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Heavy mineral response to the progradation of an alluvial fan: implications concerning unroofing of source area, chemical weathering and palaeo-relief (Upper Cretaceous Parkstein fan complex, SE Germany)

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Abstract

During the Late Cretaceous, the NE Bavarian Basement was continuously uplifted along the deep-seated "Franconian Line" fault zone. As a consequence of this vertical displacement, a fan sequence was deposited in the adjacent lowlands.

In this area Upper Triassic arkoses are unconformably overlain by a lignite-bearing arenaceous series, the Parkstein Formation, representing a meandering to anastomosing fluvial system. These deposits gradually pass upwards into the Red Claystone and Ferruginous Sandstone Member, deposited under strongly oxidizing conditions, as shown by the ubiquitous presence of trivalent Fe compounds and the lack of coal. The succeeding Friedersreuth Formation contains widespread debris flows and was deposited in an alluvial fan system. Alluvial fan progradation ended with the conglomerates of the Hesserberg Formation, which contains boulders as much as 0.5 m in diameter.

The pronounced variation in depositional environment and grain-size is (from bottom to top) accompanied by a striking variation in heavy mineral assemblages. Minerals of high chemical and mechanical stability (zircon, tourmaline, rutile) prevail among the detrital heavy minerals of the basal formation, whereas younger formations bear less stable minerals such as members of the amphibole and epidote groups. These stable detrital heavy minerals are well-rounded to rounded.

Provenance and palaeo-relief are most decisive for the coexistence of heavy minerals with different stabilities derived from a great variety of source rocks of different ages (Precambrian and Early Palaeozoic gneisses, late Variscan granites, Permo–Carboniferous volcanites, Triassic arkoses). Heavy mineral associations reflect the reverse lithological sequence of the adjacent source area, as a function of the interaction between uplift and erosion along the boundary fault ("unroofing story"). During slow uplift, chemical weathering operative in the peneplained hinterland and on the alluvial plain helped to release the minerals from the parent rocks and to remove labile constituents from the detritus of the clastic fan sediments. With increasing rate of uplift, the intermixing of minerals from the distal basement source and the proximal Permo–Mesozoic platform sedimentary source became less pronounced. Some authigenic minerals (anatase, "leucoxene", Fe-oxides, Fe-sulphides, Fe-carbonates, Fe-phosphate) in context with the absence of some heavy minerals in the sand fraction that are present in rock fragments (e.g., apatite) help determine inferences about changes in pH values and may help constrain Eh values during fan progradation.

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1. Introduction

Many papers have been published on coarsening-upward sequences in clastic depositional systems such as deltas (Dunne and Hempton 1984), storm-dominated shoreline environments (Hamblin and Walker, 1979) submarine fans (Walker, 1979) and prograding alluvial fans (Steel et al., 1977). A similar prograding alluvial fan with coarsening-upward sequences developed throughout Late Cretaceous time in the foreland of the NE Bavarian Basement near Weiden (Fig. 1), in the environs of Parkstein (Dill, 1990a) (Fig. 2a).

Sedimentological research of alluvial fans has mainly focussed on their internal structures, lithology and bedding, or discrimination of clastic successions (Gloppen and Steel, 1981; Kober, 1984; Baltzer and Purser, 1990). The study of heavy minerals has rarely been applied to alluvial fan sequences despite their being useful indicators of provenance, weathering, diagenesis and stratigraphic correlation (Friis et al., 1980; Morton, 1984, 1985). In the following, the influence of (1) source area lithologies, (2) pre-depositional chemical weathering and (3) palaeo-relief on detrital heavy minerals and alteration of them is demonstrated and discussed for the Parkstein fan complex.

Coarsening-upward successions may be a target of hydrocarbon exploration (Scholle and Spearing, 1982), but the clastic wedge in the foreland of the NE Bavarian Basement is of fundamental importance for water supply. Wells drilled for this purpose provide an excellent insight into this fan sequence and, together with samples from outcrops, form the basis of this study (Fig. 2b).

2. Geological setting

The Franconian Line is a deep-seated fault zone that separates the Upper Cretaceous Parkstein fan complex from the NE Bavarian Base-

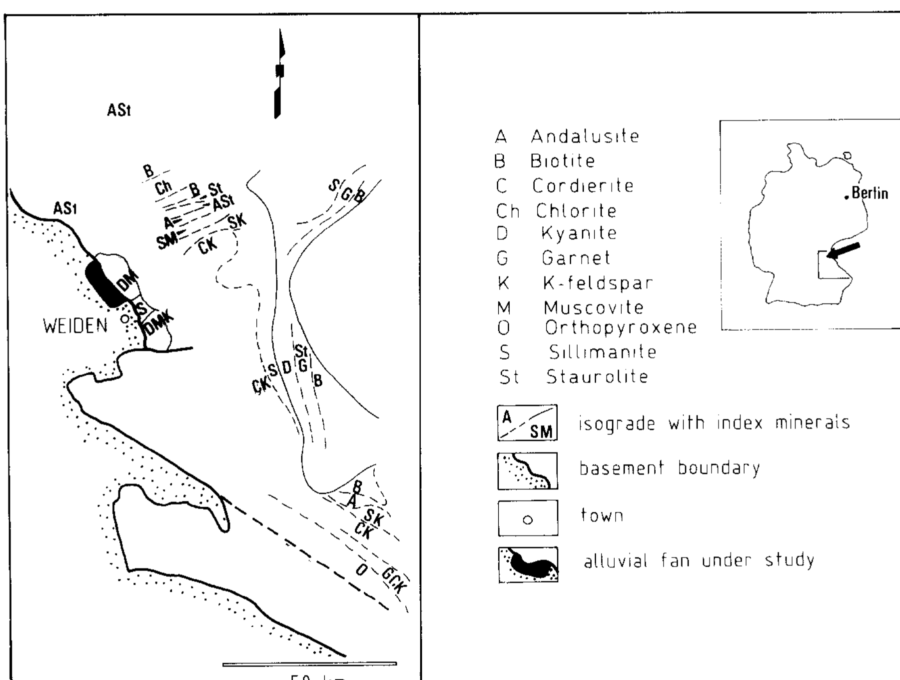

Fig. 1. Isograd map of the metamorphic country rocks in the hinterland (NE Bavarian Basement) of the Parkstein fan near Weiden. Data on metamorphic rocks from Wagner-Lohse and Blümel (1986). The inset displays the position of the study area close to the southeastern border of Germany towards the Czech Republic.

ment (Zitzmann, 1981). The structural evolution and uplift of the basement along the Franconian Line were studied in detail by Bischoff et al. (1990) and Wagner et al. (1990) using fission track analysis on apatite, zircon and sphene from the KTB (Continental Deep Drilling Programme) boreholes. They proposed a cooling model with constant rates of uplift and varying geothermal gradients showing a strong uplift in the crystalline basement, immediately northeast of the fan under study.

