Light Microscopy and X-Ray Microanalysis of Inclusion Phases in Magmatic Minerals

Robert Sturm, Elsbethen, Salzburg, Austria

INTRODUCTION
From a mineralogical point of view, inclusion phases embrace each kind of foreign substance of a gaseous, liquid, or rigid nature that is enclosed in a crystal. In principle, two main categories of inclusion phases can be distinguished: primary inclusions, which are formed during the crystallisation process of the host mineral, and secondary inclusions, whose formation commonly takes place after completion of host mineral growth (Figure 1) [1-4]. Well-known examples of primary inclusions are insects and plant fragments occurring in amber and various mineral components occurring in certain gem stones and thereby providing some information on their provenance and economic value [5-7]. In most cases, primary inclusions are older than the surrounding mineral phase, a phenomenon called ‘Hutton’s law’ in mineralogical science [1].

An extraordinary group of inclusion phases is represented by the so-called ‘fluid inclusions’ that obtain superior significance in those growth milieus where host minerals crystallise from a liquid (e.g., magmatic) or hydrous source. During crystal development small compartments filled with one or more fluid phases are automatically incorporated into the crystal structure or penetrate into fractures of the host mineral that subsequently heal [1,2]. In crystals emerging from igneous sources, fluid inclusions, among others, provide essential information on the fluid content of the magmatic medium and the approximate temperature under which crystallisation took place [1,3,4].

Besides their mineral and fluid inclusion content, magmatic crystals are commonly characterised by a third group of inclusion phases, that is the melt inclusions. In this specific case, magmatic melt is directly incorporated in the host mineral where it crystallises into either an opaque or perspicuous glass phase [4]. The development of melt inclusions is chiefly restricted to crystals that are either formed during advanced stages of granitisation or mainly occur in the matrix filling the space between the main mineral components of the rock. This specific inclusion type has an extraordinary petrogenetic value, because it contains significant information regarding the original chemical composition of the source magma and thus can be used for solving respective petrogenetic problems [1,4].

Accessory zircon is an outstanding igneous mineral and can be used to provide spectacular microscopical presentations of various inclusion phases in magmatic crystals. This mineral phase is more or less an important constituent of plutonic rocks and is reputed to be a preferential mineralogical research object due to its high resistance to any mechanical and chemical influences [8,9].

In this article, inclusion phases incorporated into accessory zircon from granites and gneisses of the Bohemian Massif were subjected to a detailed microscopical and microanalytical description by applying a wide spectrum of appropriate scientific techniques. To complete this demonstration of inclusion phases in magmatic minerals, microscopical data of K-feldspar are also provided.

Figure 1:
Formation of primary (a) and secondary (b) fluid inclusions. Regarding primary inclusions, respective material may be incorporated in the crystal structure during each stage of crystal growth, resulting in different inclusion generations [2-4]. Concerning secondary inclusions, a crystal fracture is filled with magmatic or hydrous liquid (b1). During the healing process (b2, b3), cavities are filled with recrystallised host material again, leading to the formation of small compartments, where the captured fluids partly undergo a regular crystallisation (b4) [1].
MATERIALS AND METHODS

Specimen Preparation
For the investigation of various inclusion phases in accessory zircon, crystals of this mineral phase were separated by crushing and sieving approximately 500-1000 g of the granite and gneiss samples and submitting the crushed material to a magnetic and heavy-liquid separation. About 150-200 grains of the obtained mineral fractions were transferred onto a glass slide (45/1100322 mm²) and embedded in Canada balsam.

For a more detailed documentation of mineral inclusions in zircon, 20-30 pre-selected crystals were embedded in epoxy resin and subsequently polished, thereby applying a well-defined preparation technique [8, 9].

Investigation of possible inclusion phases in the main mineral components of the granites and gneisses was carried out by the production of thin sections (thickness ~35 µm) containing the host minerals of interest.

Light Microscopy
Samples were photographed on a Leica Laborlux polarization light microscope that was appropriately equipped for petrographic investigations. The samples were observed and photographed using transmitted light in brightfield mode. Images were recorded on an integrated Sony digital camera.

