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Post-Variscan thermal and tectonic evolution of the KTB site and its surroundings

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Abstract. The post-Carboniferous crustal evolution of the German Continental Deep Drilling Program (KTB) area, as summarized in this paper, could not be predicted from surface observations: deep drilling was essential for its revelation. The most conspicuous and unexpected feature discovered in the drill hole is the absence of marked gradients with respect to the pre-Carboniferous record. There are no depth-related differences in K-Ar cooling ages of hornblende and white mica, in petrology or in lithology. All metamorphic rocks encountered, both at the surface as well as in the drill hole down to 9100 m depth, were below 300°C from the Carboniferous onward. The late to post-Carboniferous deformation is essentially confined to several fault zones. A major fault zone encountered in the drill hole at 7000 m depth is linked by a prominent seismic reflector to the Franconian Lineament, the surface boundary between Variscan basement and Mesozoic cover. This fault zone probably formed in the late Paleozoic and reactivated as a reverse fault in the Mesozoic. Two important episodes of NE-SW directed shortening by movements along reverse faults took place in the early Triassic and in the late Cretaceous, as indicated by the distribution of apatite and titanite fission-track ages, the sericite K-Ar ages of fault rocks, and the sedimentary record in the adjacent basins. Upper crustal slices were detached at a specific level, corresponding to the approximate position of the brittle-ductile transition in post-Variscan times, and form an antiformal stack that was penetrated by the KTB throughout its entire depth range.

Introduction

The German Continental Deep Drilling Program (KTB) drilling site is situated in the Bohemian Massif, close to its western margin. The Bohemian Massif is composed of Variscan (Hercynian) medium- to high-grade metamorphic basement rocks and granitic intrusions [O'Brien *et al.*, this issue]. Subsequent to a complex pre-Carboniferous tectonic evolution, an outstanding stage of regionally high heat flow resulted in high-temperature low-pressure metamorphism, followed by granitic magmatism ~310 Ma ago. The crustal unit drilled by the KTB (ZEV; Figure 1) had already reached the upper crust at that time and therefore was only marginally affected. The Falkenberg Granite (Fa; Figure 1), a few kilometers east of the KTB site, solidified at 311 ± 8 Ma [Wendt *et al.*, 1986] at a depth of 9–12 km [Maier, 1994] and suffered only localized deformation by brittle faulting. To the SW, the Bohemian Massif is separated from the Permo-Mesozoic sedimentary cover by post-Carboniferous fault zones. The NW-SE striking Franconian Lineament (FL) intersects the surface about 5 km

SW of the KTB site (Figure 1). It had been identified early on as a reverse fault [Carl, 1955], but the dip angle was unknown. The prominent dipping reflector identified in the seismic reflection studies as SE1 [Harjes *et al.*, this issue] is alleged to be the continuation of the Franconian Lineament at depth, given the dip of ~55° to the NE beneath the drill site. This allows a correlation between the cataclastic fault zone encountered in the main drill hole (KTB-HB) at ~7000 m depth and the Franconian Lineament. The drill hole subsequently penetrated about 2000 m into the footwall of this reverse fault.

The aim of the present paper is to combine various approaches in order to reconstruct the tectonic and thermal evolution of the crust at the KTB site from the time of intrusion of the Carboniferous granites. This history is unravelled using isotopic dating, fission-track (FT) thermochronology, structural studies on fault zones and related mineralizations, and consideration of the sedimentary record of the Mesozoic cover in the foreland of the Bohemian Massif. As will be revealed, these conclusions would never have been reached except through deep drilling because access to the third dimension provided the essential data.

Geological History of the KTB Surroundings From Surface Observations

Stratigraphic Record and Tectonic Evolution of the Sedimentary Cover

The position of the KTB site on the margin of the Bohemian Massif and close to the Permo-Mesozoic sedimentary basins allows the reconstruction of the denudational and tectonic history of the KTB surroundings from this sedimentary record.

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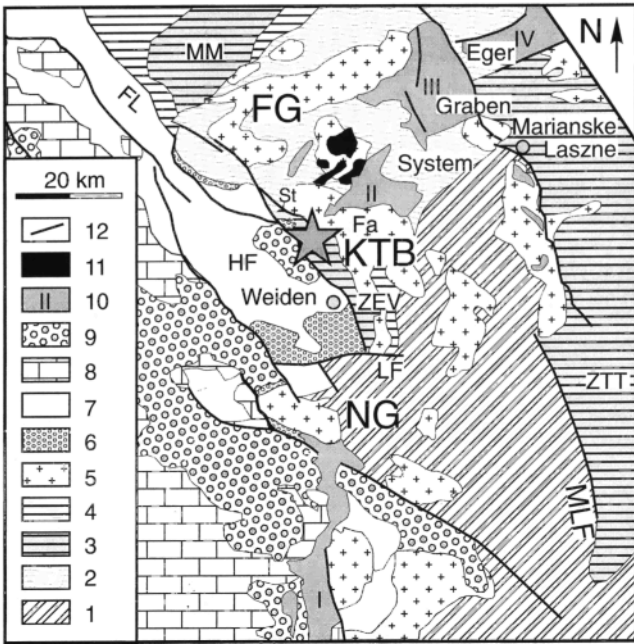


Figure 1. Schematic geologic map of the KTB surroundings. Legend and symbol definition are 1-4, tectono-metamorphic basement units (1, Moldanubikum; 2, Saxothuringikum; 3, Zone Erbendorf Vohenstrass ZEV, Münchberg Massiv MM, Zone Tepla Taus ZTT; 4, metamorphic rocks below 3); 5, granite. Sediments are 6, Permo-Carboniferous; 7, Triassic; 8, Jurassic; 9, Upper Cretaceous; 10, Neogene (I, Naab Valley; II, Mitterteich Basin; III, Eger Basin; IV, Sokolov Basin); and 11, Neogene basalts; 12, faults. FL, Franconian Lineament; LF, Luhe Fault; MLF, Marianske Laszne Fault; HF, Hessenreuther Forst; St, Steinwald Massiv; Fa, Falkenberg Massiv; FG, Fichtelgebirge; NG, Naabgebirge.

attained a thickness of some 500 m. The sedimentation has been accompanied by polyphase compression and convergent wrench deformation during the Lower Cenomanian, the latest Turonian, and the late Cretaceous/early Paleogene [Gudden, 1984; Meyer, 1989; Ziegler 1993]. In the region of the Hessenreuther Forst (HF, Figure 1) coarse alluvial fan deposits on the footwall of the FL give clear evidence for accelerated uplift and upthrusting of the basement block during the late Cretaceous to early Paleogene deformation stage [Klare and Schröder, 1989]. After this complex deformation, a tectonically quiet period led to the development of a regional peneplain. Block faulting resumed again in the late Oligocene and early Miocene. Uplift of the Fichtelgebirge (FG, Figure1), volcanic activity, and deposition of continental clastic sediments in the area north of the KTB site can be related to the evolution of the ENE-WSW trending Eger-Graben [Schröder, 1994; Malkovsky, 1980]. From the middle Miocene to early Pliocene, a system of widespread planation surfaces developed in the basement area. Differential uplifted and downthrown panels of these planation surfaces indicate fault block activity during late Neogene to Quaternary [Schröder, 1992, 1994; Peterek et al., 1996c].

Information about the evolution of the paleostress fields based on the evaluation of fault slip data (Figure 2) has been published in detail by Peterek et al. [1996a, b, 1977].

