MINERAL TRANSFORMATIONS UNRAVELED USING ELECTRON BACKSCATTER DIFFRACTION
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Introduction: Shock deformation caused by meteorite impact produces near instantaneous excursions in stress, pressure, and temperature that all drive mineral transformations. Polymorphic transformations can occur with both increasing/decreasing pressure conditions (e.g., quartz/coesite/stishovite, zircon/reidite, monazite), increasing/decreasing thermal conditions (e.g., zircon/zirconia) or elements of both variables. Some of the more difficult challenges are detecting the former presence of minerals that stabilize briefly at extreme conditions, but subsequently transform back to phases stable at ambient conditions. Here, the focus is on identification of ‘microstructural breadcrumbs’ left by the back-transformation process, such as complex transformation twins and/or neoblastic textures. Many of these complex mineral occurrences result primarily from extraterrestrial processes (e.g., meteorite impact), and with rare exception, have no endogenic equivalents. The reference list below includes recent examples.

Application of EBSD: For many phases, the crystallographic-controlled nature of the transformations leaves evidence that can readily be detected by electron backscatter diffraction (EBSD) orientation analysis. EBSD can quantify characteristic minimum misorientation relationships (termed ‘disorientation’, in EBSD parlance) defined by angle-axis relations that result from systematic transformations, with routine analysis at spatial resolution down to 50 nm scale. EBSD facilities at Curtin University include a field emission SEM (Tescan), and an Oxford Instruments Symmetry EBSD camera. Samples for EBSD analysis need a standard SEM polish, followed by a colloidal silica polish to remove polishing damage.

Phase heritage of zircon: Reconstruction of the former parent phase through orientation analysis of the stable phase using EBSD has been termed ‘phase heritage’ [1]. In the case of zircon, the concept of phase heritage is based on the systematic crystallographic pathways that form reidite during shock compression, which involve a 90°/<110> transformation [1-4]. Phase heritage analysis is used to detect the former presence of reidite in recrystallized granular neoblastic zircon, by identifying the characteristic disorientation (90°/<110>) among neoblasts in granular zircon from impact melt rocks and glass [1,5-6]. Granular zircon where orientation analysis has detected former reidite is a hallmark of high-pressure shock deformation, and is referred to as Former Reidite in Granular Neoblastic zircon, or FRIGN zircon [7]. It has since been reported from impact melt rocks and glasses from various sites [e.g., 8], and in one case, shocked bedrock associated with pseudotachylite [9]. FRIGN zircon has been demonstrated to have important geochronological implications, including preservation of impact age at two sites, including the Lappajärvi [10], Araguainha [11], and Yarrabubba [12] impact structures.
**Phase heritage of zirconia:** Baddeleyite is the only stable form of zirconia at ambient conditions, however, the former presence of high-pressure and high-temperature polymorphs have been detected through phase heritage analysis using EBSD. The former presence of the two high-temperature polymorphs, cubic and tetragonal zirconia, were detected through identification of systematic orientation relationships among twins in baddeleyite formed during high-temperature (>2370 °C) dissociation of zircon in impact melt rock from the Mistassin Lake impact structure [1,13]. Orthorhombic zirconia, a high-pressure zirconia polymorph, has also been detected through analysis of twinned baddeleyite in shocked bedrock (dolerite) from Sudbury [14]. The systematic orthogonal twinning relations observed in baddeleyite currently do not allow discrimination between high-temperature polymorphs (tetragonal, cubic) and high-pressure polymorphs (orthorhombic); in such cases, independent lines of evidence specific to the samples analyzed are needed to distinguish the likely precursor polymorph.

**Phase heritage of monazite:**

Phase heritage analysis of complex twinning was recently applied to monazite for the first time [15]. Orientation analysis of shocked monazite from crystalline target rocks at the Ries and Haughton impact structures has revealed the former presence of a previously unknown high-pressure tetragonal-CePO₄ polymorph [15]. The former phase is no longer present, but its presence was detected by the occurrence of 1-2 µm wide lamellae consisting of complexly twinned monazite domains with systematic orientation relations. The lamellae are closely spaced, and in crystallographic controlled orientations in the host monazite grain. Phase heritage analysis was able to reconstruct the twin relations, identifying a tetragonal precursor. The phase has not previously been recognized in experimental or empirical studies, and thus reveals clues about the existence of a formerly unknown high-pressure mineral.

**Phase heritage of rutile:**

Data were recently presented which identified TiO₂-II, a high-pressure TiO₂ polymorph, in shocked granitoid from Chicxulub drill core [16]. In this case, the high-pressure polymorph was present and identified by EBSD. An important observation made was the presence of intergrown rutile, inferred to have formed as a reversion product from TiO₂-II. This suggests the possibility for phase heritage analysis detection of the high-pressure polymorph in cases where it is entirely reverted, if systematic relations can be established among twins in rutile that are diagnostic to the reversion.

**Outlook:**

Phase transformations involving extreme pressure and temperature excursions are ubiquitous during impact events; the presence of impact melt (glass and/or impact melt rock) testifies that conditions capable of driving such reactions always affect some volume of rock. Accessory phases such as those described here offer abundant opportunity to record mineral transformations and provide records of phases that are no longer present. The concept of phase heritage, as applied with EBSD, is relatively recent, and has many benefits for studying impact processes on terrestrial or extraterrestrial materials, as it is effectively non-destructive for polished samples, data acquisition is relative fast with modern collection systems, and the community of users, along with discoveries, continues to grow.