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# Variation in heavy mineral associations of Permo-Carboniferous fan sequences (Southern Germany); Their implications concerning provenance and basin evolution

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**Abstract**

Fan deposits from the Stockheim, Erbendorf, Weiden and Schmidgaden Basins in the immediate surroundings of the Mid-European Variscan basement contain translucent and opaque heavy mineral assemblages which have been strongly controlled by intrabasinal (volcanism, hydrothermal activity and weathering) and extrabasinal (provenance) parameters. Sediments of this marginal facies are less intensively altered by diagenesis than equivalent beds in the basin centre. Therefore, the amount and type of heavy minerals present in these depositional basins may contribute to basin and provenance analyses of these terrigenous fan sediments.

Pyroclastic fan deposits contain smaller amounts of allogenic heavy minerals and in places they have a larger proportion of authigenic heavy minerals than found in alluvial fans. Crystal habits of zircon, apatite and anatase or mineral ratios (e.g. anatase/Fe silicate) are supplementary tools for the determination of sediment sources related to denudation of metamorphic rocks or bear a significant volcanic-derived influx. Deeply circulating waters and paleosols may be recognized on the basis of mineral transformation in the system Fe-Ti-O (giving rise to plates of anatase) and by a conspicuous depletion of particularly phosphates.

Moreover, the heavy minerals in the fan deposits are an immediate response to the basement uplift in the hinterland. The history of basin subsidence, denudation of the basemement and even the P-T slope of the metamorphic source area may by inferred from the reverse order of heavy minerals discovered in the foreland. This will work well if metapsammopelitic rocks are present in the hinterland, but less well, if ultrabasic rocks occur in the source area. This procedure may successfully be used for samples from drill cores, cuttings and even samples from outcrop from fan deposits. Under these circumstances, the impact of modern weathering and soil forming processes on the heavy minerals suites has yet to be carefully established before discussing intra- and extrabasinal factors.

## Introduction

Heavy mineral studies have numerous advantages over the light mineral analyses in that they provide a wider spectrum of silicates, sulfates, sulfides, oxides and phosphates. This is particularly true for fan deposits laid down close to source areas. Heavy minerals are mainly used for the study of diagenesis

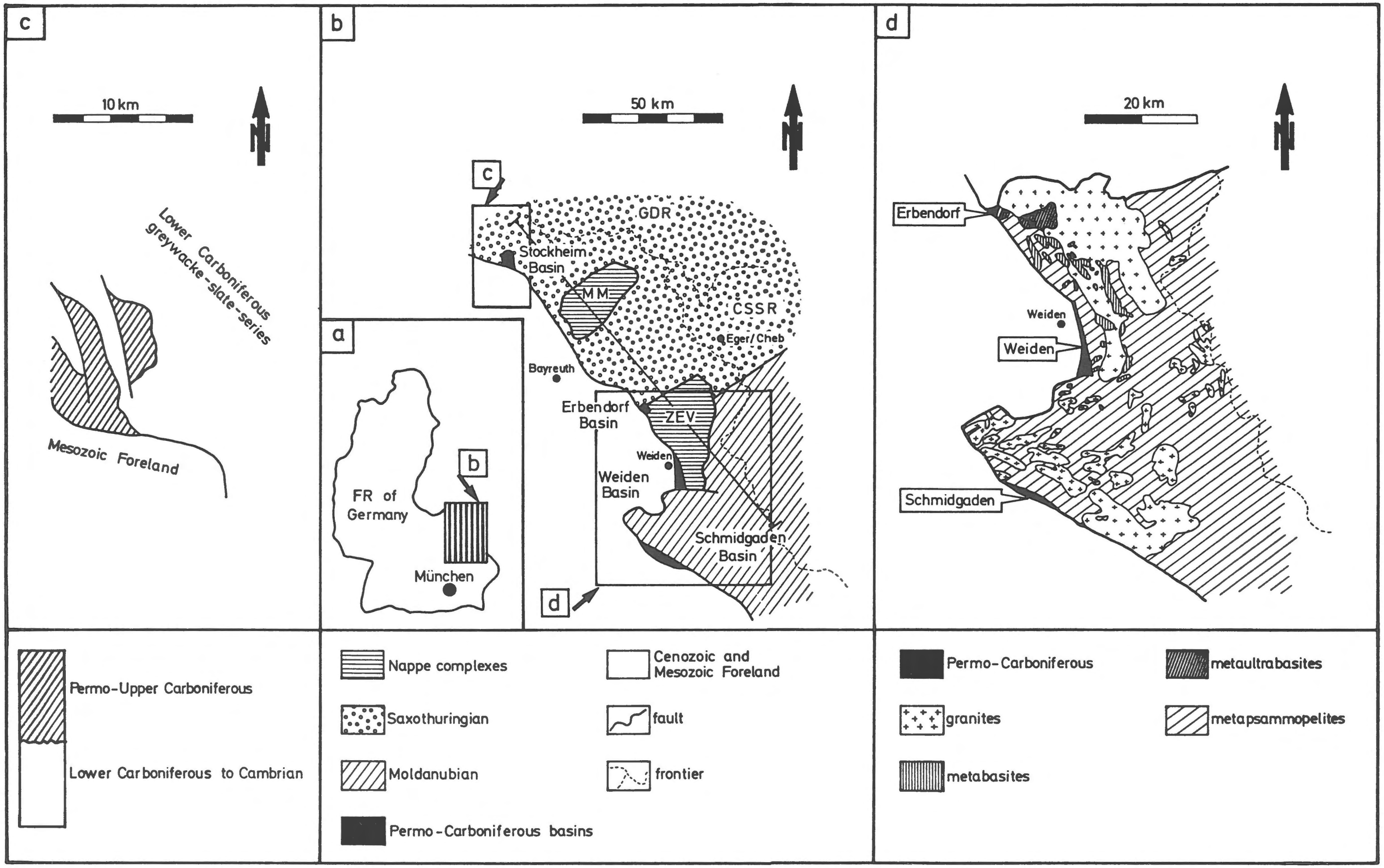


*Fig. 1.* Scetch map of the working areas. a) The position of the Mid-European Variscides in the SE part of the F.R. of Germany; b) The border zone between the Moldanubian and the Saxothuringian realms with Permo-Carboniferous fan deposits referred to in the text. The line denotes the cross section illustrated in Fig. 1e; c) Close-up of the Stockheim Basin; d) Close-up of the Erbendorf-, Weiden- and Schmidgaden Basins.