The late Variscan tectonic evolution is recorded in the Permo-Carboniferous basins (Figure 1) that originally belonged to one single trough (Naab Trough [Schröder, 1988; Müller; 1994; Peterek et al., 1996a]). The development of the Naab Trough was mainly related to wrench faulting [Schröder, 1987; Ziegler, 1993; Matern, 1995a, b; Peterek et al., 1996a]. Synsedimentary fault activity is particularly indicated by the variation of lateral thickness and changing facies of the trough sediments [Schröder, 1988]. From the late Rotliegend and Zechstein till the late Cretaceous, regional subsidence of the Bohemian Border Zone took place. The Mesozoic sedimentary cover reaches a maximum thickness of about 1500 m [Schröder, 1987]. During the early Triassic (early Buntsandstein), accumulation of coarse alluvial fan deposits west of the FL indicates rapid uplift of the BM [Klare, 1989; Klare et al., 1995]. According to Peterek et al. [1997] this significant uplift can be related to N-S directed convergent wrench deformation. During the early Cretaceous west of the FL, strong differential block faulting and denudation of some 1000 m occurred prior to the sedimentation in the Upper Cretaceous. East of the FL, rapid uplift of the basement block (>1500 m) caused the total erosion of the Triassic-Jurassic sedimentary cover [Schröder, 1987]. Within the Bohemian Border Zone the Upper Cretaceous strata

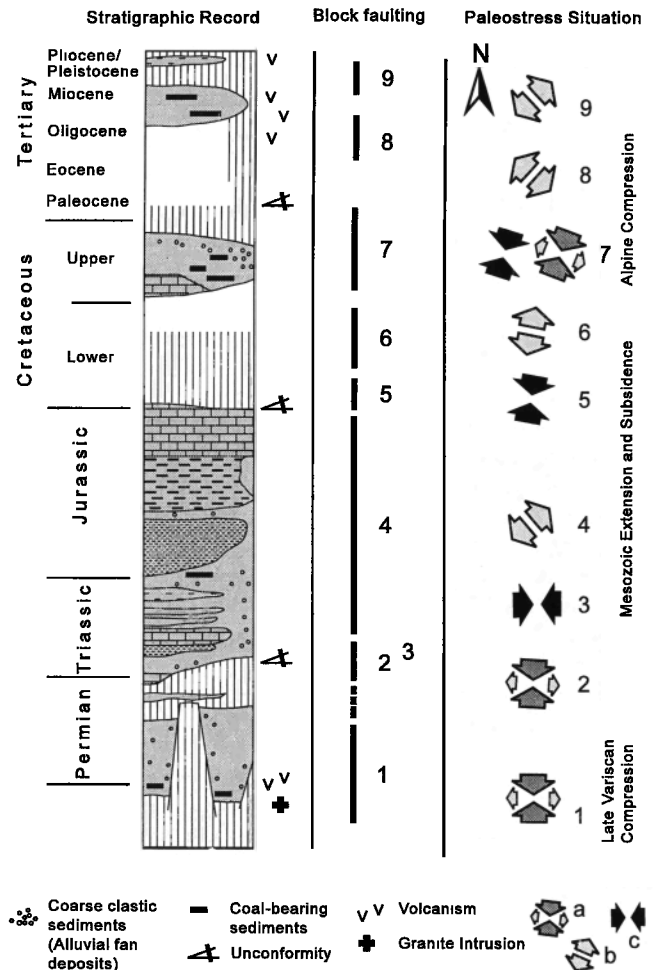


Figure 2. Stratigraphic record and tectonic evolution of the KTB surroundings. Numbered vertical lines column "block faulting" and "paleostress situation" correspond to periods of fault activity (a, predominantly strike-slip; b, extensional; c, compressional); symbols give the orientation of the horizontal stresses h and H [after Peterek et al., 1997].

Cooling History of the Basement

In addition to geological observations, geochronologic data also provide information on the thermal and tectonic history of the BM. The early postmetamorphic cooling history of the western ZEV can be deduced from K-Ar mineral ages of basement rocks well outside the contact aureoles of the middle/late Carboniferous granitic intrusives. K-Ar data of muscovites vary between ~380 Ma for the westernmost ZEV to 375-370 Ma farther east. These data indicate that the presently exposed basement of the western ZEV cooled down to temperatures of less than 400°C in middle/late Devonian time at a maximum rate of 20°C/Ma [Kreuzer *et al.*, 1989]. Toward the eastern border of the northern ZEV the K-Ar ages of biotite and muscovite are similar to those of the adjacent middle/late Carboniferous granites. This clearly demonstrates that the igneous rocks intruded the ZEV in late Variscan time.

Zircon FT ages from the closer KTB surroundings range from 280 to 220 Ma (Figure 3). Hitherto it was assumed that the track retention temperature of zircon lies somewhere between 240 and 175°C [Wagner and Van den haute, 1992]. The abundance of tracks in KTB zircons at 260°C ambient rock temperature is clear evidence that the retention temperature is much higher. Thus the zircon FT ages of the northeastern Bavarian basement record cooling to temperatures around 300 to 260°C during the Permian/Triassic and ~10 km of unroofing since then, assuming that the paleogeothermal gradient was approximately the same as the present one.

About 100 apatite FT ages were determined for surface samples taken from outcrops surrounding the KTB [Wagner *et al.*, 1989; Bischoff, 1993]. Late Cretaceous/early Tertiary FT ages (from 90 to 50 Ma) are typical for the basement area north of Weiden (Figure 4). Confined track length data indicate that all these FT ages are cooling ages to ~100°C. The oldest ages, representing early uplift/denudation, have been found near to the European hydrographic center, in the Fichtelgebirge which

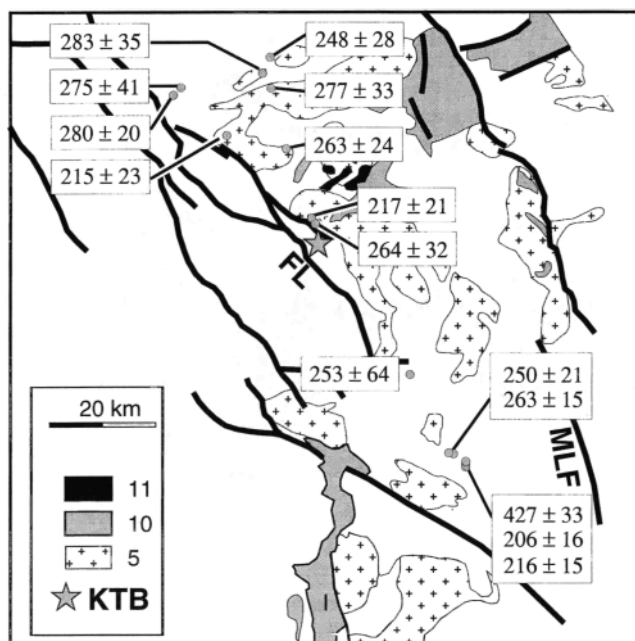


Figure 3. Zircon fission-track ages of the KTB surroundings (including unpublished results by C.W. Naeser). For legend, see Figure 1.

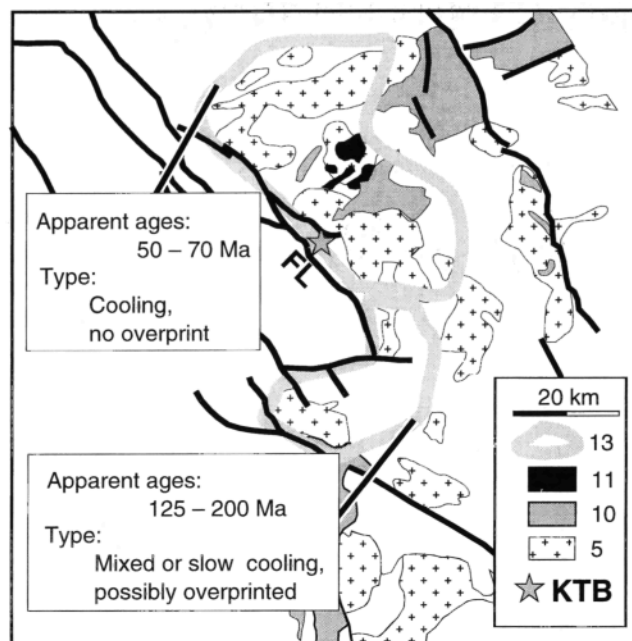


Figure 4. Apatite fission-track ages of the KTB surroundings. For legend, see Figure 1. Number 13 denotes regions with same interpretation of apatite FT ages.

