Applications of μCT in metamorphic and igneous petrology

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Aims

μCT now forms an integral part of our research in geosciences at the University of Lausanne (Switzerland). Here we would present some examples, which highlight in exemplary fashion our use of μCT in metamorphic and igneous petrology. Quantitative applications are regularly pursued to understand the growth of minerals in rocks due to changing pressure and temperature conditions while they are cycled through the earth's crust. We now mostly use μCT imaging to guide us in the choice of the locations in rocks to use with highly expensive high resolution analytical studies such as laser ablation ICP-MS elemental analysis or other advanced chemical and structural analyses.

Method

Our first machine was a Skyscan© 1072 system, which is still fully functional, but most acquisitions are now done using the Skyscan©1173 we bought in 2009 Its higher energy X-rays, and the powerful, large scale CCD is better suited for petrologic studies, because it allows to scan larger volumes of rocks with shorter image acquisition (we use scan times from 20 minutes to 20 hours depending on scope and material of the research) at a higher resolution for most samples sizes. We are an open facility and we analyses are large range of geological materials from corals to ore minerals, with occasional services in material sciences or gemology.
For reconstruction, image analysis and 3D visualization we used the Skyscan© package, for grain size analysis the geological software BLOB 3D (Ketcham 2005a, University of Texas at Austin) as well as software developed at Lausanne using the APHELION© image analysis environment.

Results

Quantitative μCT analysis: Over the last 10 years there has been a concerted effort in petrology to read the "forensic" information on the history of rocks which is contained in their fabric, e.g. crystal forms, their distribution, and their mechanical deformation. The spatial distribution of minerals, their shape and size result from the interaction of nucleation, growth, reaction, and deformation. Looking at crystal size distributions (CSD) we try to better understand and quantify these processes. The determination of CSDs became fast one of the major applications of CT in petrology, especially in regional metamorphism or igneous petrology (similar to bubble size distributions). The study of Müller et al. (2009) from the Adamello Massif (Italy) was one of the first studies to apply CSD to a mineralization driven by fluid infiltration. This work combines measured CSDs of (brucite-bearing) marbles with geochemical data to evaluate the reaction kinetics of the formations of periclase (MgO) – an index mineral in contact-metamorphism.

When magma flows – either at depth or at the surface – minerals often are aligned in flow direction. These sometimes very weak orientations are difficult to establish in the field, so that alternative methods are used, such as the anisotropy of magnetic susceptibility (AMS). Interpretation of such fabrics are difficult, since shape of minerals (it is the shape alignment that indicates flow direction) and magnetic response are not easily linked. It is here that we

showed in a study of Torres del Paine granites (Patagonia, Chile) with μCT imaging, that these measurements do indeed agree well with shape orientations of magnetic minerals such as biotite (a sheet silicate) and trails of iron-titanium oxides (Tuckermann et al. in prep). Directional analysis of the minerals was completed using Quant3D (Ketcham, 2005b)

μCT imagery interpretation: μCT is an important tool for reconnaissance imaging of samples to decide on the cut and section for advanced geochemical analysis (electron microprobe, ion-microprobe, laser ICP-MS). This involves locating morphological crystal centrals, but also locating individual fluid and solid inclusions in opaque minerals. μCT reveals the internal structure of rock and minerals (e.g. garnets or pyrites) as minerals grew and rocks evolved through time. Advanced geochemical analysis of minerals in order to decipher their geologic record requires accurate location of zonation i.e., growth patterns, which can be, if care is taken with acquisition conditions and sample preparation, accurately located with μCT. In metamorphic petrology we interpret chemical zoning within minerals (e.g. garnet) in terms of time paths of changing P-T conditions. When combined with age dating (Lu–Hf and Sm–Nd garnet geochronology) such geochemical patterns yield quantitative rates of crystal growth and finally of rates of subduction and exhumation of continental and oceanic plates (e.g. Skora et al., 2009).
To prepare samples for the following geochemical analyses, rock cores were marked with small saw cuts (~150 μm thick) and subsequently scanned. Garnets (Ca-Mg-Fe-alumosilicates) were chosen based on their sizes and shapes. Rock cores were cut slightly off center of the garnets and carefully ground down to 100 m above or below the center. A 100 lm thick thin section was prepared and ground down to obtain microprobe sections that yielded garnet cross sections corresponding to the centrally located tomographic image. Fig. 2 from Skora et al. (2006) shows the narrow peak of the element Lutetium in the garnet core in samples from the Zermatt-Saas (Switzerland). This important information is often missed in conventionally chosen cuts. Our work in this area has allowed us to obtain accurate information on the growth time of garnet during the Alpine orogenis. Growth times are 10's of million of years in this case!