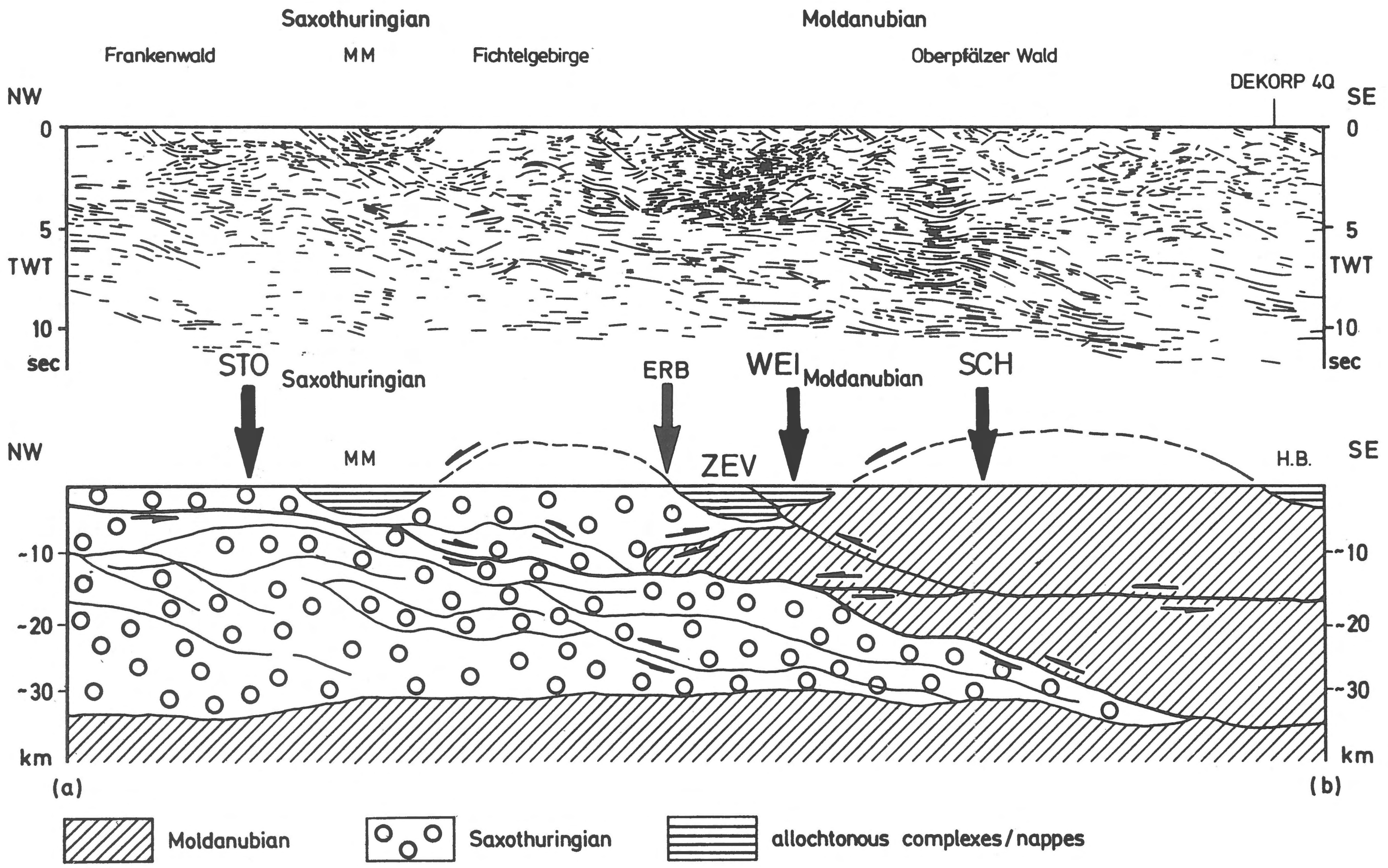


*Fig. 1. (continued).* e) Cross section through the Moldanubian-Saxothuringian border zone based on seismic investigations (line drawing upper half; interpretation lower half). STO: Stockheim Basin; ERB: Erbendorf Basin; WEI: Weiden Basin; SCH: Schmidgaden Basin; MM: Münchberg Gneiss Massif; ZEV: Zone von Erbendorf-Vohenstrauß. Sections prepared during pre-well-site studies of the German Continental Deep Drilling Programme.

(Morton 1979, Morad 1986), weathering processes (De Jong & Van der Waals 1971, Friis et al. 1980), provenance (Van Andel & Poole 1960, Morton 1985) and in stratigraphic correlation (Weisbrod & Nachimas 1986). False information about provenance and correlation mostly results from the activity of pore fluids which caused the dissolution of instable heavy minerals and an abnormal abundance of ultrastable minerals. Therefore, four basins similar in respect to their history of subsidence were selected for the present investigation (Stockheim Basin, Erbendorf Basin, Weiden Basin, Schmidgaden Basin – Fig. 1 a–d). By the end of the Variscan orogeny they were more or less contemporaneously filled with clastic and volcaniclastic rocks of Permo-Carboniferous age. Fan deposits vary as the wedges prograde from the basin-margin-fault towards the centre whereby proximal debris flows change into fine-grained distal fan plain deposits. Postdepositional alteration of the fan sediments under consideration, however, has been fairly the same as proved by coal petrography (see vitrinite reflectance) and clay mineralogy (e.g. illite crystallinity). The four small basins selected are situated close to the Bohemian Massif (Fig. 1) and contain beds showing a varied set of translucent and opaque heavy minerals.

