The lithological profile of the KTB Hauptbohrung (7200 - 8729.7 m) Results from the KTB Field Laboratory

Kontny, A., Duyster, J., Grawinkel, A., Hoffmann, A., Kamm, C., Machon, L., Rauen, A., Röckel, Th., Spangenberg, E., de Wall, H., Winter, H.
(KTB-Feldlabor, Windischeschenbach)

1. Introduction

This contribution summarizes the lithological profile of the KTB Hauptbohrung for the depth interval 7200 to 8729.70 m and presents some observations of depth-related changes in mineralization and fabric. In this section two cores (H033 and H034) with a core recovery of 5 m (47%) were drilled.

1.1. Lithological units of the KTB boreholes

The lithological profile of the KTB Vorbohrung (VB) and KTB Hauptbohrung (HB) is composed of a succession of the following three main lithological units: paragneisses, metabasic rocks and variegated metavolcano-sedimentary series (HIRSCHMANN et al. this vol.). Paragneisses predominate in the upper part down to 3150 m whereas the depth intervals 269-303 m, 1183-1410 m and 3160-7260 m comprise mainly metabasic rocks. Variegated sequences of metavolcano-sedimentary rocks occur in the sections 290-552 m, 2384-2718 m and 7260-7794 m.

1.2. Structural data from borehole measurements

FMI (Formation MicroImager) logs down to a depth of 6000 m and FMS (Formation MicroScanner) logs down to 8620 m were run. Structural information from the borehole wall, especially data for the foliation and fault plane orientation were thus obtained.

According to the dip direction of the foliation, the KTB profile can be subdivided into three structural units:

0 - 3200 m:	**SW** and NE
3200 - 7260 m:	**E** and W
7260 - 8620 m:	SW

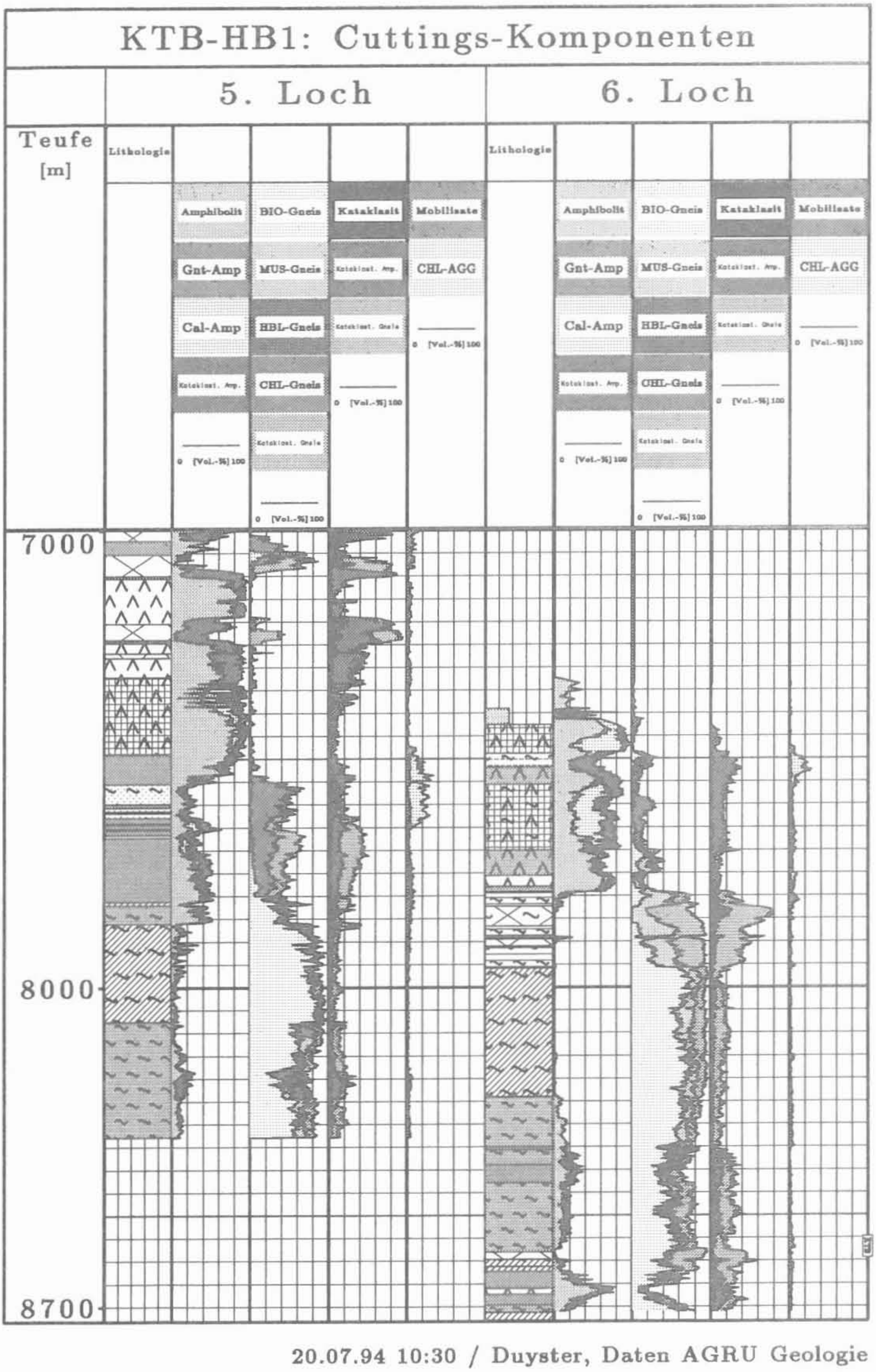
2. Results of geological, geochemical and geophysical investigations in the depth interval between 7200 and 8729.7 m