The basement comprises three major units with rocks that range in age from Late Proterozoic to Carboniferous. These units are: (1) Saxothuringian (low-grade to anchimetamorphosed clastic and volcanic rocks, Cambro–Ordovician); (2) Moldanubian (low-pressure gneisses with imprints of an older, medium-pressure metamor-

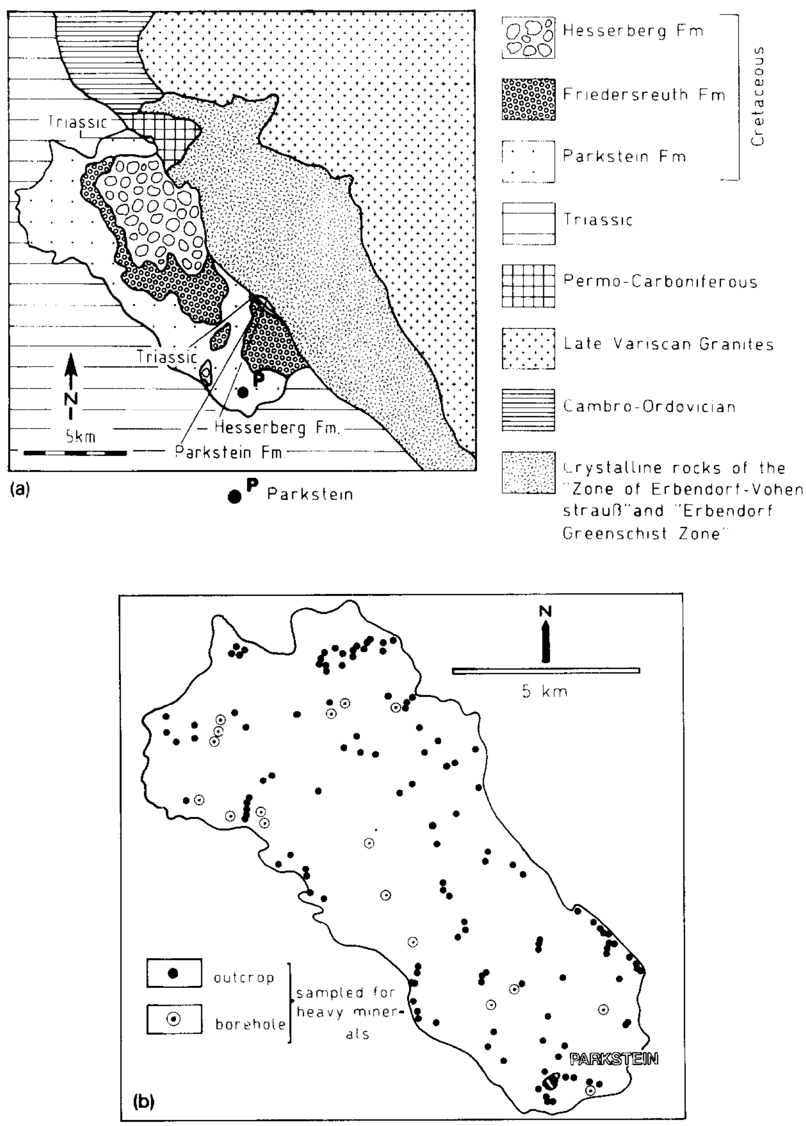

Fig. 2. (a) A close-up of the present-day geologic setting of the Parkstein study area. (b) Sketch map of the Parkstein fan complex showing the outcrops and drill holes sampled for heavy minerals. For geology and fan evolution see (a) and Fig. 5.

phism); (3) Allochthonous Nappes comprising medium- to high-pressure metamorphic rocks (Weber and Vollbrecht, 1986). Amphibolites and gneisses of the Erbendorf–Vohenstrauß Zone (ZEV) together with metamorphosed basic and ultrabasic rocks and graphite schists of the Erbendorf Greenschist Zone (EGZ) (Matthes and Olesch, 1986) crop out towards the northeast, immediately at the inferred fan head (Fig. 2a). Both units belong to the so-called Allochthonous Nappes, which are currently being drilled by the KTB. The Variscan movements in the crystalline

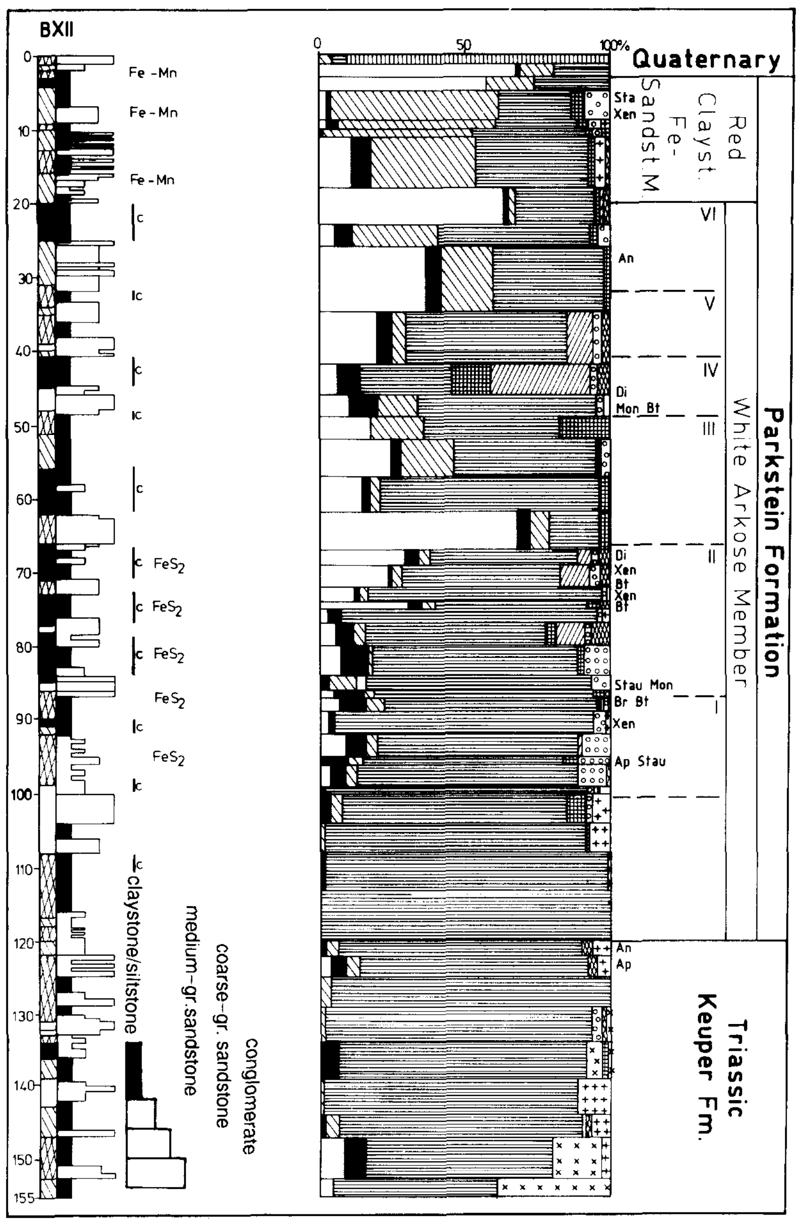

Fig. 3. Heavy mineral variation as a function of lithology and environments of deposition, well BXII (see Fig. 2b). The different fluvial cycles of a meandering to anastomosing drainage system are coded with Roman numerals.