First and foremost, this study aims at elucidating the story of uplift and denudation of the Mid-European Variscides. Secondly, an attempt is made to unravel the basin history of these fan deposits.

## Geologic setting

The sediments of the Stockheim Basin rest unconformably upon basement rocks of the Saxothuringian (Fig. 1c), the sediments of the Weiden and Schmidgaden Basins upon these of the Moldanubian (Emmert 1981) (Fig. 1d). The Erbendorf Basin occupies an outstanding position for it is an embayment at the boundary between the Saxothuringian and Moldanubian realms (Fig. 1e). The Saxothuringian comprises igneous and sedimentary rocks of Cambrian through Lower Carboniferous age which have been subjected to very low grade to high grade regional metamorphism. The crystalline rocks from the Moldanubian are strongly metamorphosed and are held to be Upper Proterozoic in age (Stettner 1981). At the transition from the Carboniferous to the Permian both domains were intruded by S-type granites (Fig. 1d).

## Results

### *Geology of Permo-Carboniferous basins*

The four basins under study are filled with Permo-Carboniferous clastic and volcaniclastic sediment with a thickness locally exceeding 700 m (e.g. Schmidgaden Basin – Helmkampf & Waeber 1983). The oldest series of the cover rocks unconformably rest on biotite-sillimanite-gneisses, as for instance in the Erbendorf, Weiden and Schmidgaden Basins (Helmkampf et al. 1982, Dill et al. 1988) or on graywacke-slate cyclothems as at Stockheim (Von Horstig 1979). The clastic sequences laid down in these basins may be subdivided into a lower grey and an upper red series (Dill & Botz 1987) (Fig. 2 a–d). Temperature determination of these rocks using vitrinite reflectance, points to about 135° C as upper T limit for the diagenetic alteration.

Sedimentary rocks common to all of these basins are course-grained conglomerates, siltstones, arenites and wackes. In the argillaceous sediments calcrete-bearing rocks are relatively widespread. They mostly form the topmost section of fining-upward sequences. Moreover there are coal seams or combustible shales in these grey series. A remarkable difference among these basins may be observed, when considering the type and size of volcaniclastic rocks. The Schmidgaden Basin is barren of volcaniclastic rocks. Tiny bentonite layers consisting of up to 100 per cent smectite are encountered in unit IV (Fig. 2b); tuffaceous interbeds (unit VI, Fig. 2c) and rhyodacites and dacites (unit VII, Fig. 2c) make up a great deal of the Permo-Carboniferous basin fill of the Erbendorf trough. Several minute tuffaceous interbeds and coarse-grained volcanic horizons have been spotted in the grey series of the Stockheim Basin (Fig. 2d).

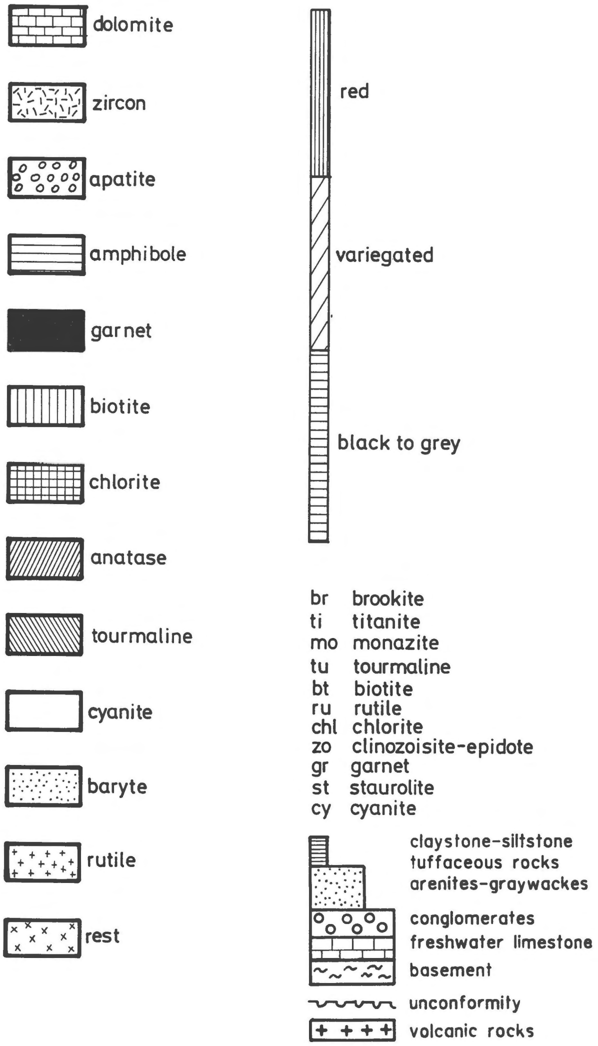


*Fig. 2.* Reference profiles from the Permo-Carboniferous basins at the western edge of the Bohemian Massif showing the variation of translucent heavy minerals throughout basin subsidence. Column a) rock colour; column b) lithology (simplified); column c) units referred to in the text.