Millimeter-sized fluid inclusions in pyrite from epithermal sulfide veins (Romania) have been studied by μCT , scanning electron microscopy (SEM) and near-infra-red light microscopy (Fig. 3). Large fluid inclusions in hydrothermal minerals are usually rare, thus the studied samples provide a unique opportunity to study relatively big volumes of real ore-forming paleofluids. Here the exact location of single individual fluid by μCT and the estimation of its volume is important to judge the feasibility for analyses with the Laser-ICP-MS (Kouzmanov in prep.)

The last example demonstrates the use of μCT in studying the relation of rock deformation and mineral growth. For two decades, considerable efforts have been made to explain the formation of so called "snowball garnets" which form by rolling garnet like steel balls in a deforming rock, while it grows. Snowball garnets have been used to reconstruct amount and direction of movements of rock stacks (i.e. nappes) at different scales (cm-100km). Robyr et al. (2007) could demonstrate that deformation is faster than growth in snowball garnets from the Alps using μCT images, electron probe microanalysis (EPMA), and electron backscattered diffraction (EBSD) techniques. They suggest that formation of these microstructures can be explained by the combination of the two previously proposed mechanisms operating *consecutively* during garnet growth. One of the key observations – only made possibly by CT imaging – is that the rotated garnets were in fact connected in 3D by thin bridges (Fig. 4), a feature which is almost impossible to detect or to interpret correctly from 2D section.

Conclusion

Our experience using μCT for now nearly 10 years has shown the versatility of these instruments in petrologic study. The fact that the images can be used as a tool to map rocks in 3D has opened up a whole series of new applications. While the quantification needs a lot of work, and still some software development, we have realized the incredible power offered by relatively simple and low-cost μCT imaging capability. Cost of analysis with high-precision tools such SIMS, LA-ICPMS and EMP is often several thousand dollars per day. A pre-selection of analysis spots using μCT reduces costs considerably, and helps interpret the chemical analysis, resulting in new and exciting interpretations in petrology. We are convinced, that the use of μCT will strongly increase in the near future in our research domain.

References:

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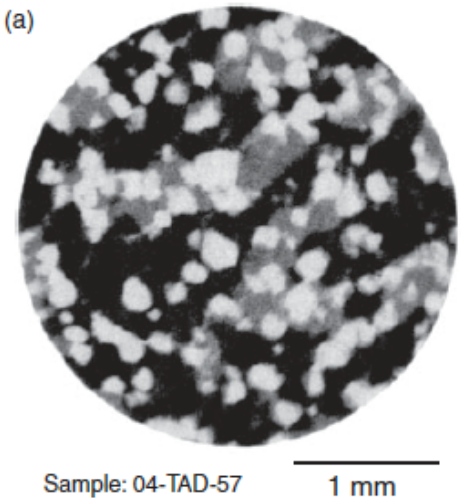
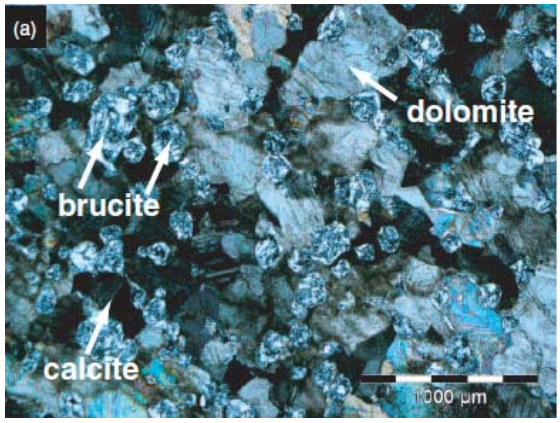




