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The plutonic rocks of the Meißen massif (Germany): evidence for open and closed system fractionation processes

by Th. Wenzel¹, I. Mercolli² and R. Oberhänsli³

Abstract

The plutonic complex of the Meißen massif (E-Germany) consists, from rim to core, of a nearly concentric sequence of diorite-monzodiorite, monzonite and some granite intrusions (classically termed Hauptgranit, Riesensteingranit, porphyrtiger Granit). Fabric and mineral chemical data as well as major and trace element compositions of whole-rock samples indicate a magmatic development of the complex by the following fractionation processes:

- The diorite-monzodiorite-monzonite sequence of Freital is due to closed system fractional crystallization of an undersaturated basaltic magma of alkaline affinities.

- Near Leuben, the monzodiorite was subsequently impregnated and partially digested by syenite melt. Mineral chemical data and fabric patterns of the resulting monzonite reflect incomplete assimilation, i.e. non-equilibrium conditions of an open system. To a lesser degree, such heterogeneity is present at Wilsdruff, whereas the monzonites sampled at Spitzgrund and Heidenschanze are virtually homogeneous. The sequence represents different stages of homogenization of hybrid melts of the Leuben type. The fractionation trend of these monzonites differs from that of the Freital series.

- For major elements the Hauptgranit and Riesensteingranit follow the monzonite trend, whereas some trace element patterns are distinctly nonlinear. Such deviations occur for samples with magmatic muscovite and are interpreted as the local result of crustal contamination.

- Finally, non-equilibrium characteristics prevail in the porphyry-like granite (porphyrtiger Granit): Embedded in a fine-grained granitic matrix are xenocrysts of plagioclase and biotite. These are chemically similar to the corresponding minerals of the Freital rocks. Assimilation of Freital-type material by a late granitic melt – perhaps by magma-mingling – is indicated.

The Variscan Meißen complex is thus interpreted as a single magmatic system reflecting, however, a range of fractionation processes.

Keywords: Plutonic complex, fractionation, monzonite trend, geochemistry, Meißen massif, Germany.

Introduction

The Meißen massif is situated in the E of Germany between the geological units of the Erzgebirge, Granulitgebirge and Lausitzer Block. It represents a part of the Elbe-valley zone (see PIETZSCH, 1956; Fig.1). The massif forms a longitudinal lens parallel to the Hercynian direction (NW/SE). A tectonic boundary (Westlausitzer Störung) separates the massif from the Lusatian granite region (Lausitzer Block) in the east. Intrusive contacts are developed between the plutonites and the

rock members of the Nossen-Wilsdruffer and the Elbtal-Schiefergebirge (e.g. PIETZSCH, 1956).

The Meißen massif has been repeatedly investigated in the past. An overview on this work was given by PFEIFFER (1964), who contributed also to the modern petrographic classification of the intrusive rocks. Further geological and petrographical details will be published by SCHMIDT (in prep.).

The plutonic complex may be subdivided in northern, central and southern parts, respectively. The rocks of the central part dominate, however.

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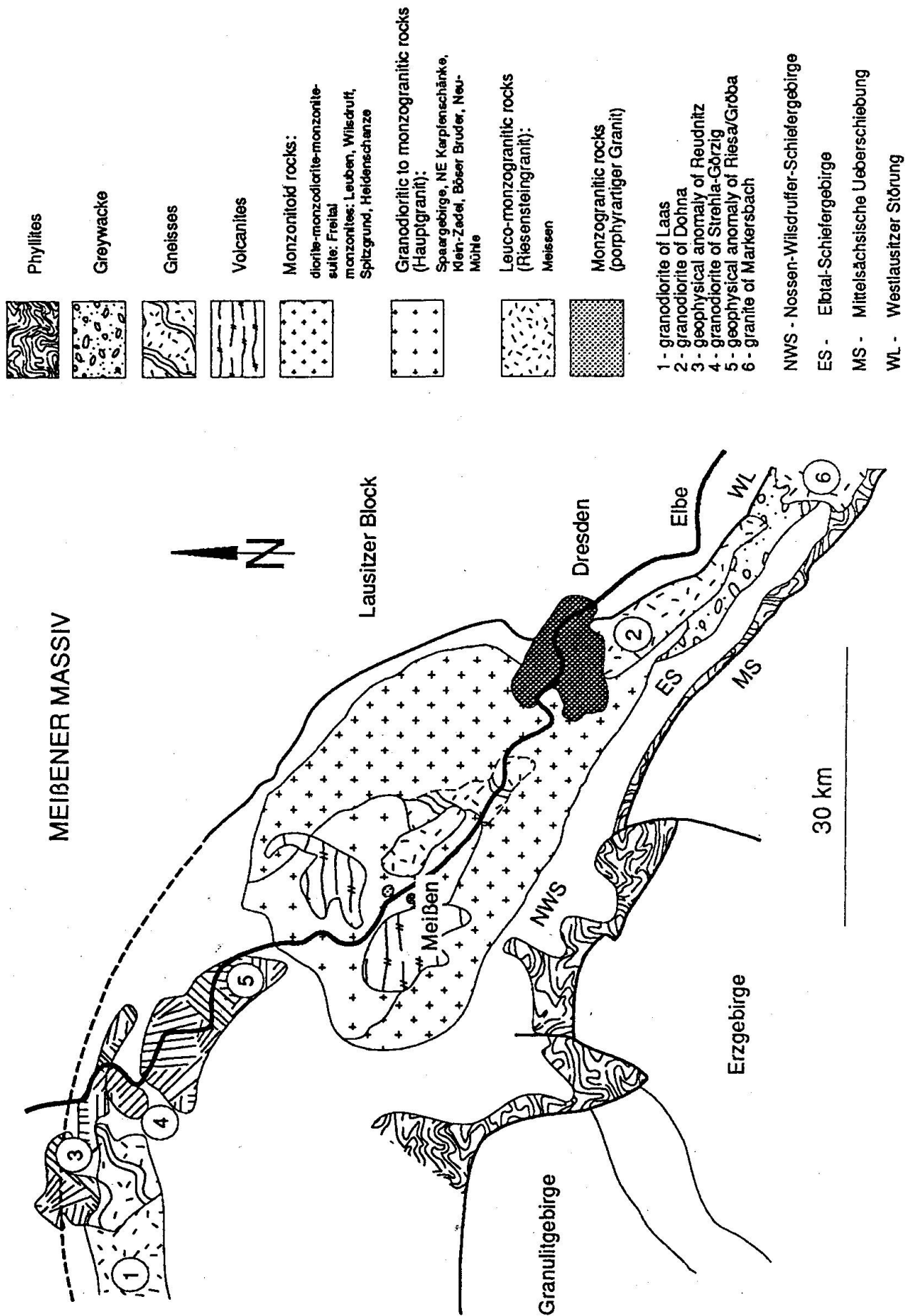


Fig. 1 Simplified geological map of the Meißener massif and the surrounding areas (after PIETZSCH, 1956, and SCHMIDT, in prep.).

A nearly concentric structure is built up by the following main rock types in this region (Fig. 1):

- monzonites and quartz-monzonites, locally with varying amounts of pyroxene, in the outer parts (Leuben, Wilsdruff, Spitzgrund, Heiden-schanze);

- granodiorites and monzogranites of the Hauptgranit in the center (Spaargebirge, NW Karpfenschänke, Klein-Zadel, Böser Bruder, Neu-Mühle);

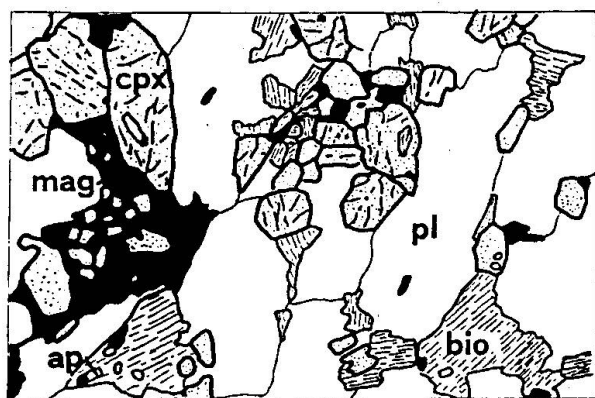
- a biotite-hornblende-bearing granodiorite which is interpreted as a reaction product between the first two types;

- a leucomonzogranite – the so-called Riesensteingranit (Meißen), and

- a porphyry-like monzogranite – the G II.

Recently, due to mining activities, a complete transitional diorite-monzodiorite-monzonite sequence near Freital has been exposed.

Furthermore, the pyroxene-monzodiorite of Gröba near Riesa (known as "Gröbait") and the pyroxene-diorite-monzodiorite-monzonite-syenite sequence of the Reudnitz drill-hole, situated in the northern part, are of special petrogenetic importance.

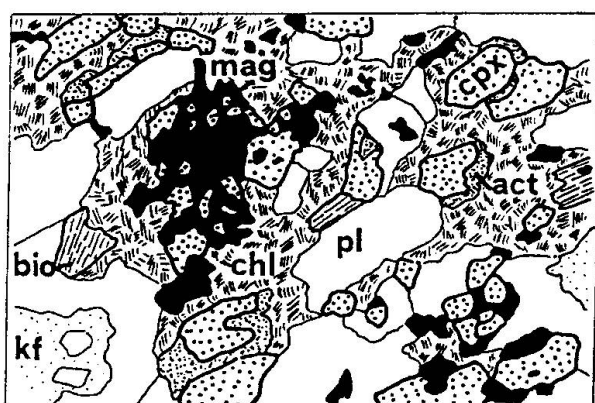


Diorite

cpx Al_2O_3 : 0-2.34 wt%, TiO_2 : 0.05-0.56 wt%
 X_{Mg} : 0.73-0.86

bio TiO_2 : 4.52-4.83 wt%, BaO : 1.13-1.55 wt%
 X_{Mg} : 0.62-0.65

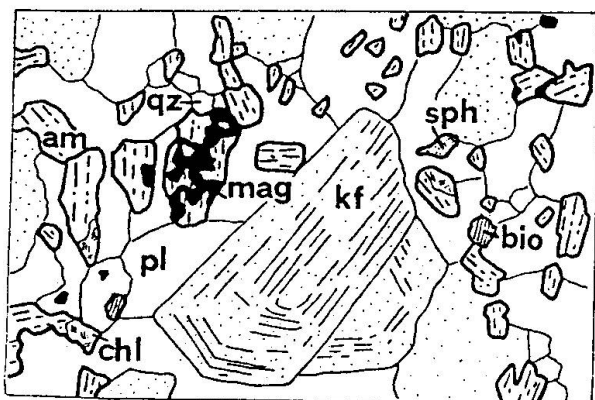
pl An: 51-56, SrO : 0.31-0.42 wt%



Monzodiorite

pl An: 34-42, SrO : 0.30-0.35 wt%

kf Or: 83-93, SrO : 0.34-0.46 wt%
 BaO : 1.67-2.00 wt%



Monzonite

am Al_2O_3 : 4.02-6.78 wt%, TiO_2 : 0.22-1.59 wt%
 X_{Mg} : 0.58-0.60

pl An: 26-29, SrO : 0.15-0.26 wt%
kf Or: 86-94, SrO : 0.15-0.21 wt%
 BaO : 0.31-0.59 wt%

Fig. 2 Fabric patterns of the Freital rock suite and concentrations of the petrogenetically most important components, measured by microprobe, in the different minerals. cpx – clinopyroxene, bio – biotite, pl – plagioclase, kf – alkali feldspar, am – amphibole, qz – quartz, mag – magnetite, ap – apatite, chl – chlorite, sph – sphene.