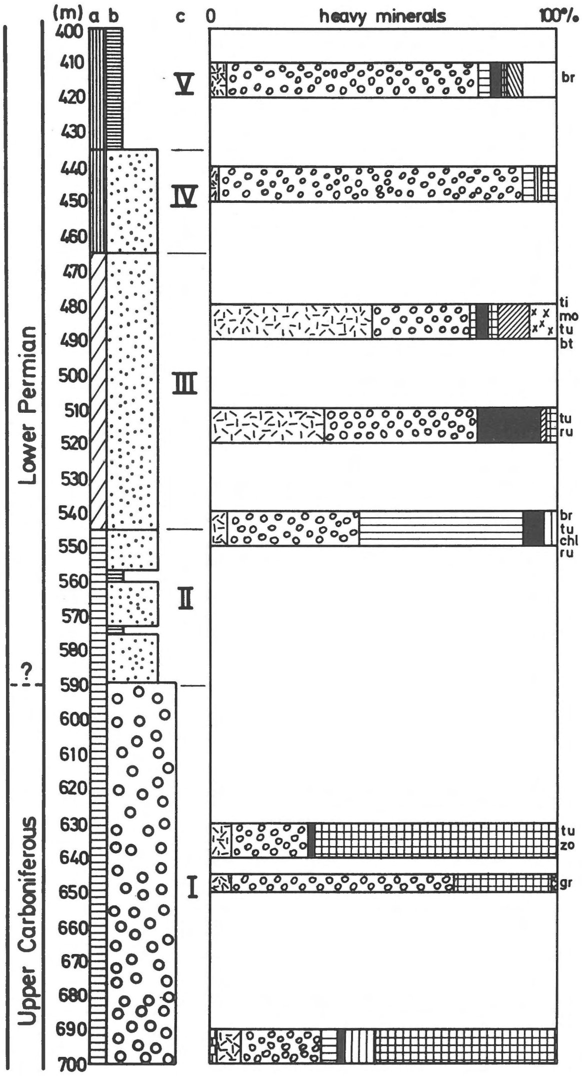


*Fig. 2a.* Schmidgaden Basin.

## *Interpretation of the Permo-Carboniferous basin fill*

Based on sedimentologic studies elsewhere (Nilsen 1982, Galloway & Hobday 1983), the deposits mapped in these basins may be interpreted as a set of fan deposits ranging from proximal fan deposits with debris flows (e.g. Fig. 2a, unit I, Fig. 2b, unit I, II, Fig. 2c, unit I) to distal fan plains originating from a swamp environment (e.g. Fig. 2b). Calcretes found in places in these playa sediments derived from soil-forming processes under semiarid conditions (Goudie 1983). The basins mainly differ from each other with respect to their volcaniclastic intercalations, which in the Stockheim Basin almost exclusively consist of pyroclastic rocks such as air fall tuffs, ignimbrites and lahars (according to Fisher & Schmincke 1984), volcanic rocks and some air fall tuffs in the Erbendorf Basin, and little air fall tuffs, exclusively, in the Weiden Basin (Dill et al. 1988).

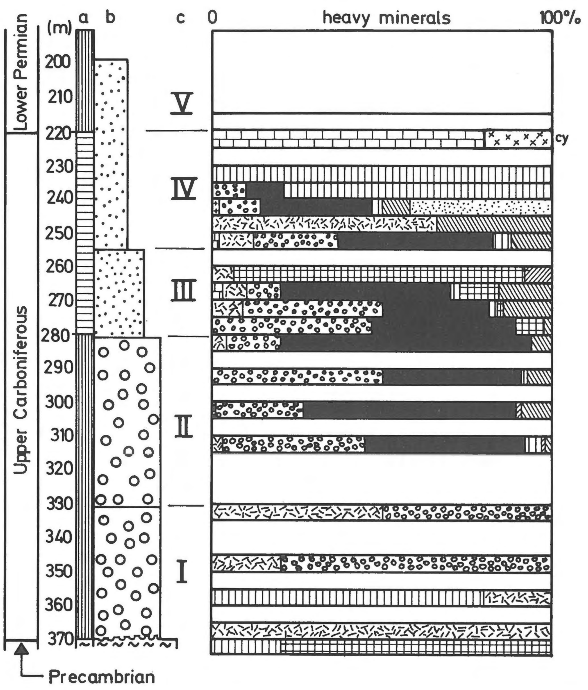


*Fig. 2b.* Weiden Basin.

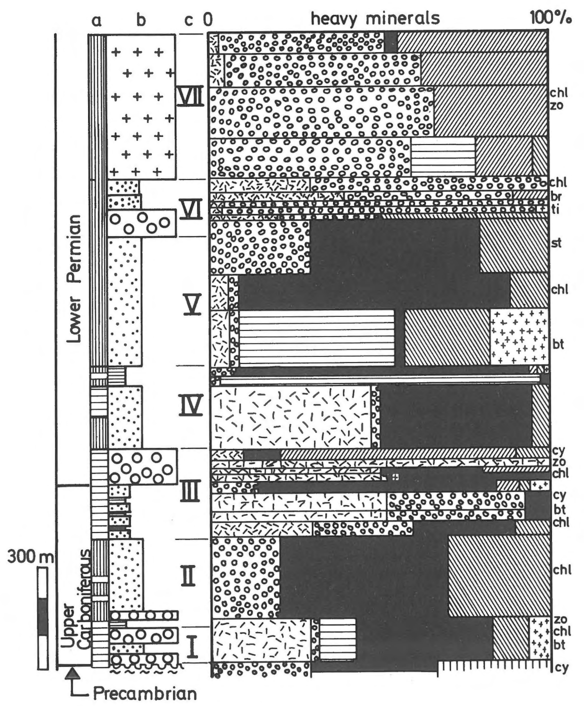


*Fig. 2c.* Erbendorf Basin.