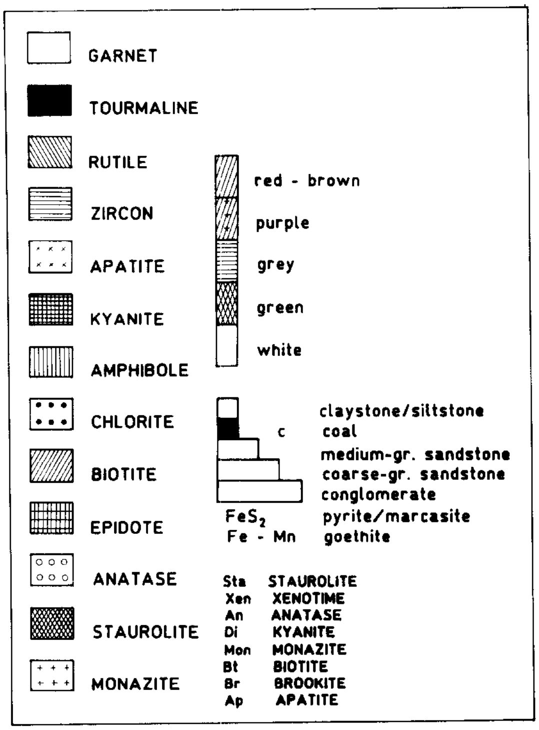

Fig. 3 (continued).

basements northeast of the fan head brought about steeply dipping S-planes in the basement producing a series of fairly monotonous gneisses and amphibolites that can be traced to a depth of more than 7000 m. At the northwestern border of the Allochthonous Nappes Palaeozoic clastic rocks of the Saxothuringian realm are exposed (Schröder and Siegling, 1966) (Fig. 2a).

During the waning stages of the Variscan orogeny, S-type granites of Late Carboniferous age were intruded into these tectono-metamorphic units (Dill, 1985a). An overview of the parent rocks exposed in the basement and the likely heavy minerals they contain, is shown in a sketchmap of isograds and their index minerals have been included (Fig. 1) based on the data of Wagner-Lohse and Blümel (1986).

During the Permo–Carboniferous, narrow troughs developed in the Bohemian Massif (Dill, 1987; Lützner, 1988) that were filled with coal, clastic and volcaniclastic rocks. The volcanics contain a variety of heavy minerals (mostly commonly apatite, biotite, zircon, rutile, staurolite, tourmaline, amphibole and garnet).

The footwall rocks of the Upper Cretaceous fan complex are Triassic in age (Fig. 3). Jurassic clastic and calcareous rocks are not exposed in the study area, but do crop out towards the southwest. The tripartite Triassic sequence (clastic "Buntsandstein", calcareous "Muschelkalk", clastic "Keuper") which is of widespread occurrence across the South German epicontinental basin is here developed as a clastic unit with arkoses, conglomerates and minor siltstone. In this area, the Triassic rocks have a relatively limited heavy mineral suite with garnet, zircon and some apatite (Salger, 1985; Haunschild and Salger, 1987; Dill, 1990b).

3. Methodology

The study area and boreholes within the fan complex sampled for heavy minerals are shown in Fig. 2b. One drill hole (BXII) has been chosen as a reference to show the vertical sample spacing and to illustrate in detail the vertical variation of heavy minerals as a function of depositional environment (Fig. 3). The study also included inspection of thin sections of silty and arenaceous host rocks and lithoclasts in arenites and conglomerates, together with coal petrography using rank determination of organic matter (vitrinite reflectance).

320 samples were taken from boreholes and surface exposures across the entire fan complex for heavy mineral study (Fig. 2b). Heavy minerals (density > 2.9) were extracted from the 63–200 μm size fraction following gentle mechanical disaggregation. To prevent dissolution of acid-sensitive heavy minerals (monazite, apatite), acids were not used in the preparation.

The resulting heavy mineral separates were identified and counted under the petrographic microscope, counting between 200 to 300 grains per sample. Biotite (and green chlorite originating from biotite), commonly excluded from heavy mineral analyses (see e.g., Mange and Maurer, 1991), were included in the grain counts in the present study. Experimental analyses prior to this investigation revealed 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 crystallographic properties of the biotite and chlorite. It has to be noted that 150 heavy mineral analyses were carried out (a detailed description of them will be given elsewhere) on the Triassic and Permo–Carboniferous clastic rocks of this region which prove that these biotites provide information relevant to the study of stratigraphy, provenance and diagenesis.

4. Results

4.1. Stratigraphy and lithology

The Upper Cretaceous succession has been subdivided during this study into three formations following the accepted stratigraphic practice (Hedberg, 1976; Johnson, 1987) and named after their type localities in this region (Dill, 1990a) (Fig. 4); the basal Parkstein Formation is overlain by the Friedersreuth Formation and then by the Hesserberg Formation. Based upon changes in redox conditions from predominantly reducing to prevalently oxidizing resulting in the lack or occurrence of coal and presence of Fe-oxides, the Parkstein Formation can be further subdivided into a lower member (White Arkose) and an upper member (Red Claystone and Ferruginous Sandstone) (Fig. 4). The upward-coarsening in the prograding fan lobes is demonstrated by the grain-size variation of these formations (Fig. 4).

Parkstein Formation (Figs. 3, 4, 5a). The White Arkose Member is 30 to 120 m thick and consists of white to yellow-brown arkoses, subarkoses, conglomerates and siltstone, with planar cross-bedding dominant over trough cross-bedding. In some places this member exhibits a pronounced cyclicity with fining-upward sequences and coalified matter finely dispersed in the topstratum (Fig. 4). The rock colour changes from grey to red towards the boundary with the overlying Red Claystone and Ferruginous Sandstone Member, with a decrease in the content of carbonaceous matter, and the appearance of various types of ferricretes: type I, goethite-bearing pisolites; type II, goethite-impregnated arkoses; type III, goethite-impregnated conglomerates; type IV, geodes with goethite; type V, massive layers of goethite some centimetres thick intercalated among arenites.

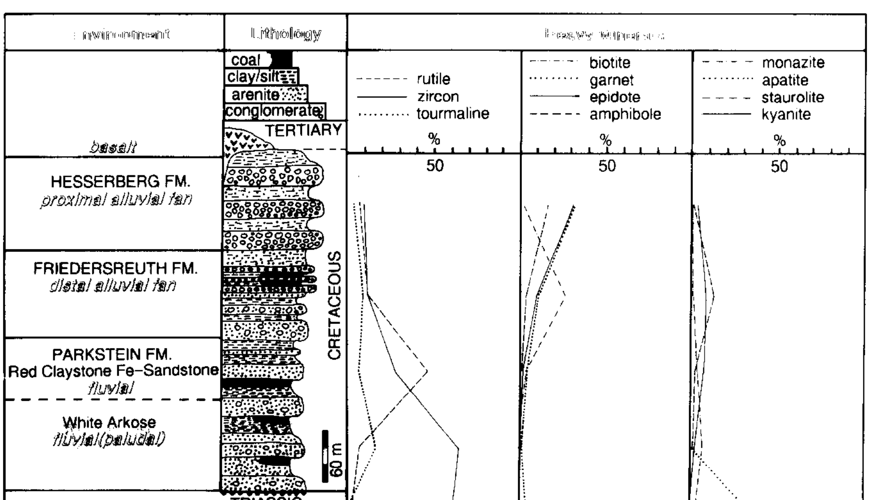

Fig. 4. Heavy mineral response to the variation in stratigraphy, lithology and palaeoenvironment in the coarsening- and thickening-upward fan sequence in the environs of Parkstein.