separate the drainage systems of the North Sea and the Black Sea. Near the KTB site, the apatite FT ages range from 70 to 60 Ma. The lowest ages, found in the Steinwald, reveal late and strong uplift/denudation of this area, probably in connection with the development of the Tertiary Eger-Graben. These apatite FT ages show that since the late Cretaceous/early Tertiary, about 3 km have been eroded from the basement around as well as north of the KTB site. Of special interest are two gneissic boulders from the late Cretaceous fan deposits of the Hessenreuther Forst. Since both samples give also late Cretaceous apatite FT age values, the gneissic source area within the adjacent Bohemian Massif must have been exhumed by some 3000 m (i.e., from 100°C to the surface) during the late Cretaceous period. On the other hand, apatite FT ages from the basement south of Weiden range between 120 and 200 Ma. According to track length criteria, this region experienced a more complex history with a thermal overprint during Jurassic subsidence which did not exceed 2500 m depth. Altogether, the apatite FT data reveal for the western margin of the Bohemian Massif a pattern of differential block tectonics during the late Mesozoic/early Tertiary that is well correlated to the sedimentary and tectonic records.

Entering the Third Dimension: KTB Data to 9100 m Depth

The KTB drill holes offer the unique opportunity to extend observations from the surface deep into the crust. Of particular interest in this context are the depth dependence of fault and vein mineralizations as well as of geochronometric systems. Such spatial data sets allow a detailed reconstruction of the thermal and tectonic history.

Faults and Veins

Postgranitic faults and veins are widespread features in both KTB drill holes. Though faults can be detected at any scale,

Table 1. Characteristics of Major Faults in the KTB

| Depth | Orientation, Dip Direction/Dip | Graphite | Seismic Reflector | Displacement | Remarks |
|---------------|-----------------------------------|----------|-------------------|--------------|--------------------------|
| 500 - 1500 m | 70/80 | | | - and + | NFZ |
| 2000 m | | + | | | |
| 4000 m | | + | | | |
| 4300 m | -60/60 | | SE2 | + | |
| 5300 m | | + | SE12? | + | |
| 6850 - 7260 m | -55/60 | + | SE1 | + (~3000 m) | FL |
| 7800 - 7900 m | SW (not NE) steep | ? | | | fluid inflow, not saline |
| 8680 m | ? | + | | | fluid inflow |

Graphite: +, indicates presence of graphite. Displacement: -, normal; +, reverse (amount). NFZ, Nottersdorf Fault Zone; FL, Franconian Lineament.

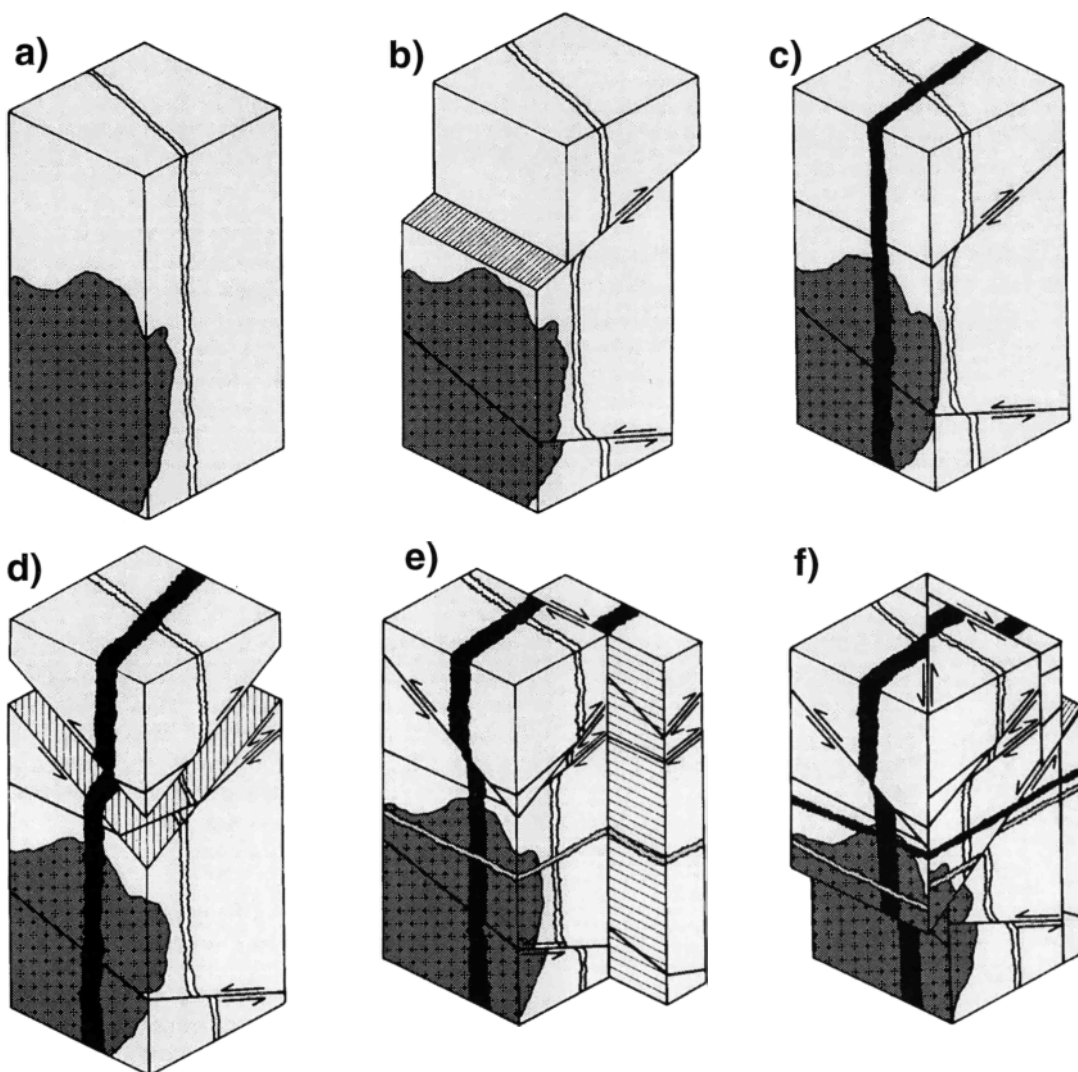


Figure 5. Schematic block diagrams showing sequence of post-Variscan deformation stages as derived from drill cores of KTB pilot hole (VB) and KTB main hole (HB). (a) Late Carboniferous subvertical tension gashes (NE-SW extension); (b) late Carboniferous reverse faulting (with graphite-enrichment in faults in the gneisses; NE-SW extension); (c) intrusion of late Carboniferous lamprophyres; (d) Cretaceous reverse faulting (N-S compression); (e) late Cretaceous subhorizontal tension gashes; (f) strike-slip faulting and possible Neogene high-angle normal faulting.

several larger fault zones can be recognized. Table 1 lists some of the strongly faulted zones in the drill holes. Locally, lamprophyres intruded into and crosscut faults as zones of weakness. In gneisses, large fault zones are often graphitized, whereas in the metabasites, open fractures with fluid inclusions prevail. Drilling logs reveal reduced electrical resistivity which is mainly due to sulfide and graphite mineralization and additionally to saline brines. Furthermore, self-potential anomalies are associated with the larger fault zones. Most faults follow the foliation and dip either to SW or to NE. Three-dimensional seismic studies show a number of planar reflections, the so-called steep elements SE [Harjes *et al.*, this issue], some of which are correlated with faults in the drill holes and at the surface [Hirschmann, 1994]. The most prominent fault system was intersected at about 7000 m depth; it is correlated with the SE1 and the FL.

