

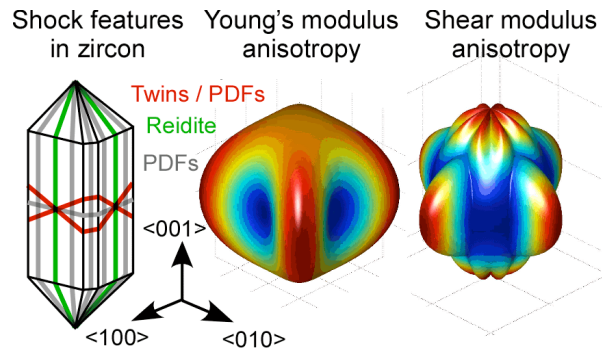
**The effects of anisotropic elastic properties on shock deformation microstructures in zircon and quartz.** N. E. Timms<sup>1</sup> and D. Healy<sup>2</sup>, <sup>1</sup>Department of Applied Geology, Curtin University, GPO Box U1987, Perth, 6845, Western Australia, <sup>2</sup>School of Geosciences, King's College, University of Aberdeen, Aberdeen, AB24 3UE, UK. Corresponding author email: n.timms@curtin.edu.au

Certain microstructures are unequivocal evidence of impact shock including thin (nanometers to micrometers) lamellae with the same composition as the host crystal containing an amorphous phase (planar deformation features, or PDFs), twins or high-pressure polymorphs. All of these features occur along a limited number of rational, low-index crystallographic planes, specific to each mineral phase [1], [2], [3]. Groups of orientations of PDF planes in quartz are indicative of different grades of shock metamorphism [2], [4]. However, particular  $\{hkl\}$  PDF formation in quartz can vary by up to 4 GPa in different rock types [1], [5]. Consequently, studies of amorphous PDFs in natural shocked grains give only a broad estimate of maximum shock pressure conditions [3], [4].

This study discusses the occurrence of shock microstructures along specific  $\{hkl\}$  by considering the elastic properties of minerals. The formation of PDFs, twins and polymorph lamellae must occur if yield conditions for plastic behavior (Hugoniot Elastic Limit) are exceeded. Minerals respond elastically before the plastic limit is reached, and therefore elastic behavior will likely exert some influence on the nature of the plastic strain component. For elastic materials, Young's modulus ( $E$ ) scales a longitudinal strain into an equivalent stress. Shear modulus ( $G$ ) describes the same relationship for shear strains and shear stresses. All minerals have anisotropic elastic properties governed by their intrinsic crystallography. In this study, we investigate the effects of intrinsic elastic properties on the formation of shock deformation microstructures in zircon and quartz.

Zircon is highly anisotropic in its elastic properties, such as its Young's modulus ( $E$ , 63.4%) and Shear modulus ( $G$ , 20.7%) with tetragonal symmetry [6], [7]. The directions normal to all the PDF plane orientations reported in zircon always coincide with high values of Young's modulus [7]. That is, zircon is elastically 'more rigid' in directions perpendicular to the PDF planes. However, PDF planes do not always align normal to directions with high shear modulus ( $G_{\max}$ ). This suggests that Young's modulus anisotropy has the greatest influence on the selection of PDF planes (i.e.,  $\{001\}$ ,  $\{110\}$ ,  $\{112\}$ ,  $\{320\}$ ), and that they are (predominantly) compression/extensional damage planes [7]. The exact planes that form PDFs (and presumably their spacing) will depend on the direction(s) and in-

tensity of the shock waves that propagate through the grain.