2.1. Lithological subdivision of the KTB Hauptbohrung (7200 - 8729.7 m)

This section is subdivided into the following units:

7200 - 7260 m:	metabasic sequence
7260 - 7900 m:	variegated metavolcano-sedimentary sequence
7900 - 8729.7 m:	paragneiss sequence

Figure 1 shows the lithological profile with the cuttings components of the drilled section. In the 12 ¼" drilling phase the drill hole was cemented and side tracked at 7440 m because of



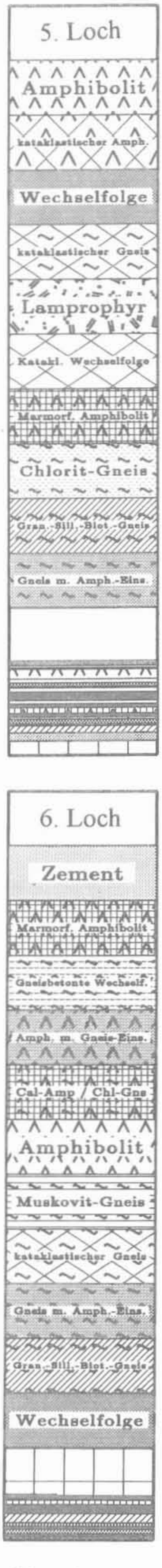


Fig. 1: Lithological profile of the depth interval 7000-8729.7 m with the cuttings components of the 5th and 6th borehole,

instabilities of the borehole wall. Therefore, for the section 7440-8320 m two profiles were obtained (Fig. 1). The physical rock properties (natural radioactivity, density, magnetic susceptibility and thermal conductivity) of both boreholes are plotted in Fig. 2. The most important geological difference between these two drill holes (5th and 6th) is an extraordinarily strong chloritization in the 5th hole. In the depth interval 7490 to 7650 m of the 5th drill hole the chloritization causes, in places, complete alteration of the amphibolites and paragneisses to chlorite felses and chlorite gneisses (see below). The chlorite content results in an anomaly in the thermal conductivity values (due to the high thermal conductivity of chlorite, 5.14 W/m/K) in the 5th hole.The decreased chlorite content in the 6th hole decreases the measured thermal conductivity. The rocks of the 6th drill hole are less altered and therefore, the following lithological subdivision relates to the less altered, 6th drill hole.

2.1.1. Metabasic sequence

Down to 7260 m an alternation of amphibolites and minor hornblende gneisses and biotite gneisses occur (DUYSTER et al. 1993). This sequence belongs to the subunit b5 (6540-7260 m; see HIRSCHMANN et al., this vol.). In this depth interval, between 6860 and 7260 m, the most prominent cataclastic fault bundle of the KTB profile was drilled. It is characterized by graphitized cataclasites, complex mineralisation and the intrusion of undeformed lamprophyric dykes. Seismic investigations detected a strong reflective zone (SE1) in this depth interval, which dips 50-60° to the NE. The prolongation of this fault zone to the surface is the Atzmannsberg-Altenparkstein fault, which belongs to the Franconian Lineament.

2.1.2. Variegated metavolcano-sedimentary sequence

From 7260 to 7900 m an alternation of metavolcanic and metasedimentary rocks occur. According to the different rock types, this sequence is divided into five subunits:

7260-7320 m:	strongly altered amphibolite with epidote
7320-7488 m:	marble-bearing amphibolite with epidote and magnetite
7488-7700 m:	alternation of partly strongly altered metasediments and metavolcanic rocks (chlorite gneisses, biotite gneisses, plagioclase-rich and zircon-rich gneisses with allanite, microcline-bearing and marble-bearing amphibolite);
7700-7794 m:	alternation of predominantly amphibolite with hornblende gneiss, sillimanite- and kyanite-bearing paragneisses

In this sequence, undeformed diorite occurs. In the KTB boreholes, dioritic rocks only occur in the variegated metavolcano-sedimentary sequence of the KTB-Vorbohrung down to 560 m.