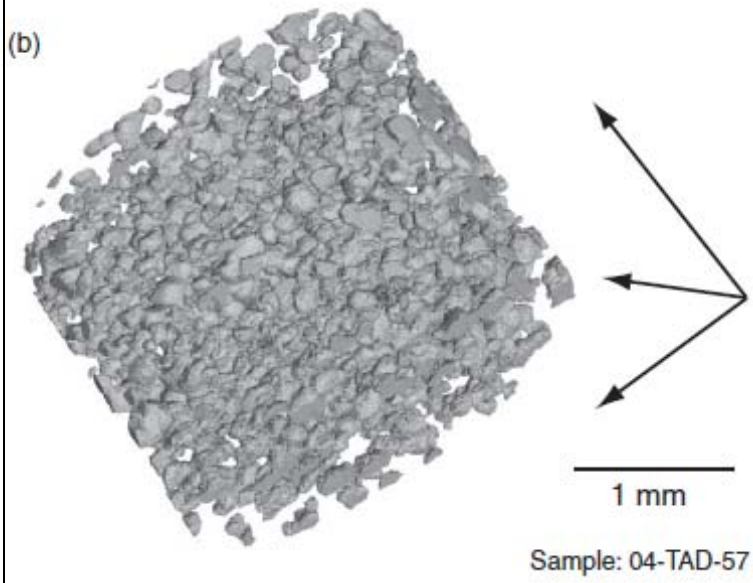
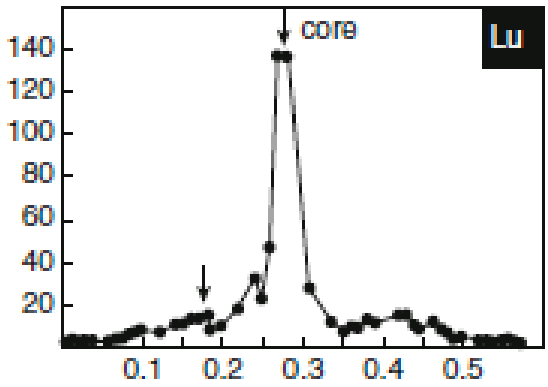


Fig. 1: Photomicrograph (above) of thin section from the periclase zone, cross-polarized light. Spherical brucite pseudomorphs replacing periclase have grain sizes of up to 200 mm in diameter.
Left: (a) Typical X-ray µ-CT image of a reacted carbonate sample (b) A 3D reconstruction of periclase distribution in a single analyzed core. Brucite crystals are uniformly distributed in three dimensions, indicating pervasive flow of reactive fluid. Modified from Müller et al. (2009)



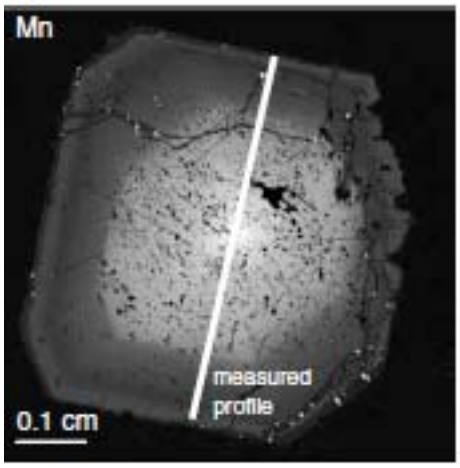


Fig. 2: Extremely narrow peak of Lutetium – only visible in a correct central cut through the garnet (modified from Skora et al. (2006).