On the basis of overprinting relations, the faults and veins can be separated into late Variscan and post-Variscan ones. Late Variscan structures include subvertical extensional veins and brittle-ductile reverse faults. Post-Variscan deformation produced subhorizontal extensional veins, brittle reverse and normal faults. Figure 5 schematically shows the crosscutting relationships of these postgranitic structures [Zulauf, 1992]. K-Ar data of mineral fine grain fractions (<2 μm) from graphite-bearing cataclastic zones reveal that during the late Jurassic/early Cretaceous the late Variscan structures were reactivated [Wemmer, 1991]. Figure 6 illustrates the synkinematic mineralization of faults and veins, with emphasis on minerals diagnostic for specific boundary conditions. Additionally, quartz deformation fabrics of late Carboniferous brittle-ductile reverse faults are present.

Late Carboniferous subvertical tension gashes trend approximately NW-SE (Figure 5a). They are filled with prehnite, actinolite, and epidote down to 4300 m depth (Figure 6). These minerals suggest that they were formed under prehnite-actinolite facies conditions (250-350°C [Liou *et al.*, 1987]). Below 4300 m, epidote/zoisite and actinolite are still present, but prehnite is completely absent, indicating the greenschist facies (>350°C). Further vein minerals include calcite, quartz, feldspar, and minor tourmaline. An upper age limit for the steep veins is given by the fact that they crosscut the marginal parts of the 311 Ma Falkenberg Granite. Late Carboniferous reverse faults I developed primarily under NE-SW compression [Zulauf, 1992]. In paragneiss, they are graphite-enriched [Zulauf *et al.*, 1990]. They cut the steep veins (Figure 5b) but were themselves intruded and cut by lamprophyres (Figure 5c) of Stephanian age (K-Ar biotite 296 ± 3 Ma [Kreuzer *et al.*, 1993]). Synkinematically formed minerals found in the reverse faults include prehnite, epidote/zoisite, and actinolite. Their distribution indicates metamorphic conditions of the prehnite-actinolite facies from 0 to at least 7500 m depth (Figure 6). This is in good agreement with the quartz deformation fabrics observed in the later Carboniferous reverse faults. Down to a depth of 1700 m, undulatory extinction, subgrains, and evidence for grain boundary migration occur in addition to abundant microcracks. Recrystallization sets in below 1700 m, although fractures and the other phenomena described above still persist until 7500 m. The simultaneous development of fracture, recrystallization, and pressure solution is characteristic for the brittle-ductile transition regime with respect to the quartz-bearing gneisses [Evans and Fredrich, 1990]. Recrystallization increases considerably below 7500 m, while cold working fabrics (fracture and undulatory extinction)

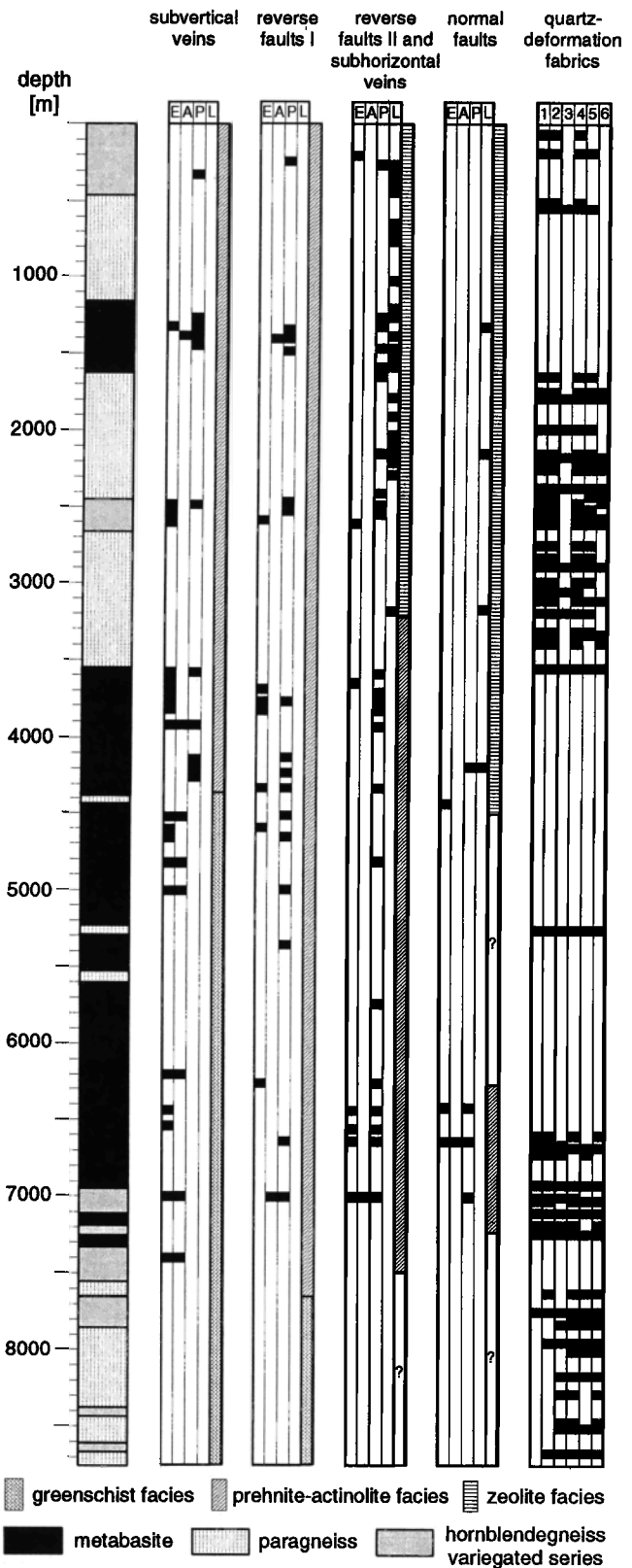


Figure 6. Occurrence of metamorphic index minerals in faults and veins of KTB-VB (0-4000 m) and KTB-HB (4000-8750 m) (E, epidote/zoisite; A, actinolite; P, prehnite; L, laumontite). Quartz deformation fabrics of the late Carboniferous graphitic reverse faults (1, fracture; 2, undulatory extinction; 3, pressure solution; 4, subgrains; 5, grain boundary migration; 6, recrystallization).

diminish. Thus, below 7500 m the deformation regime gradually changes from brittle-ductile to ductile concerning the graphite-bearing reverse faults. Cretaceous reverse faults II and subhorizontal tension gashes cut the graphitic reverse faults (Figures 5d and 5e). The reverse faults developed under N-S compression [Zulauf, 1992]. Down to 3200 m depth, the index minerals laumontite and prehnite occur, suggesting metamorphic conditions of the low-pressure zeolite facies (<250°C). Below 3200 m, laumontite is entirely absent within reverse faults and tension gashes. This is indicative for a transition to the prehnite-actinolite facies (Figure 6). The latter extends to 7000 m depth. The assemblage prehnite + actinolite + epidote is formed in subhorizontal veins. The quartz fabrics of the reverse faults change slightly with depth (increase of recovery features); recrystallization does not occur above 7000 m depth.

Some strike-slip faults have been observed in the drill cores. Their age is not well constrained. However, as they frequently cut the graphite-free reverse faults (Figure 5f), they must be younger than early Cretaceous. Apart from late joints, which do not show any mineralization, steeply inclined normal faults are the youngest deformation structures (Figure 5f). The age of these faults is only poorly constrained because they do not contain contemporaneous mineralization suitable for radiometric dating. The normal faults are likely related to the Neogene differential block faulting. For these faults, a clear trend of changing boundary conditions with depth is obvious. To a depth of 4200 m, the low-pressure zeolite facies is reflected by the growth of laumontite + prehnite. Between 6000 and 7000 m, laumontite is absent in the normal faults, and prehnite + actinolite + epidote indicate prehnite-actinolite facies (Figure 6). Reactivation of the former graphitic reverse faults by normal slip is a common feature.