Electron Microprobe X-Ray Microanalysis
Zircon sections were studied using a JEOL JXA-8600 microprobe at the former Institute of Geology and Palaeontology, University of Salzburg. Photography of respective inclusions was carried out in the backscattered electron imaging (BSEI) mode using the following settings: accelerating voltage 15 kV, beam current...
EMPA the chemical composition of melt inclusions could also be detected by LM. According to high number of inclusions, single melt inclusions was very similar to that of the surrounding minerals, thereby chiefly containing ZrSiO₄. Additionally, inclusions of quartz (SiO₂), K-feldspar (KAlSi₃O₈), plagioclase (CaAl₂Si₂O₈), and biotite (K(Mg, Fe)₃[(OH)₂AlSi₃O₁₀]) could be detected in several zircon grains. The size of the crystal inclusions was subject to high variability; for example, crystals with a length or diameter of few micrometers occurred together with other crystals which nearly reached the dimension of their host minerals (Figure 2). The main inclusion minerals were characterised by an idiomorphic shape and a more or less random intra-crystalline orientation.

As shown in Figure 3, another important category of inclusion phases occurring in accessory zircon embraced the melt inclusions. These inclusions were marked by a non-polygonal, spherical appearance, thereby showing a similar size variability as the crystal inclusions. Besides the observation of sectors containing a high number of inclusions, single melt inclusions with remarkably increased size (Figure 3b) could also be detected by LM. According to EMPA the chemical composition of melt inclusions was very similar to that of the surrounding crystal, thereby chiefly containing ZrSiO₄ and an impressive spectrum of so-called incompatible elements (U, Th, Hf and rare earth elements). For abbreviations see Figures 1 and 2. Scale bars: 50 µm in a–c; 20 µm in d–f.

Fluid inclusions incorporated in accessory zircon often occurred together with melt inclusions and could be fairly easily determined due to their specific appearance under the LM, indicating the co-existence of two fluid phases (Figures 3 and 4). This category of inclusions was characterised by small to intermediate sizes and perfectly spherical shapes. Essential fluid components were determinable by Raman spectroscopy (Figure 6), which showed major peaks at 1378 cm⁻¹, indicating the existence of CO₂ and at 3455 cm⁻¹, representing the respective line for H₂O. Water had a much higher significance than carbon dioxide, a circumstance, however, which is frequently observed for fluid inclusions in HT/HP minerals like the accessory zircon in this study.

Another mineral with a highly interesting content of inclusion phases was represented by K-feldspar (Figure 5). This mineral phase exclusively contained crystal inclusions, of which quartz, biotite, plagioclase, and ilmenite occurred at highest frequency. These inclusions were mostly formed during feldspar crystallisation from the magmatic source. Another category of inclusions (e.g. sillimanite) was produced during a subsequent metamorphic event overprinting the granitic rocks. Hence K-feldspar plays a major role as a host mineral, within which magmatic inclusion phases may coexist with metamorphic inclusion phases.

CONCLUSIONS
From the results presented here it can be concluded that magmatic minerals occurring in granites and gneises of the Bohemian Massif are partly characterised by a high number of different inclusion phases. The most spectacular primary as well as secondary inclusions may be found in accessory zircon, whereby incorporated mineral phases chiefly embrace apatite, zircon, rutile, and biotite, whilst fluid inclusions, amounting to only several micrometres in size, commonly consisted of the two phases H₂O and CO₂, which was found by Raman spectroscopy. Melt inclusions in accessory zircon may occupy a remarkable volume of the crystal structure. Based on EMPA they are mainly composed of amorphous forms of ZrSiO₄ enriched with various incompatible elements.

As underlined by light microscopy major mineral constituents such as K-feldspar mainly
incorporate mineral phases of the surrounding matrix during their crystallisation process, leading to a wide spectrum of mineral inclusions that can be used for the detailed investigation of magmatic crystallisation sequences. This and many other questions will be a main objective of future efforts.

REFERENCES

1. Roedder, E. Fluid inclusions: an introduction to studies of all types of fluid inclusions, gas, liquid, or melt, trapped in material from earth and space, and their application to the understanding of geologic processes. Mineralogical Society of America (MSA), Washington, 1984.