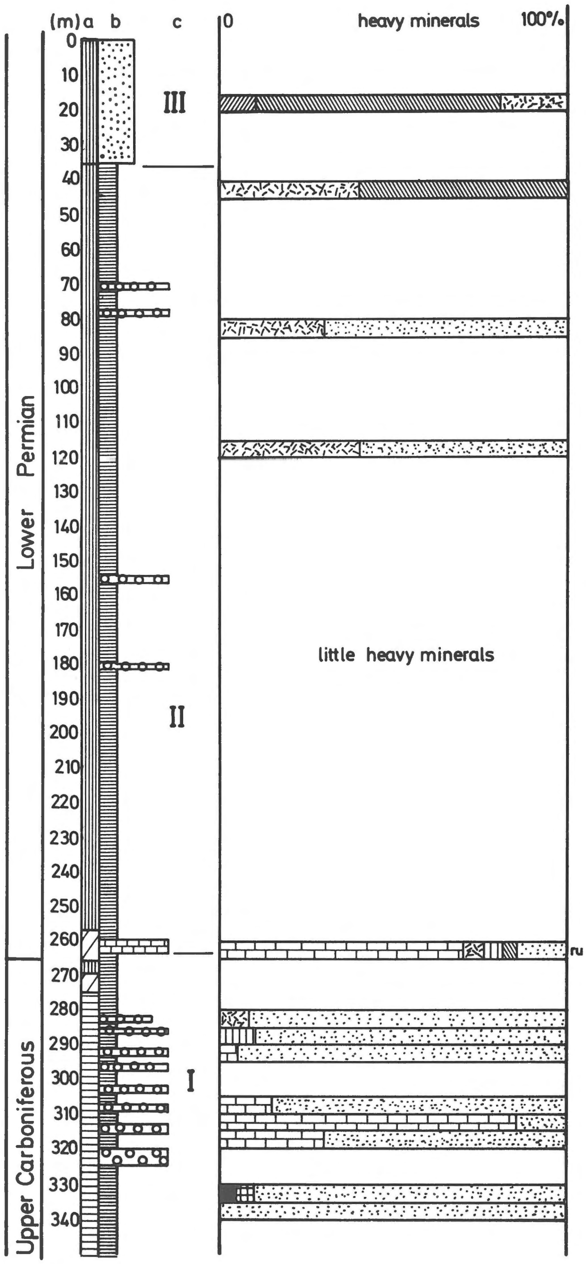


*Fig. 2d.* Stockheim Basin.

## *Heavy minerals of the Permo-Carboniferous basins*

*Schmidgaden Basin.* In the lowermost debris flows green chlorite is found which is derived from decomposition of biotite. Many of these chlorites contain slender crystals of rutile ('sagenite') and locally zircon. This Fe-rich chlorite was termed rhipidolite. Apatite found in all drill cores becomes more and more widespread in the younger sediments and attains a maximum in the fluvial environment. Zircon and garnet are most abundant in unit III, at the base of which amphibole is very widespread. Then amphibole and anatase appeared for the first time in the heavy mineral suite, whereas kyanite, an index mineral of the NE Bavarian metamorphic terrain, has been recognized for the first time in the fine-grained rocks of unit V (Fig. 5d). Alike the Weiden Basin the proportion of heavy minerals is fairly large and has a mean of 0.72% (Fig. 3).

*Weiden Basin.* Biotite is the only ferroan silicate present in the Weiden Basin to a significant degree. It is accompanied with or replaced by green chlorite in the clastic rocks of unit I. Brown biotite, however, from unit IV tuffites is fresh. Zircon, tourmaline and apatite vary quantitatively. As compared to Schmidgaden, the amount of isometric grains of apatite is reduced at the expense of needles which were frequently discovered in units III and IV volcaniclastic rocks. Ferroan dolomite and barite merit particular attention for their well-shaped rhombs and needles. In the same horizons pyrite, some galena and sphalerite occur.

*Erbendorf Basin.* Four associations, each dominated by a certain marker mineral, have been defined for the variegated spectrum of the Erbendorf Basin. Asociation I is characterized by amphibole as the leading mineral (units IV–V transitions), association II by garnet which is in abnormally high quantities in all units but units VI and VII. Among minerals of association III apatite ranks first (units VI and VII) and among association IV zircon which is prevalently encountered in the basal parts of units III and IV. As a new heavy mineral for these Permo-Carboniferous basins staurolite entered the heavy mineral association of unit V. Apatite crystal habits follow an antipathetic trend; acicular phosphates, anatase and brookite are disseminated in the tuffaceous sandstones of unit VI and volcanites of unit VII, isometric crystals are contained in the remaining arenites. Not as pronounced, but similar to apatite, zircon habits are also contrasting in the various units. Zircon needles from units VI and VII may be allocated to classes $P_3$ through $P_5$ according to the charts of Puppin (1980). Units I through V bear zircons attributable to classes $S_7$ and $S_8$ of the aforementioned classification scheme. The opaque heavy minerals spectrum is fairly homogeneous, relative to the translucent mineral suites and consists of titanomagnetite in places altered to hematite, some pyrite and minor amounts of chromite.

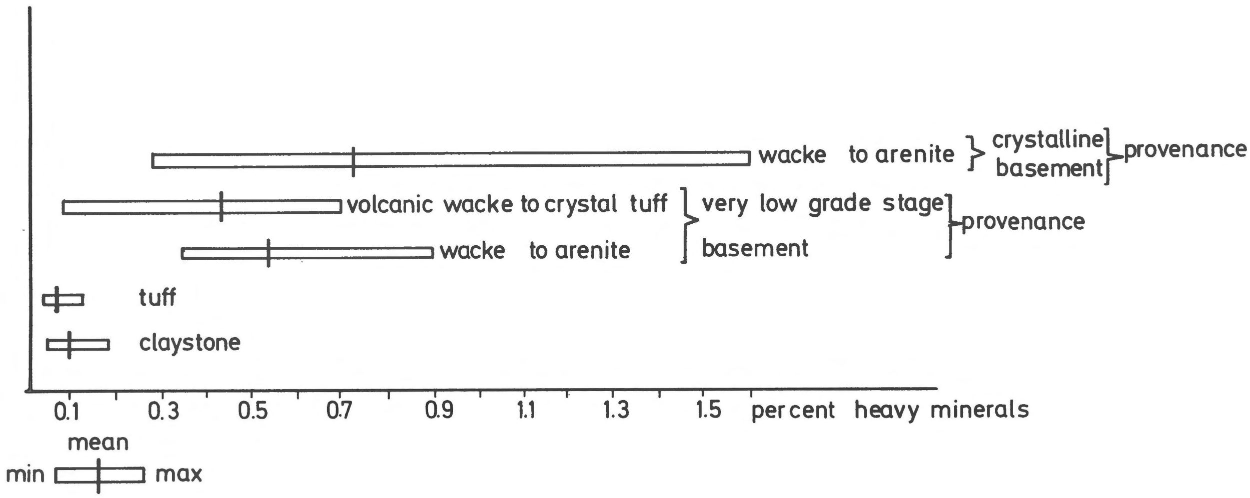


*Fig. 3.* The proportion of heavy minerals as a function of rock type.