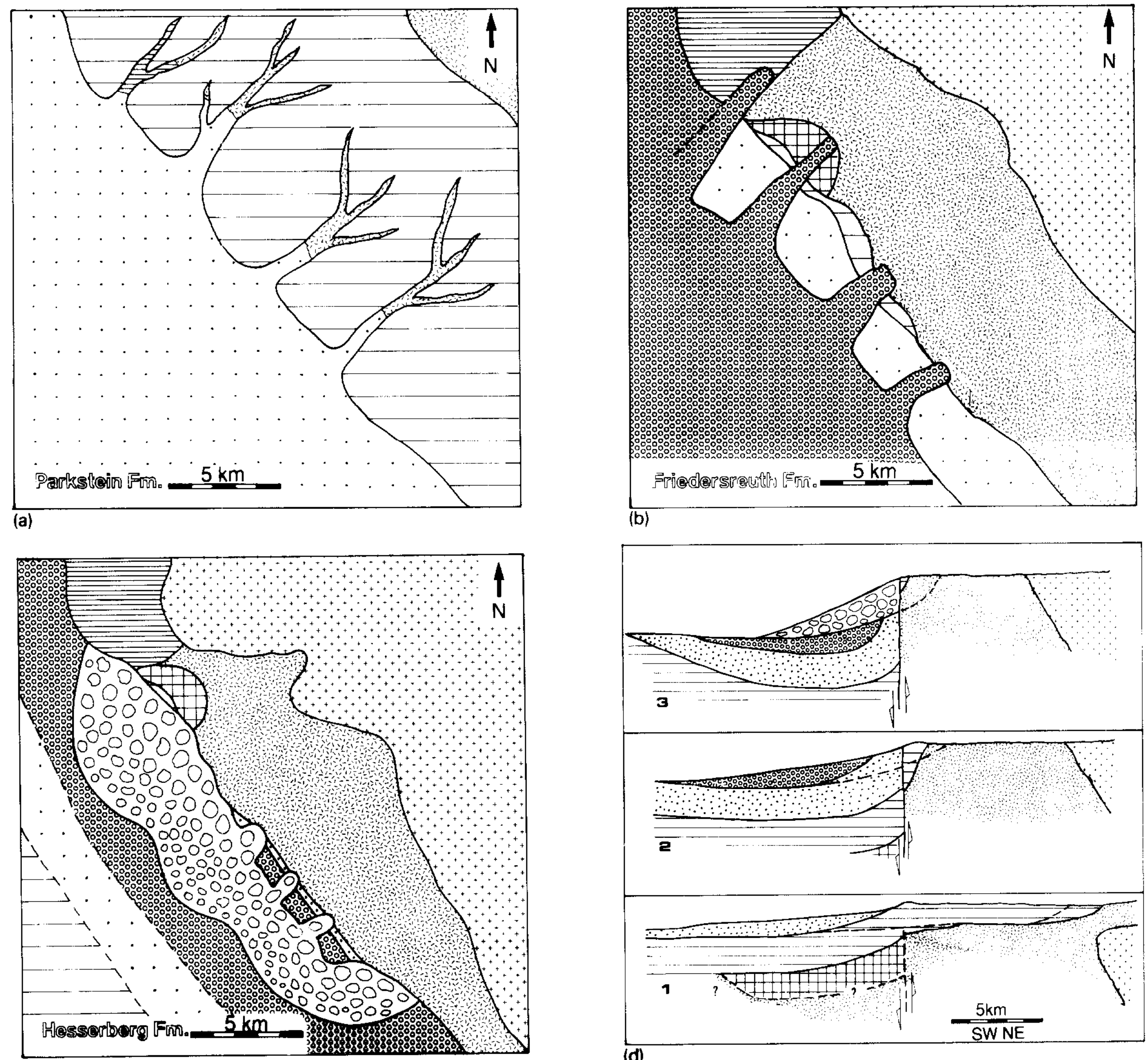

Fig. 5. The palaeogeographic evolution during fan progradation. (a) Parkstein Fm. (paludal to fluvial). (b) Friedersreuth Fm. (distal fan). (c) Hesserberg Fm. (proximal fan). (d) Cross-sections displaying the stepwise evolution from the flexure bulge towards the fault escarpment and the response of fan evolution to this vertical displacement (for legend see Fig. 2a; for plan views see a to c). *1* = Parkstein Formation; *2* = Friedersreuth Formation *3* = Hesserberg Formation. The dashed line shows how the channels and erosional forms cut into older bedrocks. Vertically, off scale.

In all other sedimentological respects, this member resembles the underlying White Arkose Member, attesting to a similar mode of deposition although under different redox conditions. The "dirty", high-ash coal of the "White Arkose" consists of an assemblage of macerals with abundant telocollinite and common inerto-detrinite, fusinite, sporinite and cutinite and has a rather low vitrinite reflectance ($R_V = 0.51\%$). Thick coarse-grained arkoses in the footwall of these high-ash coals are rich in pyrite and marcasite (see Fig. 3).

Table 1
Grain-size and modal analyses of some rudaceous sediments from the Parkstein, Friedersreuth and Hesserberg Formations (the lithologic composition of rock fragments found in the coarsest grain-size fraction ("gravel") is illustrated in Table 2)

	Parkstein Formation	Friedersreuth Formation	Hesserberg Formation
Grain site (wt. %):			
Clay	6.9	2.5	0.7
Silt	2.1	8.4	1.1
Sand	41.9	5.0	10.5
Gravel	49.1	84.1	87.7
Sorting	3.7	2.4	3.9
Clay minerals (vol. %):			
Kaolinite	60	25	35
Illite	40	40	60
Chlorite	–	20	5
Vermiculite	+	–	–
Smectite	–	15	–
Quartz	+ + +	+ +	+ +
Feldspar	–	+	+

Friedersreuth Formation (Fig. 5b). The Friedersreuth Formation (thickness up to 100 m thins towards the north-northwest, is composed of beds of multicoloured matrix- to clast-supported conglomerates up to 2 m thick (Table 1). These alternate with siltstones rich in plant debris, and with a maximum thickness of 1 m. Three discrete sequences can be defined that show sharp contact with the footwall rocks. Erosional features, however, such as scour and pool structures or rudites cutting down into the underlying siltstones have not been observed. Both clast imbrication and bedding are vaguely expressed in the conglomerate. Grain-size analyses show a true bimodal succession, poor in sand-sized material relative to the contents in pebbles and clay-size material. The matrix is made up of disintegrated metamorphic and igneous clasts which reach up to as much as 10 cm (Backfisch, 1984).

