in search of detrital gold, similar catchment areas elsewhere—e.g., Canada—are still considered as lucrative plays for placer gold (Eyles and Kocsis, 1989). A consistent increase in gold grains was reported to occur with decreasing age of the host formation in alluvial fan deposits from New Zealand (Youngson and Craw, 1996). Size sorting streams resulted in transport of fine-grained gold and retention of small nuggets in proximal fan deposits.

3.2. Classification of fan types based on the type and amount of HM

3.2.1. Geological setting of Permo-Carboniferous basins

In southeast Germany, four basins—the Schmidgaden, Weiden, Erbendorf, and Stockheim basins—became filled with Permo-Carboniferous clastic and volcaniclastic sediments with thicknesses locally exceeding 700 m (e.g., Schmidgaden Basin, Helmkampf and Waeber, 1983). These basins are lined up like pearls on a string alongside the southwest boundary of the northeast Bavarian basement (western edge of the Bohemian Massif) (Fig. 1BFig. 4).

The deposits mapped in these basins may be interpreted as a set of fan deposits ranging from proximal fan deposits with debris flows and braided stream sediments to distal fan plains originating from swamp environments (Helmkampf et al., 1982; Helmkampf and Waeber, 1983; Dill, 1989) (Table 2). In some places calcretes and lacustrine deposits developed. The basins under study mainly differ from each other with respect to the volcaniclastic intercalations. In the Stockheim basin, these volcaniclastic rocks consist almost exclusively of pyroclastic deposits such as air fall tuffs, ignimbrites and lahars (according to Fisher and Schmincke, 1984). From the Erbendorf Basin, volcanic rocks together with air fall tuffs may be recorded, whereas in the Weiden well and V 16 bore hole, both of which were drilled in the Weiden Basin, volcaniclastic rocks are scarce (Fig. 4). Minute layers of air fall tuffs are the sole representatives of pyroclastic deposition among the Permo-Carboniferous rocks (Dill, 1989). In the well Schmidgaden S 1, located further towards the south, no longer any volcaniclastic rocks were observed (Fig. 4, Table 2).

The spectrum of phyllosilicates is varied, especially in the Erbendorf Basin (Table 3). The same holds true for the interval of vitrinite reflectance which has a spread from $R = 0.49\%$ in the Erbendorf Basin through 1.74% obtained from samples in the Stockheim Basin. Using vitrinite reflectance and phyllosilicate assemblages the maximum temperatures of diagenesis are around 135°C.

3.2.2. HM analysis of Permo-Carboniferous basins

3.2.2.1. Results. The HM spectrum of the Permo-Carboniferous fan deposits is very varied (Fig. 5) running the gamut from unstable to ultrastable constituents. Chlorite and green biotite locally containing slender crystals of rutile and zircon are widespread in debris flow and proximal braided stream deposits. Apatite, tourmaline, amphibole and garnet are common constituents of fluvial deposits. Kyanite and staurolite are present in the basin fill of all sites except Stockheim, where medium-grade regional metamorphic rocks are absent in the hinterland. Brown biotite and amphibole, slender crystals of zircon and apatite, acicular anatase and brookite are disseminated in the tuffaceous sandstones, pyroclastic deposits, and the intermediate to acidic volcanic rocks. Ferroan dolomite and barite merit particular attention for their well-shaped rhombs and needles. They commonly co-occur with pyrite, galena, chalcopyrite and sphalerite. Other opaque HM such

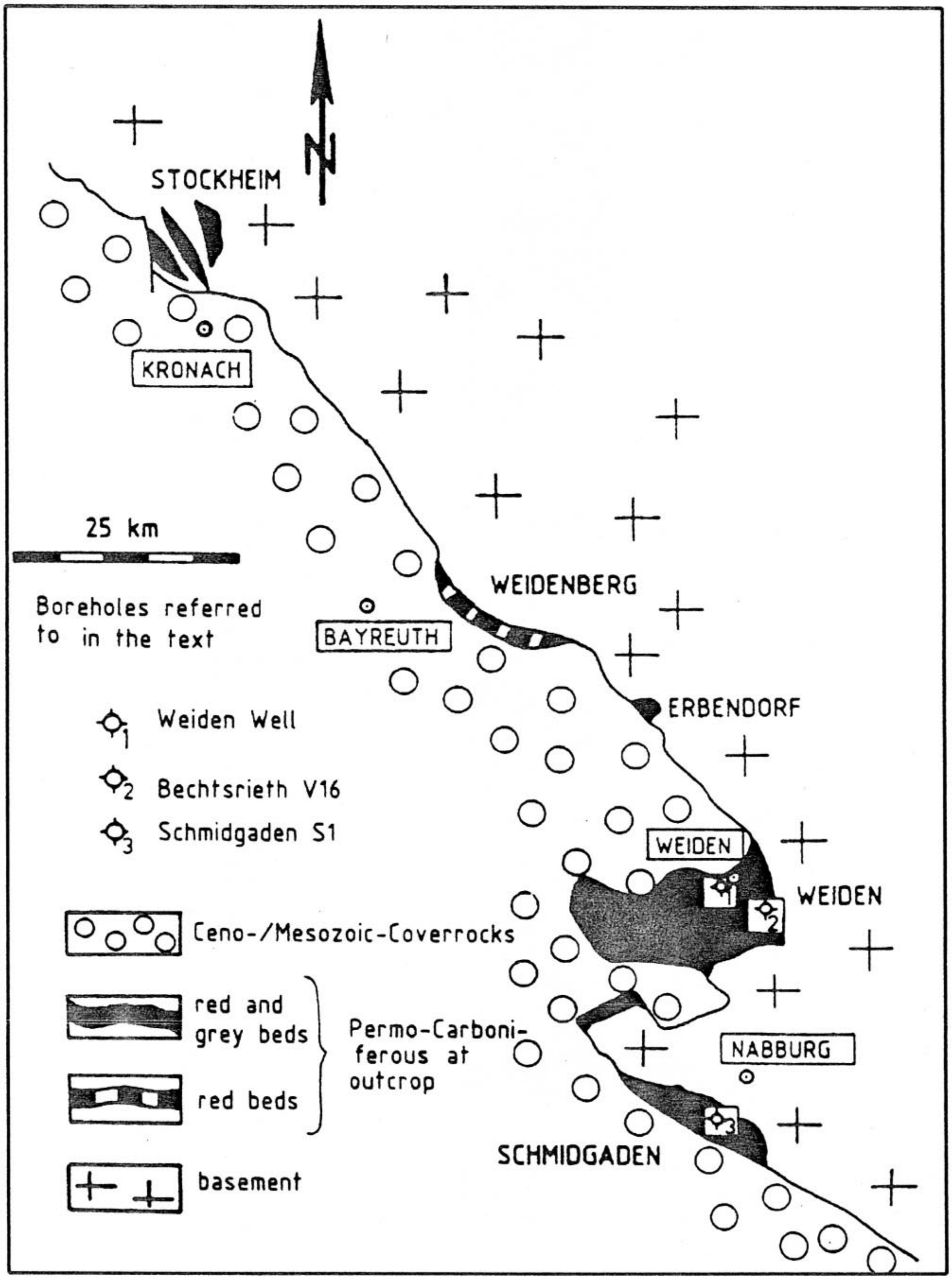


Fig. 4. The Permo-Carboniferous basins along the southwestern edge of the Bohemian Massif.

Table 2
Lithological characteristics of the Upper Carboniferous and Permian fan complexes

Fan type	Rock color	Lithology and grain size	Bedding type	Mineralogy	Environment
Stockheim type I	grayish green to red brown	welded and unwelded tuffs, vitric tuffs, lapilli tuffs, lahars, volcanic wackes, ignimbrites, debris flows, siltstones, conglomerates, coal, silcretes	massive, lensoid and discontinuous layers, cross bedding	quartz, feldspar, open illite kaolinite, chlorite, Fe-, Pb-, Cu-, Zn-, As sulfides, U oxides	swamps, lacustrine deposits, fluvial deposits, alluvial fan
Erbendorf type II	black to gray green, red brown	tuffs, siltstone, sandstone, arkoses, conglomerates, carbargillites, calcretes	massive, lensoid and discontinuous layers, cross and parallel bedding	quartz, feldspar, illite, kaolinite, chlorite, smectite–illite mixed layers, smectite, vermiculite mixed layer	swamps, lacustrine, fluvial, alluvial fan
Weiden type III	black, gray, white, brown, red	tuffaceous mudstones, claystones, carbonaceous claystones, arkoses, conglomerates, calcretes	lensoid and discontinuous layers, cross and parallel bedding	quartz, feldspar, illite, smectite–illite mixed layers smectite, kaolinite, chlorite	lacustrine, fluvial and alluvial deposits
Schmid-gaden type IV	gray, white, brown	siltstones, arkoses, conglomerates	massive, cross and parallel bedding	quartz, feldspar, illite	fluvial and alluvial deposits

as ilmenite, titanomagnetite, hematite, magnetite and minor amounts of chromite predominate among the HM suites of pyroclastic deposits. In silcretes and calcretes, goethite modifications, plates of anatase, and brookite are the only species of HM present. Considering the total amount of HM, tuffs and clay-

Table 3
Lithological characteristics of the Upper Triassic (‘Keuper’) fluvial deposits

Formation	Rock color	Lithology and grain size	Bedding type	Rock-forming minerals	Environment
Feuerletten	red brown	mudstones, siltstone, marl,	parallel bedded	quartz, feldspar, calcite, irregular mixed layers, illite, sudoite, kaolinite	playa
Burgsandstein	white, gray, brown	claystones, arkoses, conglomerates, silcretes, calcretes, phoscretes, carbonaceous siltstones	parallel bedding, trough and planar cross stratification, fining-upward sequences	quartz, feldspar, dolomite, calcite, chalcedony, apatite, illite, tosudoite, smectite, chlorite, ± palygorskite, ± corrensite, anhydrite	fluvial deposits
Coburg Sandstein	gray, brown	claystones, arkoses, conglomerates	parallel bedding and undifferentiated cross stratification, fining-upward sequences	quartz, feldspar, illite, corrensite	fluvial deposits

Stratigraphical order: youngest formation at the top.

stones are least suitable as host rocks (Fig. 6). Wackes and arenites in the foreland of an uplifted crystalline basement, however, have fairly good host rock qualities, with amounts totaling as much as 1.7 wt.% of rock-forming minerals.