The metavolcanic rocks of the variegated volcano-sedimentary sequences (alkaline type) differ geochemically from the metabasic rock sequences (enriched MORB type). The boundary between metabasic and metavolcano-sedimentary rocks at 7260 m is marked by a distinct increase of the P_2O_5-, Nb- and Zr contents (Fig. 2a und 2b). Especially, high Nb contents are typical for these alkaline source rocks (HOFFMANN, this vol.).

The upper boundary (Franconian Lineament) as well as the lower boundary of this unit is marked by graphite-rich and sulfide-rich cataclastic zones.

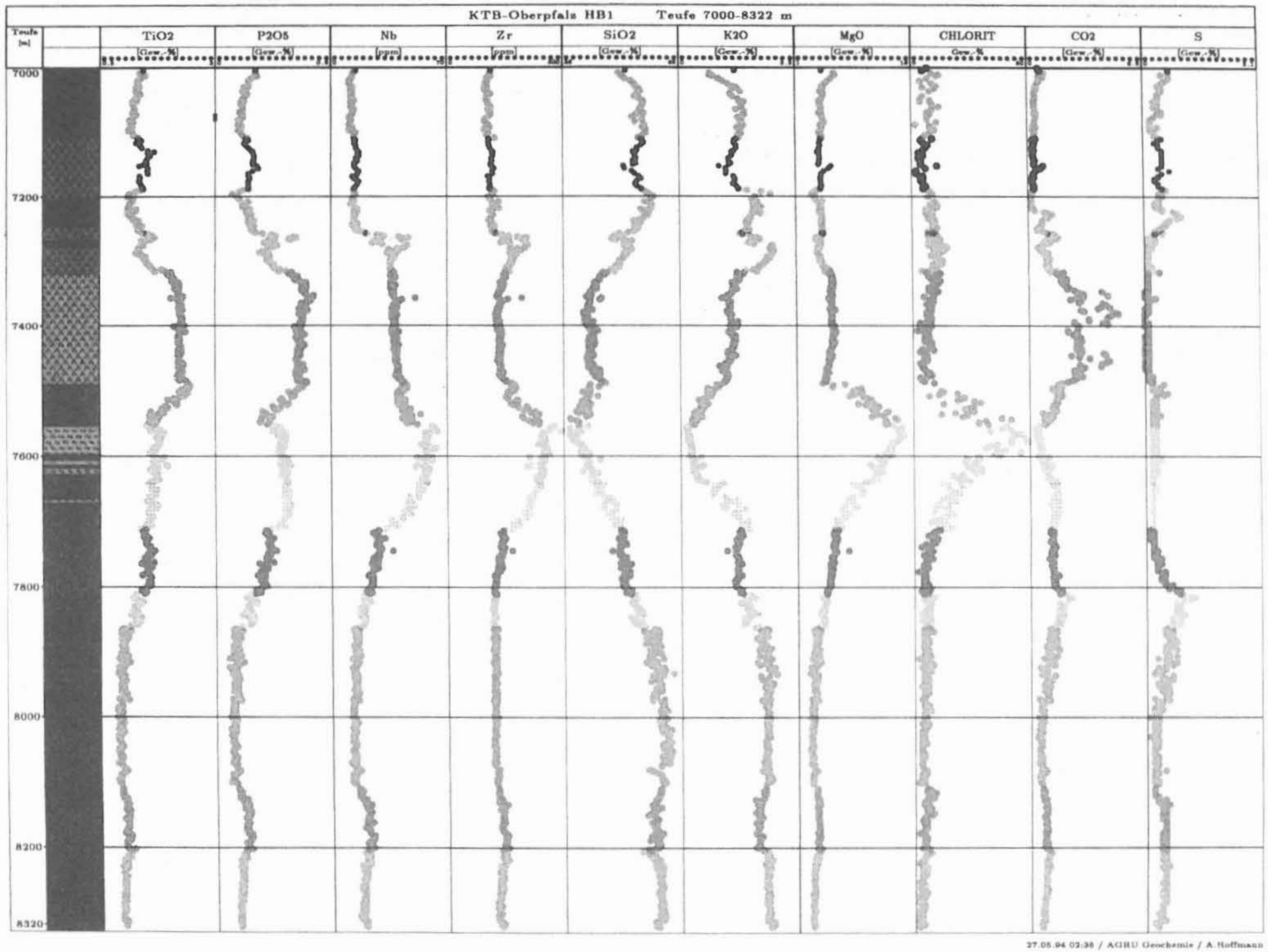


Fig. 2a: Variation of selected chemical components and the alteration specific parameter, chlorite, versus depth from the 5th borehole (lithology see text).