Since in the deeper parts of KTB-HB (below 7500 m) investigations are largely restricted to cuttings, an unequivocal identification of the mineralized structures is not possible. Prehnite fissure mineralization was frequently found until 7250 m. Between 7250 and 7610 m prehnite occurs sporadically, and below, it is completely absent: this indicates that below the major fault zone related to the FL, metamorphic conditions of the greenschist facies must have been reached at least with respect to the most common late Variscan and Cretaceous structures [Duyster *et al.*, 1994]. This is consistent with observations that the KTB-HB profile shows a decrease in cataclastic overprint below the FL. At 8700 m, a further fault zone, characterized by open fissures and fluid inflows, within hornblende gneiss was drilled.

The distribution of mineral facies versus depth shows a significant trend (Figure 6): The prehnite-actinolite facies vertical range is considerably larger in the late Carboniferous reverse faults I compared to the Cretaceous reverse faults II and the younger normal faults. Below 7600 m depth, the prehnite-actinolite facies mineralization is absent in all three fault types. This leaves a depth interval of ~4500 m for the prehnite-actinolite facies in the reverse faults II and a maximum of 2500 m in the younger normal faults. Therefore the vertical extent of the prehnite-actinolite facies in faults I is about 1.5 times larger than in faults II and 3 times larger than in the young normal faults. These are minimum values because it is unknown how far the prehnite-actinolite facies in fault system I reached upward into the rock column lost by erosion. Only in the normal faults is the vertical extent (2500 m) of the prehnite-actinolite facies in good agreement with the assumed pressure interval for

this facies [Liou *et al.*, 1987]. The enlarged vertical extent of this facies in the fault systems I and II indicates tectonic repetition.

Geochronological Data

Apatite fission-track analysis is the lowest-temperature thermochronometer (~100°C) applied to rocks from the KTB. Apatites were collected at 100-m intervals down to 3900 m from the KTB pilot hole (KTB-VB) [Hejl and Wagner, 1990]. Results of age determinations are given in Figure 7. Down to ~2000 m the ages range between 58 and 70 Ma. Although these ages decrease slightly with depth, they show a distinct scatter which suggest profile repetition caused by reverse faulting [Coyle *et al.*, 1997]. Confined track lengths of 13.2-14 μm identify them as cooling ages [Gleadow *et al.*, 1986]. This is supported by age-spectra based on length measurements on surface tracks [Wagner and Hejl, 1991; Wagner *et al.*, 1994]. Below 2000 m a strong decrease of the apatite FT ages down to 6.2 Ma at 3900 m is observed, and the mean track lengths decrease with depth. They reflect track in situ fading within the recent partial annealing zone (PAZ) between 60 and 120 °C.

FT analysis has been carried out on titanite samples to a depth of 8700 m in the KTB-HB (Figure 7). The investigations include dating by the external track detector technique and length measurements of horizontal confined tracks. One of the main aims of examining the FT system in titanite was to determine the thermal stability of FT in the geologic environment. Previously, estimates of the "closure temperature" for FT in titanite had been in the range 240-280°C [Wagner and Van den haute, 1992]. The analysis of samples at a present temperature of ~250°C at 8700 m shows that the FT are experiencing no demonstrable annealing. The complete titanite FT age profile of the KTB-HB contains an uplifted PAZ beginning at ~4000 m depth. The thickness of this zone in temperature terms is ~45°C, and from this, it can be concluded that FT in titanite are unlikely to be completely annealed at temperatures less than 295°C (= 250°C + 45°C). This temperature estimate can be further refined by "backstacking" the observed uplifted PAZ using the reconstructed thermal history of the KTB site (see section on the temperature-time path). This yields a revised PAZ in the range 265-310°C, which is much higher than hitherto assumed. Such basic data are essential for the interpretation of FT analyses used in the reconstruction of the thermal evolution of sections of the brittle upper crust. The profile of titanite FT ages (Figure 7) shows clear evidence of two periods of significant cooling of the KTB rock column. One, occurring at ~240 Ma (Triassic) is evidenced by the 4000-m profile of unchanging ages between the surface and 4000 m depth. This does not mean, however, that a vertical block of 4000 m cooled in the early Triassic due to 4000 m of uplift/denudation, because there is evidence that this upper section has experienced substantial thickening through stacking during the late and post-Cretaceous. Reasonable estimates of the amount of this stacking are in the range 1500 m, yielding a net Triassic cooling through 2500 m. This Triassic event is documented as a retrograde process that affected the entire series of drilled rocks. Similar to the titanite FT ages, fine-grained sericites (<2 μm) yield K-Ar ages ranging from 220 to 260 Ma in the KTB-VB [Wemmer, 1991] and in the KTB-HB down to 4000 m. The second major cooling event occurred in the Cretaceous, as evidenced by the vertical profile of ages between ~5500 and 7000 m depth and by the young component

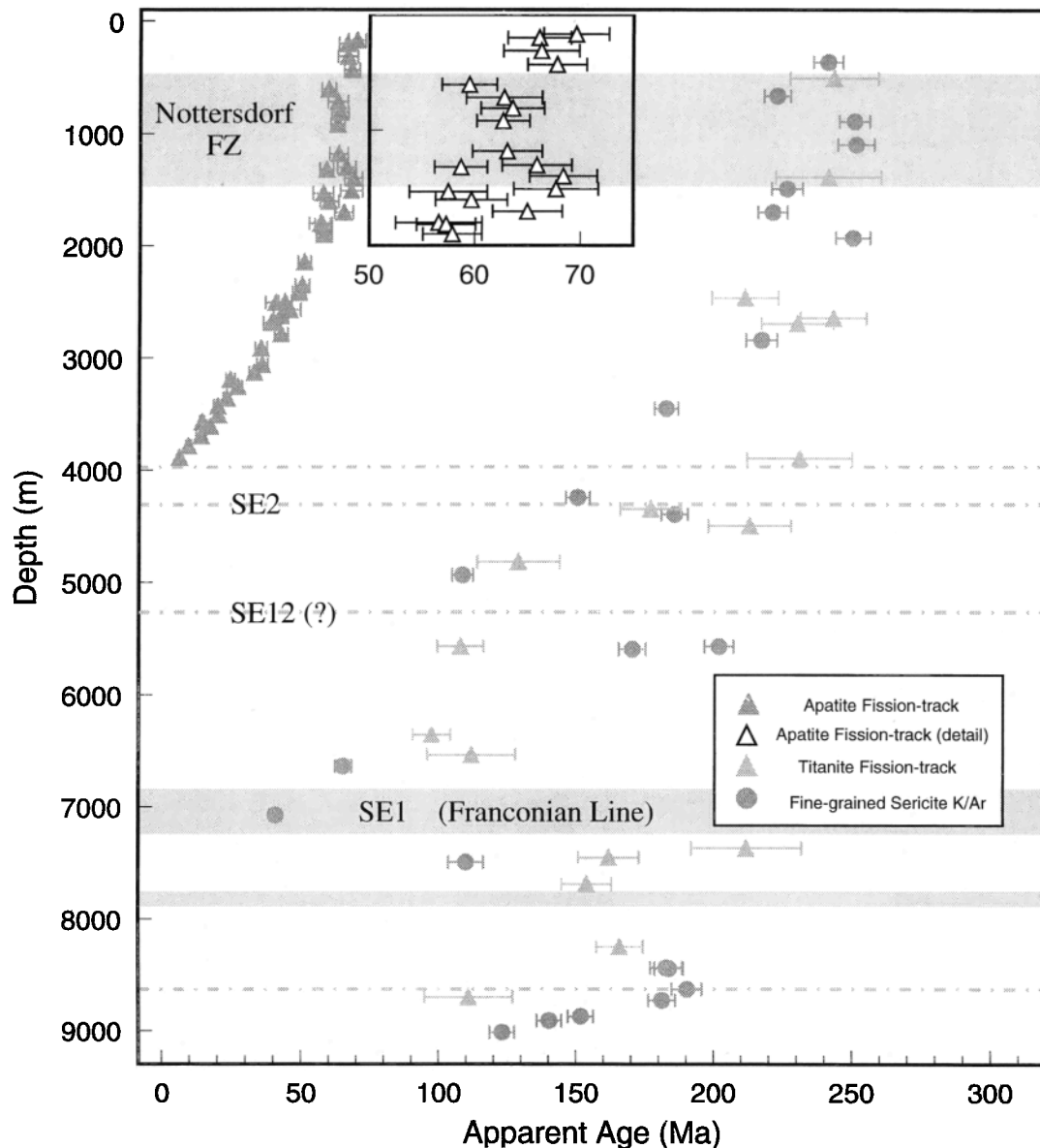


Figure 7. Depth-profile of Rb-Sr, K-Ar, and FT cooling ages, with major faults and fault zones of the KTB-HB.