3.2.2.2. Interpretation. The peripheral position of these fan deposits relative to their more central equivalents rules out deep burial and implies a good preservation potential for the original HM suite. Intrastratal solution controlled by late diagenesis may

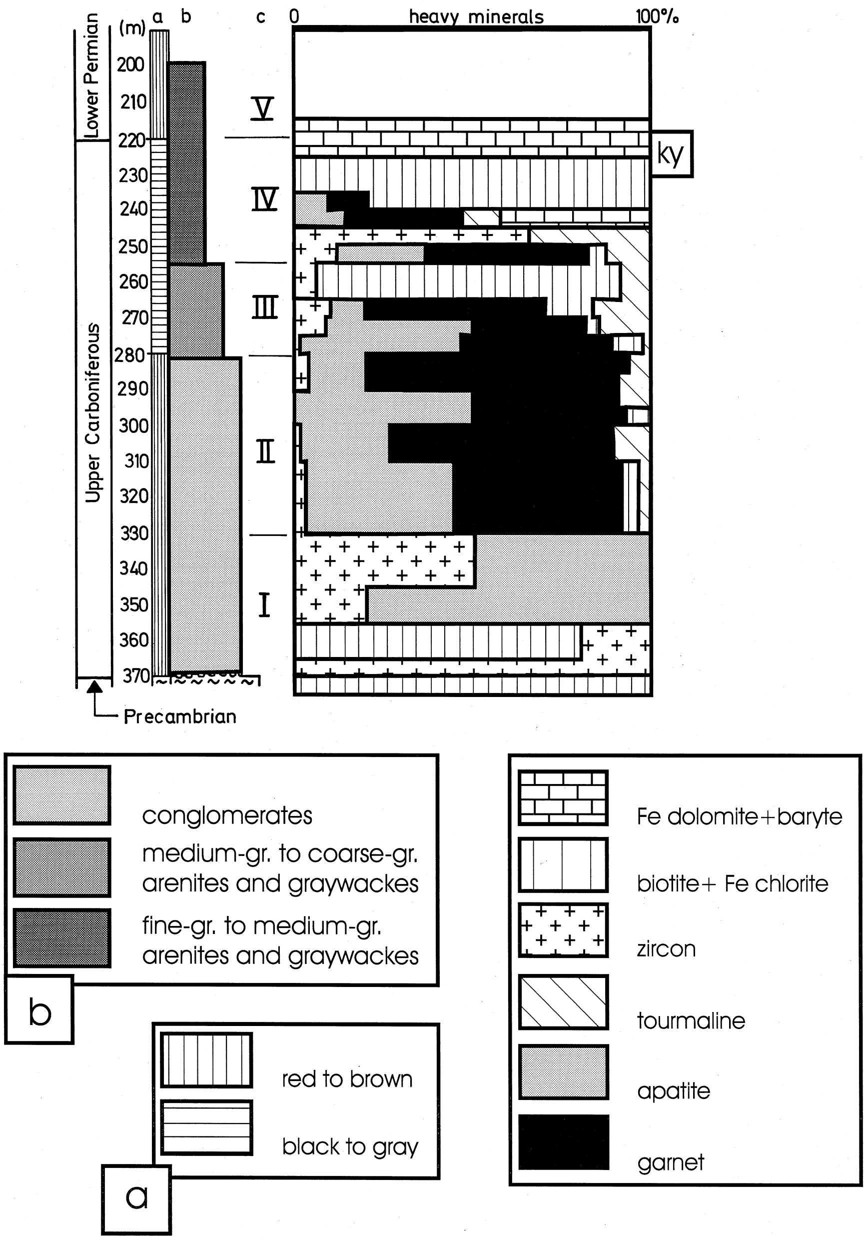


Fig. 5. Reference profile through the Permo-Carboniferous basin fill at the SW edge of the Bohemian Massif (Weiden Basin) showing the varied spectrum of HM and lithologies. Legend: a: rock color, b: lithology, c: formations; ky = kyanite.

be disregarded in this marginal part of the basin. Lavas vented during the late Paleozoic were responsible for the high heat flow and high thermal gradient which are witnessed by the fairly high *R*-values of vitrinite reflectance. The igneous processes also favored the circulation of hydrothermal solutions. These endogenous processes have a further impact on the amount and composition of HM present in these clastic rocks. Similar effects on HM have recorded from elsewhere, among others by Markwort (1991) from the Triassic Karoo Beds, Tanzania, which were laid down in intramountain basins similar to that under study with respect to the environment of deposition.

By means of authigenic and allogenic HM, four types of fans may be distinguished (Fig. 7):

I: pyroclastic fans,

II: mixed fans (alluvial input > pyroclastic input),

III: alluvial fans (alluvial input > > > pyroclastic input), and

IV: alluvial fans sensu stricto.

The pyroclastic fans (type I) are abundant in authigenic HM (e.g., barite, ferroan dolomite, specularite), cementing detrital minerals or filling vugs and fissures. Opaque mineral grains of the system TiO_2–FeO–Fe_2O_3 bear witness of high temperatures in a sedimentary environment which otherwise shows overall low-temperature, near-surface diagenetic alteration. Allogenic HM are very scarce and consist almost exclusively of well rounded tourmaline, zircon and rutile. The high ZTR index (sensu Hubert, 1962) indicates strong redeposition and derivation from a provenance of very low grade to low grade regionally metamorphosed rocks.

The mixed fan (type II) shows all the features of pyroclastic fans, yet there is a much greater input from the uplifted basement. This endogenous influx diminishes in the type III fan, but it is still detectable in the HM spectrum. The amount of HM is large, except for some fine-grained distal deposits of the fan plain. The nearness to the provenance area and the resulting short transport distance allow even labile constituents from calcsilicates (e.g., sphene), medium-grade regionally metamorphosed rocks (e.g., kyanite) and opaque minerals from greenstone belts (e.g., chromite) to survive. Bipyramidal anatase which precipitated from hydrothermal solutions (Tröger, 1969; Yau et al., 1987) occurs side-by-side with plates of anatase which formed from alteration of Fe–Ti-bearing minerals at near-ambient conditions. The last-mentioned species of TiO_2, anatase, offer a clue to paleo-weathering and has features associated with paleosols (Schellmann, 1986, 1994). Garnet and apatite in and below such saprolites, on the other hand, are often corroded by fluids during soil-forming processes.

Alluvial fans s. st. (type IV) in the study area rarely contain authigenic minerals and do not host any opaque minerals characteristic of volcanic and hydrothermal activity. Regarding the group of allogenic minerals, type IV fans closely resemble types II and III. In the coarse-grained sediments which debouched from the uplifted basement into the immediate foreland, flakes of brown biotite indicative

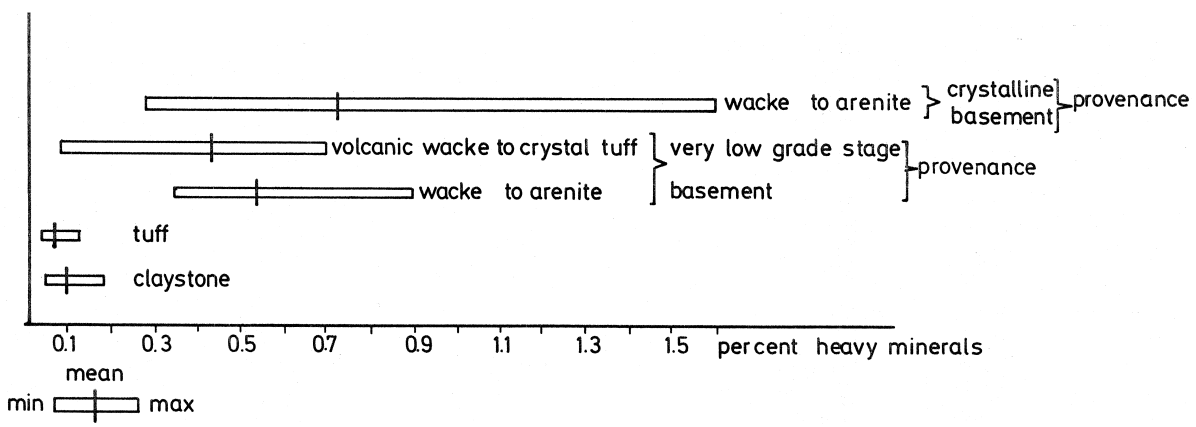


Fig. 6. The proportion of HM as a function of type of host rock.