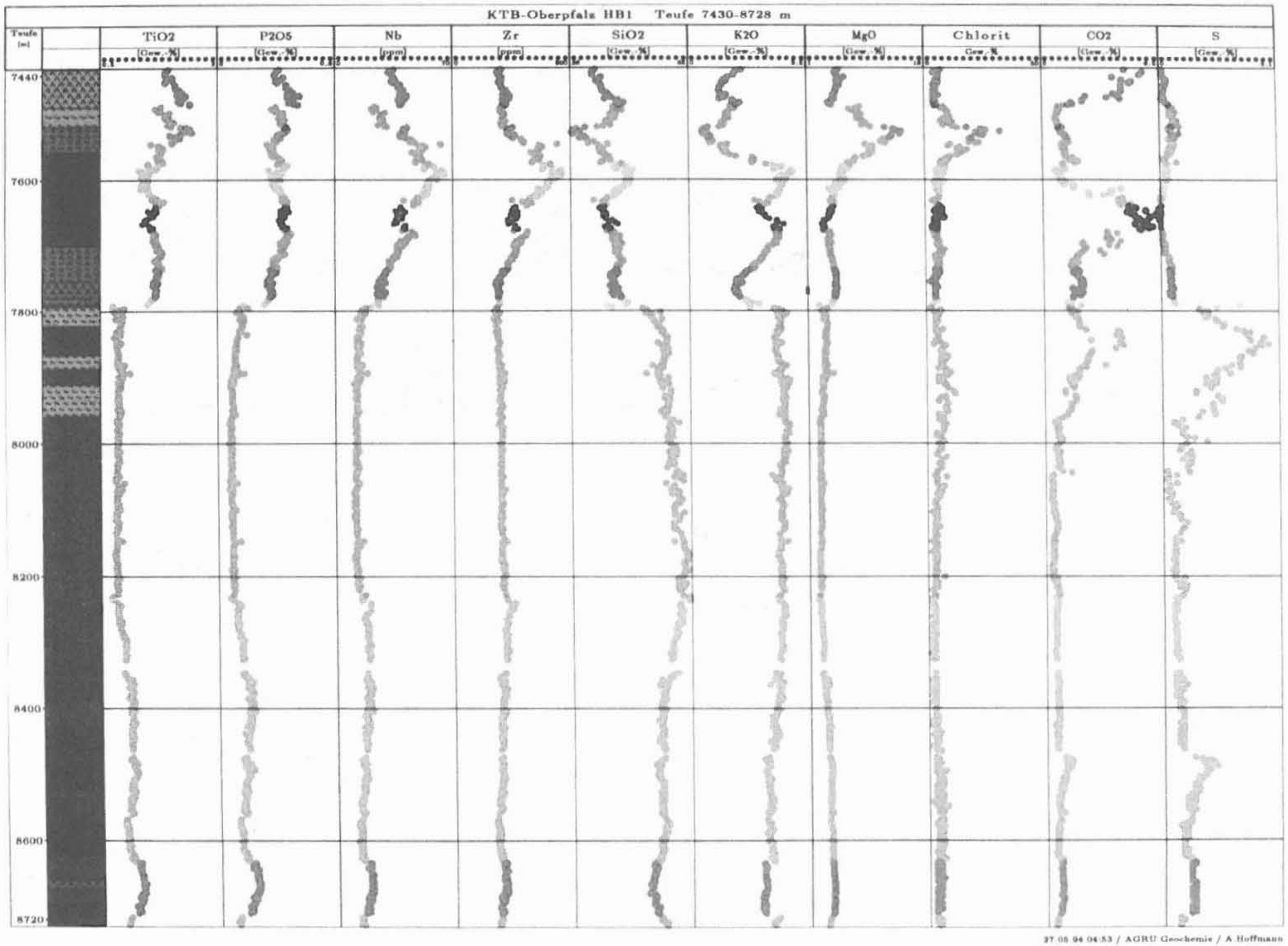


Fig. 2b: Variation of selected chemical components and the alteration specific parameter, chlorite, versus depth from the 6th borehole (lithology see text).

A large diameter core H033 ($9^{1}/_{4}$") with a core recovery of 3.05 m (65%) was drilled from 7400.30 to 7405 m depth. Fine grained amphibolite with calcsilicate and folded marble layers shows a steeply inclined foliation and a pronounced subhorizontal stretching lineation. A strong epidotization and numerous calcite fissures are obvious in places. The amphibolite-rich layers contain green hornblende, plagioclase, garnet (andradite), chlorite, titanite, Fe-Ti-oxides and minor quartz. In the calcsilicate layers clinopyroxene, plagioclase, epidote, clinozoisite, calcite, titanite, apatite, magnetite and few pyrite occur. Chemically this rock type is characterized by relatively low SiO_2 (44 wt-%) and high TiO_2 (2.7 wt-%), P_2O_5 (0.75 wt-%), Fe_2O_3t (13 wt-%), Zr (230 ppm) contents and significantly high Nb contents (42 ppm). The higher TiO_2 and Fe_2O_3t contents are in good agreement with a high amount of Fe-Ti oxides (locally up to 10 vol.-%). The marble-bearing amphibolite shows generally high densities and high values of magnetic susceptibility. Cuttings exhibit a maximum susceptibility of $90x10^{-3}$ SI in the 6th hole (Fig. 3) but, the highest value of magnetic susceptibility measured so far in the KTB boreholes ($181x10^{-3}$ SI, main axis of susceptibility tensor) came from a sample of the H033 core. This magnetic anomaly is caused by a high amount of magnetite (see KONTNY & DE WALL and de WALL et al. this vol.). In addition to magnetite, Fe^{3+}-rich ilmenite, Ti-rich hematite, rutile, pyrite, chalcopyrite and a little bornite and chalcocite are seen. The ore mineral paragenesis in the marble-bearing amphibolites points to more oxidizing conditions whereas the paragenesis ilmenite-pyrrhotite, usually occurring in the metabasic rocks, reflects more reducing conditions.