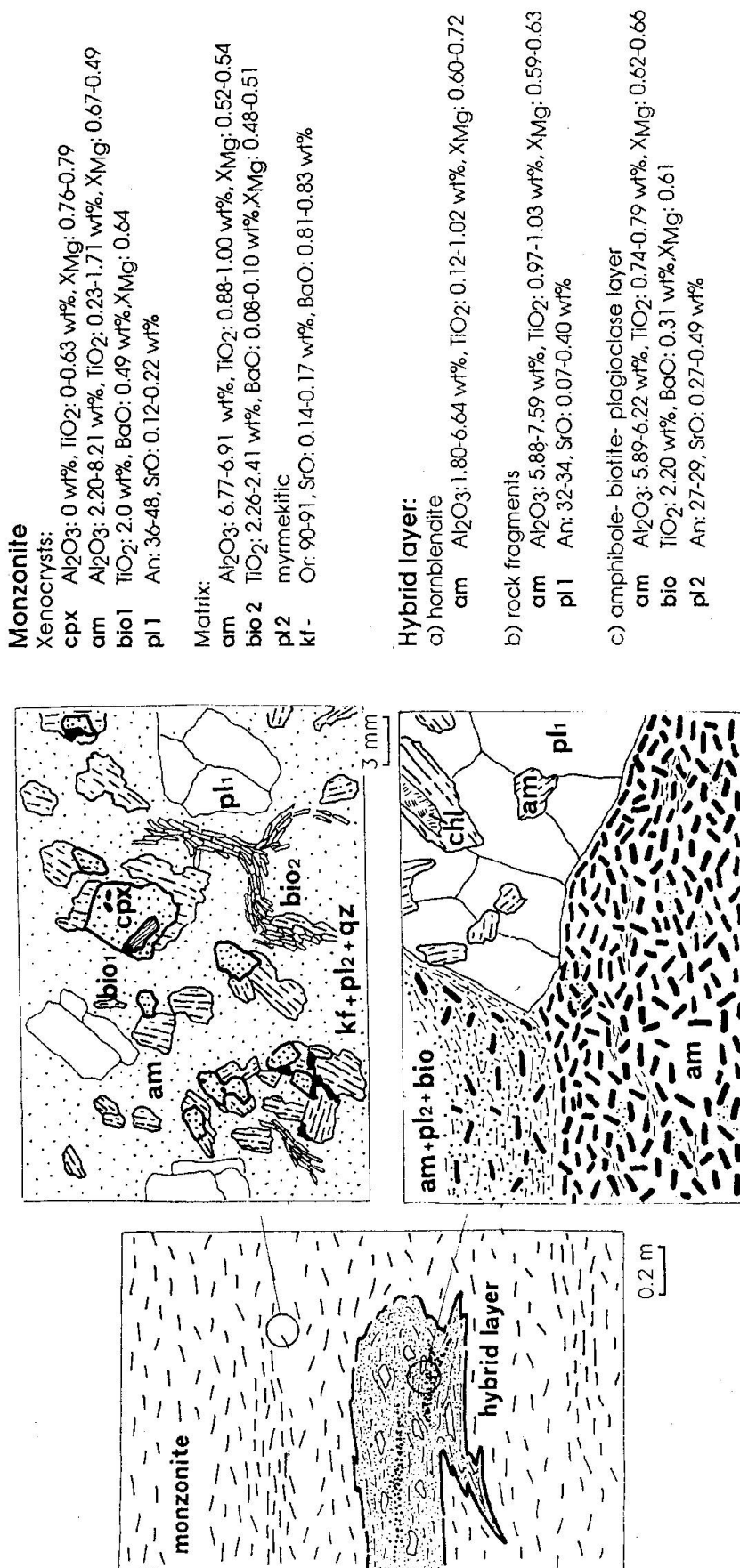


Fig. 3 Characteristic structure of the gneissoid type of the Leuben monzonite. The windows show fabric patterns of the monzonitic rock and a dark inclusion (hybrid layer) in detail; see text for further explanation. Abbreviations as in figure 2.

The plutonic rocks of the Meissen massif were emplaced during the Variscan orogeny, according to field geological evidence (PIETZSCH, 1927; GALLWITZ, 1934). Previous chronological data (WENZEL et al., 1990) support this view. However, there are also intrusions of Cadomian age in the same area (granites of Laas and Dohna, see figure 1).

PFEIFFER (1964) proposed that a monzonitic magma was produced from a crustal source region by anatexis. Granitic intrusions followed, generated by pressure release.

The objectives of this paper are:

- the identification of petrogenetic processes as fractional crystallization, contamination, mixing/mingling,
- a discussion of the magmatic development within the different intrusions and
- the characterization of the parental melts.

Petrographical descriptions

THE DIORITE-MONZODIORITE-MONZONITE SEQUENCE OF FREITAL

Five samples were taken in a diorite-monzodiorite-monzonite sequence which was exposed by mining near Freital. The transitions between the different rock types are gradual within some tens of meters. Irregular changes of light and dark rock constituents cause an impression of a weakly aligned structure. Simplified fabric patterns as well as mineralogical and mineral chemical compositions of the Freital rocks are given in figure 2:

The mineral chemistry of diopside and Mg-rich biotite indicates transitional to alkaline affinities of the parental melt (cf. BERGMAN, 1987). Crystallization of biotite and diopside prior to amphibole, as in the diorite, is restricted to relatively low water activities in the melt (discussion in HEWITT and WONES, 1984). The occurrence of biotite in the diorite refers to a high activity of potassium in the magma.

Orthopyroxene is completely absent. Hence, it may be concluded that the potassium-rich melt was not produced from calcalkaline magma by fractional crystallization of orthopyroxene under high pressure, as proposed by MEEN (1987) for some shoshonitic rocks. The absence of orthopyroxene is typical for alkali basalt series (YODER and TILLEY, 1962).

Associations of sericitized plagioclase and strongly chloritized biotite, enclosed by diopside, could be regarded as relics of crustal contamination, since the chemistry of both minerals is quite different to the biotite- and plagioclase-composi-

tion in the groundmass. The occurrence of yellow-luminescing cores in apatite crystals yielding violet color under cathodoluminescence further supports the source contamination hypothesis (WENZEL and RAMSEYER, submitted).

Thus, the sequence diorite-monzodiorite-monzonite is the result of the progressive crystallization of a basic magma, showing interactions between early segregations and the residual melt.

MONZONITE FROM LEUBEN

Monzonite samples from Leuben show distinct variations of the fabric characteristics within some tens of meters. There are nearly non-oriented as well as gneissoid types. The latter contain coarse-grained plagioclase or plagioclase aggregations and xenocrystic amphibole within a fine-grained matrix. The matrix consists of alkali feldspar, albitic plagioclase, biotite and minor quartz. Sometimes amphibole encloses diopside cores, partly intergrown with biotite. Frequently, the plagioclases have myrmekitic rims.

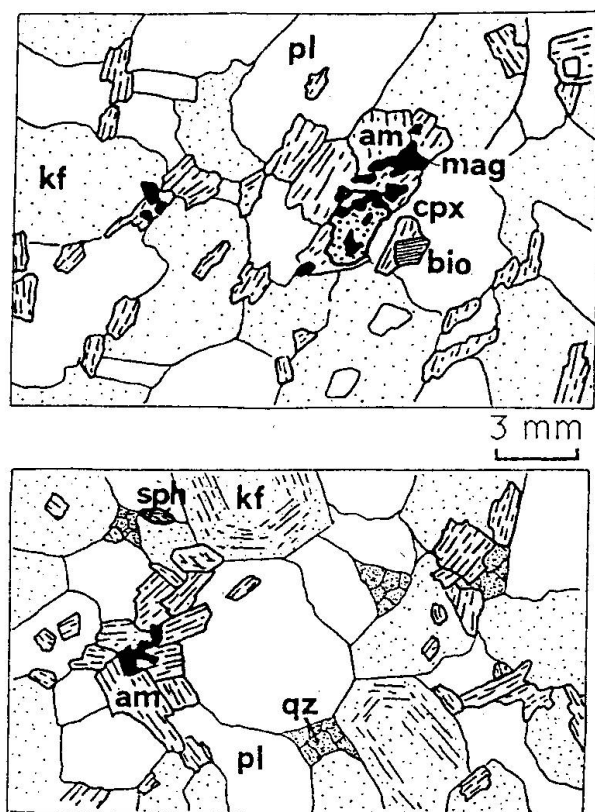
Amphibole- and biotite-rich inclusions of the Leuben monzonite were investigated. They are oval-shaped with meter sizes. Generally, the internal structure in thin sections yields amphibole-rich and amphibole-biotite-plagioclase-bearing parts. The latter enclose rock fragments; biotite layers partly surround them. The fragments are composed of sericitized plagioclase, xenocrystic amphibole and minor alkali feldspar. Alteration reactions, especially on plagioclase, and destruction of the structure take place in the boundary regions.

The main fabric features and mineral chemical data are summarized in figure 3:

There are important arguments for disequilibrium of the mineral associations in the Leuben monzonite: Coarse-grained plagioclase as well as diopside-Mg-biotite-intercalations within xenocrystic amphibole represent basic constituents dispersed in a more evolved matrix of granitic or syenitic composition. The fabric pattern looks like an impregnation and resorption of preexisting mineral associations of dioritic or monzodioritic affinities by acid melts. As a result, the reaction diopside → actinolite → edenite took place. Edenite has coexisted with an Fe-enriched biotite for a time. Coarse plagioclase became unstable and was altered.

Investigations of dark inclusions of the Leuben monzonite support the assumptions discussed above:

- Amphibole-dominated parts are interpreted as hornblendites, probably resulting from the



Monzonite Wilsdruff

cpx	Al ₂ O ₃ : 0 wt%, TiO ₂ : 0.30 wt%, X _{Mg} : 0.79
am	Al ₂ O ₃ : 5.48-6.41 wt%, TiO ₂ : 0.99-1.26 wt% X _{Mg} : 0.59-0.63
bio	TiO ₂ : 2.82-3.52 wt%, BaO: 0.09-0.14 wt% X _{Mg} : 0.56-0.64
pl	An: 22-33, SrO: 0.12-0.21 wt%
kf	Or: 84-92, SrO: 0.09-0.35 wt% BaO: 0.41-1.23 wt%

Monzonite Heidenschanze

am	Al ₂ O ₃ : 6.55-6.91 wt%, TiO ₂ : 0.98-1.43 wt% X _{Mg} : 0.56
pl	An: 19-27, SrO: 0.10-0.36 wt%
kf	Or: 87-93, SrO: 0.24-0.32 wt% BaO: 0.78-1.07 wt%

Fig. 4 Fabric patterns of the monzonites from Wilsdruff and Heidenschanze showing a progressive homogenization of their mineral assemblages in comparison to Leuben. Abbreviations as in figure 2.

conversion of pyroxene to actinolitic amphibole in a melt with higher water activity. The amphibole compositional trends within parts of the inclusion are comparable to those in the zoned xenocrystic amphibole of the monzonite (see Fig. 3).