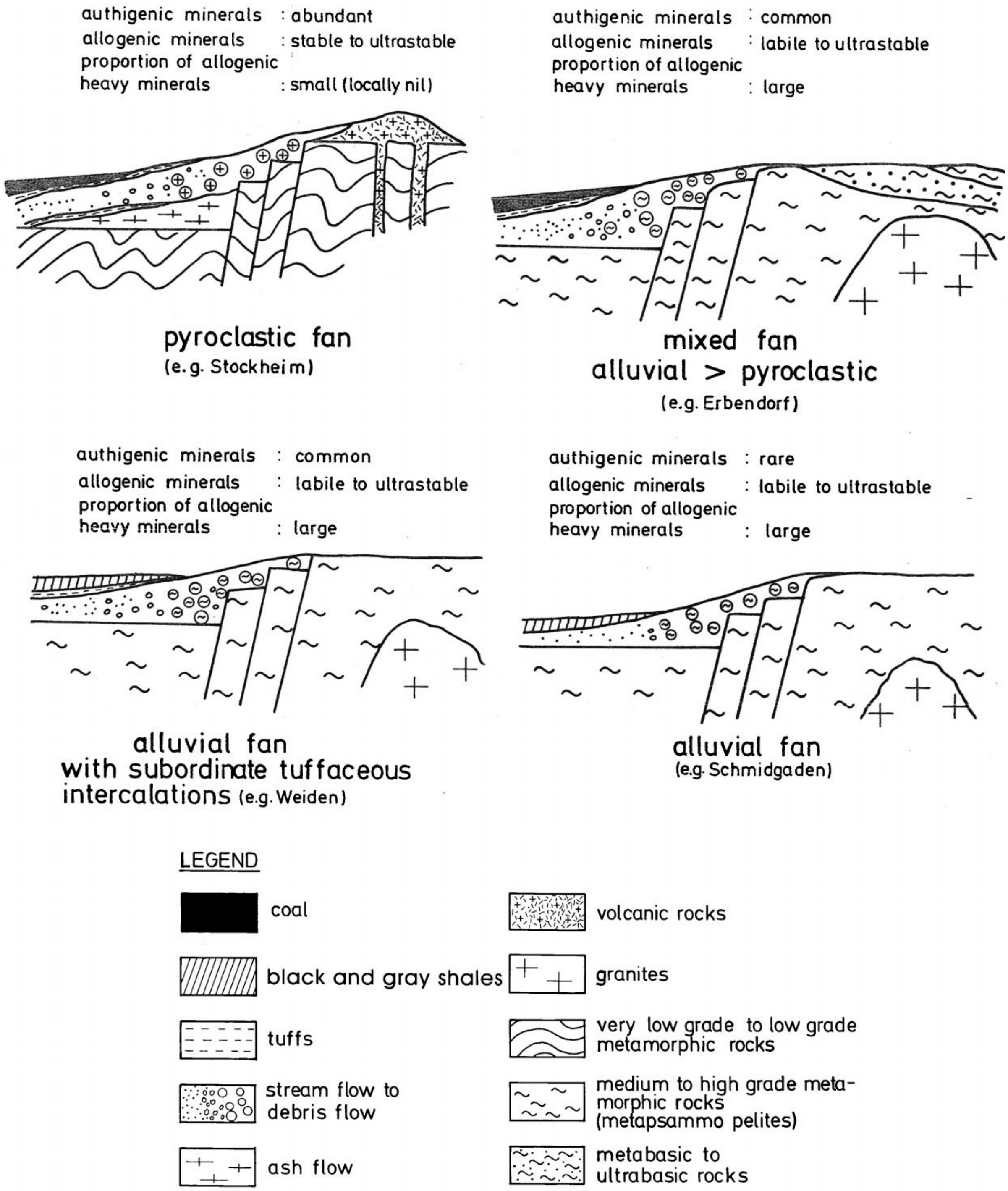


Fig. 7. Classification of fan types based on the type and amount of HM present in the clastic rocks. For detailed lithological, description see Table 3.

of pyroclastic processes are substituted for by green biotite and chlorite–biotite aggregates which attest to retrograde regional metamorphism.

3.2.3. Economic geology

This procedure of fan distinction based on HM may successfully be applied to cores, cuttings, and even to samples from outcrop of fan deposits, provided that alteration of HM through modern soil-forming and weathering processes during the Quaternary can clearly be distinguished from paleopedological processes (Dill and Zech, 1980).

During the recent past, these Permo-Carboniferous series have been under exploration for uranium and hydrocarbons and were mined until the late sixties for hard coal (Dill, 1994a). Uranium is preva-

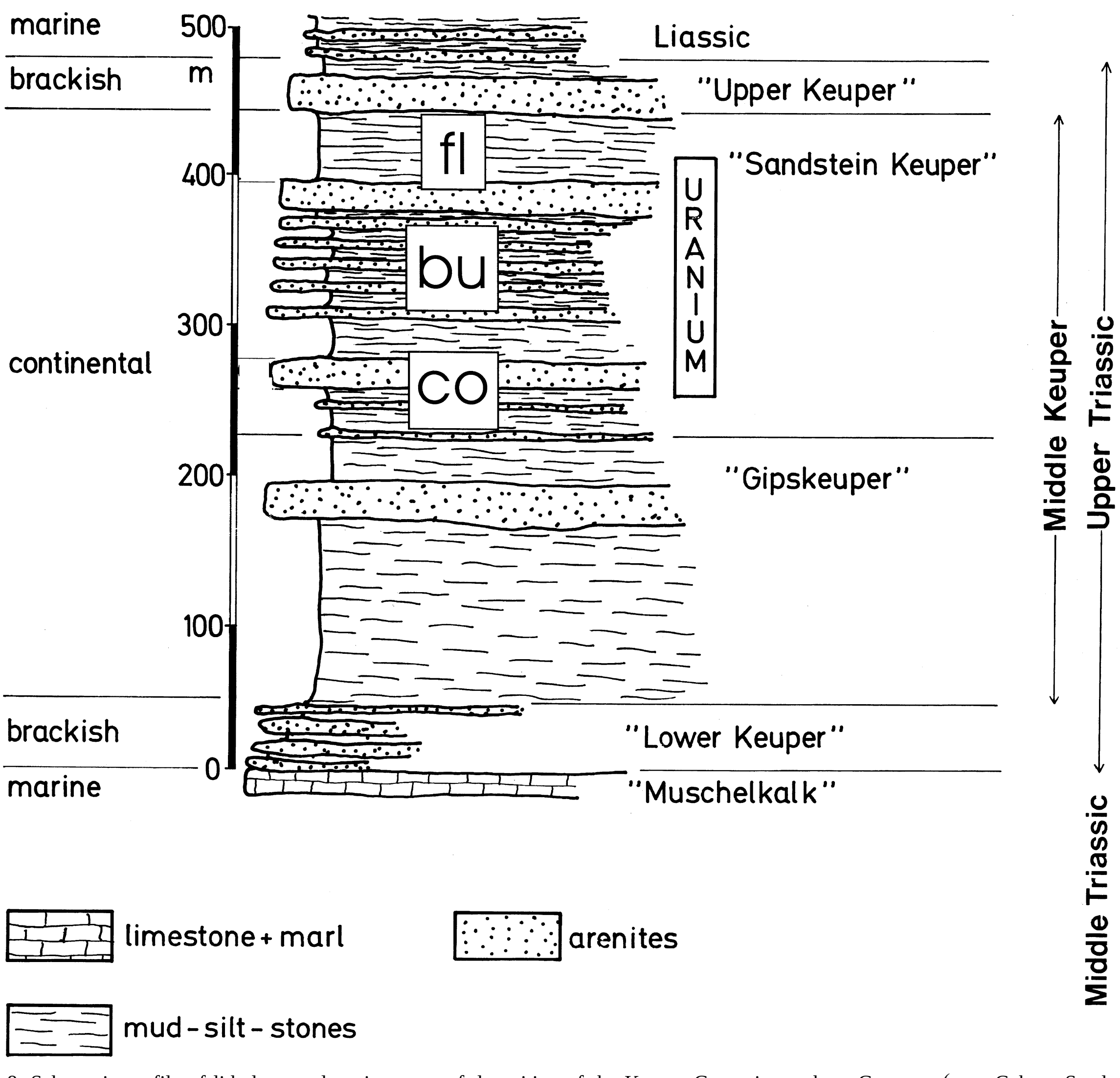


Fig. 8. Schematic profile of lithology and environment of deposition of the Keuper Group in southern Germany (co = Coburg Sandstein, bu = Burgsandstein, fl = Feuerletten). For detailed lithological description, see Table 4.

lently contained in the coalified matter accumulated in the swamps of the pyroclastic fan (type I), medium volatile bituminous coal was mined from fan types I and III, and oil was found in lacustrine sediments of fan type III (Dill et al., 1988, 1989). Opaque HM may be used for lithostratographic correlation and to delineate the ore-bearing horizons as well as help decipher the complicated environment of deposition in the various fan complexes. Similar to the Late Cretaceous Parkstein fan deposits which were discussed previously gold is also enriched in the Permo-Carboniferous fan deposits (Dill, 1990c). It is the type III alluvial fan with subordinate pyroclastic input and type IV alluvial fan sensu stricto where gold is enriched to contents of as much as 0.355 ppm Au. In the Permo-Carboniferous fans others than in the Late Cretaceous Parkstein fan gold was accumulated in the distal fan section near the redox interfaces reflecting alternating ground water tables. Although different with respect to internal fan position both catchment areas near Parkstein and in the Weiden Basin are characterized by mineral assemblages made up of unstable transparent HM which attest to an overall rugged relief and a very steep fan gradient.

3.3. Tracking changes in Fe budget of Triassic clastics by HM variation

3.3.1. Geological setting of the late Triassic sediments in southern Germany

The U-bearing ‘Sandstein Keuper’ forms part of a continental series between the marine Muschelkalk beneath and the fluvio-marine clastic rocks of the Liassic above (Figs. 1C and 8) (Emmert, 1964; Richter, 1985). The series under study is composed of gray and red medium- to coarse-grained arenites which show parallel and cross stratification (Table 3). Calcretes, silcretes and phoscretes are concentrated at various stratigraphic levels. In the finer-grained dark interbeds carbonaceous lenses may locally be encountered. The mineral assemblage has been investigated in great detail by Salger (1985) (Table 3). His list of phyllosilicates contains sudoite and corrensite as minor constituents among kaolinite and illite, which dominate the mineral assemblages. These rare phyllosilicates are stable under very different physicochemical conditions controlled by hydrothermal processes and postsedimentary alteration. Their field of stability extents across the boundary into the field of very low grade metamorphism (Theye and Seidel, 1993; Dubinska et al., 1995; Anceau, 1996). In the area under study the varied composition of phyllosilicates is merely a function of the environment of deposition and the strange element composition brought about along with formation of playa and fluvial overbank deposits rather than diagenesis (Salger, 1985). The organic matter (OM) present in these rocks is not amenable to measurements of vitrinite reflectance, yet the chemical composition of the OM may offer a tool to constrain the vitrinite reflectance and thereby shed some light on the diagenetic history of these Mesozoic rocks. The maturity of the type III kerogen (coalified matter) gave a mean value of 433°C during RockEval analysis and is equivalent to a vitrinite reflectance of 0.5%. Vitrinite reflectance points to a postdepositional alteration of the OM in the field of subbituminous coal (Stach et al., 1982), conforming to a maximum temperature of between 60°C to 70°C (McTavish, 1978; Teichmüller, 1979).