of age extracted from the lowermost samples. The magnitude of uplift/denudation that caused this cooling was ~1500 m for the section above the SE1 reflector and is indeterminate for the lower section, though certainly only 1000 m or less. The possibility of section repetition in the section above 5500-7000 m cannot be excluded. The offset in ages across the fault zone at 7000 m indicates reverse faulting and gives a clear measure of the timing and amount of vertical displacement along the FL, which is correlated with this fault zone. This movement amounts to some 3000 m and must have occurred ~100 Ma ago, most likely already in the late Cretaceous, the period when the thermal history paths for the upper and lower blocks diverged. The above mentioned 1500 m of Cretaceous uplift is included in this amount.

K-Ar dates on muscovites and amphiboles of the KTB-VB and KTB-HB yield maximum ages of ~370-375 Ma and 370-390 Ma for micas and amphiboles, respectively (Figure 8). These ages are similar to the K-Ar dates obtained from muscovites and amphiboles of the western ZEV which were

thermally not affected by the middle/late Carboniferous granitic intrusions [Kreuzer *et al.*, 1989]. Therefore the 370-390 Ma K-Ar ages on minerals from core samples indicate that post-metamorphic cooling of the KTB rock column from ~550°C to less than 400 °C occurred in the middle/late Devonian. K-Ar dates ranging between 360 and 310 Ma (Figure 8) were obtained from fine-grained muscovites of moderately to strongly retrograded paragneisses, suggesting that localized low-grade alteration processes affected the Devonian high-grade metamorphic rocks in the middle/late Carboniferous. Likewise, the 370-360 Ma dates of coarser-grained muscovites from KTB paragneisses may be explained by a partial resetting of the K-Ar systems of micas with primary cooling ages of 370-375 Ma in response to middle/late Carboniferous hydrothermal processes. For KTB biotites, K-Ar dates higher than 350 Ma were only obtained from core samples at <1000 m and at ~8000 m depths. Most other biotites, irrespective of their grain sizes, yield K-Ar dates in the range of 325-295 Ma. There are, however, some intermediate biotite dates of 345-330 Ma from the depth

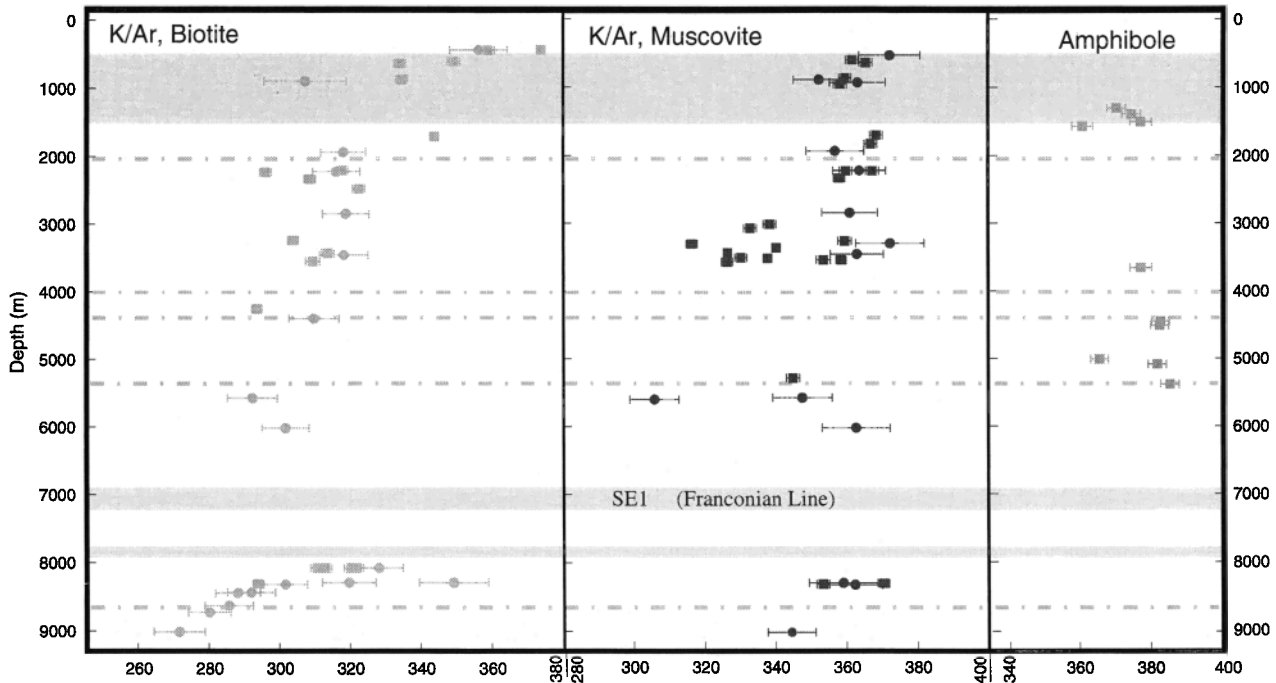


Figure 8. Depth-profile of K-Ar formation ages.

interval 1000-2000 m which may indicate a gradual decrease in biotite K-Ar age with increasing depth of the KTB-VB. Whereas the biotite dates of ≥ 350 Ma from <1000 m depth and from ~ 8000 m depth most likely date the time of postmetamorphic cooling down to ~ 350 - 300 °C, the geological meaning of the biotite dates of ~ 350 Ma is still a matter of discussion. A decrease in biotite ages with increasing depth, as found for the depth interval 0-4000 m, may suggest a slow postmetamorphic cooling to temperatures of less than 350-300 °C. Alternatively, the decreasing biotite ages may be due to late to post-Variscan thermal overprints of the rocks in response to deep-seated hydrothermal processes and/or granitic intrusions. Similar to the FT data of KTB titanites, the offset of the K-Ar biotite dates across the SE1 reflector to higher mineral ages below ~ 7000 m clearly indicates profile repetition due to tectonic stacking of the KTB rock column in post-Variscan time.

Geochronologic Discontinuities and Faulting

The most important faults, as listed in Table 1 and also shown on Figures 7 and 8, express themselves in the record of the low-temperature geochronothermometers. Significant offsets, from younger ages above to older ages below, are taken to be direct evidence of reverse faulting. The age data presented in Figure 7 and 8 show that ages suddenly increase with depth across fault zones. Considering only the most important faults, as listed in Table 1 and also shown on Figures 7 and 8. The Nottersdorf Fault Zone (NFZ) correlates with discontinuities in the apatite FT record, and also with K-Ar ages of fine-grained sericite. Most notable is a normal offset at ~ 700 m depth which is recorded by both, the FT and K-Ar systems. There is a significant discontinuity in the K-Ar data at ~ 4300 m, corresponding to the position of the SE2 reflector. The titanite FT data also show a discontinuity immediately below the SE1

reflector, but it is uncertain whether it involves a splay of the SE2 or not. The sericite K-Ar ages are significantly offset between 5000 and 5500 m, corresponding to a cataclastic zone associated with the SE12 reflector. Across the SE1 reflector around 7000 m, the most significant discontinuities are observed. Titanite FT ages jump from 112 Ma to 212 Ma, sericite K-Ar ages jump from 41 to 110 Ma, and the biotite K-Ar ages (Figure 8) appear to increase as well. Two fault zones, at ~ 7800 m and at 8680 m, also correlate with discontinuities in both the titanite FT and the sericite K-Ar age distribution.