– The rock fragments resemble the monzodiorite of Freital. This is especially indicated by similar An- and SrO-contents of plagioclase and the occurrence of chlorite inclusions in amphibole (compare Fig. 2). The fragments seem to be relics of greater rock units which were overprinted and partly digested by a separate (exotic) melt.

– The surrounding layers are characterized by the successive dissemination of such fragments. The observed "adaptation" of biotite-crystals on the surface of rock fragments is interpreted as depositional fabric.

Consequently, the dark inclusions in the Leuben monzonite do not represent xenoliths of amphibolites from the "region of mobilization of different source rocks" as proposed by PFEIFFER (1964), but monzodiorites taken up from a precursor intrusion.

MONZONITES FROM WILSDRUFF, SPITZGRUND AND HEIDENSCHANZE

In opposition to Leuben, the monzonite from Wilsdruff has mainly oriented structures, caused

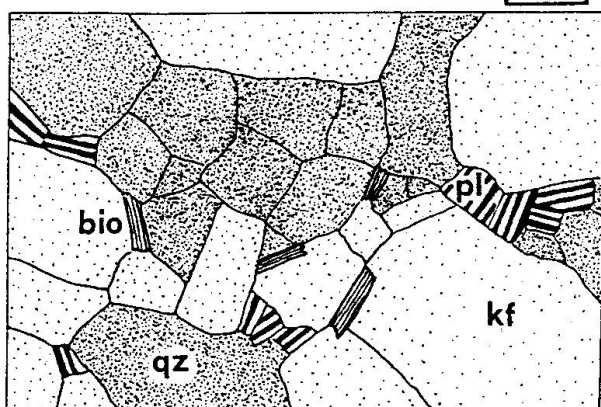
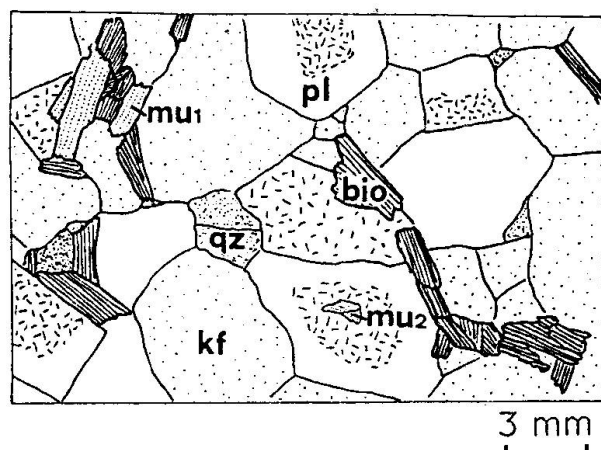
by alkali feldspar laths. Similar monzonites have been repeatedly described within the Meißner massif (e.g. REINISCH, 1928; HÄRTEL, 1931). Generally, these patterns are interpreted as flow structures.

Monzonites from Spitzgrund near Coswig are non-oriented. Grey and red varieties were observed within one and the same quarry. While the grey samples contain pyrite and to a lesser amount magnetite, the red ones bear magnetite and hematite. The $\delta^{34}\text{S}$ -values of pyrite group around 0 per mil, supporting a magmatic origin. Thus, contemporaneous differences in the redox state may be assumed.

The monzonite from Heidenschanze is a red-coloured, weakly oriented rock. It contains biotite-amphibole-rich inclusions of cm-dimensions or dispersed constituents of former inclusions ("Streuzonen" of PFEIFFER, 1964).

Fabric patterns as well as mineral compositions are presented in figure 4:

Monzonites from Wilsdruff, Spitzgrund and Heidenschanze have less heterogeneous fabric characteristics and mineral associations than the Leuben type. While biotite and diopside still occur beside amphibole in Wilsdruff, the rocks of the Spitzgrund and Heidenschanze contain only edenite as mafic constituent. This is interpreted as progressive homogenization of the magma.



Monzogranite Klein-Zadel

bio	TiO ₂ : 2.73-2.81 wt%, BaO: 0.11-0.13 wt% X _{Mg} : 0.42-0.43
mu1	TiO ₂ : 0.38-1.16 wt%, FeO: 3.84-5.26 wt% MgO: 0.88-1.66 wt%
pl	An: 4-21, SrO: 0.10-0.26 wt%
kf	Or: 89-97, SrO: 0.0-0.14 wt% BaO: 0.27-0.47 wt%

Monzogranite Riesensteingranit

bio	TiO ₂ : 2.78-3.05 wt%, BaO: 0 wt% X _{Mg} : 0.43-0.54
pl	An: 6-20, SrO: 0 wt%
kf	Or: 92-95, SrO: 0 wt% BaO: 0 wt%

Fig. 5 Fabric patterns and mineral compositions of the monzogranite from Klein-Zadel (Hauptgranit) and the leuco-monzogranite from Meißen (Riesensteingranit). Abbreviations as in figure 2. Note the occurrence of magmatic (mu1) and late- to post-magmatic (mu2) muscovite.

MONZOGRANITES FROM SPAARGEBIRGE, KARPFENSCHÄNKE, KLEIN-ZADEL, BÖSER BRUDER AND NEU-MÜHLE ("HAUPTGRANIT")

The monzogranites from several outcrops of the Hauptgranit differ mainly in their contents of biotite, ranging from 3 to 8 wt%. The occurrence of intergranular and intercrystalline white mica, especially in some samples from Klein-Zadel, is a local peculiarity of this rock type. Figure 5 shows fabric characteristics and mineral chemical data, measured on samples from Klein-Zadel:

In the TiO₂-Fe₂O₃-MgO-space, according to SPEER (1984), the intergranular muscovite is of magmatic origin, while the intracrystalline generation corresponds to postmagmatic muscovite.

The magmatic muscovite indicates crustal influences on the parental melt of the Hauptgranit.

LEUCO-MONZOGRANITES FROM MEISSEN ("RIESENSTEINGRANIT")

Samples of the Riesensteingranit are non-oriented and medium- to coarse-grained. Furthermore, they are nearly depleted in biotite. Figure 5 sum-

marizes the main compositional data of this rock type:

In comparison to the Hauptgranit, plagioclase and alkali feldspar of the Riesensteingranit are more depleted in Sr. The same is true for the Ba-contents of alkali feldspar and biotite. Intergranular white mica such as in Klein-Zadel, was not observed.

THE PORPHYRY-LIKE BIOTITE-MONZOGRANITE ("G II")

This intrusion is probably the youngest one in the magmatic succession discussed above. It is only of small extension. The sample from the junction of the streets toward Riesa and Zadel contains xenocrysts of biotite, plagioclase and minor amphibole in a fine-grained tight groundmass. Its structure corresponds to the microgranular texture of hypovolcanic rocks after BARD (1986). Fabric characteristics as well as mineral compositions are given in figure 6:

Obviously, there is a chemical disequilibrium between coarse- and fine-grained minerals as in the case of the Leuben monzonite. In opposition to Leuben, the coarse constituents of the G II are

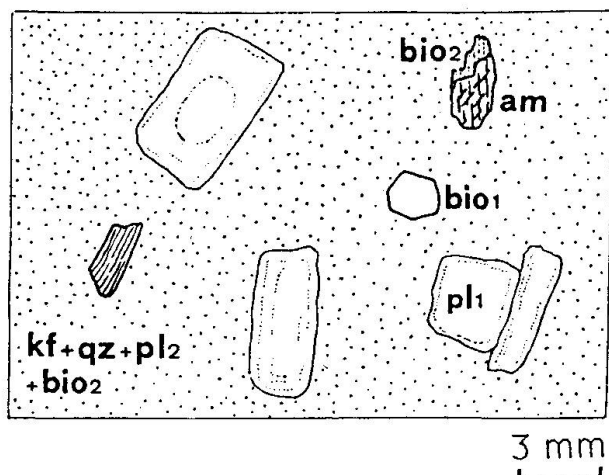


Fig. 6 Microgranular fabric of the porphyry-like monzogranite G II Abbreviations as in figure 2.

xenocrysts, but there are no relics of solidified rock fragments. High concentrations of Sr in plagioclase and high TiO_2 - and BaO-contents of Mg-biotite xenocrysts are similar to the corresponding minerals of the Freital diorite and monzodiorite, respectively. Amphibole was mostly converted into Fe-biotite and its chemistry could not be determined.

THE PYROXENE-MONZODIORITE FROM GRÖBA ("GRÖBAIT")

The pyroxene-monzodiorite from Gröba near Riesa is a medium-grained dark rock with alkali feldspar phenocrysts. Some of the fabric features resemble those of the Freital diorite and monzodiorite. The occurrence of Fe-enstatite (PFEIFFER, 1964) and the replacement of Fe-enstatite and diopside by biotite are peculiarities of this rock type.

Plagioclase + diopside + Fe-enstatite + biotite + quartz-bearing areas in thin section, showing a dioritic to quartz-dioritic composition, are inter-

Monzogranite GII

Xenocrysts:

bio1 TiO_2 : 3.96-4.42 wt%, BaO: 0.56-1.74 wt%
 X_{Mg} : 0.58-0.61

pl1 An: 28-33, SrO: 0.20-0.36 wt%

Matrix:

pl2 An: 4-7, SrO: 0 wt%

kf Or: 87-94, SrO: 0 wt%
BaO: 0-0.12 wt%

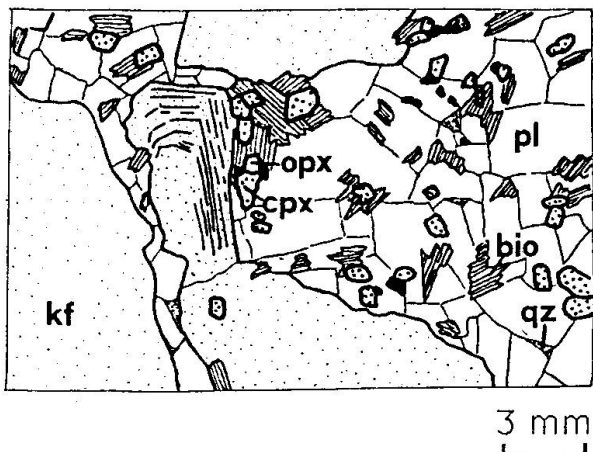
sected by large alkali feldspar individuals. Plagioclase has myrmekitic rims along the contact with such alkali feldspar; biotite is decomposed.