Hesserberg Formation (Fig. 5c). The uppermost series is named after the highest mountain in the study area and attains a thickness of at least 100 m. The Hesserberg Formation is a conglomeratic, grey to brown unit with a wide variety of clasts that include granite, acid volcanics, quartzites, chert, phyllites, gneisses, metabasic rocks and pyroxene–garnet fels (Tables 1, 2). The unit locally includes boulders with diameters greater than 0.5 m, and these conglomerates are mostly clast-supported. The clasts have a high sphericity. Unstable metamorphic and igneous clasts have decomposed to form a soft matrix. Silt and claystones are irregularly distributed among the conglomerates. Thick horizons of this grain-size are missing. The conglomerates which predominate in this series are massive to crudely bedded.

Table 2
Rock fragments with the heavy mineral association they contain, together with their first appearance during fan evolution

Rock fragments	Heavy minerals	First appearance in
Pyroxene–garnet fels	Garnet, Mg-rich orthopyroxene, hornblende, clinopyroxene	Hesserberg Fm.
Metabasic igneous rocks	Clinozoisite–epidote s.s. amphibole	Hesserberg Fm.
Granitoids	Biotite, little apatite	Friedersreuth Fm.
Arenites/greywackes	Chlorite	Friedersreuth Fm.
Porphyritic volcanics	Chlorite, biotite, apatite	Friedersreuth Fm.
Gneisses	Biotite, Sillimanite, little kyanite	Friedersreuth Fm.
Quartzites	Zircon, tourmaline, biotite	Parkstein Fm.
Phyllite	Chlorite, biotite	Parkstein Fm.
Quartzose, mobilizates	Chlorite, fibrous sillimanite	Parkstein Fm.
Chert	–	Parkstein Fm.
Silcretes	–	Parkstein Fm.

4.2. Heavy mineral associations

4.2.1. The Parkstein fan complex and its immediate surroundings

Heavy minerals in arenaceous host rocks.

Minerals of high chemical and mechanical stability (zircon, tourmaline, rutile) leading to a high ZTR index (Hubert, 1962), prevail among the detrital heavy mineral assemblage of the Parkstein Formation (Table 3). In the White Arkose Member zircon is predominant, whereas rutile is the marker mineral of the Red Clay and Ferruginous Sandstone Member. Another important species among detrital heavy minerals of the Parkstein Formation is tourmaline. Minerals of lower stability, such as staurolite, epidote-group minerals, monazite, sphene, amphibole and biotite are present in subordinate quantities (Table 3). Occasionally, garnet attains quantities of up to 60% in the heavy mineral suites (Fig. 3, cycle III). Al_2SiO_5 polymorphs are characteristic of the Cretaceous and Tertiary arenaceous beds in NE Bavaria (Kalogiannidis, 1981; Dill, 1990a), but kyanite is entirely missing from the Mesozoic strata underlying the Parkstein Formation (Fig. 4) and is a very rare constituent of the Late Palaeozoic terrigenous clastic rocks, where it was only found in carbonaceous clastic rocks of Stephanian age (Dill, 1989). Although andalusite is widespread in the neighbouring basement rocks (see Fig. 1), it has not been encountered in sedimentary rocks older than the Miocene (Dill, 1991). By contrast, apatite is common in Triassic and Permo–Carboniferous arenites, but is absent in the Cretaceous sediments under consideration (Salger, 1985; Haunschild and Salger, 1987; Dill, 1990b). The ultrastable zircon, tourmaline and rutile are well-rounded to rounded according to the classification of Pettijohn et al. (1972). The other heavy minerals such as anatase, kyanite and amphibole are angular to subangular. Skeletal minerals have not been observed in the Parkstein Formation. The Parkstein Formation deposits are well known for their massive FeS_2 nodules in the coarse-grained arenaceous interbeds of the car-

Table 3
Heavy mineral composition (with ZTR index) of host formations

	Zircon			Rutile			Anatase			Toumaline			Biotite			Monazite		
	min.	mean	max	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.
Hesserberg Fm. ZTR = 18.6	0	8.2	45	0	6.8	26	0	0.4	4	0	3.2	30	1	1.2	5	0	0.6	5
Friedersreuth Fm. ZTR = 30.5	0	10.5	44	0	10.8	41	0	1.2	10	0	8.0	32	0	26	90	0	0.4	4
Parkstein Fm. Red clay–Fe sdst. ZTR = 81.8	5	27	74	0	46.6	75	0	1.4	7	0	6.8	25	0	3.6	32	0	2.9	13
White arkose ZTR = 87.6	11	65.4	98	0	5.7	21	0	0.5	4	0	16	83	0	0.8	5	0	4.8	17

	Kyanite			Staurolite			Epitote–Zoisite			Garnet			Sphene			Amphibole		
	min.	mean	max	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.
Hesserberg Fm ZTR = 18.6	0	3.1	11	0	0.9	15	1	28	77	4	29	77	0	0.5	5	0	16	79
Friedersreuth Fm. ZTR = 30.5	0	7.6	24	0	12	75	0	10	57	0	11	75	0	0.3	4	0	1.7	8
Parkstein Fm. Red clay–Fe sdst. ZTR = 81.8	0	6	20	0	1	8	0	1.7	9	0	3.7	40	0	0.2	3	0	1.0	7
White arkose ZTR = 87.6	0	1.7	10	0	0.9	5	0	0.9	5	0	1.4	60	–	–	–	0	1.4	12

bonaceous lowermost White Arkose (Fig. 3). Except for As, Mn, Pb, Ni and Sb marcasite and pyrite are very low in trace elements (Table 4).

Another group of opaque minerals contains some Fe–Ti oxides (titanomagnetite, ilmenite) and ferricretes made up of different types of goethite and some "leucoxene"(see Sect. 4.1). These ferricretes locally are associated with biotite as well as chlorite–biotite intergrowths which were bleached and gradually replaced by goethite. Earthy mineral aggregates of "leucoxene" comprise another group of minerals in the Friedersreuth Formation which formed in situ.

Passing into the Friedersreuth Formation, the ultrastable mineral assemblages show a striking change towards a biotite–staurolite–garnet association complemented by zircon, rutile and epidote-group minerals. The brown plates of biotite are treated as detrital heavy minerals. Biotite is abundant in the 63 to 200 μm fractions of the Friedersreuth Formation arenites (Table 3). In places it is rimmed and replaced by green ferroan chlorite (ripidolite-type). These biotite–chlorite aggregates display a shape similar in appearance to that of fresh biotite.

