Recent progress in the study of accessory minerals

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Accessory minerals are a common species in igneous and metamorphic rocks that are not considered characteristic of the host rock and hence do not affect its root name. Accessories tend to be complex in terms of their chemical and isotopic composition and their structural state. In spite of not being major rock constituents, they are, however, of enormous petrologic interest as they contain a record of the formation and post-formation history of their host rock. The study of accessory minerals hence has increased continuously during the past years, and still increases (Fig. 1). Recent progress is driven by new analytical opportunities of (*in situ*) micro-techniques. More and more the internal textures, that is, elemental, isotopic, and/or structural distribution patterns within individual grains, have come into the focus of researchers; a few examples are compiled in Fig. 2.

The present special issue aims at providing an overview of recent progress in the study of accessory minerals. It was compiled on the occasion of CAM–2017, the *Conference on Accessory Minerals* (September 13–17, 2017, Vienna,

Austria). This conference was a follow-up of the *Workshop on Accessory Minerals* (September 25–26, 2014, Warsaw, Poland), organised by Ray Macdonald and Bogusław Bagiński.

The continuing interest in accessory mineral research is also underlined by the fact that Mineralogy & Petrology released a special issue “Accessory minerals in igneous and metamorphic rocks” just six years ago (vol. 102; October, 2011). The present special issue, devoted to the very same topic, contains 13 research articles. Even though zircon seems

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Fig. 1 Publications referenced in the WoS (Web of Science; Thomson Reuters™) whose topic contains “accessory” and “mineral”. The search was limited to the four research areas of geology, geochemistry, mineralogy and crystallography, for the last 30 years (1987–2016). Red circles, number of publications in each year; underlying grey histogram, number of citations in other WoS publications

Fig. 2 Four examples of diverse analytical studies of accessory minerals. **a** Electron probe micro-analyser (EPMA) chemical mapping of metamic fergusonite from Berere, Madagascar, that suffered chemical alteration near a fracture (centre). Thorium and Pb are enriched adjacent to the fracture whereas Y is depleted; the fracture filling itself is Y rich. Sample courtesy C. Schnier, analyses D. Rhede. **b** Photoluminescence (PL) spectrum of zircon from the Gold Butte block, Nevada, with reference spectra of flux-grown, Dy- and Sm-doped ZrSiO₄. Colour-coded images of a group of three crystals were generated from hyperspectral mapping of the 17,210 cm⁻¹ line (marked with an asterisk), which belongs to the crystal-field-split ⁴F_{9/2} → ⁵H_{13/2} transition of Dy³⁺. The two images visualise distribution patterns of Dy

concentration (increasing intensity) and radiation damage (increasing FWHM, full width at half maximum), respectively. Sample courtesy P.W. Reiners and C. Lenz, analyses C. Chanmuang. **c** Electron backscatter diffraction (EBSD) map of a zircon in polycrystalline sillimanite from the Val d'Ossola, Italy, highlighting lattice misorientation with respect to a reference point in the lower right of the grain. Sample courtesy E. Kovaleva, analysis G. Habler. **d** High-angle annular dark field (HAADF) image of a zircon from the Mount Sones paragneiss, Enderby Land, Antarctica, showing several Pb nanospheres (bright), along with an energy-dispersive X-ray (EDX) spectrum. Sample courtesy M.A. Kusiak, analyses R. Wirth

to continue the prime accessory mineral being studied, the present issue presents a fairly broad range of species investigated and topics covered. Breiter and Škoda have studied Zr/Hf ratios of accessory zircon grains and their host rocks in the Teplice caldera, and they found Hf/Zr values to be sensitive indicators of fractionation in the granitic melt. Shumlyansky

et al. found that accessory zircon in gabbroic rocks from the Ukrainian Shield has unusually high concentrations of REEs (rare earth element) and other non-formula elements – which they assign to growth from residual melts enriched in incompatible elements – whereas zircon from a pegmatite, in contrast, is depleted in such trace elements. A rather extreme,

radiation-damaged zircon from the Ural Mountains, with interior regions whose UO_2 content exceeds 10 wt%, was studied by Zamyatin et al. The zircon's internal zoning is assigned to diffusional and fluid-driven alteration processes; one of them likely has led to the formation of uranyl that is detected in Raman and PL (photoluminescence) spectra. Other actinide-rich and radiation-damaged species, namely zirconolite and the pyrochlore-supergroup mineral oxycalcioberafite, from Adamello, Italy, are described by Lumpkin et al., who found that both minerals have retained the actinides for 40 myr despite having undergone high self-irradiation on the order of 10^{19} α/g . Variations in the composition of "silicate apatites" (i.e. minerals of the britholite group) from pegmatites in the Keivy province, Kola peninsula, allowed Zozulya et al. to unravel large changes of physico-chemical conditions in the fluid. Macdonald et al. demonstrate the different susceptibilities of different accessory species to secondary alteration under hydrothermal conditions, for example a quartzolite from Rova, Kola peninsula, Russia. These authors found that zircon underwent stronger alteration, when compared to chevkinite-(Ce), monazite-(Ce), and fergusonite-(Y), and they discuss the importance of fractures as migration pathways for alteration fluids. The paper of Betkowski et al. is devoted to accessory phosphate species in the Sn porphyry deposit near Llallagua, Bolivia. These authors use the accessories in unravelling the formation, and post-formation alteration, history of the deposit. Elliott et al. describe accessory REE-bearing minerals, magnetite, zircon, Fe-rich biotite, and hematite from the Round Top laccolith, Texas. These authors assign the sequential enrichment of the REE (and other incompatible elements) by the prolonged removal of compatible elements in the source magma. Hydrothermally formed titanite from the Fe-skarn deposit of

Chengchao, Daye district, China, is characterised by Hu et al., who propose that this mineral, whose common-Pb content is negligible, be used as a reference material in U-Pb geochronology. Bačík et al. discuss chemical peculiarities including substitution mechanisms, and formation details, of tourmaline-group minerals in Sb-bearing hydrothermal veins from Slovakia. Tourmaline-group minerals, in this case from pegmatites, are also the subject of Novák et al. The authors found that elevated Mg contents in these minerals originate from serpentinite host rocks and hence record external contamination of evolved acidic pegmatite melts. Finally, accessory borate minerals with significant internal zoning, originating from a Mg-rich skarn deposit in the Štiavnica stratovolcano, central Slovakia, were studied by Bilohuščin et al. The composition of these borates provides a record of skarn evolution during contact-metasomatic to late hydrothermal stages.

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