*Stockheim Basin.* There are exceptionally few heavy minerals in the siltstones, air fall tuffs and volcanic wackes of the Stockheim Basin (Fig. 3). The spectrum is poor in general and built up only of well-shaped Fe dolomite, barite, some biotite, little apatite and zircon, which were encountered in the playa as well as in the fan depositions. Heavy mineral abundance improves near the boundary between playa and near shore marine sediments, the arenites of which contain numerous Fe tourmalines and zircons. In contrast with poor assemblage of translucent heavy minerals, the opaque heavy minerals are ubiquitous.

Titanomagnetite with exsolution lamellae of ilmenite occurs frequently in the volcaniclastic rocks and is replaced by anatase and hematite. Next to its specularite, locally intergrown with ferroan dolomite, occurs. Sulfides, which are restricted to the coal-bearing grey series and to some tuffites, constitute secondmost abundant category of opaque minerals. Octahedra, octahedra-dominated crystal aggregates, cubes, fambroids, pyrite replacing plant tissues and pyrite replaced by chalcopyrite are the most common forms, which cannot be treated in full detail in this paper.

## Discussion

### *Diagenesis*

Morton (1984) distinguished several orders of stability in detrital heavy minerals that were studied in a great number of different sedimentary basins. In view of that the question arises whether the striking scarcity of heavy minerals in samples from the Stockheim Basin, compared to their Permo-Carboniferous equivalents elsewhere in N Bavaria, is due to diagenesis. As the rate of subsidence of the Stockheim Basin did not exceed that of the adjacent basins (see also vitrinite reflectance) and since no significant pH variation may be inferred from the overall presence of pyrite, diagenesis could hardly have contributed to the poor composition of the mineral assemblage in this basin. Pyrite instead of marcasite is held to be a reliable marker for neutral pore solution throughout diagenesis (Murdowich & Barnes 1986).

Consequently, the ultrastable minerals zircon and tourmaline do not represent the remainder of a pervasive dissolution which has decomposed all the minerals of lesser stability – minor amounts of apatite would also contradict this hypothesis – they only reflects the mineralogy of the surrounding source area. Authigenic minerals such as Fe-dolomite and barite formed during early diagenesis, but the crucial control over this assemblage was brought about by post-volcanic, hydrothermal processes; that is why these special phases are better discussed under that heading.

The co-existence of unstable heavy minerals (e.g. amphibole, kyanite – see Morton (1979) and stable minerals like zircon and apatite in the mineral assemblages from the three other basins may disprove that these heavy mineral assemblages have been strongly affected by dissolution processes. Otherwise a continuous increase of unstable heavy minerals at the expense of more stable minerals should be observed in the individual profiles towards the top (Fig. 2a, b, c). In addition to illite crystallinity and vitrinite reflectance, anatase may also work as an index mineral for the burial temperature, because it formed in the T-range from 115° C to 260° C (Yau et al. 1987). Beyond 260° C rutile or titanite, in case of a Ca-enriched pore solution, would have replaced anatase in these alluvial fan deposits. This is consistent with the results obtained from vitrinite reflectance studies which yielded a temperature of as much as 135° C (Dypvik 1983). On the other hand, the peripheral position of these fan deposits relative to their central equivalents precludes deep burial and strong subsidence and implies a good preservation potential for the original heavy mineral suite.

### *Paleo-weathering*

Alteration of minerals at near ambient condition in various climates is mostly accompanied by oxydation, that is why the oxides among heavy minerals may offer a quick clue to paleo-weathering. Iron dissolution from detrital titanomagnetite in the Stockheim Basin leads to ilmenite. If Fe were completely released then only *plates* of anatase – which are typical of low temperature formation – are left in aggregates of 'leucoxene'. *Bipyramides* of anatase precipitate from a hydrothermal solution (Tröger 1969). Hematite which locally penetrated into magnetite-ilmenite grains along crystal planes is likely to have formed during weathering and/or transport when these grains were exposed to oxidizing ground waters, as can be surmised for these subaerial pyroclastic fan deposits. Poor oxidizing conditions locally caused preservation of ilmenite (Ramdohr 1975). While in the pyroclastic fan deposits of the Stockheim Basin no discrete anatase-bearing horizons may be defined, in units I to V, inclusively of the Erbendorf fan sediments, anatase plates and brookite are locally abnormally enriched in certain strata (e.g. upper half of units III and V). Both Ti-oxides may have been derived from alteration of Ti-magnetite, amphiboles and biotite. It is widely known, that $TiO_2$ (except rutile) formed on ancient peneplains under subtropical conditions (Thiry et al. 1983). Therefore, authigenic anatase, abnormally enriched, is envisaged as a marker for pedologic processes (e.g. lateritization) and peneplanation during built-up of this fan wedge at the basin edge. These anatase plates have featured as markers for paleosols and may be used even if cuttings alone are available from drill holes. Anatase correlates with zircon and anticorrelates with ferroan silicates like amphibole, biotite, chlorite or the easy-to-leach phosphates, when formed from descending meteoric water. In anticipation, there are exceptions to this rule and these will be discussed under the heading 'volcanism and hydrothermal activity' (see below), since this anatase resulted from ascending fluids. Apart from these authigenic minerals only the phosphates also offer a reliable clue pointing to weathering or diagenesis. Detrital apatite corroded by fluids during soil-forming processes exhibits a characteristic skeletal shape, similar to that observed in modern soil horizons (A- and B-horizon). Garnets facetted by etching are found from the Erbendorf to the Schmidgaden Basins certainly did not result from weathering (Borg 1986).

*Volcanism and hydrothermal activity*

Ferroan dolomite, barite and specularite are among minerals which can be used to distinguish volcanic intercalation and hydrothermal alteration. They were encountered in air fall tuffs of the Stockheim Basin and unit IV of the Weiden Basin. Isotope studies carried out on these Fe-carbonates have established that these minerals which were disseminated amongst pyroclastic fan deposits have formed from hydrothermal fluids (Dill & Botz 1987).