Figure 7 presents an overview on the fabric and mineral chemistry:

Cummingtonite, surrounded by actinolite, has replaced orthopyroxene in the sample, available for the microprobe investigations. Nevertheless, the occurrence of orthopyroxene (described by PFEIFFER, 1964) and quartz in the monzodiorite from Gröba indicates silica saturation of the parental melt.

THE PYROXENE-DIORITE-MONZODIORITE- MONZONITE-SYENITE SEQUENCE OF THE REUDNITZ DRILL-HOLE

This sequence was described in detail by GORTESMANN (1968). Diorite, monzodiorite and monzonite show characteristics similar to the corresponding rock types from Freital. There are intercalations of diopside and biotite, diopside



Monzodiorite Gröba

cpx Al_2O_3 : 3.25-4.23 wt%, TiO_2 : 0.18-0.21 wt%,
 X_{Mg} : 0.41-0.44

opx converted to cummingtonite

bio TiO_2 : 3.10-5.31 wt%, BaO: 0.17-0.31 wt%
 X_{Mg} : 0.29-0.31

pl An: 53-58, SrO: 0.11-0.23 wt%

kf Or: 89-93, SrO: 0.21-0.30 wt%
BaO: 0.83-2.46 wt%

Fig. 7 Characteristic fabric pattern of the monzodiorite from Gröba. Abbreviations as in figure 2. Note the occurrence of orthopyroxene and the separation of the diorite-like fragments from the large alkali feldspar-crystals.

accumulations in xenoblastic magnetite and the replacement of plagioclase by alkali feldspar. Biotite from Reudnitz is somewhat lower in TiO_2 and BaO . The former component is consumed by sphene; the latter is incorporated by alkali feldspar. Plagioclase has a similar An-content as in the Freital monzonite. It is not as rich in Sr as in Freital, because Sr is enriched in alkali feldspar.

General geochemical trends

The presentation of the rock modes in the QAP-diagram illustrates that the sequences of Reudnitz and (less pronounced) of Freital show alkaline affinities (Fig. 8). The rest exhibit calcalkaline characteristics according to LAMEYRE and BOWDEN (1982). While the monzonites as well as the monzogranites of the Riesensteingranit plot mostly into the "calcalkaline high-K monzonitic field", the samples of the Hauptgranit tend to "calcalkaline medium-K granodioritic" characteristics (see also PFEIFFER, 1964, and SCHMIDT, in prep., for rock modes).

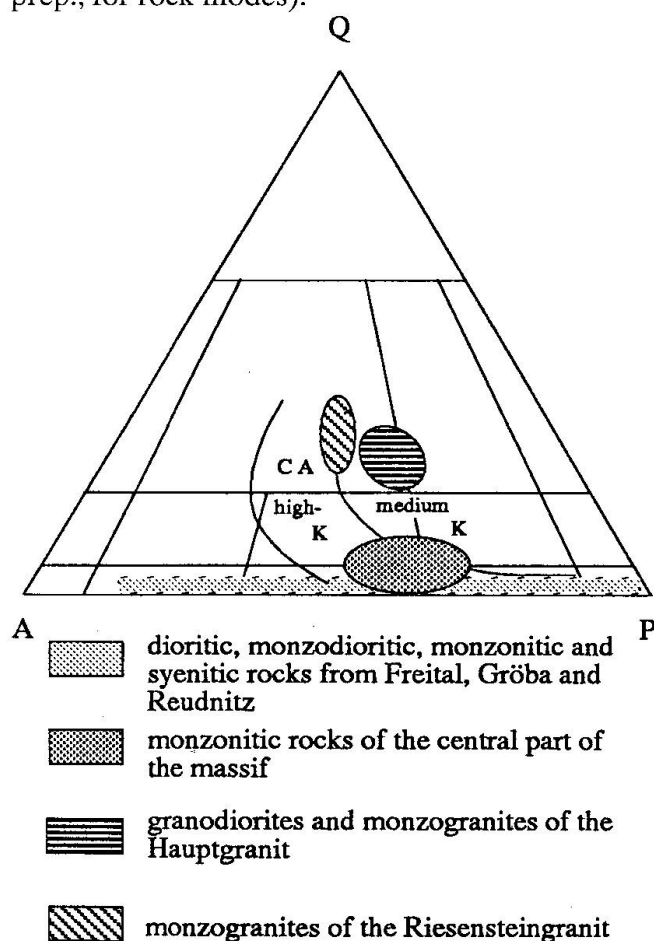


Fig. 8 QAP-diagram of the main rock types of the Meissen massif. Own data and from PFEIFFER (1964). Areas of calcalkaline (CA), high-K and medium-K rocks after LAMEYRE and BOWDEN (1982).

Using the T(otal)A(lkali)S(ilica)-diagram, the rocks from Reudnitz, Gröba and Freital are arranged along the alkaline evolution line (see Fig. 9; cf. LAMEYRE, 1987). The other rock types vary between "alkaline" and "monzonitic", showing a nearly constant total ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) over the whole range of SiO_2 -values. Once more, they do not form a homogeneous rock suite.

DE LA ROCHE et al. (1980) proposed a classification of magmatic rocks on the base of the parameters R1 and R2. In contrast to the TAS-diagram, all major elements are included in the classification. Two main trends were identified (Fig. 10): The first is defined by the dioritic to monzonitic rocks of the Freital and Reudnitz sequences including the pyroxene-monzodiorite from Gröba. The monzonitic and granodioritic to monzogranitic intrusions of the central part of the Meissen massif produce the second one, showing a basically different tendency toward quartz enrichment.

Fractionation processes

It was shown that there are generally two different genetic types of rocks within the plutonic complex of the Meissen massif:

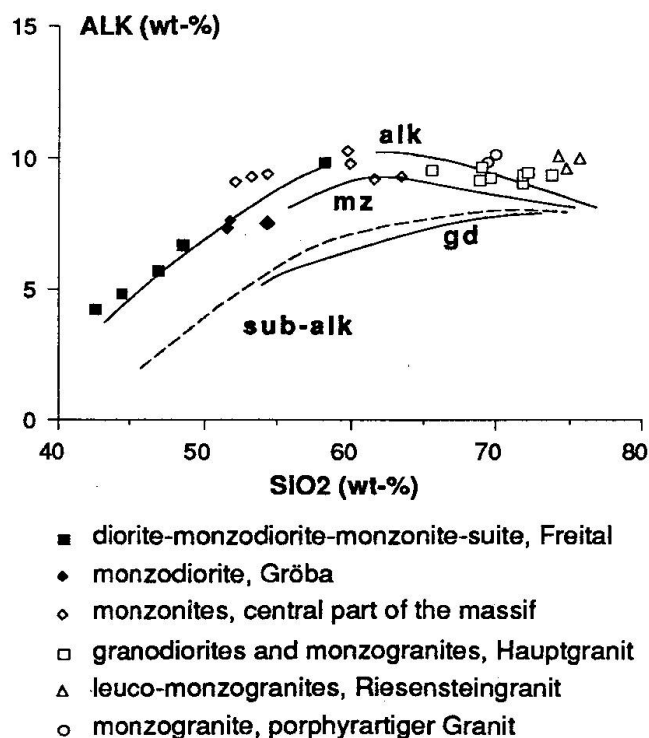


Fig. 9 Distribution of the different plutonic rocks in the T(otal)-A(lkali)-S(ilica)-diagram (LAMEYRE, 1987). ALK = $\text{Na}_2\text{O} + \text{K}_2\text{O}$; alk – alkaline series; mz – monzonitic series; gd – granodioritic series; broken line separating alkaline from subalkaline (sub-alk) series.

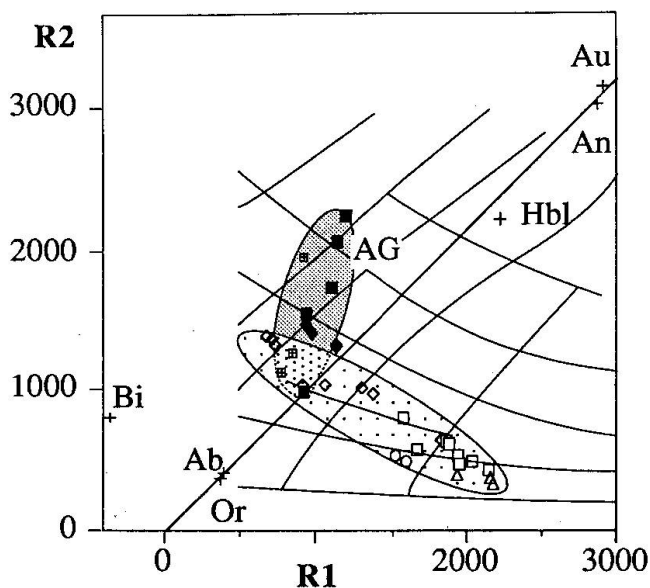


Fig. 10 Arrangement of the Meißner plutonic rocks in the $R1 (= 4Si-11(Na+K)-2(Fe+Ti))-R2 (= 6Ca+2Mg+Al)$ -diagram (DE LA ROCHE et al., 1980). Symbols as in figure 9; data of Reudnitz (crossed squares) and of the pyroxene-monzodiorite from Gröba (filled diamonds) were added. The points of augite (Au), anorthite (An), hornblende (Hbl), biotite (Bi), albite (Ab) and orthoclase (Or) as well as of alkali gabbro (AG) are shown for comparison (data of DE LA ROCHE et al., 1980).

The first one is characterized by fabric patterns and mineralogical compositions which favour a magmatic development in a nearly *closed system*. The second genetic type is marked by fabric and mineralogical *disequilibria*.

CLOSED SYSTEM FRACTIONATION

As an example, the diorite-monzodiorite-monzonite suite from Freital is thought to represent a sequence, mainly generated by *fractional crystallization*. Our observations imply a case in which early segregations were not separated from the residual melt, thus allowing a successive interaction of melt and segregations.

The mineral association of the Freital diorite as well as Ti- and Ba-rich Mg-biotite and Sr-rich plagioclase suggest alkaline affinities of the original melt. This is strongly supported by the occurrence of Eu^{2+} , Sm^{3+} and Dy^{3+} enriched apatites known from alkaline rocks (WENZEL and RAMSEYER, submitted). Cores in apatite and inclusions of sericitized plagioclase with chloritized biotite in diopside crystals may be interpreted as relics of a (weak) source contamination.