Towards the top of the Cretaceous sediments, the proportion of ultrastable minerals tends to decrease, leading to a ZTR index (Hubert, 1962) of 18.6 in the Hesserberg Formation, well below that of the basal Parkstein Formation with 87.6. The heavy mineral suite of the Hesserberg Formation is a garnet–epidote/zoisite–amphibole association. The pinkish to pale coloured garnet (probably almandine-rich) locally exhibits moderate etching, but does not display large-scale facets recorded from the underlying Upper Triassic Keuper beds (Borg, 1986). Green amphiboles show dissolution at their edges developing slender needle-like terminations. The Hesserberg Formation contains a mineral assemblage of siderite and vivianite that coat the surfaces of flattened quartz pebbles facing upsection. Rare pyroxene and apatite are discernible in the topmost part of the Hesserberg Formation, where the mud-supported conglomerates have been reworked by Quaternary solifluction.

In comparison with the heavy mineral assemblages of the Cretaceous, the mineralogy of the Triassic footwall rocks is simpler (Fig. 4). Amphibole, epidote, and kyanite, common in the Cretaceous, do not occur in the Triassic, whilst apatite by contrast is widespread (Dill, 1990b).

Heavy minerals in conglomerates.

Heavy minerals are not only minor constituents of Cretaceous arenites (Table 3), but also occur in rock fragments of rudaceous interbeds (Table 2). The Parkstein Formation contains conglomeratic beds with chert, phyllites and quartzites, that are poor in accessory minerals other than tourmaline, zircon and biotite partially altered to chlorite. Some clasts from quartz mobilizates are host to "fibrolite", a fibrous variety of sillimanite, partly replaced by white mica. Granites, rhyolitic and dacitic volcanics, and biotite–sillimanite gneisses appear in the clast assemblages at the base of the Friedersreuth Formation (Table 2). Petrographic studies reveal that this is the only place where apatite occurs in the Cretaceous series. This porphyry also includes some biotite and chlorite. Granite and gneiss clasts in the Friedersreuth Formation contain a limited variety of accessory minerals such as brown biotite and minor apatite.

The heavy mineral composition of the clasts in the Hesserberg Formation is more variable. In addition to the afore-mentioned rock types, minor amounts of amphibolite clasts, containing epidote and green amphibole besides quartz and feldspar have been identified. Aggregates, dis-

Table 4
Trace element contents (given in ppm) of Fe-disulphides from the White Arkose of Parkstein Formation

Ag	As	Au	Cd	Co	Cu	Mn	Ni	Pb	Sb	Se	Te	Ti	Zn
0.95	214	0.07	0.98	39	13	230	182	290	81	1	0.72	24	11
1.40	435	0.13	0.44	44	20	300	146	115	205	1	1.50	29	22
0.63	256	0.04	5.00	30	16	270	225	100	345	1	0.95	49	9
0.80	217	0.07	320	35	14	270	159	150	305	8	1.10	52	12

playing irregular intergrowth of garnet, Mg-rich orthopyroxene, amphibole, quartz, plagioclase and minor clinopyroxene represent clasts of pyroxene granulite or pyrigarnite (after Lorenz, 1980). In this metamorphic rock kelyphite and symplectite rims were encountered around garnet porphyroblasts. Minor amounts of arenite and greywacke clasts were also found, but these contain no heavy minerals.

4.2.2. The Bavarian Basement

To determine which heavy mineral species were derived from the adjacent NE Bavarian Basement, two different approaches have been taken. A large-scale sketchmap, showing the metamorphic isogrades, gives information on the marker minerals that can be expected in the clastic rocks of the foreland (Wagner-Lohse and Blümel, 1986). In addition, the accessory minerals of the late Variscan granites intruded into these crystalline rocks (apatite, zircon, tourmaline and monazite), have been taken into account (Schnitzer, 1957). The effect of source area weathering during the recent geological past has been considered in the second approach. Steinwede (1990) studied heavy mineral variations in the saprolite on gneisses and granites of the NE Bavarian Basement penetrated by shallow percussion drillings. Anatase makes up a large part of the heavy mineral assemblage of the granites. Besides zircon and tourmaline, amphibole and apatite are both fairly widespread in the weathering loam of the various crystalline bedrocks.

5. Discussion—fan progradation and factors controlling the heavy mineral compositions of clastic rocks

5.1. Fan progradation and evolution of the environment hosting heavy minerals

The large amounts of siltstone and fine-grained sandstone within the Parkstein Formation furnish evidence of mixed-load to suspended-load deposition (Galloway and Hobday, 1983). The total absence of thinly laminated black silt- or mudstones (continental black shales) precludes the occurrence of anoxic lakes during the incipient stages of fan progradation (see Demicco and Gierlowski-Kordesch, 1986; Dickinson, 1988). At the beginning of the Cenomanian, the drainage pattern of this region has been interpreted as an anastomosing fluvial system (see Cant, 1982). In those parts of the sequence where fining-upward cyclothems predominate, rivers meandered through a swamp environment, rich in organic matter derived from plant remains and water-laid logs (Figs. 3, 5a). The ubiquitous "limonitic" matter encountered in the topmost Parkstein Formation lithologies indicates that redox conditions changed from low to high Eh values though the mode of fluvial deposition remained unaltered (Fig. 3).

Unstratified matrix-supported conglomerates of the Friedersreuth Formation are interpreted as some form of debris flow. The non-erosive base implies limited turbulence and suggests laminar flow. A hyperconcentrated stream flood deposit may be inferred from the crudely bedded clast-supported and imbricated rudites (Arguden and Rodolfo, 1986). Carbonaceous siltstones indicate periods of minor stream floods and a relatively high water table which allowed organic matter in the form of peat swamps to be preserved lateral to or in between alluvial fan lobes. Absence of rootlet beds suggests that this distal fan section was not vegetated.

The alluvial fan deposits of the Hesserberg Formation debouched closer to the mountain front than those of the Friedersreuth Formation, although the excellent rounding of clasts in a proximal fan position still needs some explanation. These large boulders are interpreted as rock fall boulders, subsequently reworked by floods. Sand-sized material was probably derived from waning sheet floods and dewatering of debris flows. Silt- and clay-sized matrix material originated from in-situ weathering of rock fragments, and not from settling of suspended matter that takes place in more distal fan sections.

5.2. Uplifting, unroofing and heavy mineral variations

Heavy mineral mixing (dual provenance) and variations in palaeo-relief are responsible for the coexistence of heavy minerals with different stabilities in this arenaceous series. They are governed by the two processes, uplifting (tectonic) and unroofing (erosion).

During deposition of the Parkstein Formation, relief was low and the rate of erosion slow as indicated by the high-sinuosity fluvial drainage system (see Sect. 5.1) and fission track studies (Wagner et al., 1990). Meteoric waters could attack minerals for long periods, reducing quantities of unstable heavy minerals (Fig. 5d/1) such as phosphates in the Triassic. The well-rounded to rounded ultrastable heavy minerals are without any doubt of detrital origin. The major portion of the heavy mineral suites (zircon, Ti-oxides, tourmaline) was recycled from Triassic "Sandstein Keuper" which was dragged along the boundary fault and eroded at the flanks of the domed crystalline basement (proximal source) (Fig. 5d/1). Away from the fan apex, medium-pressure metamorphic rocks with kyanite as the index silicate and Cambro-Ordovician gneisses were intermittently exposed during the incipient stages of fan progradation; distal sources: ZEV (Erbendorf-Vohenstrauß Zone); ZTT (Tepla-Taus Zone); see index map Figs. 1, 2a, 5d/1. During deposition of the Parkstein Formation, the Mesozoic cover of the crystalline basement was progressively eroded and, consequently, the distal crystalline source rocks also contributed to the upper Parkstein Formation (Table 3) in increasing amounts.