Following the basic studies dedicated to fluvial environments and comprehensive reviews of terrigenous clastic depositional systems (Bristow and Best, 1993; Martin, 1993), the paleogeography of this series in that region may be compared with a fan-playa environment, displaying a great variety of fluvial drainage patterns from distal braided stream to meandering stream. A similar paleogeographic interpretation has also been recorded for the Upper Triassic sedimentary rocks exposed in the immediate surroundings of Halle, N-Germany by Bachmann and Beutler (1996). The Coburg Sandstein and Burgsandstein represent the fluvial section of the fan complex, whereas the Feuerletten is representative of the most distal part, the playa (Fig. 8).

3.3.2. HM analysis of late Triassic clastic rocks

3.3.2.1. Results. Mineralogical investigations were focused on HM which were sampled in drill holes spudded during a uranium exploration campaign targeted to the Burgsandstein, the uppermost part of the Coburg Sandstein and the lowermost part of the

Feuerletten (Figs. 8 and 9). The allogenic non-opaque HM constitute a monotonous stable to ultrastable mineral association constituting of zircon, monazite, garnet, apatite and subordinate tourmaline, staurolite and rutile. In addition inspection of polished sections of HM lead to the identification of magnetite, titano-magnetite, ilmenite, different types of Ti-oxides, base metal sulfides, Fe sulfides and 'sooty' pitchblende rimmed by coffinite. The sulfide-U mineralization developed at the boundary between permeable channel sediments and sealing overbank fines interbedded with crevasse splay deposits. The sulfide-U mineralization developed close to the interface between the garnet and the zircon–monazite assemblages (Fig. 9).

3.3.2.2. *Interpretation.* The understanding of the behavior of Fe-bearing minerals during diagenesis is decisive when interpreting the origin of the sulfide-U mineralization. Fe may be released from etched or decomposed almandine, which is very widespread in the Mesozoic beds. This is corroborated by sulfide layers at various sites containing abrupt shifts of garnet-dominated to zircon-dominated HM suites. Another source for Fe can be looked for among the Fe–Ti oxides, where dissolution features and corrosion of mineral grains is widespread. Groundwater percolating downslope in the fan caused alteration of the HM. Fe released during upslope breakdown of these minerals favored the precipitation of Fe sulfides downslope when the groundwater stagnated at

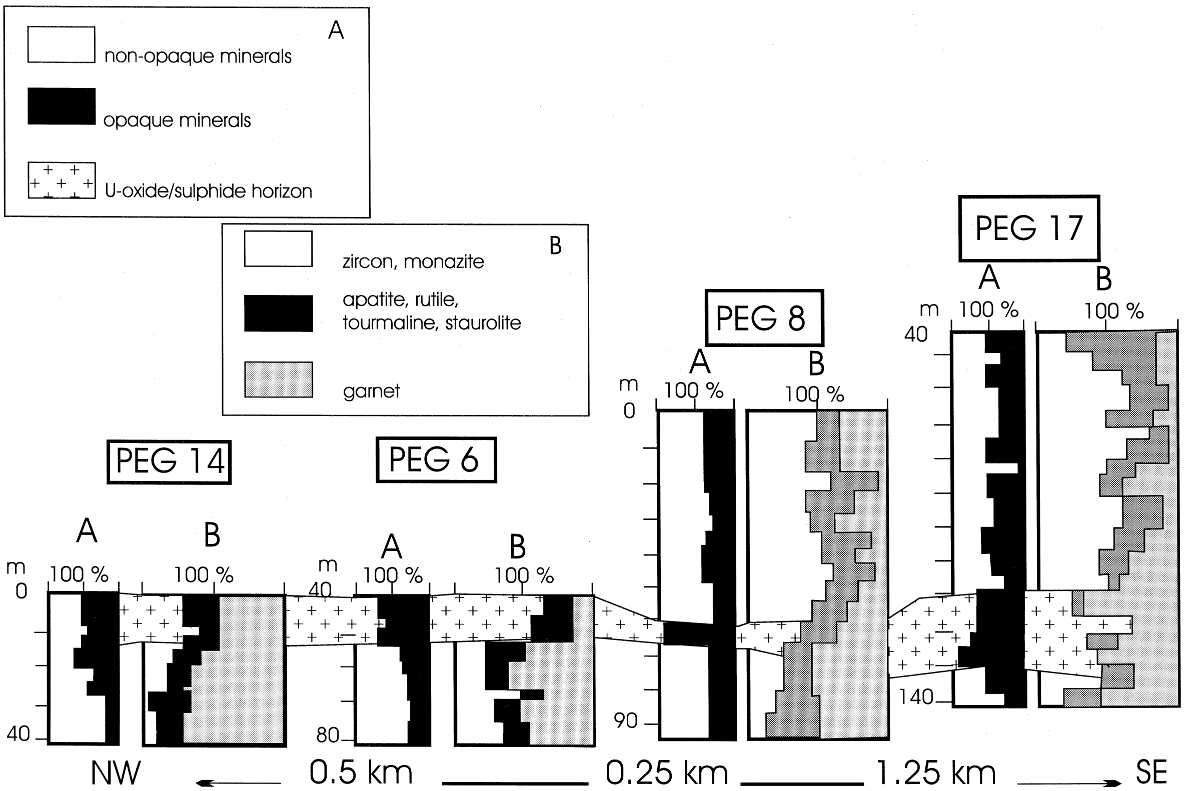


Fig. 9. HM in arenites of the late Triassic in southern Germany. The proportion of non-opaque and opaque HM (column A, given in percentage) relative to drill depth. The variation of non-opaque HM (column B) relative to drill depth. The U oxide and sulfide-bearing horizon referred to in the text is marked in the section with a band connecting the percussion holes that are aligned along approximately 2 km of a track line parallel to the paleoslope of the fan. The sulfides and U oxides developed near the boundary between the zircon–monazite and garnet assemblages.

the interface between permeable channel sediments and less permeable overbank fines or playa deposits. Any modification of the HM composition triggered by deep burial or high temperature alteration along with hydrothermal processes may be excluded for these sites of mineralization. Formation of authigenic HM and alteration of HM along with concentration of U oxides and sulfides originated from weathering and groundwater movement during epidiagenesis. The diagenetic conditions these Triassic clastic host rocks went through are quite similar to those of the Upper Cretaceous fan complex near Parkstein (see previous chapter); the Upper Cretaceous clastic rocks, however, were laid down at a more proximal position relative to the source rock.

3.3.3. Economic geology

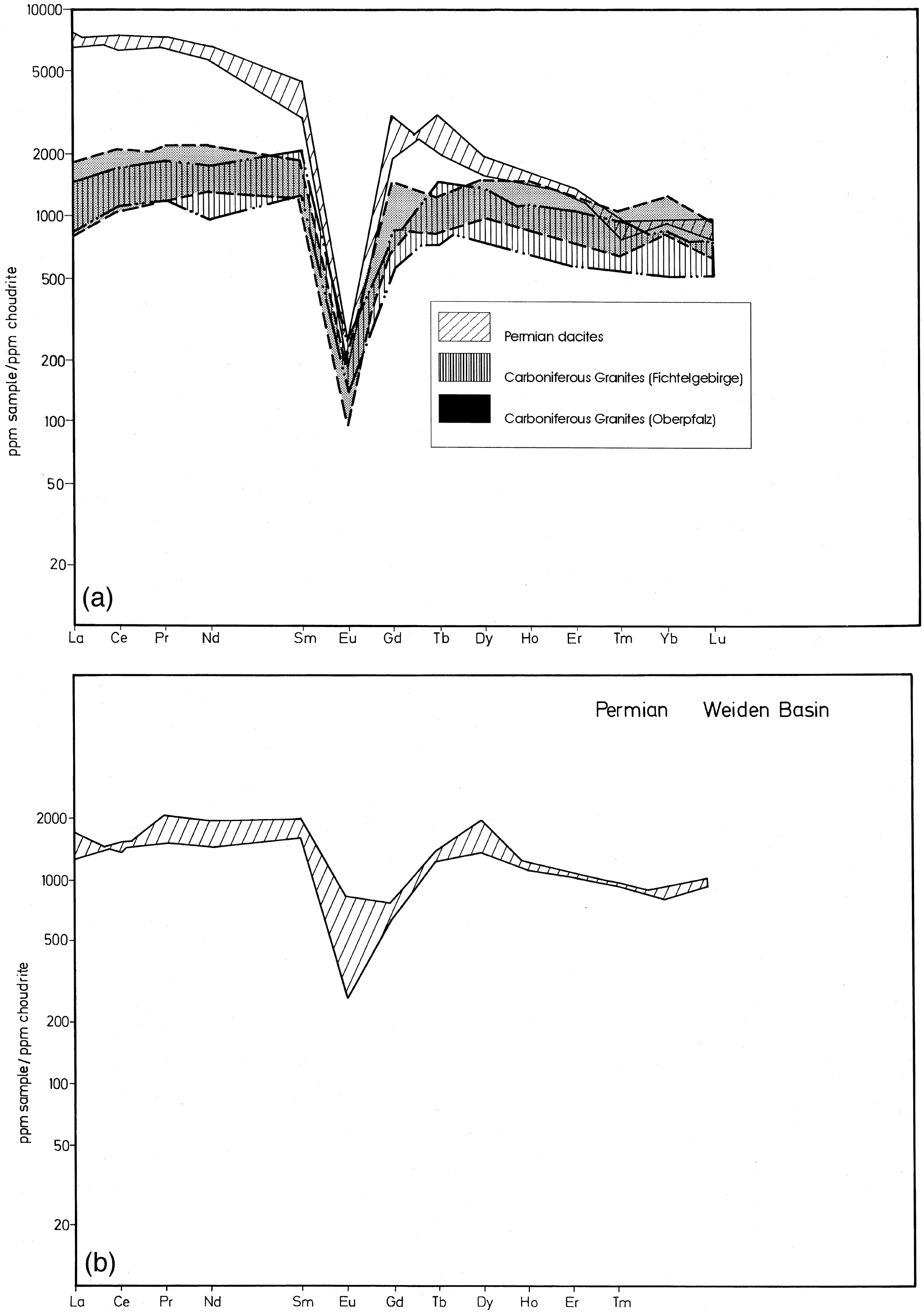
Allogenic and authigenic HM in the Triassic host sediments immediately respond to ore-forming processes and, therefore, may be used as an ‘ore guide’ to delineate the ore-bearing interbeds in the sedimentary record. Eh changes were controlling the sulfide and black ore U concentration as well as Fe mobilization in the HM assemblage. HM separated from cuttings of percussion drill holes may assist in tracing the paleoredox interfaces and thereby help localize ore-bearing horizons. The amount of opaque minerals in the drill samples combined with the readout of the wireline log may assist in delineating the horizons most promising for U concentration (Fig. 9).

