Characteristics of fluid inclusions and their relationship with saline water and gases in crystalline rocks

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One of the major objectives of fluid inclusion (FI) investigations in the KTB was to study the depth-dependent evolution of fluid systems. Due to the steeply inclinaed structure it is most unlikely that one can observe higher metamorphic conditions preserved by FI in the critical mineral assemblages of gneisses and metabasites increasing with depth. The only fluids which reflect a depth dependent evolution are Ca-Na-Cl fluids formed after tilting the rock series to a subvertical position during younger alteration stages under greenschist facies conditions.

Review of PTt-dependent evolution of fluid systems

In general three major systems can be distinguished:
- low saline FI occuring over the entire drilled depth range
- gaseous FI in the CO_2-CH_4-N_2 system
- moderate to high saline Ca-Na-Cl FI up to NaCl saturation (sometimes containing additionally KCl or $MgCO_3$ as daughter mineral).

Especially gaseous and Ca-Na-Cl inclusions are well suited for reconstruction of the evolution of different fluid systems which can be correlated with distinct stages of the tectonometamorphic history (fig. 1).

Relictic **N_2- and N_2-CO_2-rich FI** were formed during **crustal compression and transpression** under amphibolite facies metamorphic conditions. They are restricted to local occurences in plag-qtz mobilisates within gt-sil-bio gneisses.
N_2-rich fluids appear to be characteristic for higher grade metamorphism, similar to other occurences e.g. in the Münchberg gneiss massif (s. REUTEL 1992, KLEMD et al. 1991). They were partly found in close connection with eclogite facies rocks (KLEMD et al. 1991).

The next group of gaseous FI **(CO_2-CH_4+/-N_2)** can be correlated at least with the graphite cataclasis at the end of **crustal transpression** and the **beginning of crustal extension.**
Refering to graphite crystallinity studies by Laser Raman microprobe it can be demonstrated that graphite deposition in the cataclastic zones must have been occured over a considerable temperature range of about > 500 °C to < 300 °C.

The last stage at which gaseous FI can be proved is connected with **crustal extension** formed after steepening of the metamorphites and the intrusion of the Upper Carboniferous granites. The fluids can be characterized as **CH_4-N_2-mixtures** which reveal a distinct compositional relationship with gases of free fluids encountered in the KTB pilot hole. They are genetically linked with **highly saline Ca-Na-Cl** bearing inclusions (basement brines).

Ca-Na-Cl FI show characterisic features by which they can be well distinguished from all the previous systems:

- due to their occurence in young mineralisation and in undeformed quartz, sometimes aligned along rhombohedral cleavage planes, they strongly suggest a younger origion. They are the only FI which can undoubte be classified as primary.
- in older quartz grains they are often restricted to secondary inclusion trails which sometimes transect grain boundaries. In the SEM-Cl images these FI can be correlated with dark channelway structures crosscutting CL-contrasts of older FI.

Depth-dependent evolution of fluid systems

In view of a depth-dependent control of formation conditions most of the fluid inventory of the drilling seems to be less expressive than the highly saline FI.
For these Ca-Na-Cl FI the following can be stated:

- increase of inclusion size with depth with an average of 8-10 µm and 20-40 µm for the upper and lower section respectively (Fig. 2-3). From the analysis of SEM-image we know that the mean values of open pores occuring in channelway structures of crystalline rocks of the Variscan basement now found at surface exposures are in the range of 4-6 µm.
- a trend of increasing salinities and Ca/Na-ratios with depth. At depth below ca. 3600 m the first FI containing NaCl and KCl daughter minerals can be observed. Investigations on FI in samples at a depth of 8060 m show that these highly saline fluids occur as secondary inclusions along twinning lamellae of altered plagioclase as well (fig. 4-5).
- decreasing variation of homogenization temperatures of Ca-Na-Cl FI with depth (fig. 6). In the upper section down to a depth of about 4 km Th-values vary over a large range between 100 °C and >350 °C. Below this depth the variations become less pronounced until in the depth range of ca. 5-8 km only small variations have been observed.
- none of the FI can be correlated with the recent geothermal gradient whitch can be infered from the curves in Fig. 6 showing the expected Th-values for FI trapped along a geothermal gradient of 28 °C/km. Thimplies a formation of FI during an earlier event at greater depth and/or a higher geothermal gradient.

Trying to explain the depth-dependent trend of variation of Th data and the increase of inclusion size we have to consider two aspects:

the cataclastic overprint and the uplift history.

Because variation is observed in cataclastic and non-cataclastic rocks as well it seems to be more likely that the uplift history is mainly responsible for the large variation.