2.1.3. Paragneiss sequence

In the depth interval between 7794 and 8240 m garnet-sillimanite-biotite gneisses and chlorite-muscovite gneisses occur. Below 8240 m the paragneisses show intercalations of hornblende gneisses and amphibolites. The paragneisses are still typical ZEV paragneisses. The amphibolites tend to have an alkaline geochemical character. In the "mixed" cuttings analyses, the intercalations are visible by an increase of Nb, P_2O_5 and TiO_2 contents. The ore mineral paragenesis (Pyrrhotite, pyrite, chalcopyrite, rutile, ilmenite and graphite) is comparable to that of the upper gneiss series. However, pyrrhotite occurs more often in its antiferromagnetic, hexagonal modification. The occurrance of pyrite decreases significantly below about 8100 m.

From 8079.1 to 8085.1 m depth the core H034 with a core recovery of 1.95 m (33%) was drilled with a roller cone core bit (4"). The weakly altered garnet-(sillimanite)-biotite gneiss alternates with fine intercalations of amphibolite. Sulfide mineralization, mainly pyrrhotite, occur on fault planes. Although the pyrrhotite content of the rocks is relatively high (locally up to 4 vol.%), there is no anomalous magnetic susceptibility (see Fig. in FÜRNROHR et al., this vol.). Mainly, the antiferromagnetic, hexagonal modification of pyrrhotite was observed. Further ore minerals are graphite, pyrite, ilmenite, rutile/anatase and some chalcopyrite.

2.2. Fault zones

Fault zones were determined by mapping the amount of cataclastically-overprinted cuttings. Prominent fault zones in the KTB are often characterized by fluid influxes and / or a higher sulfide mineral and graphite content. The electronic conductivity of sulfides and graphite and additionally the electrolytic conductivity of saline fluid influxes reduce the measured electrical