Tectonic Evolution of the KTB Rock Column

A most conspicuous and unexpected feature discovered in the KTB column is, with respect to the pre-Carboniferous record, the absence of depth-dependent gradients in the petrologic record and the K-Ar cooling ages of hornblende and mica. This indicates stacking of slices rather than rigid body rotation of the entire block for the following reasons:

There are no gradients in the metamorphic record at the surface which would be expected in the case of tilting.

Geochronologic discontinuities are related to reverse faults.

The subvertical orientation of the last principal stress related to the late Carboniferous reverse faulting does not markedly change with depth in the KTB-VB [Zulauf, 1993].

The subvertical attitude of the oldest veins is largely maintained throughout the entire drilled section and is also found in surface outcrops near the KTB site [Zulauf, 1993].

Further remarkable features are the repetitions of the apatite and titanite FT ages as well as the K-Ar sericite ages along the KTB profile and the differing vertical widths of the prehnite-actinolite facies in different fault types. The deformation mechanisms in the Carboniferous reverse faults are unchanging down to ~ 7600 m depth. The vertical extent of the prehnite-actinolite facies in the late Carboniferous reverse faults is

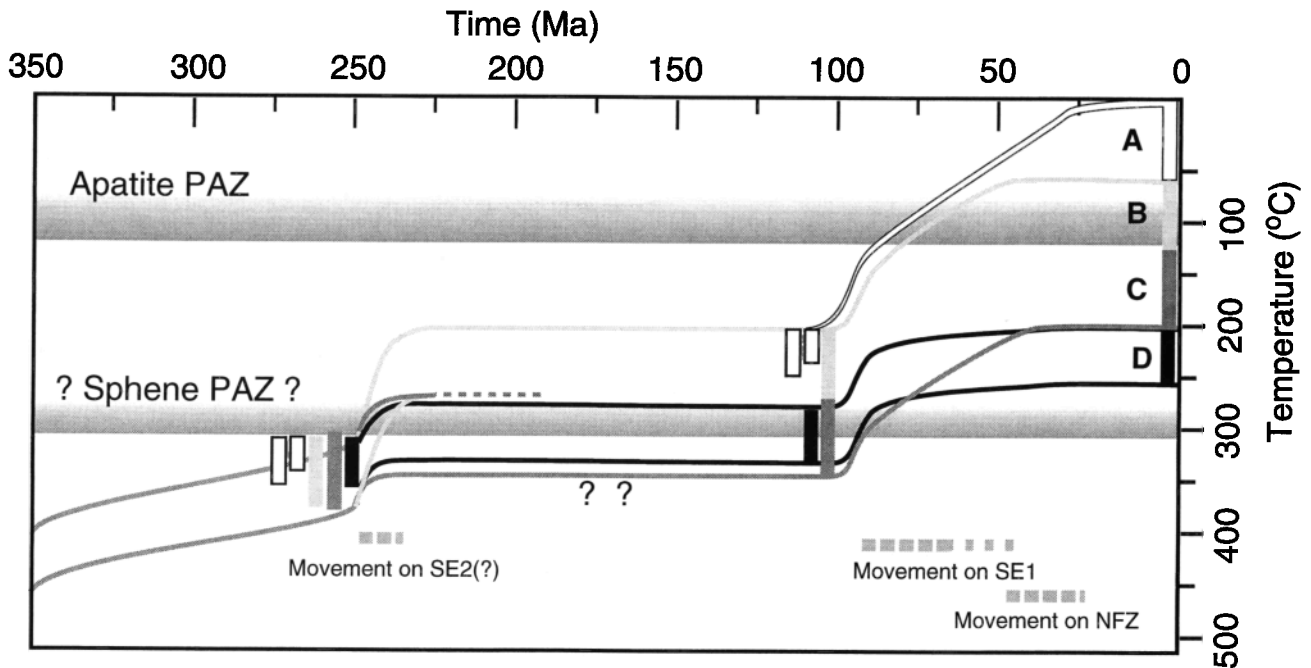


Figure 9. T-t-paths of different KTB sections (A, 0 to ~1800 m; B, ~1800 to ~4300 m; C, ~4300 to ~7000 m; D, ~7000 to 9100 m) since 310 Ma. PAZ refers to the fission-track partial annealing zone.

significantly larger compared to younger faults and at least 3 times larger than the expected width of about 2500 m [Liou *et al.*, 1987], which is actually observed in the youngest faults. These different widths are the result of post-Carboniferous upper crustal stacking along reverse faults which tripled the original extent of the prehnite-actinolite facies in the Carboniferous fault zones.

Temperature-Time Path of the KTB Rock Column

The timing, position, and inferred offsets of reverse faults are synthesized and presented schematically in Figure 9, which traces the T-t-paths of the rocks drilled by KTB, starting at 350 Ma. Although the kinematic framework is much more complex, the principal movements have taken place between four blocks now stacked atop each other in the KTB drill hole (Figure 9).

From Carboniferous till Permian, the rocks that now form a stack of 9000 m were located in a crustal layer with a thickness of ~2000 m that was slowly cooling. The homogeneous nature of this unit is evident from the total lack of variation in higher-temperature geochronometric data (K-Ar muscovite and amphibole: Figure 8), and minor gradients in the lower-temperature biotite K-Ar system. The steady decrease in mean ages obtained from amphibole through muscovite, to biotite, indicate slow cooling. Toward the end of the Permian, and through the early Triassic, blocks A and B were uplifted out of the titanite PAZ, and blocks C and D were slightly uplifted, remaining partially within the titanite PAZ. FT data provide a minimum temperature constraint on blocks A; B; and C: these blocks never entered the upper PAZ (~265°C) again. It is postulated that differential movements between blocks A-B and C-D occurred along the fault zone corresponding to the SE2 reflector. This rapid uplift event is recorded in the foreland of

the Bohemian Massif by early Triassic alluvial fan deposits. Concomitant differential movements between blocks C and D cannot be ruled out.

Tectonic quiescence prevailed from the late Triassic till the end of Jurassic, when the Bohemian Border Zone was overstepped by sedimentation. During the early Cretaceous, the FL was active, separating blocks C from D. Both blocks were uplifted and brought out of the titanite PAZ, as documented by titanite FT and sericite K-Ar ages. A third uplift phase during the latest Cretaceous and Paleocene is recorded by the sediments of the adjacent basin as alluvial fans, as well as by the apatite FT data from the KTB-VB. Movement across the FL apparently ceased by the Eocene. At that time, the NFZ became active, causing thickening of blocks A and B along sets of reverse faults. The sedimentary input derived from the KTB surroundings and deposited into the foreland west of the FL occurred in several pulses [Schröder, 1987; Klare and Schröder, 1989]. The sedimentary record allows to estimate the amounts of uplift and erosion in the source area: 4000-5000 m during the late Carboniferous and the Permian, 2500 m during the lower Triassic, >1000 m during the lower Cretaceous, and >2000 m during the late Cretaceous. The ages of the last three uplift events match those revealed by the FT and K-Ar data. The late Carboniferous to Permian uplift and erosion are not seen in the age data, probably, because only the footwall of the associated fault has been preserved. Summarizing, a rock pile of about 15 km was exhumed and eroded since the intrusion of the Variscan granite.