In shock-twinned zircon, micro-twin lamellae occur within  $\{112\}$ -parallel PDFs, and the host-twin geometric relationship is described by  $65^\circ$  rotation around a  $\langle 110 \rangle$  direction [7], [8], [9]. In this configuration,  $65^\circ$  is exactly the amount of rotation required to translate  $\langle 112 \rangle$  directions along a  $\{110\}$  plane. However, the twin mechanism is most likely a martensitic (shear) transformation that involves short-range lattice reconfiguration and requires considerably less than  $65^\circ$  actual rotation.  $\{112\}$  in zircon are special in that they contain high shear modulus ( $G_{\max}$ ) values and are normal to directions of high Young's modulus [7]. This permits the formation of shear twins along  $\{112\}$  PDFs. Shear twins are likely to form along optimally orientated  $\{112\}$  planes for maximum shear stress, possibly at  $45^\circ$  to the maximum principal stress (shock wave direction) [7]. However, this remains to be verified. The fact that some planar features contain a combination of amorphous and twinned material could suggest that these  $\{112\}$  planes were oriented oblique to the shock wave(s) such that both twinning and the formation of amorphous material could occur. Alternatively, the narrower, non-twinned domains represent 'tip' (or 'process') zones where the shock energy was not sufficient to displace the lattice to form a twin.  $\{110\}$  PDFs have very low  $G_{\max}$  and do not form shear twins, which is probably due to the lack of a viable twin law and low shear modulus along those planes [7].

Zircon transforms to reidite along  $\{100\}$ . In zircon,  $\{100\}$  corresponds to the minima of  $E$  and maxima of  $G$  ( $G_{\max}$ ) [7]. There are no reports of  $\{100\}$  PDFs in zircon, probably because the localization of longitudi-

nal damage planes is inhibited along  $\{100\}$  (they have low plane-normal Young's modulus), which could be a pre-/co-requisite facilitation for the nucleation of shear transformations. The fact that shock pressures over  $\sim 20$  GPa are required to transform zircon to reidite along  $\{100\}$  suggests that this difficulty can be overcome at high shock pressure conditions.

Quartz is also highly anisotropic in its elastic properties, with systematic variations in Young's modulus of 61% with trigonal symmetry [6], [10]. Preliminary investigation of shock microstructures in quartz reveals similar relationships with elastic anisotropy as found in zircon. PDFs in quartz form perpendicular to crystallographic directions moderate to high E values. With increasing shock pressures, PDFs normal to directions of lower Young's modulus are activated. However, at extremely high shock conditions, PDFs normal to high Young's modulus values prevail. The trigonal symmetry of Young's modulus anisotropy provides an explanation why PDFs only form along some  $\{hkl\}$  in quartz of a particular sign (either the positive or negative form). Brazil twins form along  $\{11\bar{2}0\}$  at moderate to strong shock conditions in quartz. Brazil twins form normal to directions of moderate Young's modulus, perhaps indicating that shear modulus also plays a key role in their formation. Further analysis is required to determine whether the relationships described here are applicable to other minerals, all of which are elastically anisotropic.

**References:** [1] Grieve, R. A. F. & Robertson, P. B. (1976) *Contribs. Mineral. and Petrol.* 58(1), 37-49. [2] Langenhorst F. (2002) *Bull. Czech Geol. Surv.* 77(4), 265-282. [3] Stöffler D. & Langenhorst F. (1994) *Meteoritics* 29(2), 155-181. [4] Robertson, P. B. & Grieve, R. A. F. (1977) In: *Impact and explosion cratering: Planetary and terrestrial implications; Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Ariz., September 13-17, 1976.* (edited by Roddy, D. J., Pepin, R. O. & Merrill, R. B.). Pergamon Press, Inc., New York, 687-702. [5] Langenhorst F. & Deutsch A. (1994) *Earth Planet. Sci. Lett.* 125(1-4), 407-420. [6] Hearmon, R. F. S. (1984) In: *Landolt-Börnstein Tables III* (edited by Hellwege, K. H. & Hellwege, A. M.) 18. Springer-Verlag, New York, 559. [7] Timms N. E. *et al.* (2012) *Meteoritics & Planet. Sci.*, 47(1), 120-141. [8] Leroux H. *et al.* (1999) *Earth Planet. Sci. Lett.* 169(3-4), 291-301. [9] Moser D. E. *et al.* (2011) *Can. J. Earth Sci.* 48(2), 117-139. [10] Timms N. E. *et al.* (2010) *J. Geophys. Res.* 115(B7), B07202.