The Freital suite is characterized by non-linear continuously increasing Zr-, Rb-, Nb-, Pb-, Th- and U-concentrations in connection with decreasing

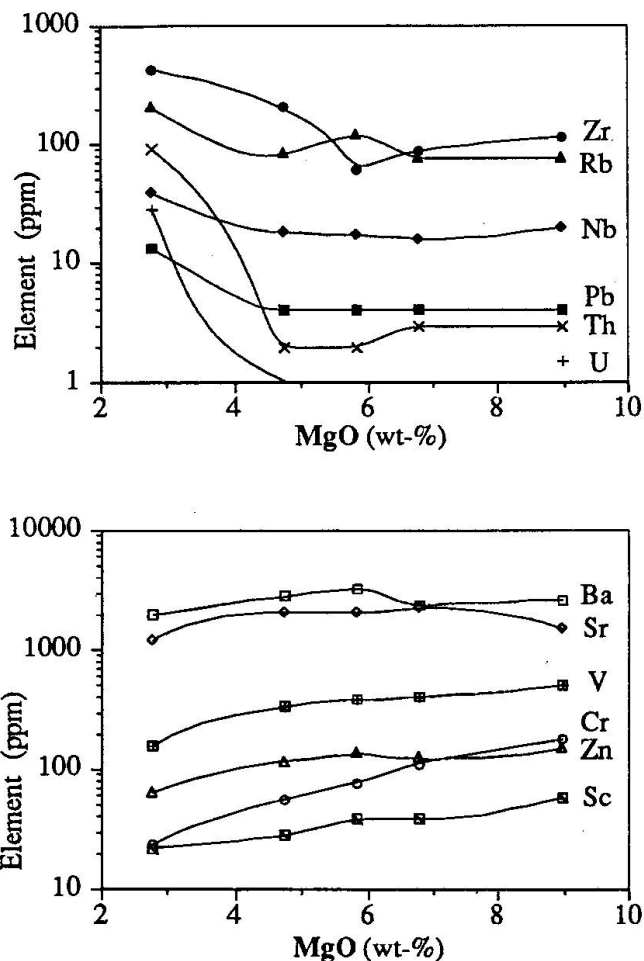


Fig. 11 Trace element distribution in the diorites, monzodiorites and monzonite of the Freital sequence using MgO as fractionation index. U was only in the monzonite (sample 10, Tab. 1) above the detection limit.

ing MgO-values, used as fractionation index (Fig. 11). On the contrary, the contents of Ba, Sr, V, Cr, Zn and Sc decrease. The elements of the first group are incompatible, i.e. mainly incorporated by minerals of the late monzonitic stage. The increase of Rb is surprising because dark micas have generally higher D_{Rb} than alkali feldspar (e.g. COX et al., 1984; HENDERSON, 1982).

On the other hand, the elements of the second group are fractionated by the earlier crystallizing phases of the diorite in a high degree. A step within the Ba-trend is due to the beginning of crystallization of alkali feldspar in the monzodiorite which has a higher Ba-partition coefficient than Mg-biotite (e.g. HENDERSON, 1982). Sr is enriched until monzodiorite is formed (MgO ~ 4) despite of distinct Sr-incorporation by the dioritic plagioclase. A decrease is noticeable after the precipitation of greater amounts of alkali feldspar, hence its Sr-partition coefficient is higher than D_{Sr} of plagioclase (COX et al., 1984; HENDERSON, 1982).

There are many similarities between the dioritic and monzodioritic rocks of Freital and Reudnitz, indicating a narrow genetic relationship. The pyroxene-monzodiorite from Gröba contains orthopyroxene + quartz in addition to diopside, biotite, plagioclase and alkali feldspar. Consequently, its parental magma was more silica saturated. The corresponding elements of the pyroxene-monzodiorite from Gröba adapt mostly to the tendencies, discussed above.

Summarizing these results, we suggest that the diorite-monzodiorite-monzonite sequence of Freital was generated by closed system fractional crystallization.

OPEN SYSTEM FRACTIONATION

The monzonites and several granites of the central part of the Meißen massif behave in a different manner. While the major elements form nearly linear trends, there are no simple correlations between the trace elements and MgO. Different mineral associations and different partition coefficients, respectively, as well as influences of late-magmatic fluids must be taken into account. There are, for instance, unsystematic deviations of the U/Th-ratio (Tab. 1). This indicates a remobilization of mobile U or high f_{O_2} during crystallization. Similarly, Rb seems to behave as a very mobile element.

A first irregularity is related to the Leuben monzonites which consist of monzodioritic frag-

ments in a fine-grained, more acidic groundmass. We believe that they are a mixture of diorites or monzodiorites of the Freital type and a granitic or syenitic melt. Such a model is supported by the following arguments:

- The diopside relics within amphibole-xenocrysts of the Leuben monzonite are identical to the diopside of the Freital diorite as well as of the Reudnitz diorite (Fig. 12).

- These relics are sometimes intergrown with biotite which is chemically similar to the dark mica of the Freital diorite.

- The xenocrystic plagioclase of the Leuben monzonite resembles plagioclase of the Freital diorite and monzodiorite, as far as An- (Fig. 13) and Sr-contents are concerned (compare Figs 2 and 3). This is true for plagioclase of the rock fragments within the dark inclusions, too.

- The chemical variations in zoned amphibole around diopsidic cores are the same as in amphibole of different parts of the dark inclusions (Fig. 14).

- The distribution of Zr, Th, Pb, Sr and Ba (Fig. 15) does not follow the trend of the other monzonites.

In order to characterize chemically the mixing components, we carried out the following model calculations: Assuming the Freital monzodiorite (sample 9 in Tab. 1) as equivalent of the coarse-grained parts of the rock and comparing them to rock fragments of the inclusions in the Leuben monzonite (sample 4 in Tab. 1), the balance equation is

$$k \cdot \text{monzodiorite}_{\text{Freital 9}} + (1 - k) \cdot \text{melt} = \text{monzonite}_{\text{Leuben 4}}$$

The results of models with positive, i.e. real solutions, are summarized in table 2. Projecting these compositions into the R1-R2-diagram of DE LA ROCHE et al. (1980), a syenitic melt could have impregnated and digested the monzodiorite.

On the other hand, the behaviour of some trace elements of the Leuben samples does not favour a simple mixing. In the case of such process, the values should generally be arranged along a straight line connecting the Freital monzodiorite as one end-member and the sample from Wilsdruff, which is regarded as the nearly homogenized mixture. This is only true for V, Zn, Cr and Sc (Fig. 16a, case 2, decreasing tendency) and Th \pm U (Fig. 16a, case 1, increasing tendency). Pb \pm Zr lie markedly above the theoretical mixing line (Fig. 16b), while Sr- and Ba-values are lower (Fig. 16c). This indicates changes in the composition of the syenitic melt during the overprint of the monzodiorite. BARBARIN (1988) described similar circumstances in hybrid rocks produced by

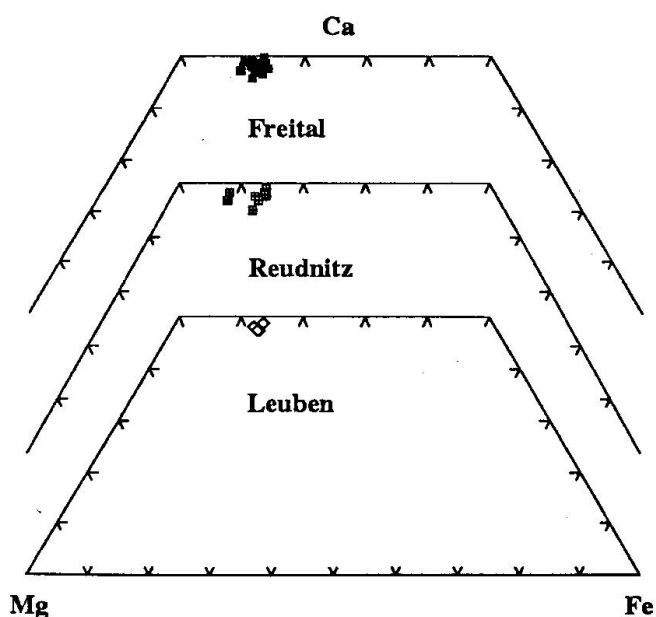


Fig. 12 Comparison of clinopyroxene compositions (normalized to 6 O-atoms) of the Freital diorite and the Reudnitz monzodiorite with clinopyroxene relics in xenocrystic amphibole of the Leuben monzonite.

Tab. 1 Major and trace element compositions of the plutonic rocks of the Meißner massif.

Major elements (Wt.-%)	Gröba			Freital			Spitzgrund			Hei		Leuben		Wi		Neu		Klein-Zadel	
	104	9	10	12	14	15	1*	3*	4*	1*	4*	1*	1*	1*	1*	1	1*	1*	3
SiO ₂	54.34	46.85	58.30	48.64	42.47	44.31	61.70	63.50	59.90	60.00	52.30	53.40	54.50	73.87	69.50	71.69			
TiO ₂	1.01	1.24	0.65	1.06	1.52	1.28	0.09	0.13	0.13	0.20	0.34	0.35	0.21	0.11	0.00	0.22			
Al ₂ O ₃	18.13	17.09	16.00	17.62	11.97	15.79	14.85	16.12	15.92	16.37	17.27	17.01	16.89	14.68	15.85	14.80			
Fe ₂ O ₃	8.70	10.94	5.84	9.85	14.34	12.54	2.02	1.13	2.08	2.38	3.07	2.81	3.22	1.07	0.25	1.67			
FeO	0.00	0.00	0.00	0.00	0.00	0.00	2.37	2.46	2.51	1.71	4.71	4.57	3.36	0.00	1.34	0.00			
MnO	0.16	0.19	0.12	0.20	0.27	0.21	0.10	0.09	0.12	0.10	0.14	0.14	0.13	0.03	0.05	0.04			
MgO	3.37	5.85	2.78	4.73	8.96	6.77	2.43	2.14	2.90	2.30	3.99	3.76	3.66	0.47	1.03	0.82			
CaO	6.69	9.07	4.41	7.90	13.26	12.00	4.99	4.58	4.84	4.85	6.95	7.06	6.82	0.88	2.03	1.30			
Na ₂ O	4.19	3.35	4.30	4.06	2.23	2.94	4.79	4.80	4.65	4.69	4.02	4.05	4.54	4.68	4.52	4.70			
K ₂ O	3.22	2.36	5.49	2.59	1.99	1.83	4.31	4.46	5.54	5.05	5.01	5.13	4.78	4.60	4.67	4.34			
P ₂ O ₅	0.51	0.93	0.46	0.81	1.51	1.12	0.56	0.49	0.58	0.49	0.82	0.83	0.75	0.05	0.27	0.11			
LOI	0.95	1.90	1.25	2.47	1.82	1.35	0.75	0.73	1.18	0.73	0.71	0.59	0.64	0.89	0.80	0.88			
Total	101.27	99.77	99.60	99.93	100.34	100.14	98.96	100.63	100.35	98.87	99.33	99.70	99.50	101.33	100.31	100.57			
Trace elements (ppm)																			
Ba	1968	3270	1941	2804	2631	2373	1869	1960	2296	2233	1975	2049	2580	2197	1719	1444			
Rb	103	119	202	82	77	78	155	172	192	176	232	227	167	140	167	146			
Sr	1089	2062	1218	2077	1480	2208	1784	1747	1651	1748	1299	1294	1850	1067	845	719			
Pb	<5	<5	13	<5	<5	<5	29	17	22	63	109	204	38	18	57	43			
Th**	13	2	91	2	3	3	40	42	54	40	47	35	63	45	35	25			
U**	2	<1	28	<1	<1	<1	17	18	11	5	9	4	15	2	2	2			
Nb	20	17	38	18	20	16	26	27	29	68	81	28	39	6	28	20			
Y	40	47	38	44	58	45	34	35	39	59	68	29	45	17	32	25			
Zr	318	62	428	204	114	86	284	251	321	331	418	323	326	178	165	125			
V	261	387	157	336	510	403	175	154	205	165	348	317	266	67	64	25			
Cr	31	78	24	56	177	111	38	23	54	37	86	191	64	9	<6	<6			
Ni	15	32	12	22	49	41	14	11	17	15	16	14	19	8	5	9			
Cu	55	78	82	91	37	122	64	25	23	44	72	108	90	13	10	8			
Zn	109	135	64	116	147	123	52	44	62	71	104	88	81	46	39	44			
Ga	25	25	23	25	21	23	23	21	22	27	27	23	24	19	23	23			
Sc	29	38	22	28	58	38	8	9	13	12	27	24	21	8	5	5			
U/Th	0.12	--	0.31	0.11	--	--	0.42	0.42	0.21	0.13	0.18	0.11	0.24	0.05	0.04	0.07			