Furthermore, the crystal shape of zircon and apatite, the crystal elongation of which increases with increasing temperature, allows to assign these two minerals to a volcanic or a metamorphic/plutonic source (Mehnert 1971). Slender prisms of zircon and apatite are rarely met in the lower part of the Stockheim profile, more often, however, in units VI and VII of the Erbendorf Basin derive from Permo-Carboniferous volcanism. Apatite and zircon, fed into the basin from the nearby late Variscan granites and metamorphic rocks, show a strikingly smaller crystal elongation. Roundness or angularity of mineral grains often held to be in response to transport and attrition, cannot be used as such to characterize these proximal fan depositions. Anatase bipyramides, as already mentioned in the discussion of paleoweathering, occur in units VI and VII volcanites and volcaniclastic rocks of the Erbendorf Basin and in unit III of the Weiden Basin.

In case of hydrothermal alteration anatase is mostly associated with Fe-chlorite, amphibole and rarely with biotite, from which it derived. The ratio of anatase/Fe silicate denotes the intensity of hydrothermal alteration to which these arenaceous host rocks were subjected. The anatase contents increase at the expense of these Fe silicates during ongoing hydrothermal alteration. Comparing clastic and volcaniclastic rocks of equivalent grain size intervals one can demonstrate that the mean abundance of pyroclastic rocks averages below that of equivalent epiclastic arenaceous and argillaceous rocks (Fig. 3). It is, however, a little premature to lay claim to a general rule, since error bars of the standard deviations overlap (Fig. 3). The statement has to be tested by additional samples from various pyroclastic and epiclastic series elsewhere. Biotite, which Weaver (1955) considered characteristic of tuffs could not work well as an indicator of volcanic activity in that proximal fan deposition, since there is too much biotite derived from the continental run-off of the enclosing crystalline basement. A short distance of transport did not severely alter the amount and shape of biotite.

Titanomagnetite found in the volcaniclastic rocks cannot be used as an index mineral for pyroclastic deposition. These rounded detrital mineral grains of the system $TiO_2$-$FeO$-$Fe_2O_3$ altered by meteoric waters solely attest that volcanic rocks are exposed in the hinterland, but do not bear witness of air fall tuffs or even of in-situ formation from high temperature fluids (Petersen et al. 1979; Reynolds 1982).

*Provenance*

The heavy mineral assemblages under study allow a distinction between provenance areas of very low grade to low grade stage regionally metamorphosed rocks (e.g. Stockheim) and those of medium to high grade metamorphic rocks (e.g. Erbendorf, Weiden, Schmidgaden). Paucity of detrital heavy minerals in the Permo-Carbonifeous playa sediments, and exceptionally stable minerals coming up in the younger series are due to denudation of Lower Carbiniferous graywacke-slate cyclothems in the Variscan basement surrounding the Stockheim Basin (Fig. 1c). Moderate regional metamorphism did not cause formation of characteristic minerals such as staurolite in these Lower Carboniferous arenaceous and argillaceous rocks.

By contrast, kyanite and, to a lesser extent, staurolite from the fan deposits in front of the Moldanubian basement may clearly be referred to the medium pressure metamorphic (= MP) rocks (Winkler 1976) of the Erbendorf-Vohenstrauß Zone (ZEV) (Fig. 1d, e). Both silicates have been reported as minor constituents from the adjacent Precambrian gneisses (Wagner-Lohse & Blümel 1986). As kyanite was discovered in carbargillites, which paleobotanically have been dated to be Stephanian C/D in age, the onset of denudation of these nearby MP-rocks may precisely be defined.

Assuming that gneisses of different metamorphic grades were truncated by the erosion during the Carboniferous, the relative rate of uplift may be concluded from the mineral association that is found in the drill holes. The metapelites of Schmidgaden provenance area were subjected to a lower grade of regional metamorphism for the amount of chlorite overtakes that of biotite in the Schmidgaden Basin relative to the Weiden Basin. The lower units of the Erbendorf fan deposit are devoid on any mineral suite indicative of low grade regional metamorphism. Consequently, the basement uplift was more intense in the NW part of the Moldanubian than in the SE part (Fig. 1d, e). This evidence supplied by heavy minerals accords well with the nearness of the Erbendorf Basin to the thrust plane between the Moldanubian and Saxothuringian realm.

What about metabasic and ultrabasic rocks in the crystalline basement? Only disrupted lenses, but no continuous greenstone belts have been mapped in the neighbouring basement (Stettner, 1975) (Fig. 1d). Not surprisingly, green amphibole occurs only sporadically in the mineral spectrum of the foreland. Accompanying sphene in the heavy mineral log points to calcsilicate rocks which in time and space are associated with these metabasic rocks in the metamorphic hinterland.

To proof metamorphosed ultrabasic rocks in the hinterland from the heavy mineral association of the fan deposits is much more problematic, because of the amount of labile constituents (e.g. actinolite, augite) that are present in these greenstones and the scarcity of rocks exposures. For these reasons, minerals diagnostic of ultrabasic rocks may be expected in the heavy mineral spectrum of Erbendorf Basin, only.

Among the translucent group minerals no species may be recorded indicative of greenstones. Solely chromite, spotted in polished sections of unit I of Erbendorf Basin, may be assigned to the serpentinites of the Erbendorf greenstone series.