Alteration of detrital magnetite–ilmenite was used as an ‘ore guide’ in U-bearing continental sandstones of the Morrison Formation, New Mexico in the way as Fe sulfides were applied to localize ore shoots in the uraniferous Keuper Series, Germany (Adams et al., 1974). HM concentrated from drill-hole cuttings were used for the interpretation of the alteration of detrital magnetite–ilmenite which has taken place in oxygen-deficient ground waters through selective dissolution of iron from magnetite and ilmenite. The sites of altered Fe and Fe–Ti oxides are now occupied by clots of Ti oxides such as brookite and anatase. The chemical conditions which produced the alteration assemblages described here are essentially those under which the U deposits formed. HM extracted from drill cuttings have proven to be a useful exploration guide in those deposits where is an antipathy between detrital ilmenite and magnetite and U mineralization (Adams et al., 1974).

3.4. REE patterns and U / PB isotope ratios as tools for determining provenance of detrital apatite and age of source rocks

In spite of its low stability during epidiagenesis, apatite is fairly widespread in continental Permo-Carboniferous (Fig. 1B) and Triassic clastic rocks (Fig. 1C), the geological setting of which has been described earlier (Morton, 1986). This phosphate mineral offers a good tool to determine more precisely the provenance of HM (Dill, 1994b). Other common detrital minerals such as zircon or monazite are less suitable, as they suffer strong reworking, and their precise source is hard to determine. Apatite is known for its rare earths contents (REE) and is amenable to U/Pb age dating. In Fig. 10, chondrite-normalized REE patterns of apatite from potential source rocks (Fig. 10a) are compared with apatite from lower Permian arenites of the Weiden Basin (Fig. 10b). Dacite REE patterns display a strong fractionation of heavy rare earths (HREE) and light rare earths (LREE), whereas apatites from granitic rocks and Permian arenites are devoid of such REE fractionation. HM separates from Permian arenites abundant in apatites were selected for special mineral dressing procedures. Multistep heavy liquid and magnetic separations were applied to these samples in order to enrich the apatite to concentrations of greater than 90%. HM such as zircon, allanite, monazite or titanite abundant in U and Pb and thereby often some impact on the radiometric age dating were not spotted in the HM concentrate under study. It is mostly some quartz coated with iron-oxide–hy-

Fig. 10. Comparison of chondrite-normalized REE patterns of (a) potential apatite source rocks (dacites, granites) and (b) apatite host rocks of Permian age.


10000
5000
2000
1000
500
200
100
50
20
ppm sample / ppm choudrite
Permian dacites
Carboniferous Granites (Fichtelgebirge)
Carboniferous Granites (Oberpfalz)
(a)
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Permian Weiden Basin
2000
1000
500
200
100
50
20
ppm sample / ppm choudrite
(b)
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm

droxides which escaped from mineral purification and still lingers in the apatite concentrate. It has no meaning for the radiometric age dating of apatite as the content of U and Pb which might be scavenged by the iron-oxide–hydroxides is too low to reshuffle the U/Pb ratios of apatite. Based on the $^{206}Pb/^{238}U$ ratios, radiometric age dating yielded ages between 281 Ma and 311 Ma. From the concordia plot, an age of formation of 346 Ma was obtained. The amount of common lead present in the detrital apatite precludes Pb/Pb ratios for age determination:

Pb_{common} 204/206: 0.054827
0.000043
207/206: 0.855545
0.000653
208/206: 2.087780
0.001326.

Conclusively, apatite from Carboniferous crystalline rocks, which were truncated by erosion during the early Permian, were delivered into the basins subsiding into the Variscan basement. K/Ar cooling age of muscovite and biotite derived from crystalline rocks of the adjacent basement fall in the range 360 to 370 Ma (Wemmer, 1991). The older suite of Variscan granites was intruded between 325 to 310 Ma, whereas the younger intrusions took place down to 280 Ma (Stettner, 1992). Even if the detrital apatite grains did not originate from one single source rock, the isotopic data obtained may be used as a reasonable age information to geochonologically constrain the age of formation of a granitic source area. Supplementary data concerning U/Pb dating of HM have been published by Dörr and Franke (1989) for the metasedimentary rocks being exposed in the neighboring basement. Dating of detrital zircon yielded primary U/Pb ages from 2400 Ma to 500 Ma with a late reshuffling of the U/Pb system at around 150 Ma when the source rocks were uplifted. There exists a gap between zircon of Precambrian to early Paleozoic age which was derived from metasedimentary rocks and apatite which was formed throughout Late Variscan granite intrusions.

This is a more sophisticated method which opens up new perspectives in paleogeographic studies similar to the studies of Darby and Tsang (1987) focused on ilmenites or Owen (1987) focused on zircon. Detrital apatite acts as a geological clock which is not set back by the sedimentary processes. Its low stability allows for better constraining the immediate source rock than the refractory minerals (e.g., zircon).

3.4.1. Economic geology

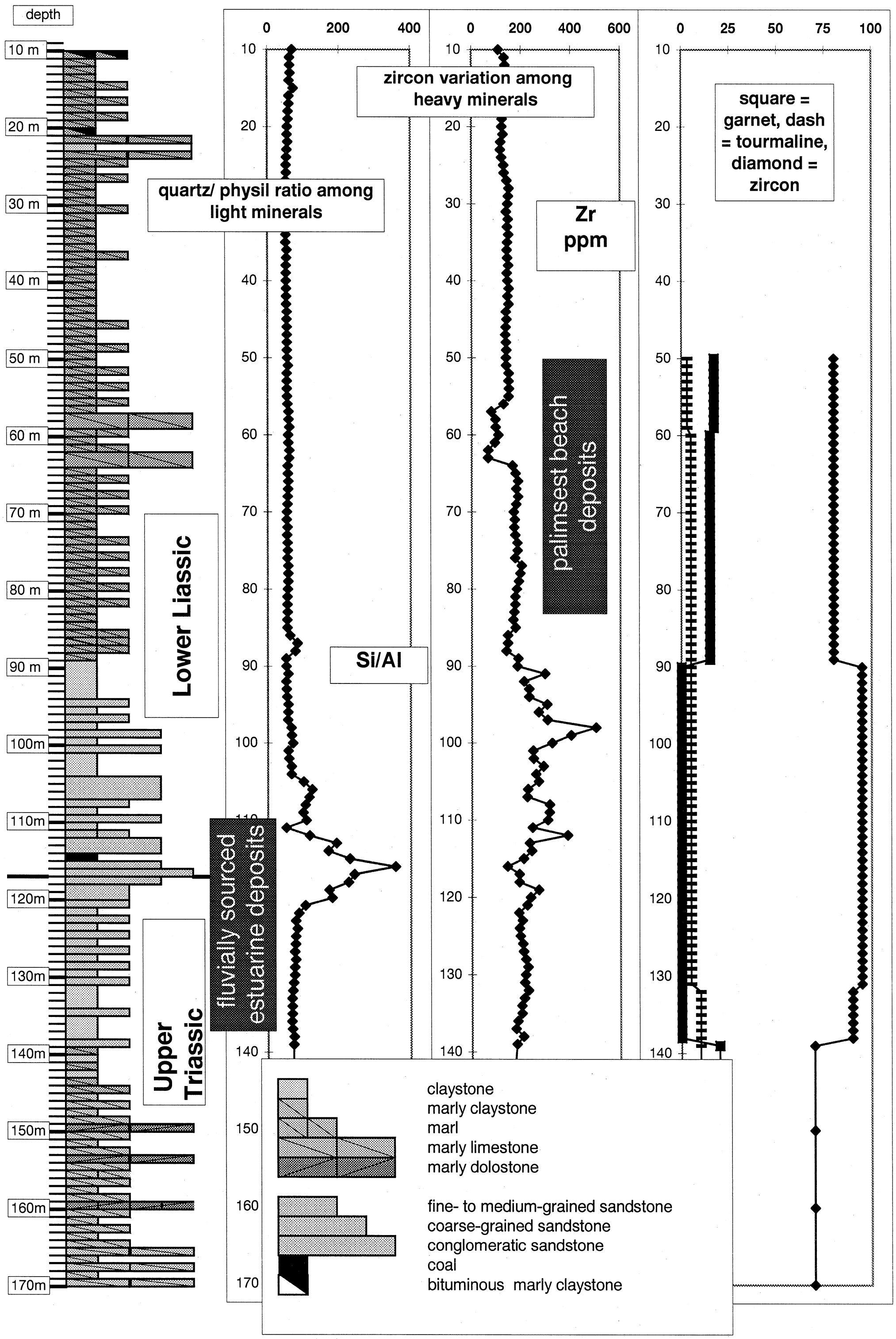
The method may also be applied in exploration. Placer apatite rich in REE, U or Th may be used as an ‘ore guide’ to sort out metalliferous ‘hot granites’ in the hinterland, which may contain economically significant amounts of Sn, W, U, Th and REE (Halls, 1985). It may be an efficient tool also in basement areas with metamorphic and granitic host rocks of Sn, W and U concealed by thick weathering crusts (Westerhof, 1986). In this case, however, other phosphate minerals such as xenotime or monazite or even zircon are recommended for radiometric dating in search of metalliferous ‘hot granites’, since apatite is expected to be removed from the HM assemblage in saprolites and even some saprocks. Morey and Setterholm (1997) found that the elements considered in this chapter may be mobilized and fractionated by strong weathering and that sediments derived from the weathered materials can display modifications of the original patterns.