Major elements (Wt.-%)											Major and trace elements were determined by X-ray fluorescence on a Philips sequential spectrometer (PW - 1450). The relative errors for oxides can be given as follows (STERN, 1972): 100 wt% +/- 1%, 50 wt% +/- 1%, 10 wt% +/- 2%, 5 wt% +/- 3%, 1 wt% +/- 5%. For trace element concentration: 1000 ppm +/- 5%, 100 ppm +/- 10%, 10 ppm +/- 20%, 5 ppm +/- 50%. STERN, W.B. (1972): Zur röntgenspektrometrischen Analyse von silikatischen Gesteinen und Mineralien. Schweiz. Mineral. Petrogr. Mitt. 52, 1-25.
Klein-Zadel		BB		Sp		Ka		Meißen			
4	6	6	6	1*	1*	1	2	3	GP1	GP2	
SiO ₂	72.20	69.45	71.74	68.90	65.50	74.92	74.34	75.81	70.03	69.40	
TiO ₂	0.21	0.29	0.22	0.01	0.01	0.19	0.21	0.15	0.44	0.42	
Al ₂ O ₃	14.95	15.94	14.88	15.23	16.12	13.21	13.55	13.18	14.79	15.39	
Fe ₂ O ₃	1.60	2.40	1.72	0.92	1.09	1.35	1.49	1.12	2.94	2.68	
FeO	0.00	0.00	0.00	1.07	1.30	0.00	0.00	0.00	0.00	0.00	
MnO	0.05	0.05	0.07	0.06	0.08	0.03	0.03	0.02	0.04	0.04	
MgO	0.83	0.90	0.61	1.11	1.97	0.24	0.33	0.13	1.25	1.25	
CaO	1.19	1.88	1.79	2.34	3.24	0.79	0.87	0.46	1.03	1.40	
Na ₂ O	4.99	5.17	4.91	4.64	4.16	4.59	5.04	4.24	5.04	5.81	
K ₂ O	4.43	4.45	4.38	4.48	5.32	4.88	4.94	5.62	5.01	4.03	
P ₂ O ₅	0.11	0.16	0.12	0.28	0.52	0.05	0.07	0.03	0.13	0.14	
LOI	0.86	0.75	0.68	1.04	1.04	0.49	0.49	0.62	1.28	1.21	
Total	101.42	101.44	101.12	100.08	100.35	100.74	101.36	101.38	101.98	101.77	
Trace elements (ppm)											
Ba	1422	1276	1497	1847	2341	252	355	275	787	973	
Rb	178	191	203	165	159	251	257	272	218	125	
Sr	636	549	940	1192	1384	106	136	73	223	437	
Pb	44	72	60	58	34	16	14	20	9	22	
Th **	20	16	36	47	52	43	38	41	26	17	
U **	2	2	22	9	2	9	1	1	3	1	
Nb	24	30	31	32	30	26	25	22	27	17	
Y	27	51	29	32	38	32	39	29	38	28	
Zr	128	126	156	218	231	141	147	125	282	215	
V	22	<10	28	94	135	13	20	10	59	59	
Cr	<6	<6	<6	13	18	<6	<6	<6	<6	<6	
Ni	10	7	11	10	22	7	9	8	7	7	
Cu	8	8	9	10	11	<3	<3	<3	7	<3	
Zn	45	37	45	50	55	25	30	23	65	59	
Ga	25	26	24	23	22	23	23	23	25	25	
Sc	6	2	6	6	8	5	7	6	8	7	
U/Th	0.10	0.12	0.61	0.18	0.04	0.02	0.03	0.03	0.12	0.08	

* Major elements determined by wet chemical analysis (SiO₂, TiO₂, P₂O₅ spectrophotometric; Al₂O₃, FeO tot volumetric; CaO, MgO, MnO, atomic absorption; Na₂O, K₂O flame-photometric; LOI gravimetric

** Special calibration for XRF measurements of U and Th

Abbreviations:

Hei	Heidenschanze
Wi	Wilsdruff
Neu	Neumühle
Sp	Spaargebirge
Ka	Karpfenschänke

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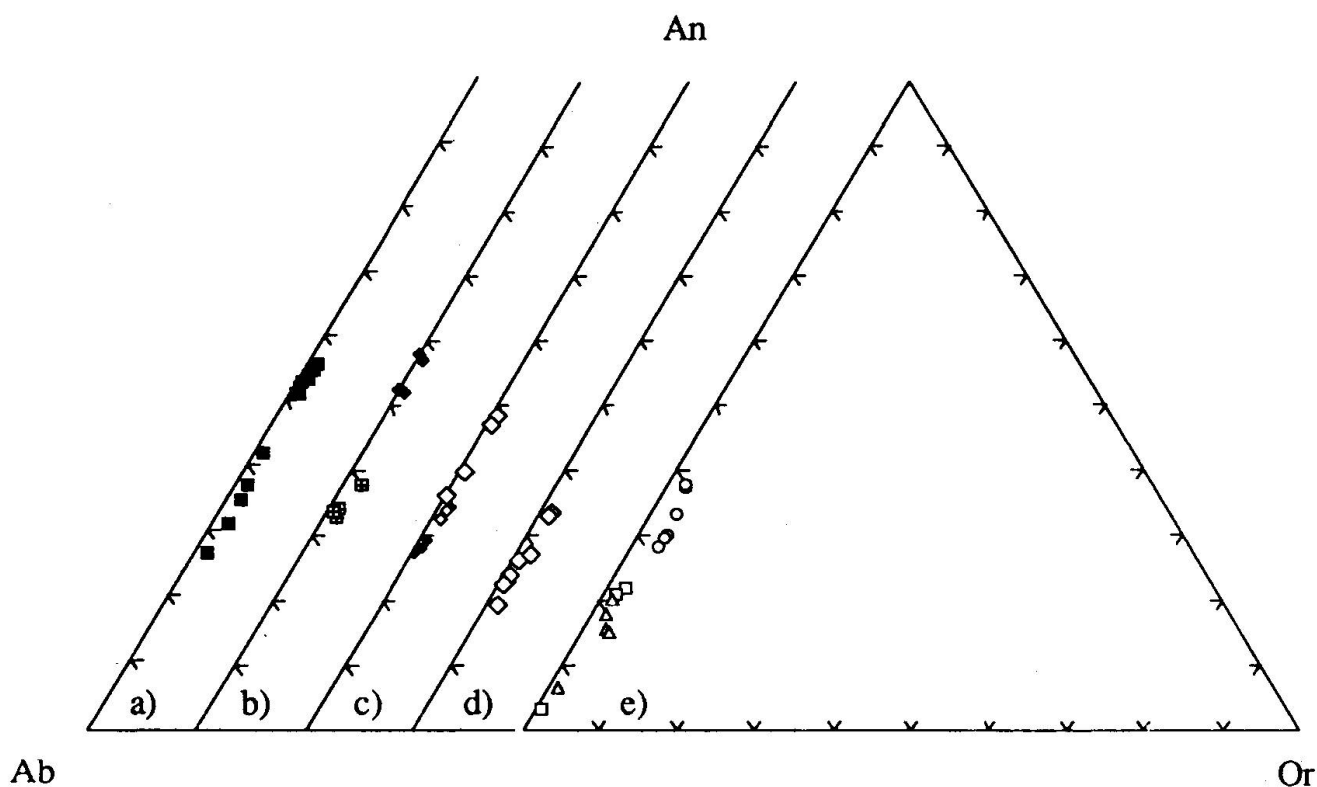


Fig. 13 Mineral chemistry of plagioclase (normalized to 8 O-atoms) of the different rocks.

- a) ■ = diorites to monzonites from Freital;
 b) ◆ = monzodiorite from Gröba and ◻ = monzodiorite from Reudnitz;
 c) ◇ = monzonite from Leuben (large symbols), rock fragments (medium symbols) and dispersed plagioclases within the dark inclusion (small symbols);
 d) ◇ = monzonites from Wilsdruff, Spitzgrund and Heidenschanze;
 e) ◻ = monzogranites of the Hauptgranit, △ = monzogranites of the Riesensteingranit, ○ = monzogranites of the GII;

Tab. 2 Results of modelling the composition of the melt representing the fine-grained rock parts of the Leuben monzonite; see text for details.

Monzodiorite Freital 9	Monzonite Leuben 4	k =						
		0.6	0.5	0.4	0.3	0.2	0.1	
SiO ₂	47.9	52.7	59.9	57.5	55.9	54.8	53.9	53.2
TiO ₂	1.3	1.0	0.6	0.7	0.8	0.9	0.9	1.0
Al ₂ O ₃	17.5	17.4	17.3	17.3	17.3	17.4	17.4	17.4
FeO _{tot}	11.2	7.8	2.7	4.4	5.5	6.3	7.0	7.4
MgO	6.0	4.1	1.3	2.2	2.8	3.3	3.6	3.9
CaO	9.3	7.0	3.6	4.7	5.5	6.0	6.4	6.7
Na ₂ O	3.4	4.1	5.2	4.8	4.6	4.4	4.3	4.2
K ₂ O	2.4	5.1	9.2	7.8	6.9	6.3	5.8	5.4
P ₂ O ₅	1.0	0.8	0.5	0.6	0.7	0.7	0.8	0.8

Monzodiorite Freital 9	Monzonite Wilsdruff 1	k =			
		0.4	0.3	0.2	0.1
SiO ₂	47.9	55.0	59.7	58.0	56.8
TiO ₂	1.3	0.6	0.1	0.3	0.4
Al ₂ O ₃	17.5	17.0	16.7	16.8	16.9
FeO _{tot}	11.2	6.6	3.5	4.6	5.5
MgO	6.0	3.7	2.2	2.7	3.1
CaO	9.3	6.9	5.3	5.9	6.3
Na ₂ O	3.4	4.6	5.4	5.1	4.9
K ₂ O	2.4	4.8	6.4	5.8	5.4
P ₂ O ₅	1.0	0.8	0.7	0.7	0.8

mixing and mingling of dioritic and monzogranitic magmas.