Geometric Model

Such a large amount of exhumation and uplift seems incompatible with the late Carboniferous K-Ar ages of biotite obtained from 8300 m drill core depth. Adding the eroded 10

SW

NE

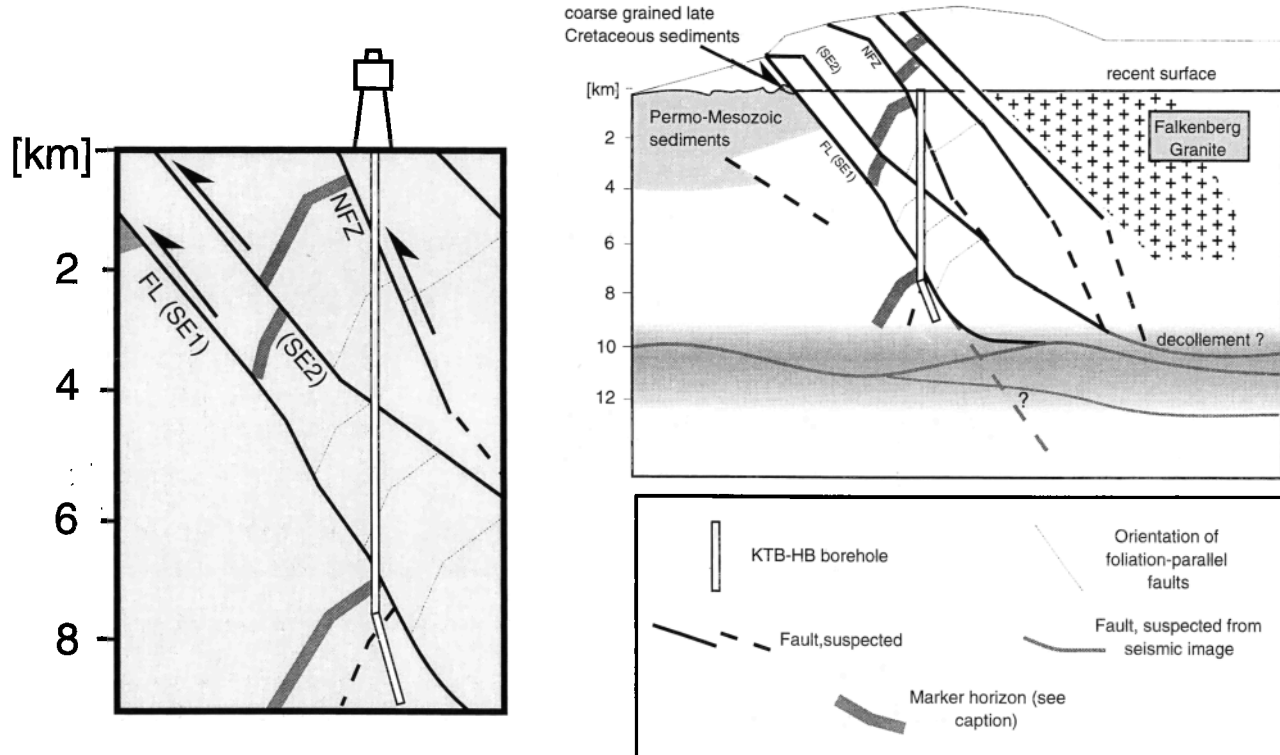


Figure 10. SW-NE oriented cross section through KTB-HB during the late Cretaceous. Orientation of faults and displacements interpreted from well data. Tectonic model for the Bohemian border zone. FL, frontal ramp of Franconian Lineament; NFZ, Nottersdorf fault zone; SE, seismic reflectors corresponding to faults [Hirschmann, 1994]. The marker horizon does not represent a lithological unit but illustrates the dip of foliation and relative displacement along faults.

km to the drilled depth would imply that the rocks from the deeper parts of KTB should show evidence of amphibolite facies condition in Triassic time. However, contrary to this, these K-Ar ages prove that the rocks from this part of the profile were never hotter than the closure temperature of the K-Ar system in mica since the late Carboniferous. The recorded metamorphic conditions described above, and the pattern of radiometric cooling ages throughout the drilled section, suggest that crustal slices were upthrust along reverse faults. Originally, these crustal slices were about 2000 m thick and located within the same upper crustal level, immediately above the brittle-ductile transition for quartz-rich rocks near the 300°C isotherm. The uplift of a 10-15 km thick sequence of crustal rocks, exhumed and eroded east of the FL, was achieved by movements along NE dipping reverse faults soling out near the late Cretaceous brittle-ductile transition zone for quartz-rich rocks (Figure 10). Even assuming a slightly elevated geothermal gradient during the stacking events, this indicates that the rocks drilled by KTB, and which crop out at the surface in the ZEV, were never located at levels deeper than ~9-10 km since the intrusion of the Variscan granite. In this depth interval, seismic reflection profiles show the presence of strong horizontal reflections east of the FL. This level coincides with a horizon of increased electrical conductivity [ELEKTB Group, this issue], probably enriched in graphite and sulfide minerals. The phases of compressional intraplate deformation resulted in upthrusting of upper crustal slices at NE dipping reverse faults. The most likely geometric model to explain the enormous

amount of localized supracrustal thickening and uplift is an antiformal stack, the frontal ramp of which corresponds to the Franconian Lineament.

Conclusion

The crustal structure encountered in the KTB drill hole turned out to be completely different from what was expected prior to drilling. Models based on surface geology, in combination with early interpretations of seismic profiles, had suggested a pile of nappes stacked in a Variscan suture zone. Whereas the post-Variscan displacement along the Franconian Lineament, which separates the basement of the Bohemian Massif from the Mesozoic sediments covering the Franconian platform, was clearly evident, the importance of faulting in the outcrop area of the basement was grossly underestimated.

In fact, from top to bottom, the KTB drill hole has encountered uniform amphibolite facies metamorphic rocks, which resided near the base of the upper crust in a temperature range of about $300 \pm 50^\circ\text{C}$ by the Carboniferous. During the Mesozoic, slices detached from this crustal horizon were piled up to form an antiformal stack. The fault systems sole out in a decollement horizon, which apparently was controlled by the brittle-plastic transition.

Some major fault zones identified in the drill hole are correlated with the approximate positions of seismic reflectors. Reflector SE1 links the fault zone drilled at a depth of ~7000 m the Franconian Lineament at the surface. As such, this fault dips

approximately 55° to the NE and presumably represents a reactivated wrench fault that developed during the Stephanian-Autunian phase of wrench faulting [Ziegler, 1990]. Reverse movements culminated during the latest Cretaceous and Paleocene deformation of the entire Bohemian Massif and the inversion of major tensional hanging wall basins along its norther periphery [Ziegler, 1995]. This concept is supported by both the age data and contemporaneous alluvial fan deposits in the foreland of the Bohemian Border Zone.

Apart from the marked late Cretaceous tectonic activity, a sequence of stages of brittle deformation has been identified, recorded by minor structures in the drill cores, as well as in basement and cover outcrops. Several reference systems allow to constrain the timing of these stages. The regional stress field has changed several times over this period, leading to creation and reactivation of fault sets of differing character and variable orientation.

A prominent stage of shortening of the upper crust by reverse faulting, in a manner similar to the late Cretaceous activity and above the same kind of detachment zone, occurred during the early Triassic. Likewise, this earlier Mesozoic tectonic activity is clearly recorded by alluvial fans in the foreland and the cooling age distribution in the drill hole. The titanite FT data clearly indicate that this event was not just part of a slower, continuous unroofing of the Bohemian massif but rather was a short-lived event in which some 2500 m of material was removed. Finally, minor block faulting accompanied stages of uplift during the late Oligocene/early Miocene, concomitant with widespread but localized basaltic volcanism [Todt and Lippolt, 1975] and again in the latest Neogene/early Quaternary.

The KTB deep drill hole has shed light onto the post-Variscan tectonic evolution of the Bohemian massif and revealed an unexpected structural evolution. Fission-track and K-Ar dating on samples from the drill hole turned out to be a very successful approach to unravel this evolution in combination with structural studies on fault rocks and fault-related mineralizations recovered by the drill hole. The tectonic activity is consistently reflected by the sedimentary record in the foreland. Finally, the annealing behaviour of fission tracks in titanite and zircon could be studied for the first time on a natural timescale. The effective closure temperatures turned out to be significantly higher than previously assumed.

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