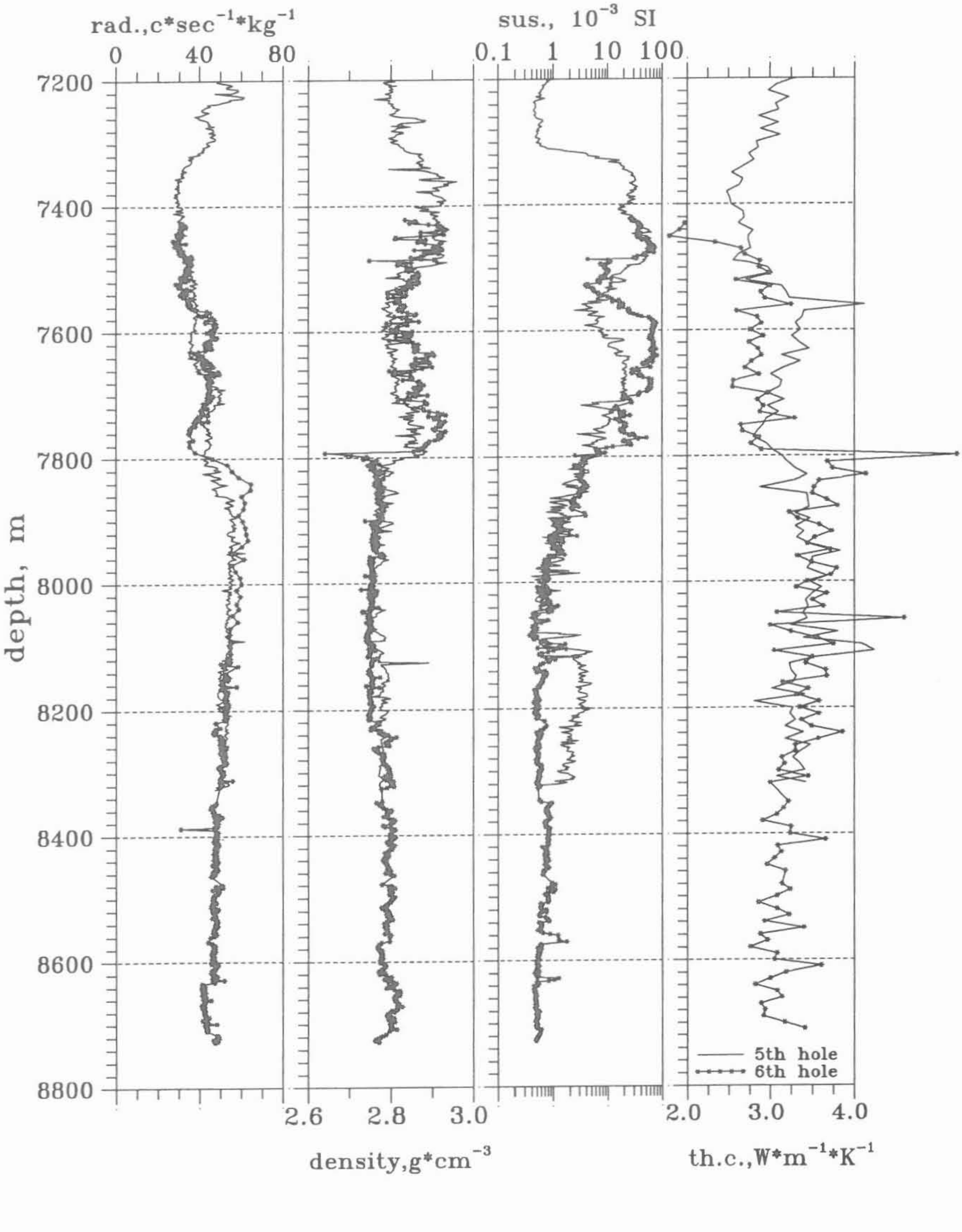


Fig. 3: Results of petrophysical investigations on cuttings from the 5th and 6th borehole. From left to right: natural gamma ray activity (total counts), density, magnetic susceptibility, thermal conductivity.

resistivity. Therefore, geoelectrical borehole measurements are a suitable method for the detection of fault zones. The good correlation between geoelectrical borehole measurements and the occurrence of higher graphite and sulfide contents as well as fluid influxes is shown in WINTER et al. (this vol.). The low resistivity in the fault zone at 7000 m and in the deeper fault zones is mainly caused by electronic conductors (sulfides and graphite).

Below the prominent fault zone between 6680 and 7260 m (SE1), which dips toward NE with an inclination of 50-60°, fault zones with cataclasis as well as graphite- and sulfide-mineralization were also observed e.g. in the depth interval 7820-7950 m and 8580-8610 m.

2.3. Chlorite zone

The variegated metavolcano-sedimentary rock sequence is strongly altered between 7490 and 7650 m (5th drill hole). The alteration causes a strong chloritization of the gneisses and amphibolites which results in the formation of chlorite gneisses and chlorite felses. The chloritization of this zone is accompanied by a distinct depletion of alkaline elements, Rb, Sr and SiO_2 and a remarkable enrichment of MgO (Fig. 2a and 2b). The chlorite content of this zone, estimated from XRD bulk analyses, reaches up to 50 wt-% and the H_2O content up to 7.5 wt-%.

In the chlorite gneisses and chlorite felses different types of chlorite are found. Whereas in the chlorite gneisses intermediate chlorites with Fe/(Fe+Mg+Mn)-ratios of 0.53 (type 1) predominate, in the chlorite felses two Mg-rich chlorites occur (Fe/(Fe+Mg+Mn)-ratios of 0.42, type 2, and 0.24, type 3).

Chlorite of types 1 and 2 forms pseudomorphs after biotite and amphiboles in the gneisses and amphibolites, has titanite on cleavage planes and MnO contents of 0.6 wt-% (type 1) and 0.7 .wt-% (type 2). However, the Mg-rich chlorite (type 3) with low Mn contents is a newly formed phase from hydrothermal fluids. Microscopically it is characterized by an irregular fabric.

The following characteristics can be deduced for an alteration fluid, causing the strong chloritization observed in the depth interval 7490-7650 m:

- an alkaline character because of the dissolution of SiO_2
- supply of Mg (derived from nearby serpentinization of ultramafic rocks, fluids or marble?)
- oxidizing conditions are indicated by the chlorite chemistry and ore mineral paragenesis (new formation of pyrite and hematite)
- calculations of chlorite formation temperatures yield 270-300°C (from thermodynamic modell of WALSHE 1986) and 320-330°C (from empiric Al^{IV}-thermometer of CATHELINEAU 1988).

2.4. Fluid influxes

Fluid influxes were detected down to the bottom of the KTB Hauptbohrung. The strongest influxes were detected at the following depths:

depth	fluids	lithological situation
7010 m:	He, CH_4, Cl^-	boundary cataclastic amphibolite to cataclastic gneiss, alternating with amphibolite
7544 m	He, CH_4	boundary gneiss/amphibolite alternation to chlorite gneiss
7725-7790 m:	He, CH_4, Cl^-	amphibolite with intercalations of gneiss
7812 m, 7848 m:	He, CH_4	graphitized fault zone in paragneisses (hydrocarbon-rich)
8657 m:	He, CH_4, Cl^-	amphibolites in cataclastic alternation

All chloride-bearing zones were accompanied by enrichments of helium and methane.