Following a Rayleigh melting model, the contents of trace elements with bulk distribution coefficients < 1 will be higher than the original concentration C_0 at small melt fractions F , but will fast decrease with increasing degree of melting (model I in Fig. 16b). On the contrary, elements with $D > 1$ are just enriched in the melt ($C_1/C_0 > 1$) at high degrees of melting (model II in Fig. 16c). They are depleted in the first melt portions.

There is a second, basically different explanation of the deviation of some trace elements from the theoretical mixing line: The syenitic melt derived from two or more sources and resulting melts interacted with the monzodiorite (see discussion in Cox et al., 1984, p. 338 ff.).

Whether the granitic or syenitic melt is the differentiate of a basic magma which has impregnated early crystal fractions remains as an open question. However, the observation of rock fragments in the dark inclusion ("hybrid layer") lead us to assume a foreign melt generated somewhat

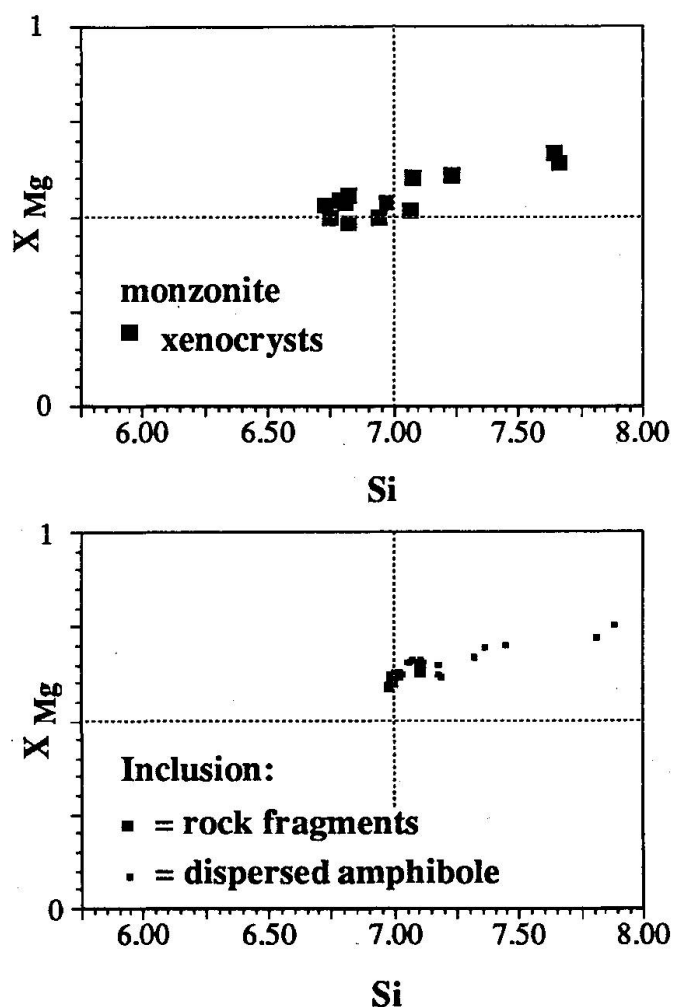


Fig. 14 Chemistry of amphibole (normalized to 23 O-atoms) of the Leuben samples: amphibole-xenocrysts in the monzonite; amphibole in the rock fragments and dispersed in the hybrid layer.

later intruding the nearly solidified dioritic and monzodioritic segregations. It may be, in this case, a product of melting of crustal rocks caused by a deep-seated basic magma-chamber. Isotope geochemical investigations are necessary to select the correct explanation. However, it should be noted that occurrences of pyroxene-biotite-rich rocks in areas of "normal" hornblende monzonite were described from several outcrops of the Meissen massif (e.g. REINISCH, 1928; EBERT et al., 1934).

The other monzonites from Wilsdruff, Spitzgrund and Heidenschanze show a progressive homogenization of the fabric pattern. Additionally, the general Ba- and Sr-enrichment in alkali feldspar from Leuben to Heidenschanze indicates a tendency toward equilibrium (Fig. 17).

A nearly linear distribution of the trace elements starts at Wilsdruff where the mixture became homogeneous. Only the concentrations of

Zr, Pb, Zn and Nb from the sample from Heidenschanze (Hei) deviate from the linear dependence. The rock contains a lot of small dark inclusions or dispersed relics of them (PFEIFFER, 1964) indicating a lower degree of homogenization.

The question whether monzonites and the different granitic rocks are connected by fractional crystallization cannot be answered unequivocally.

The regular geochemical tendencies within the monzonite series, starting at Wilsdruff, are probably due to fractional crystallization from a homogenized hybrid Leuben-type melt. These general tendencies continue partly in the series of the Hauptgranit and Riesensteingranit (Figs 15, 16). Decreasing An-contents of plagioclase in the order monzonites-Hauptgranit-Riesensteingranit (Fig. 13) argue for such relations. The same is true regarding SrO- and BaO-values of alkali feldspar (Fig. 17). These tendencies may be, however, influenced by variations of the PTX conditions in the magma (e.g. LONG, 1978).

Distinct non-linear variations of the several trace elements are detectable within the sample collection of the Hauptgranit. Obviously, Zr, Th, Sr, Ba, V, Zn and Cr vary similarly, only Pb is opposed to them (Fig. 15). There is a probable relation between the second step in the element concentration patterns (field b in Fig. 16) and the occurrence of intergranular white mica in the samples of Klein-Zadel. However, changes in the bulk partition coefficients, caused by the local crystallization of muscovite beside biotite, can hardly have influenced the Zr-, Th-, Sr- and Ba-balance. Assuming the formation of muscovite as result of a contamination with Al-rich material, this process was accompanied by a "dilution" of the Zr-, Th-, Ba-, Sr- and probably V-, Zn-, Cr- and Sc-contents, but a supply of Pb.

Although only relative tendencies of trace element balances can be estimated, it seems that both the syenite melt (step a in Fig. 16) and the Al-rich contaminant (step b in Fig. 16) were poor in Ba, Sr, V, Zn, Cr and Sc but rich in Pb. As a difference, the syenite melt led to an enrichment of Zr and Th, while the contaminated samples of the Hauptgranit are depleted in both elements. They show a trend to the "strongly differentiated granites" of EL BOUSEILY and EL SOKKARY (1975).

The detection of Proterozoic zircon relics by first single-grain age determinations strongly supports deep-crustal influences on the magma of the Hauptgranit (WENZEL et al., 1990).

Based on preliminary results of investigations on zircons and isotopic studies, the Riesensteingranit has the most distinct crustal signature of the Meissen plutonics (WENZEL, unpubl. data).

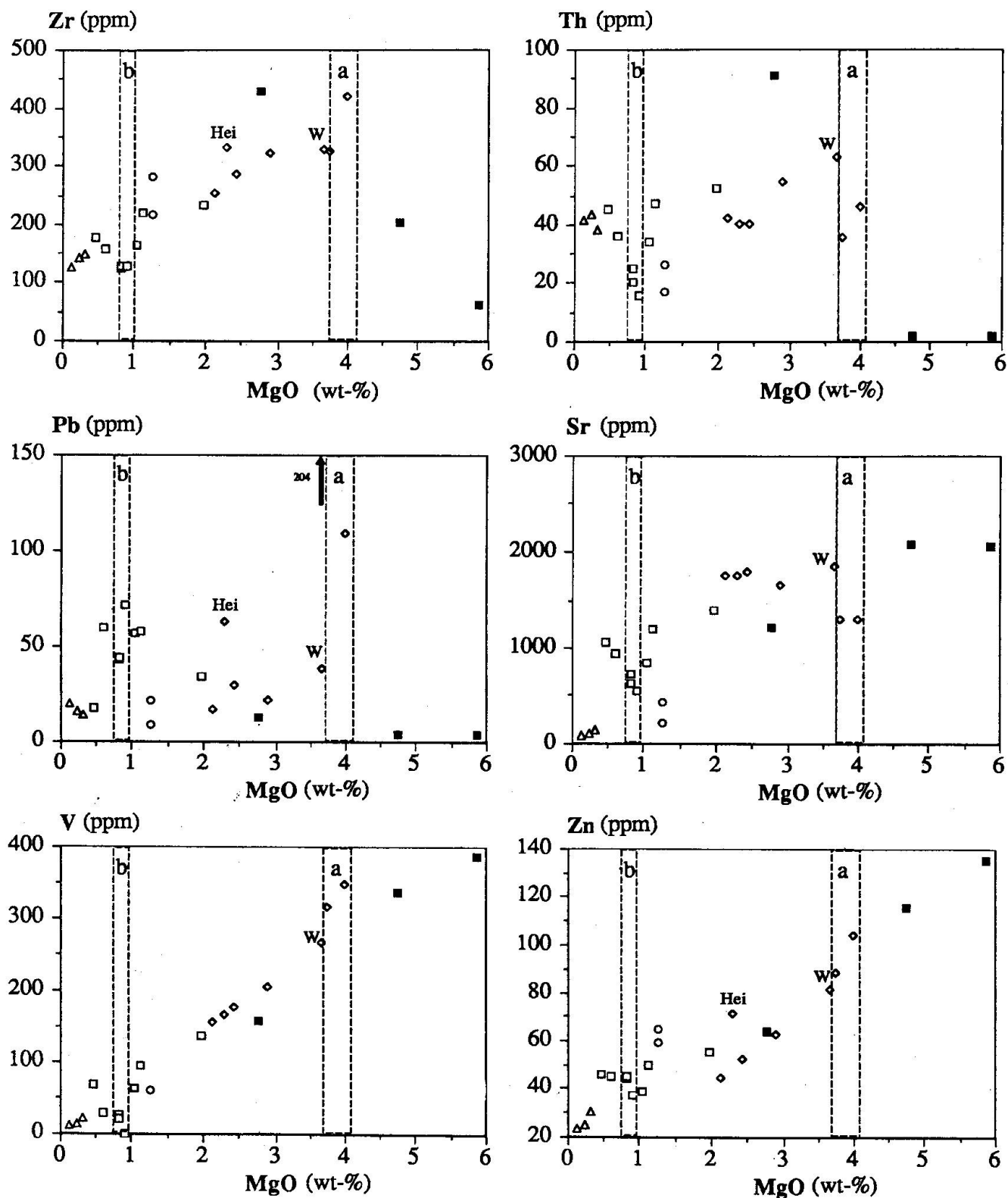


Fig. 15 Characteristical trace element patterns of the plutonic rocks of the central part of the Meißen massif. Symbols as in figure 9. W – Wilsdruff monzonite, Hei – Heidenschanze monzonite, fields a) and b) mark influences of mixing or contamination; see text for further explanation.