In the Friedersreuth Formation ultrastable heavy minerals no longer predominate, so that the distinction of proximal from distal source areas becomes difficult or even impossible (Figs. 4, 5d/2). A considerable increase in the abundance of staurolite, epidote, garnet and biotite occurs at the boundary of the Parkstein and Friedersreuth formations (Fig. 4). Staurolite is also present in the heavy mineral suites of the Jurassic iron-bearing sandstones (Tillmanns, 1978), and can survive recycling even when highly etched and corroded (Allen and Mange-Rajetzky, 1992). In this case staurolite should appear earlier than the typical Triassic heavy minerals in this fan sequence (e.g., Parkstein Formation). The rocks of the Fichtelgebirge and Waldsassen-Schiefergebirge contain staurolite together with andalusite in medium-grade metamorphics (Mielke et al., 1979) (Fig. 1). Since andalusite is completely missing in the Cretaceous beds of the area another metamorphic parent rock has to be invoked. Röhr and von Gehlen (1989) gave a brief description of staurolite-bearing garnet gneisses from the ZEV that may explain the "placer like" occurrence of staurolite (Fig. 1). Biotite contents in the Friedersreuth Formation deserve particular attention, because such anomalously high contents are often said to be indicative of tuffaceous input (Weaver, 1955, 1989). Cretaceous pyroclastics are known only from the NW German Basin (Kemper and Zimmerle, 1982). In NE Bavaria, volcanic and volcaniclastic rocks abnormally rich in biotite are found in the Permo-Carboniferous (Dill, 1990a, c). However, biotite gneisses from the ZEV are more likely to have been the source of the abundant biotite and biotite-chlorite aggregates. The finer-grained gneiss detritus is concentrated in the Friedersreuth Formation, deposited in an intermediate fan setting, whilst the larger pebbles and boulders of the biotite gneisses, which have survived mechanical disintegration, are found in a more proximal fan position closer to the highland boundary fault (Table 2). The data suggest a hydraulic control on mica abundance, with biotite predominantly enriched in a more distal fan position. Epidote and amphibole originated from the breakdown of metabasic rocks and, to a lesser degree, from the decomposition of Permo-Carboniferous volcanic rocks. The number of boulders of metabasic rocks is some orders of magnitude less than that of volcanic rocks and shows an antithetic trend to the heavy mineral variation (Table 2).

The abrupt appearance of biotite, staurolite and the increase of epidote, amphibole, kyanite and garnet (Fig. 4) in the heavy mineral association as well as their persistence despite intense chemical weathering may be explained in terms of continuously increasing uplift that led to increasingly high relief, hindering chemical weathering (Fig. 5d/2). The rate of erosion was sufficiently high at this time to protect unstable constituents from being decomposed (Fig. 5d/2) and to guarantee a continuous supply of heavy minerals from relatively homogeneous sources in the crystalline basement and the Permo–Carboniferous strata (Dill, 1990c; Hirschmann, 1992).

In the proximal section of this prograding alluvial fan, represented by the Hesserberg Formation, labile heavy minerals prevail over stable and ultrastable minerals. After the virtually complete denudation of the Mesozoic cover, metamorphic rocks and granites were widely exposed towards the northeast of the fan apex and were the only source for the fan detritus at that time (Fig. 5d/3). The sedimentary features of the Hesserberg Formation attest to a rugged relief and a steep fan gradient, which allowed unstable minerals to persist even under extreme conditions of chemical weathering.

5.3. Climate, chemical weathering and heavy mineral variations

Periods marked by higher temperature and humidity have been recorded for the Late Cretaceous (Robert and Chamley, 1990). A more humid climate in Late Cretaceous time is also suggested by Mack (1991), who stressed the absence of calcic Bk and Bkm horizons in Late Cretaceous palaeosols as the climatically most diagnostic features. Except for little Fe-carbonate (see below) calcareous encrustations or cements do not play a part among authigenic mineralizations. Skocek and Valecka (1983) showed that there was a direct influence of the climate on the heavy mineral association. The central European basement highs were subject to strong kaolinitic weathering (see e.g., kaolinite of the Parkstein Formation) under a warm humid climate. As a consequence of this, arenaceous sediments of Late Cretaceous age contain minor amounts of apatite and are characterised by a high ZTR index. The ZTR index of the Parkstein Formation heavy mineral association is much greater 87.6 and 84.8) than that of the younger Upper Cretaceous formations which can be interpreted in terms of a higher degree of source area weathering, or more intense recycling of heavy minerals throughout Parkstein Formation deposition. Weakly acidic pore fluids can be inferred from the absence of apatite, which is ubiquitous in the "Keuper Beds" and in the basement rocks. According to the experimental data of Nickel (1973), apatite dissolution is more rapid than that of amphibole in groundwaters of pH 5.6. A downstream loss of apatite by dissolution during periods of alluvial storage on the flood plains (A. Morton, pers. commun., 1993) may be applicable for some backswamp sub-environments as well as the channel facies (H. Friis, pers. commun., 1994) of the Parkstein Formation, but need not account for the overall absence of apatite in this fan wedge, particularly in the more proximal Friedersreuth and Hesserberg formations.

As deduced from the phyllosilicate assemblage and the absence of apatite among the heavy mineral assemblage, the approximate fluid composition during pedogenesis/chemical weathering was not very different from that of the underlying Parkstein Formation (Table 3). Needle-like apatite is present only in volcaniclasts and granitic fragments, where it was protected from dissolution of the pore fluids by the siliceous matrix of porphyritic volcanites and by quartz and feldspar densely intergrown with each other in the granites (Table 2).

Authigenic siderite and vivianite in the Hesserberg Formation that resemble Fe mineralization of bog iron ores (Postma, 1981) furnish evidence of changing pH- and Eh-values and increasing humidity. Based upon chemical distribution of aqueous complex species in a natural system, a stability diagram has been calculated for the siderite–vivianite mineral assemblage using: CO_2^{2-}, 10^{-5} mol/l; HPO_4^{2-}, 10^{-4} to 10^{-7} mol/l (Wagman et al., 1968/1969; Lindsay, 1979; Nriagu, 1976; Nriagu and Moore, 1984) (Fig. 6). This diagram illustrates that pH increased during fan evolution and attained values between 6.5 and 9.5 in the Hesserberg Formation. The increase of epidote and amphibole well accords with this variation of composition of pore fluids to get more alkaline.