The character of the fluids seems to be strongly influenced by the wall rock.

Generally, in the KTB boreholes three different types of fluid influxes were discriminated according to the He/CH_4-ratio (MACHON & KAMM, this vol.):

- influxes in gneisses and amphibolites
- influxes in marble-bearing amphibolites
- hydrocarbon-rich influxes in graphitized fault zones in paragneisses

The He/CH_4 ratio of fluid influxes in gneisses and amphibolites correlates with the uranium and thorium content of these rocks. This corresponds to the mostly (about 97 %) radiogenic origin of ^{4}He (WEISE 1991).

Influxes in marble-bearing amphibolites are characterised by low CH_4-contents due to conditions favoring more oxidation (KONTNY, this vol.).

Contrary influxes in strongly graphitized fault zones in Paragneisses are extraordinary rich in CH_4. Different to all other influxes they are not accompanied by saline waters.

2.5. Depth dependent variations: mineralization and quartz fabrics

At a maximum depth of 8729.7 m an overburden pressure of about 2.4 kbar and in situ-temperatures of about 260°C occur. Therefore, changes in vein mineralization and in the quartz fabrics should be obvious.

2.5.1. Vein mineralization

Vein mineralization under prehnite-actinolite facies conditions can be traced down to 7500 m depth. Prehnite dominates down to 7260 m and then down to 7500 m it occurs only in minor amounts before it disappears entirely (Fig. 4). BORCHARDT & EMMERMANN (1993) report only one single finding of pumpellyite at 5012 m. In the deepest part of the drilled section, mostly plagioclase, epidote and actinolite was observed (ZULAUF & DE WALL, this volume).

Mineralization under prehnite-actinolite facies conditions indicates an elevated geothermal gradient (about 40°/km) and is restricted to a pressure of <2 kbar (LIOU et al. 1987). At a geothermal gradient of 50 C°/km, for example, it should occur only between depths of 1.3 and