3.5. Zircon and zirconium contents to distinguish fluvial from nearshore-marine deposits

3.5.1. Geological setting of the Triassic–Liassic sediments in southern Germany

The upper Triassic continental clastic sediments as they were described in the previous chapter (see also Fig. 8—uppermost section) give way step-by-step to Rhaeto-Liassic fluvio-marine sediments (Meyer, 1985; Schmidt-Kaler, 1985) (Figs. 1D, 8 and 11). The lowermost Liassic series in the study area, consist of alternating fine- to medium-grained

Fig. 11. Litholog, chemologs and heavy mineral log (heavy mineral data from Salger, 1982) through the transition zone from the Triassic into Liassic fluvio-marine sediments.


depth
10 m
20 m
30 m
40 m
50 m
60 m
70 m
80 m
90 m
100m
110m
120m
130m
140m
150m
160m
170m
Lower Liassic
Upper Triassic
fluvially sourced estuarine deposits
quartz/ physil ratio among light minerals
Si/Al
zircon variation among heavy minerals
Zr ppm
palimsest beach deposits
square = garnet, dash = tourmaline, diamond = zircon
claystone
marly claystone
marl
marly limestone
marly dolostone
fine- to medium-grained sandstone
coarse-grained sandstone
conglomeratic sandstone
coal
bituminous marly claystone

sandstones interbedded with gray claystones and marls (Meyer, 1985). In some of these clay beds plant debris and coalified matter are common (Table 4). Dolomitic encrustations are present in the Triassic–Jurassic transition zone which reflects the transgression of the Jurassic sea towards the southeast with some funnel-shaped estuaries incising into the Variscan basement (Table 4). Sedimentary characteristics, bedding type and the overall mineral assemblage suggest that the lower Jurassic rocks were deposited in a shallow nearshore-marine environment. Biodata suitable for age dating or constraining the paleoecology of the basin are missing. The stratigraphic subdivision is therefore controversial as it is the precise interpretation of the environment of deposition, which is supplemented by the succeeding HM analysis. The diagenetic history resembles that of the Triassic rocks immediately underlying the Rhaetian and Liassic host rocks. The reader is referred to the description of the Upper Triassic lithologies earlier in this paper.

3.5.2. HM analysis of Triassic–Liassic sediments

3.5.2.1. Results. The amount of HM is low and the spectrum fairly monotonous in the Triassic–Liassic transition zone. Salger (1982) has recorded zircon, garnet, tourmaline and sporadic amounts of staurolite from the Triassic–Liassic transition zone (Fig. 11). Zircon is across the section under study the prevailing HM. Staurolite is present only in trace amounts in the lowermost part of the drill section under consideration and for that reason not shown in the HM log of Fig. 11. Zirconium may reside in various accessory minerals of igneous and metamorphic rocks. In the sedimentary realm it is only zircon which plays a major part among the HM and thereby becomes the principal host of zirconium in clastic rocks (Mange and Maurer, 1991). Considering the spectrum of light minerals, stratigraphic subdivision or paleogeographic interpretation do not become much better. A combination of light and HM analyses seems most appropriate to shed some light on the environment of sedimentation. The distribution of the zircon content is expressed by the downhole plot of zirconium which covaries with the zircon content of the HM log (Fig. 11). As the HM assemblage is rather poor with respect to quantity and only of low diversity fairly wide sampling intervals were chosen to achieve reasonable results throughout investigation of this Triassic–Liassic transition zone (Fig. 11). Silicium and aluminum in the samples under study is accommodated in the crystal lattice of quartz and phyllosilicates, including kaolinite, illite, smectite and chlorite, and quoted as the Si/Al ratio in Fig. 11. The observed variation in the downhole plot of Zr follows that of the Si/Al ratio, yet attains its maximum, in terms of paleogeography, more basinward.

3.5.2.2. Interpretation. Zr and the Si/Al ratio both are grain-size-controlled and reflect sediment reworking and continental run-off. The Zr and the Si/Al ratio, or in other words, the HM and phyllosilicates (physils) are representative of the bed load and suspended load, respectively, which were carried by the rivers draining into the basin throughout late Triassic and early Liassic times. Zircon is commonly

Table 4
Lithological characteristics of the Upper Triassic ('Keuper') to Lower Liassic mixed continental-marine deposits

Formation	Rock color	Lithology and grain size	Bedding type	Rock-forming minerals	Environment
Lower Liassic Beds	gray, black	claystones, marly claystones, sandstones, marls, marly limestones, marly dolostones phosphorites, carbonaceous claystones ('coal')	parallel bedded, trough cross bedding	quartz, calcite, dolomite, siderite, phosphate, irregular mixed layers, illite kaolinite, chlorite	nearshore marine, beach deposits
Upper Triassic Beds (Feuerletten plus Rhaetian Beds)	red brown	claystones, siltstones, marls	parallel bedded	quartz, feldspar, calcite, irregular mixed layers, smectite illite, sudoite, kaolinite	playa, fluvial, coastal marine

accumulated together with other HM such as magnetite and Ti minerals in coastal sediments and in placers interbedded with sandy beach deposits (Sutherland, 1985; Pham Van Man, 1994). Similar placerlike reworking in the littoral zone was at a maximum during the early Liassic. The amount of zircon in these coastal strata is a function of reworking of older sediments or of debris newly delivered into these distal parts. The varietal placer-like zircon concentrations in the arenaceous rocks which may be recognized across the drill section from 110 m to 95 m proved especially informative, demonstrating reworking in palimpsest beach deposits. High Zr or zircon contents are considered as palimpsests resulting from transgressive reworking of older HM deposits in a nearshore-marine environment. Anomalously high contents of zirconium in the chemical log and correlative high read-outs of zircon in the HM log attest to strandline deposits and mirror the edge of the sea. HM enrichment in the shore zone is derived from a combination of sorting mechanism; that is mineral grains are maintained on the beach as a whole according to the equivalence of their settling velocities (Peterson et al., 1986). Present-day placer deposits are exploited down to a water depth of 50 m (Zimmerle, 1973). Quartz influx indicated by the anomaly of the Si/Al between 110 and 120 m drill depth was at maximum during the latest Triassic and is fluvially sourced from one of the estuary opening up into the Jurassic sea. This abundance in quartz occurs stratigraphically lower in the downhole plot than the series abundant in Zr. Owing to their lack of any contemporaneous enrichment of zircon strong reworking of these Lower Liassic clastic sediments may be ruled out. The HM signal which was used to paleogeographic interpretation of coastal sediments cannot be blurred by any diagenetic or hydrothermal alteration, as zircon is known to be the most stable HM in the sedimentary realm (Müller, 1996). This is also valid for the Si/Al ratio which is governed by the most stable light mineral in clastic rocks, quartz.

3.5.3. Economic geology

The stratigraphic section shown in Fig. 11 is of interest for hydrogeologists as well as economic geologists, owing to the thick pile of claystones and marls that form base of a flourishing ceramic industry. To precisely correlate the various drill holes even a mineral assemblage impoverished with respect to HM may offer valuable services. The joint use of the downhole plot of element ratios sensitive to changes in the paleoenvironment with the HM logs may be supplementary in the study of reservoir rocks for hydrocarbon exploration (Hatch and Leventhal, 1992; Jones and Manning, 1994). The stacking pattern of highly and less permeable rocks across the drill section under study is well illustrated by the downhole variation of Zr or, in terms of HM, the zircon contents. Abrupt changes of both parameters in the downhole plot furnish evidence of coarser-grained interbeds being encased by finer-grained less porous sediments, which may act as some sort of sealing horizon for fluid and gas-bearing reservoir rocks. The results from this study can predominantly be used towards prediction of placer deposits in ancient and modern littoral environments (Syamsudin, 1994; Palmer, 1994—further literature cited thereunder). This technique may successfully be applied to percussion holes and drill cores alike.