It has to be stressed that the beginning of denudation of the Late Variscan granites causes difficulties. Minerals such as zircon, tourmaline and apa-

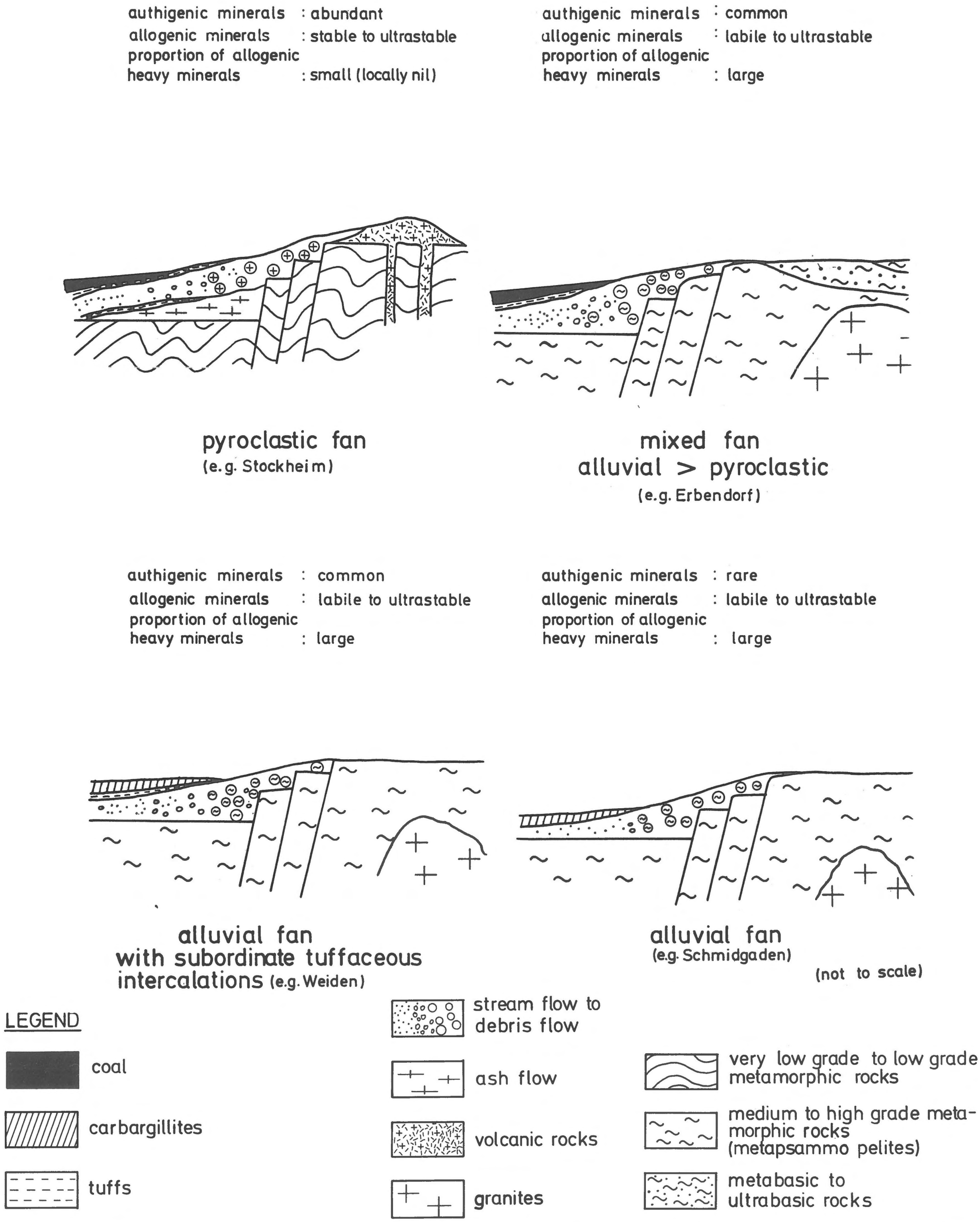


*Fig. 4.* Cartoon illustrating the various types of fans under consideration and the type and amount of heavy minerals present in these clastic and volcaniclastic rocks.

tite were found in the granites as well as granitic mobilizates of the metamorphic wall rocks. Blue fluorite, locally abundant in alteration zones near the margin of these Late Variscan granites, was not encountered in the heavy mineral spectrum of the foreland – fan deposits. The excellent cleavage of fluorspar obviously caused its complete removal from the heavy mineral spectrum even over such small distances of transport. The appearance of monazite in the 'Bunter Series' of the Lower Triassic following to the SW of these basins in the first evidence for these granites to have been exposed in the NE Bavarian crystalline basement (Schnitzer 1957).

## Conclusion and summary

Considering the intrabasinal (volcanism, hydrothermal activity, weathering) and extrabasinal (provenance) factors which control the heavy mineral association of the four basins, that association determines that the Stockheim Basin, above all, is filled with pyroclastic fan deposits (Fig. 4). In Erbendorf a mixed type evolved throughout the Permo-Carboniferous, while in the Weiden embayment the volcanic influence became reduced and is only vaguely recorded in the alluvial fan deposits. In the alluvial fan of the Schmidgaden Basin the volcanic activity runs to nil. From NW towards the SE coal seams gradually pass into carbargillites.

From the heavy mineral contents of these fan deposits the following conclusions may be drawn:

1. The variegated heavy mineral association of the fan deposits did not significantly suffer from diagenetic alteration.
2. By and large, these varied associations are a mirror of basement uplift and denudation of the neighbouring provenance area.
3. The metamorphic grade and the path of metamorphic temperature and pressure change in the basement may be deciphered from the reverse order of minerals such as staurolite, kyanite, biotite-chlorite in the sedimentary deposits.
4. Ultrabasic rocks and granites often escape clearcut recognition in the heavy mineral sequences due to their abundance in labile constituents and to their coincidence with other minerals from metamorphic terrains. Opaque minerals such as chromite may be helpful for the determination of ultrabasic source rocks.
5. Crystal habits of zircon, apatite and anatase may be used to discriminate derivation from plutonic/metamorphic or volcanic rocks and to distinguish hydrothermal activity from weathering.
6. Mineral transformation in the system Fe-Ti-O and depletion of certain minerals like phosphates were controlled by meteoric waters and are indicative of paleo-weathering.
7. Volcanic intercalations among sediments may be inferred also from low proportions of heavy minerals, the mean of which is smaller than that of time-equivalent non-volcaniclastic rocks in the same area.

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