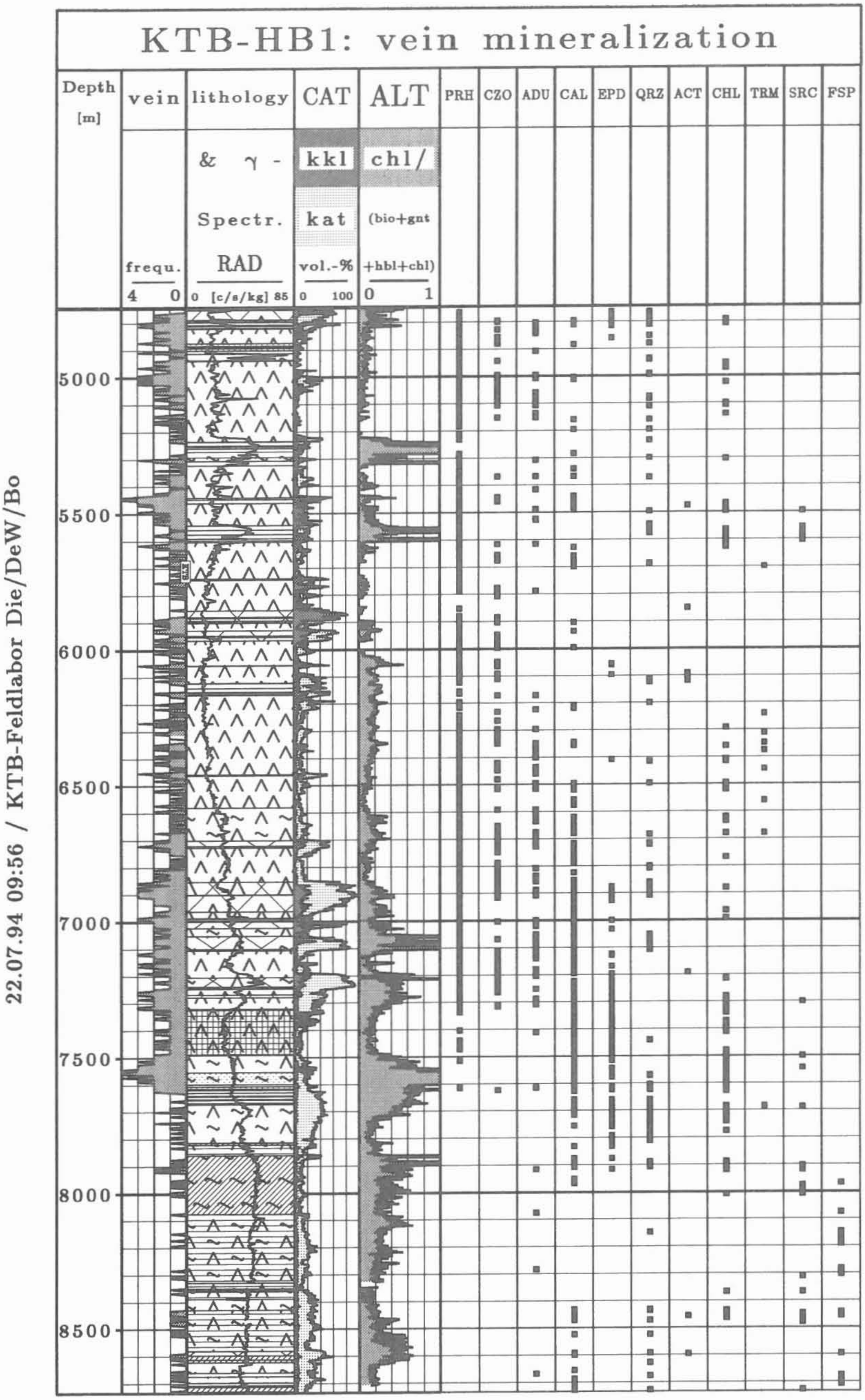


Fig. 4: Vein mineralization in the depth interval 4800 - 8729.7 m (CAT: amount of cataclastic overprinted rock, ALT: degree of alteration (Chl/(bio+gnt+hbl+chl), PRH: prehnite, CZO: clinozoisite, ADU: adularia, EPD: epidote, QRZ: quartz, ACT: actinolite, CHL: chlorite, TRM: tourmaline, SRC: seicite, FSP: feldspar.

2.0 kbar. However, in the KTB main hole mineralization under prehnite-actinolite facies conditions was observed down to 7500 m.

The abundance of fissures decreases dramatically below 7600 m. This part of the profile consists mainly of paragneisses, alternating with amphibolites and hornblende gneisses. The observed fissures are mostly related to the intercalated amphibolites.

2.5.2. Quartz fabrics

In post variscan times the drilled profile was extensively faulted. Cataclastic shear zones are widespread throughout the whole profile. The brittle-ductile transition for quartz is expected to take place at temperatures of about 300° for deformation under natural strain rates. Therefore, quartz deformation fabrics in cuttings where mapped in order to detect depth dependant variations.

No gradients regarding quartz deformation fabrics could be observed down to 7500 m. Brittle and brittle-ductile fabrics occur together. Below 7500 m, brittle features such as tectonic breccia and fractures in quartz diminish, probably due to elevated temperatures.

From cuttings microscopy alone it is not possible to decide about the age of a shear zone. According to ZULAUF (1991) graphite bearing shear zones have formed in upper carboniferous times. At 7011 m depth (core H031), graphite bearing shear zones with brittle and brittle-ductile quartz deformation fabrics where observed. In graphite bearing shear zones at 8500 m depth, quartz behaved ductily. DUYSTER & ZULAUF (this vol.) present these results in more detail.

The lack of gradients regarding quartz deformation down to 7500 m is in agreement with the observations derived from vein and fissure mineralisation (ZULAUF & DE WALL, this vol.). This could be explained by supracrustal stacking (ZULAUF et al., this vol.).

3. Summary

The lithological profile between 7200 and 8729.3 m, one of the most interesting sequences drilled so far, can be subdivided into three sections: (1) metabasic rocks with intercalations of hornblende gneiss and biotite gneiss, (2) a variegated metavolcano-sedimentary sequence with different amphibolites and paragneisses and (3) a paragneiss sequence with minor intercalations of amphibolites.

In the depth interval between 6860 and 7260 m the KTB Hauptbohrung drilled through a prominent reverse fault with a displacement of several km. This fault zone was also detected by seismic investigations and belongs to the Franconian Lineament.

Below this fault zone, a variegated metavolcano-sedimentary sequence occurs which is similar to the variegated sequence in the uppermost part of the KTB Vorbohrung down to 560 m. The metavolcanic rocks of the variegated volcano-sedimentary sequence, characterized by a key rock - marble-bearing amphibolite of alkaline type - differ geochemically from the metabasic rock sequences (enriched MORB type).

The marble bearing amphibolites show the highest susceptibility, measured in the KTB Hauptbohrung. This magnetic anomaly is caused by a high amount of magnetite.

No gradients regarding vein mineralization under prehnite-actinolite facies conditions and quartz deformation fabrics could be observed down to 7500 m. Brittle and brittle-ductile fabrics occur together. Below 7500 m, brittle features such as tectonic breccia and fractures in quartz diminish, probably due to elevated temperatures.

An extremly strong chloritization, which transformed gneisses and amphibolites into chlorite gneisses and chlorite felses occurs between 7490 and 7650 m. An alkaline, Mg-bearing and oxidizing alteration fluid is assumed to cause the strong alteration.

Fluid influxes, detected by helium, methane and chloride, were observed down to the bottom of the borehole. The character of the recent fluids seems to be strongly influenced by the wall rock.

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