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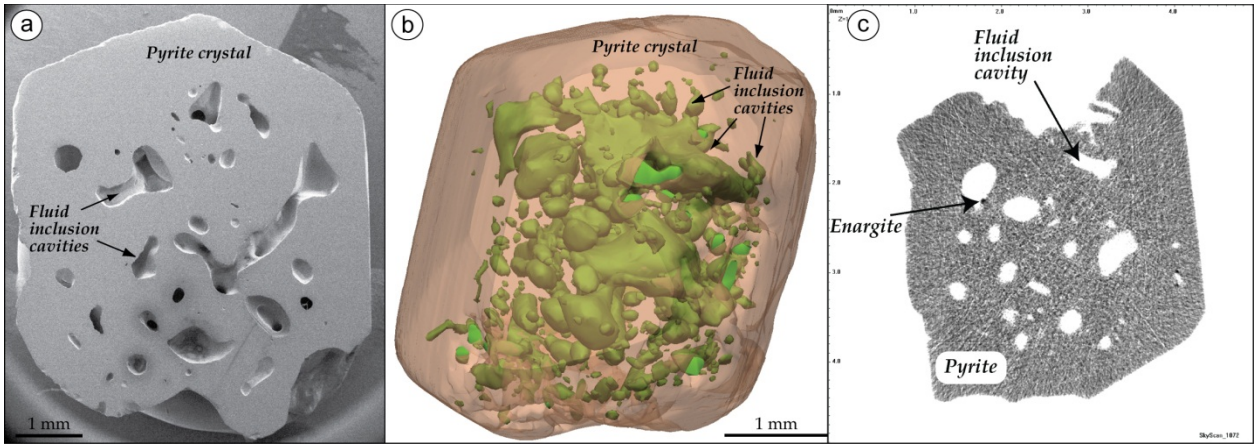

Fig. 3 Fluid inclusions in pyrite: a) SEM image of single pyrite crystal cut. Fluid inclusion cavities (from <10 mm to >2mm in size) have negative crystal shapes and are randomly distributed in the central part of the crystal; b) 3D – computed tomography reconstruction of the pyrite crystal, projection c) Single slice image of the crystal. Note the tiny enargite inclusion trapped in one of the fluid inclusion cavities. Enargite is commonly present as solid inclusions in pyrite matrix. Modified from Kouzmanov et al. (in prep).

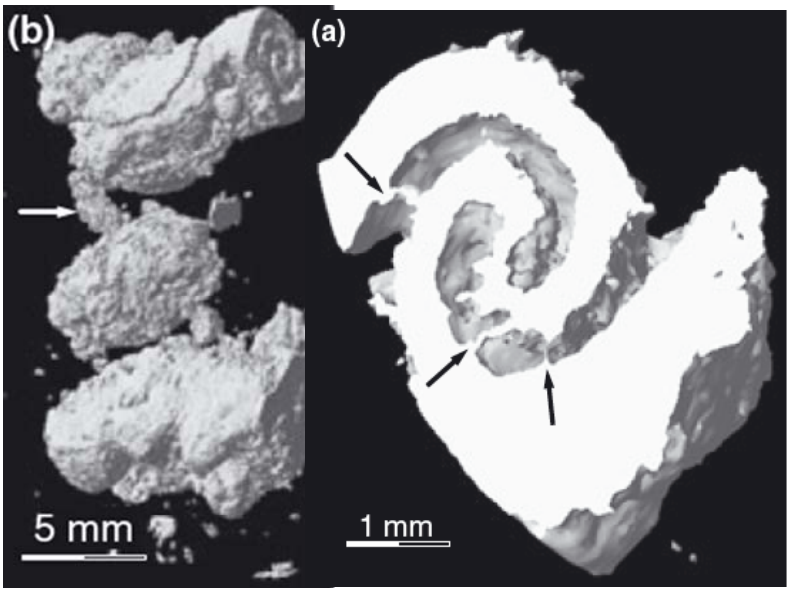

Fig. 4: (a) µCT image of garnet-bearing sample (Luk_02_5) illustrating the typical spiral morphology of snowball garnets. The core region of the spiral is connected to the arms by thin curved bridges (black arrows). (b) µCT view of three vertically aligned garnets. The two porphyroblasts on top are connected to each other by a thick garnet appendage (white arrow). Modified from Robyr et al. (2007)