3.6. Allogenic *vs.* authigenic HM in nearshore-marine deposits

3.6.1. Geological setting of the Paleogene sediments in northern Germany

The lower Tertiary successions of the North German basin predominantly consist of shallow marine, fine-grained shelf sediments which grade towards the southeast and south into continental deposits infilling embayments and estuaries (Lotsch, 1969; Krutzsch, 1992; Dill et al., 1996). The lithological record in the Gorleben area is very monotonous consisting of siltstones and claystones and some interbedded glauconitic sandstones (Figs. 1E and 12, Table 5). Air fall tuffs form thin layers in the lower Eocene and upper Paleocene sections (Fig. 12, see stratification between drill depth 710 m and 670 m). The Tertiary rocks under consideration have undergone only moderate postsedimentary alteration under conditions of epidiagenesis. The phyllosilicate assemblage is mainly controlled by the volcaniclastic input—smectite—and the Fe limitation and redox conditions in the shallow marine environment (see glauconite, siderite, pyrite). Deep burial did not exist and resultant alteration of the fine-grained clastic rocks can be neglected.

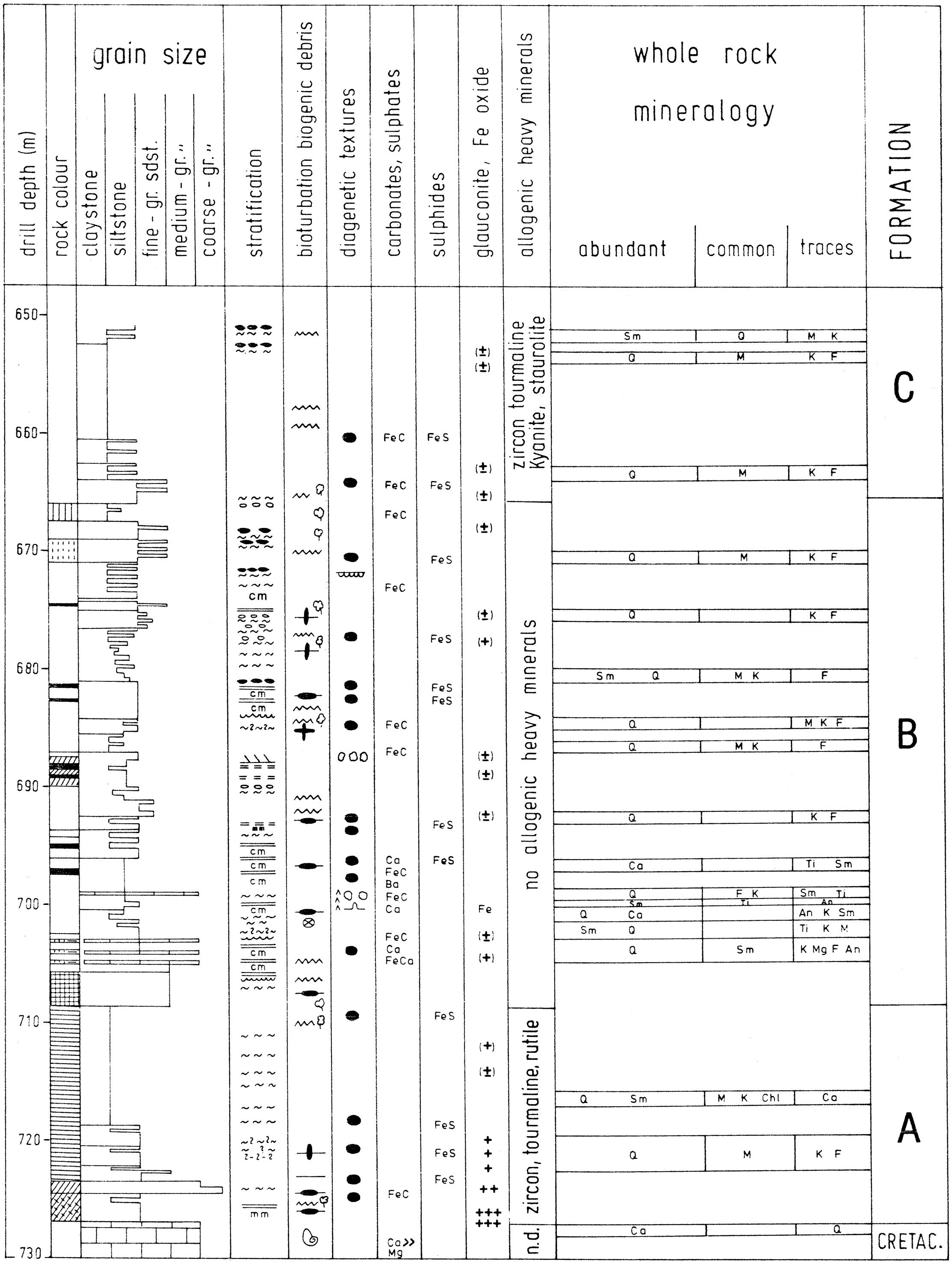


Fig. 12. Litholog and mineralogy of the Paleogene rocks in the lower parts of the rim sink of the Gorleben salt dome.

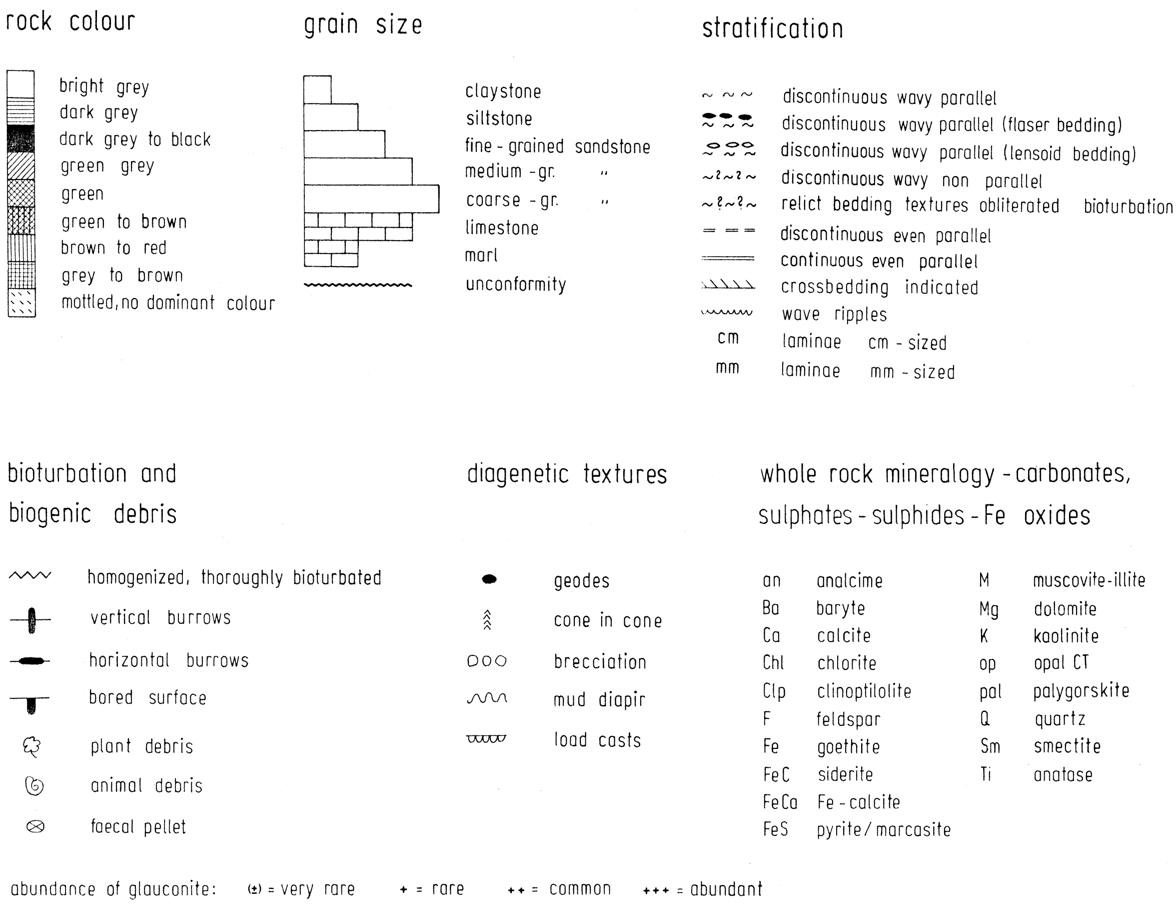


Fig. 12 (continued).

3.6.2. HM analysis of late Paleogene sediments

3.6.2.1. Results. Formations A and C of the Paleogene sedimentary rocks contain allogenic HM assemblages of low to high stability (epidote, staurolite, kyanite, amphibole, zircon, tourmaline and rutile (Fig. 12). Formation B merits attention as its rocks do not bear allogenic HM. The only non-ferrous minerals of the HM suite are barite and apatite. Brown biotite and anatase are exclusively confined to tiny tuff layers within unit B. The ferriferous compounds in this unit are Mg siderite, pistomesite, and pyrite. Glauconite does not belong to the category of HM and is not considered further throughout this assessment.

3.6.2.2. Interpretation. Most of the allogenic HM in the Paleogene formations A and C derived from the southern and northern basements. It is a source area underlain by prevalently medium-grade metamorphics subject to intensive chemical weathering. The co-occurrence of HM of different stabilities has been discussed at length in previous chapters. Biotite and anatase which accumulated in thin interbeds of formation B are of pyroclastic origin. The HM biotite and anatase are neither typical of a special igneous rock nor do they assist in siting of the venting system. Due to the short distance between the working area in northern Germany and the Rockall and Greenland-Faroes eruptive center in the northern Atlantic it seems a most plausible explanation to corre-

Table 5
Lithological characteristics of the Late Paleocene to Early Eocene nearshore-marine deposits

Formation	Rock color	Lithology and grain size	Bedding type	Rock-forming minerals	Environment
Formation C	bright gray	claystones, siltstones, sandstone	massive, discontinuous wavy	quartz, smectite, kaolinite, chlorite, calcite, siderite, pyrite	subtidal shelf mud and sand sheets
Formation B	bright gray, black, green gray	claystones, siltstones, sandstone, carbonaceous claystones, marls, tuffs	parallel and cross bedding, discontinuous wavy	quartz, smectite, kaolinite, chlorite, calcite, siderite, pyrite, barite	tide-dominated delta, intertidal to supratidal
Formation A	mottled, green gray, dark gray	claystones, siltstones, sandstone	parallel, discontinuous wavy	quartz, glauconite, smectite, kaolinite, chlorite, calcite, siderite, pyrite	subtidal shelf mud and sand sheets

Stratigraphical order: youngest formation at the top.