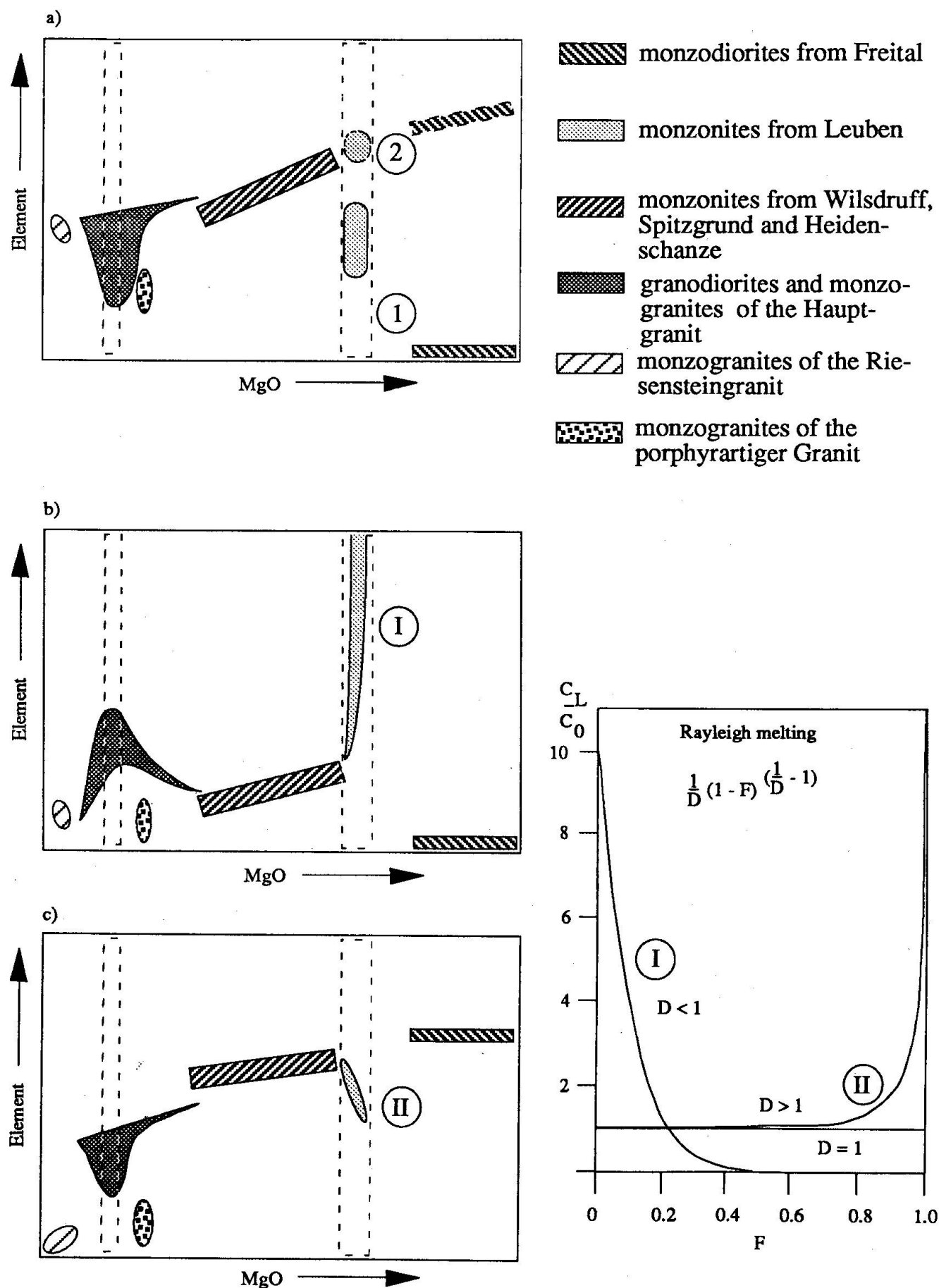


Fig. 16 Simplified tendencies of the different trace elements in the rocks of the central part of the massif, based on figure 15. The Rayleigh melting models were taken from Cox et al. (1984, p. 340). See text for further details.

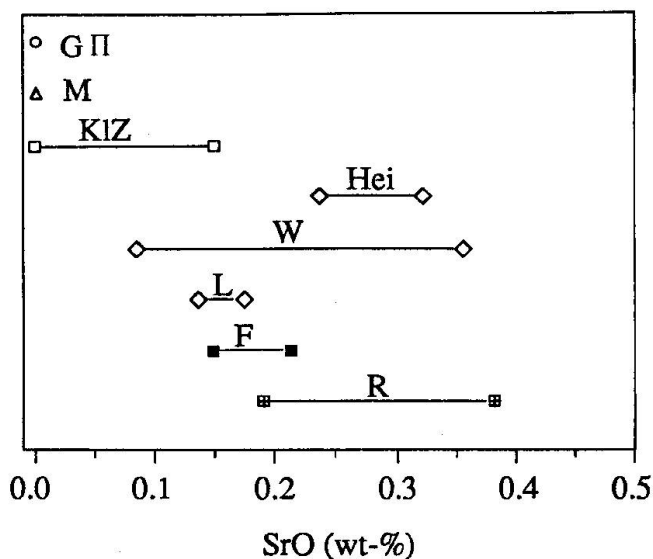


Fig. 17 Ranges of SrO- and BaO-concentrations in alkali feldspars of different rocks: G II – porphyry-like granite, M – monzogranite from Meißen (Riesensteingranit), KlZ – monzogranite from Klein-Zadel (Hauptgranit), Hei – monzonite from Heidenschanze, W – monzonite from Wilsdruff, L – monzonite from Leuben, F – monzonite from Freital, R – monzodiorite from Reudnitz.

Summarizing, fractional crystallization as well as contamination (or mixing) might have produced the rock sequence, indicating a complex multistage open system evolution.

Another type of *disequilibrium* fabric patterns is realized in the porphyry-like granite G II. In opposition to the Leuben monzonite, xenocrysts but no rock fragments are dispersed in a fine-grained granitic matrix: Sr- and An-contents (Fig. 13) of plagioclase individual crystals are similar to those in the Freital monzodiorite. Euhedral Mg-biotite is enriched in TiO_2 and BaO as it is known from dark mica of the Freital diorite. This minera-

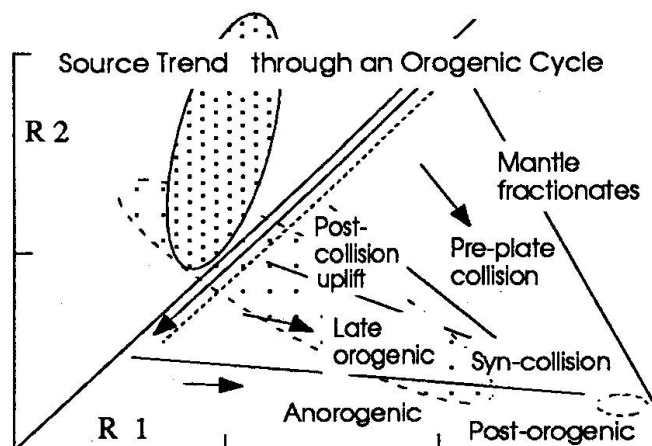


Fig. 18 Attempt to determine the geotectonic characteristics of the plutonites of the Meißen massif (see also Fig. 10) using the classification of BATCHELOR and BOWDEN (1985).

logical disequilibrium is reflected by a strong scattering of the data points which do not coincide with any other suite of the Meißen rocks (Fig. 15). We infer a stratified basic magma chamber, where plagioclase + Mg-biotite + amphibole (or pyroxene?) were fractionated leaving a granitic residual melt. It seems also possible that the xenocrysts represent a basic magma which has generated an anatectic crustal melt. Both segregations and melt were mixed/mingled by tectonic disruption of the stratification and extraction of the melt.

A comparison of the Meißen rocks and the similar diorite-monzonite-monzogranite suite of the Ballons massif (Vosges, France; PAGEL and LETERRIER, 1980) shows that the basic end-members (i.e. mantle components) of each series determine especially the Ba- and Sr-contents of the other rocks of the sequences. On the one hand, the basic melts yield alkaline affinities, with generally high concentrations of Ba and Sr in the Meißen massif. On the other hand, tholeiitic diorites (cf. GAGNY, 1984) are related with medium to low Ba- and Sr-values throughout the Ballons massif. Concentrations of elements like e.g. U and Th are mainly dependent on crustal influences. As opposed to the Th- (and U-?) poor contaminant of the Hauptgranit, the participation of Th- and U-rich crust led to high values of both elements in the rocks of the Ballons massif (PAGEL and LETERRIER, 1980).

GEODYNAMIC FRAME

The different rock types of the Meißen massif belong to one plutonic scenario between about 360 and 300 Ma (WENZEL et al., 1990). There are chemical and geochronological arguments which

allow to regard the sequences of Freital, Reudnitz and the pyroxene-monzodiorite from Gröba as plutonic continuation of the Upper Devonian basic volcanism in the Elbtal-Schiefergebirge described by FANDRICH (1965) and RÖSLER and WERNER (1979):

Comparable to the alkaline affinities of the Freital and Reudnitz plutonic suites, a transitional to alkaline character of the majority of basalts and diabases can be detected using analytical data of RÖSLER and WERNER (1979) and WERNER et al. (1987). Most of them are hypersthene-olivine-normative, some contain olivine and nepheline in the norm. This is typical for transitional and alkali basalts, respectively (cf. HYNDMAN, 1985). Spider-diagrams of diabases and basalts show similarities to the "transitional within plate basalt pattern" of the Gregory-Rift (see PEARCE, 1982). Last but not least, the rocks plot into the "array of basalts from non-subduction settings" of the Th/Yb-Ta/Yb-diagram of PEARCE, 1983. They seem to indicate a within plate enrichment.

First single-grain age determinations on zircons from the Gröbait yielded values between 350 and 360 Ma (WENZEL et al., 1990). This is in narrow relation to Upper Devonian ages ranging from 375 to 360 Ma (ODIN and ODIN, 1990).

The further development of the magmatism is influenced by the change of the tectonic regime from extension (Upper Devonian) to compression (Sudetic phase of the Variscan orogeny; see KURZE and TRÖGER, 1990). Recently, similar correlations were propagated by ARAKAWA (1990) from Japanese granitic complexes.

Obviously, the compressive tectonics led to progressive interactions of the basic (mantle) melts with crustal components resulting in changes of the "tectonic character" of the plutonic rocks (see Fig. 18) and transitions from open- to closed-system fractionation, described above.

Conclusions

Summarizing, we propose the following genetic model for the Meissen plutonics:

- The intrusion and closed system fractional crystallization of slightly contaminated basic melts of transitional to alkaline affinities (Freital and Reudnitz suites).
- A progressive interaction of basic melts and crustal components caused by transitions from extension to compression tectonics.
- The overprint of earlier monzodioritic rocks (type Freital) by a syenite melt to form hybrid rocks (monzonites from Leuben).

– The further development of the magmatic system by fractional crystallization as well as increasing crustal contamination under open system conditions (e.g. Hauptgranit suite).

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