Of the Cretaceous fan deposits the Parkstein Formation is notably enriched in Fe- and Ti-minerals. The lithostratigraphic subdivision into the White Arkose Member and the Red Claystone and Ferruginous Sandstone Member is

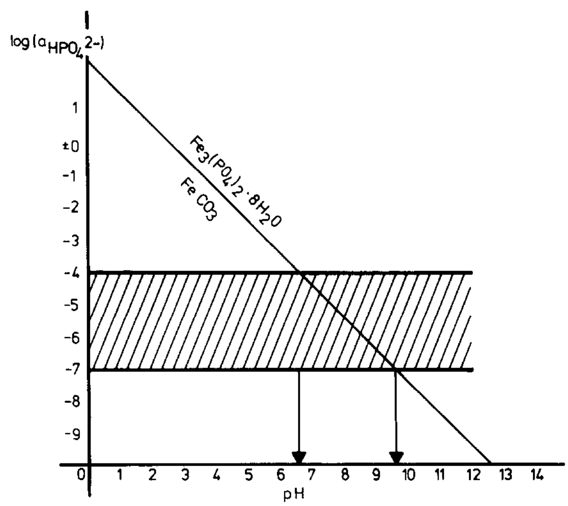

Fig. 6. Stability diagram, pH vs. log activity HPO_4^{2-} of vivianite–siderite mineralisation from the Hesserberg Formation.

partly based upon the various Fe compounds in the deposits of the fluvial environment. A relatively high water level of the meandering to anastomosing fluvial drainage pattern was responsible for the authigenic formation and preservation of Fe-sulphides as well as of carbonaceous matter (Figs. 3, 4). The Ni/Co ratios of Fe-bisulphides (Table 4) well agree with ratios typical of sedimentary, early diagenetic origin (Dill, 1985b; Dill et al., 1993). This origin from pore solutions in a continental environment is also corroborated by the increased contents of Ni and As. According to Brinkmann (1976) and Patterson et al. (1988) the source of Ni and As may be looked for in the humic organic matter. Pb and Sb were derived from gneisses; a source for the increased influx of Mn cannot be delineated. The coexistence of marcasite and pyrite attests to reducing conditions with pH values fluctuating around 6 (Murowchick and Barnes, 1986). In the upper Parkstein Formation, these hydraulic conditions changed with trivalent Fe substituted for bivalent Fe in ferroan minerals, and the development of eogenetic red beds came into being. Basin subsidence was retarded and the change in geomorphological fan setting allowed free drainage and oxidizing conditions. Fe-sulphides, some Fe-bearing micas and Fe–Ti oxides were pervasively altered to yield Fe-oxides, and Ti was released to give "leucoxene", grading at its final stage into anatase. Although relict soil horizons were not observed, red staining of quartz grains may be of pedological origin. The "limonitic" and "leucoxene"-bearing crusts found in this formation were derived from some detrital biotite and biotite–chlorite aggregates, which were found in this formation, yet not in the same quantity as in the overlying Friedersreuth Formation, where duricrusts of this type are absent. The ferricretes more closely resemble those of podzols rather than of latosols. Such soils contain ferruginous nodules (Pye and Goudie, 1983) and are widespread in the fan deposits. Red podzolic soils have been reported from areas with high rainfall and deep siliceous parent material, similar to the arkosic sediments of the Parkstein Formation (Andriesse, 1970). This kind of reddening and the resultant palaeoclimatic conclusions corroborate classification of these alluvial fan deposits as "wet fan".

Some authigenic platy anatase and some angular rutile may have been formed during the pedogenetic processes or after deposition and burial. Bailey et al. (1957) and Flinter (1957) gave detailed accounts of the alteration of Fe–Ti oxides to rutile with a diffuse XRD pattern. Authigenic rutile is also reported from the Lower Triassic "Bunter" of the W Eifel (Mader, 1980). However, rutile is not the TiO_2 mineral which forms commonly under near-ambient conditions (see Keesmann, 1966; Yau et al., 1987). Other processes are likely to have caused the preponderance of rounded rutile. A plausible explanation may be the concentration of rutile in a palaeoplacer during sheet floods as a result of periodic heavy rainfalls at the boundary between the Parkstein and Friedersreuth formations. It is assumed that intensive weathering caused rutile redeposition in the hinterland of this fan wedge which led to a preconcentration of TiO_2. A similar rutile placer was reported from the Bonthe and Mogamba districts (Sierra Leone), in this case forming on a Late Quaternary alluvial outwash fan plain (Raufuss, 1973).

5.4. Burial, diagenetic alteration and heavy mineral variation

The Parkstein Formation is the lowermost stratigraphic unit in the fan and abundant in organic matter, which is more sensitive to burial and diagenetic alteration than heavy mineral species. The *R*-values of 0.51% obtained from vitrinite reflectance measurements of coalified matter in the paludal "White Arkose Member" corresponds to a burial depth of about 500 m (Teichmüller et al., 1984), which was obviously too low to promote significant replacement of detrital minerals (no skeletal minerals, no etch pits) or precipitation of new minerals other than those related to weathering (no cementation with quartz, calcite or barite as found in the underlying Permo–Triassic bedrocks) (Dill, 1990c).

6. Summary and conclusions

Heavy minerals have been useful in the reconstruction of the palaeo-relief close to the edge of the South German Basin because of their regular variation throughout fan progradation. They provided little information, however, on mesodiagenesis, since the overburden was relatively thin. The proximity of the fan wedge to the source region caused a greater variety in the heavy mineral association than elsewhere in the basin, where a monotonous heavy mineral suite resulted from the combined effects of long transport (hydraulic differentiation) and deep burial (intrastratal solution). In contrast to deposits of a lacustrine or marine environment, the subaerial fluvial and alluvial fan deposits are strongly affected by chemical weathering controlled by the particular climate during fan progradation (e.g., wet fan). This is counteracted by syndepositional movements along the highland boundary fault which caused increased palaeo-relief of the source terrain and fan wedge. The heavy mineral associations in this prograding fan mirror the reverse order of the lithology of the adjacent source area as a function of interaction between uplift and erosion (Figs. 4, 5d).

This study demonstrates how erosion cut into the Triassic cover and unroofed the basement. As uplift continued, the extent of mixing of heavy minerals from proximal and distal source rocks becomes increasingly more difficult to estimate (Fig. 4). The rate of uplift was sufficiently high to permit unstable constituents such as amphiboles and epidote to be transported intact into the basin. However, this rate of uplift was not high enough to protect the apatite of the source rocks from dissolution during chemical weathering, with the exception of that present in clasts and sheltered by a siliceous matrix. The rates of subsidence and burial were fast enough in the incipient stages of basin evolution to protect minerals bearing bivalent Fe (FeS_2, Fe–Ti oxides) from being dissolved in this meandering to anastomosing fluvial environment. Retarded subsidence and slow burial during deposition of the Red Claystone and Ferruginous Sandstone Member promoted alteration of these minerals under oxidizing conditions and formation of ferricretes, whilst intensive source area weathering and re-deposition of saprolitic material gave rise to a placer-like accumulation of TiO_2 minerals, predominantly rutile, in the foreland. It is important to note that in an environment characterized by a pronounced grain-size contrast such as the area of the present study, the heavy mineral composition of both the rudaceous and the silt/sand-sized fraction have to be investigated relative to their position in the fan section (Tables 2, 3). For example within a few kilometres the predominance of biotite in distal fan arenaceous beds may grade into a proximal fan pebbly horizon, containing biotite gneiss clasts.

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