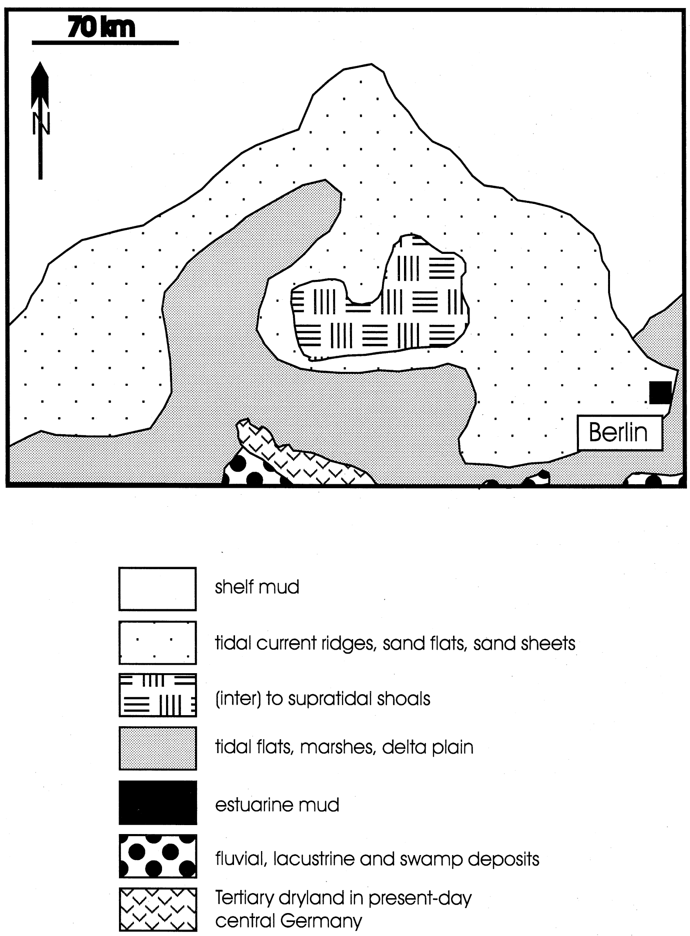


Fig. 13. Environment of deposition in the surroundings of the Gorleben salt dome during deposition of formations A through C (see Fig. 12 for lithology).

late deposition of these airfall tuffs observed in formation B with vent systems active during the early Eocene in the northern Atlantic Ocean (Zimmerle, 1982; Knox, 1989). Formation B, however, barren with respect to siliceous HM and abundant in authigenic HM, needs a closer look (Fig. 12). Apatite was determined as francolite, which based upon the texture of phosphate particles is likely to have derived from shark teeth and bone fragments. No rounded terrigenous apatite grains as recorded from many sites in southeast Germany—see previous chapters—are present in this environment under study. Apatite was reworked in a 'closed system' with no continental run-off from an extrabasinal source fed into this part of the basin. Sulfates and carbonates among the authigenic HM are compelling evidence for a shallow basin which became supersaturated as a result of a high rate of evapo-transpiration. Siderite implies an environment with alternating oxic and suboxic to anoxic conditions for most of the time in a nearshore environment (Mozley and Carothers, 1990). Mg siderite may plausibly be explained by Mg being provided by the seawater (Laverne, 1993). The carbonate was produced by $MgCl_2$ brine reflux as a result of a high rate of evapo-transpiration in a subtidal environment. The results of HM analysis are consistent with the geological data. Both data sets suggest a muddy lagoon, which was, in parts, open towards the open sea and sheltered by a shoal towards land. Allogenic HM were scavenged in a sedimentary trap close to the land (Fig. 13, see 'tidal flats, marshes, delta plain') and did not reach this depocentre near Gorleben.

3.6.3. *Engineering geology*

Much attention has been drawn to the Paleogene fine-grained shelf sediments in the study area in search of a permanent repository for radioactive waste (Jaritz, 1993). A large salt dome which in part is overlain and flanked by these lower Tertiary sediments is currently under investigation in search of a final waste disposal site. The Tertiary rocks under study with respect to their HM assemblage deserve special attention, as they act as sealing horizon for the repository for radioactive waste. The total amount of HM and the composition of the HM suites may both contribute to assess the petrophysical properties of the host rocks they contain. In the chapter before a perspective has been given in as much HM may be used as a marker for increased permeability and favorable source rock conditions. The HM assemblages of the various Paleogene formations overlying and flanking the salt dome warrant consideration when the sealing of the repository is evaluated. Clastic rocks poor in HM but with assemblages rich in allogenic ultrastable HM have good sealing qualities, clastic rocks abundant in authigenic HM have to be viewed more critically with respect to their sealing properties and impermeability. The term authigenic applied to HM such as phosphates, sulfates, sulfides and Fe-bearing carbonates is meant to be another term for strong susceptibility of rock-forming minerals to intrastratal solutions, which have been high up on the agenda of petrophysical investigations since the very beginning of this programme in search of a nuclear waste disposal.

4. Summary and conclusions: the strong points of HM analyses of continental and nearshore-marine deposits

Considering the various intrabasinal (e.g., weathering)) and extrabasinal (e.g., source area lithology) processes and variables that control HM variation, the strong points of HM analyses are discussed below.

HM analysis may contribute to understanding of *provenance* characteristic. Fluvial deposits usually contain abundant and varied suites of HM. The HM logs of alluvial sequences may, as a first approximation be interpreted as the 'basement upside-down'. Source mixing is due to differential unroofing of the basement when overlain by a thick blanket of platform sediments or by dragging of foreland sediments along the highland boundary fault. To pin-point the provenance of clastic rocks becomes more difficult in nearshore-marine sediments. Yet the source of sediments may still be constrained when a smaller grain-size fraction is used and some marker minerals are present. Radiometric age dating of HM, using purified HM concentrates of apatite or sphene, will only yield reasonable results in proximal fluvial and alluvial sediments. It allows a more precise record of the unroofing story of the basement. In sediments of the distal fan or in nearshore-marine deposits, even single grain dating seems not worth the trouble because of strong reworking of the host sediments. Dating of refractory minerals in sediments (e.g., zircon) may lead mostly to inherited U–Pb ages (see among others Hansen et al., 1989) and point to obscure source rocks which formed in the area under study in the range 2400 to 2600 Ma.

Paleogeography results from the interaction of weathering and uplift and both processes must therefore be discussed together. Chemical weathering is more pervasive and of greater impact on HM in host rocks truncated by a peneplain than on those with incised valleys, where erosion is accelerated by continuos uplift. Labile HM may survive decomposition by meteoric fluids in a rugged relief while being completely leached from the HM assemblage in a flat-lying topography.

The absence of allogenic HM may result from strong chemical weathering or from hydraulic conditions during transit. Intervening sedimentary traps which may filter certain size fractions and thereby cause clastic sediments to become deprived of their HM play a more significant part in nearshore-marine environments than in fan deposits close to the hinterland. In nearshore-marine environments with little or no emergence the influence of weathering and vertical displacement is of little impact on the HM host rocks. The amount of HM in distinct coastal strata or the variety of HM is a function of reworking of older sediments or of debris newly delivered into these distal parts (palimpsest vs. fluvially sourced). With the quantity of allogenic HM getting smaller, the amount of HM formed in situ usually increases. Carbonates, sulfates, sulfides and oxides may originate from pedologic and hydraulic processes, both of which are coupled with the climatic conditions. Translucent and opaque HM can help determine the Eh and pH of intrastratal solutions percolating through the near-surface sediments.

HM assemblages in *volcanic and hydrothermal fields* may significantly differ from equivalent HM assemblages formed outside areas not affected by those endogenous processes. An abrupt appearance of Fe–Ti-bearing silicates and oxides, of heavy metal-bearing carbonates and sulfates in the HM assemblages, or decomposition of detrital HM in clastic rocks may furnish evidence for hydrothermal processes. Hydrothermal alteration of the HM assemblages is more widespread in environments close to the basin edge, as there is a more favorable structural setting for hydrothermal solutions to ascend along fault zones and discharge at shallow depth into clastic rocks. The resultant corrosion of preexisting HM and in-situ formation of minerals at shallow depth induced by hydrothermal solutions may lead to similar mineral assemblages and textural effects (reduction of porosity and permeability) as were found when studying the diagenetic story of deeply buried clastic rocks in the basin center (Salvino and Velbel, 1986; Smale and Mortan, 1987; Cavazza and Gandolfi, 1992; Diekmann, 1993). To distinguish diagenetic overprinting from hydrothermal alteration of HM may in places be difficult. As the host rock under study, laid down close to the basin edge, were not subject to deep burial, an important bearing of diagenetic intrastratal solutions on the HM record may be ruled out. HM originating from volcanic eruptions elsewhere can settle in each of the environments under study and may therefore be expected in all sediments from the fan apex to the nearshore-marine deposits.

Economic and applied geology may benefit from HM analysis, because it is an easy-to-use method applicable to diamond drilling as well as to cuttings from open holes. Moreover it has proved to be a cheap method, as far as the routine procedures are concerned, which does not need intensive training of personnel and complicated techniques of mineral dressing. Flow sheets for the use in mineral exploration have been designed among others by Westerhof (1986) and tested in various sites of mineralization. In hydrocarbon exploration, hydrogeology and engineering geology, HM assemblages may offer a quick look at the permeability properties of the host rocks and give a rough idea of the sealing and/or reservoir qualities of the sedimentary rocks.

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