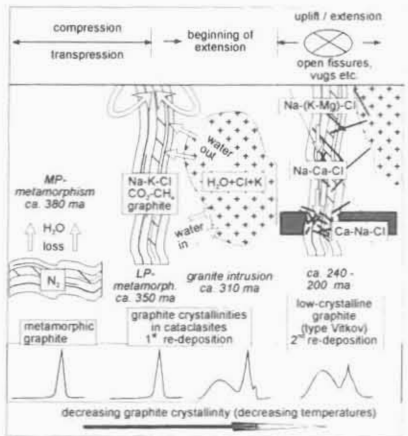

Fig. 1: Tectonometamorphic characteristics of the fluid evolution in the KTB

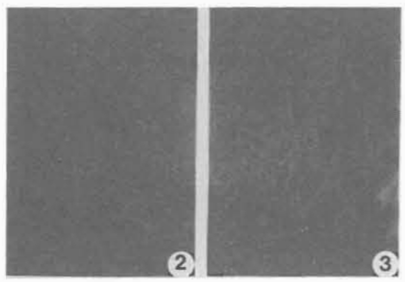

Fig. 2: Fluid inclusions (8-10 µm) in quartz grains, KTB HB 2000 m

Fig. 3: High saline FI's (20-40 µm) with daughter minerals in quartz grains, KTB HB 7956 m

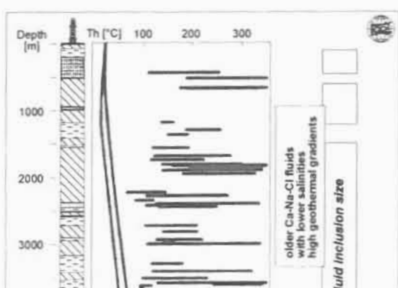

Fig. 6: Depth dependent features of saline Ca-Na-Cl bearing inclusions (for explanation see text)

Based on experimental studies (a.o. BODNAR et al. 1989, STERNER & BODNAR 1989) it is well known that an uplift trajectory which deviates from the isochore position to a certain extent may lead to decrepitation of FI due to internal over- or underpressures. WALTHER & ALTHAUS (1986) already discussed such mechanisms theoretically for the re-equilibration of metamorphic FI in the Black Forest.

Decrepitation of FI is mainly controlled by their size and the chemistry of the entrapped fluid: larger FI decrepitate first, highly saline FI are more susceptible to post-entrapment modifications.

With regard to the above implications we can interprete the observations in terms of implosion phenomena and reconstruct the **evolution of Ca-Na-Cl rich FIs**:

- for **FI in the upper section** we have to assume that they were entrapped under a higher geothermal gradient. This propably happened during exhumation of the U'Carboniferous granites and surrounding metamorphic rocks which reach the erosion level at least in the Rotliegend.
- the lower salinities in this drilled section can be explained by a lack of salinar formations at this time.
- the combination of uplift motion and decreasing geothermal gradients up to now leads to **strong implosion and subsequent re-equilibration** of these older group of saline fluids **causing a lowering of Th values**.
  this assumption is also supported by the smaller FI sizes. By experimental investigations on synthetic and natural FI VITYK & BODNAR (1994) could demonstrate that FI exposed to conditions of **internal underpressure** reveal **re-equilibration features** which **are inversely proportional to the FI size.**
- **FI in the lower section show no or only little decrepitation features** (large inclusion sizes and small ranges of Th values are preserved). Thus it follows that they were not subjected to dramatical internal pressure differences.
  according to the empirical formula of BODNAR et al. (1989) FI with sizes of 20-40 µm should decripitate at differential pressures of about 0.9-1.2 kbar corresponding to depth of ca. 3-4 km. This is in the range of the Createceous uplift rate (JAKOBS & WAGNER 1993).
- as a result of the stability considerations FI in samples of 8060 m should have been entrapped at conditions not exceeding temperatures more than ca. 350 °C and depth of ca. 12 km.

In summary the results demonstrate long term activity of Ca-Na-Cl brines. Early formed FI of this system were subjected to strong post entrapment alteration and therefore the primary PVT information was obliterated while younger FI preserved their original formation conditions.
However by implosion characteristics, combined with microthermometric and other geological information the PT history can be delimited.
FI found in the section down to ca. 4 km were formed during a period of high uplift rates and high geothermal gradients. FI at depth of 6-8 km were entrapped under conditions of crustal extension and much lower geothermal gradients. The higher salinities in these fluids give evidence of the increasing influence of subsiding residual brines of the Zechstein and formation waters, infiltrated along tension and shear zones of the crystalline basement.

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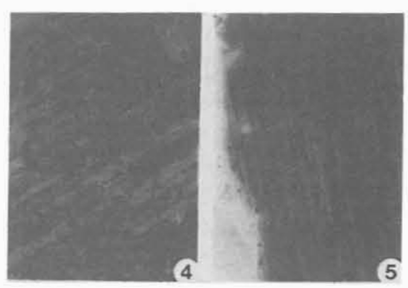

Fig. 4: Blue-green luminescent plagioclase, KTB HB 8080 m

Fig. 5: High saline FI's along twinning lamellae in plagioclase, KTB HB 8060 m