The effect of nuclear radiation on the structure of zircon

RODNEY C. EWING*

University of Michigan, Ann Arbor, MI 48109 USA
(correspondence: rodewing@umich.edu)

In 1955, Heinrich Holland and David Gottfried published a remarkable paper in *Acta Crystallographica* on radiation damage accumulation in a suite of natural zircons from Sri Lanka [1]. The purpose of their study was to investigate the possibility of using radiation damage accumulation as a method of age determination. This was one of the first quantitative studies of damage accumulation and annealing in a complex ceramic and provided a solid basis for extrapolating radiation damage effects in actinide-bearing nuclear waste forms over geologic periods [2,3]. The paper is not only remarkable for the data, measurements of unit cell parameters and optical properties, as a function of increasing dose, but also because the interpretation of the data was in the context of a damage ingrowth model that quantifies the accumulation of amorphous domains, the accummulation of isolated defects, the formation of new crystalline structures and the change in crystallite size. The authors also recognized the possibility of alpha-particles enhancing the effects of damage accumulation and annealing caused by the alpha-recoil atom.

Subsequent studies of radiation effects have utilized Pu-doping experiments [4] and ion beam irradiations (MeV to GeV energies) [5,6]. Most recently, high-energy irradiations have been completed at high pressures using a diamond anvil cell [7]. These studies have provided a fundamental understanding of the radiation damage processes that has supported the use of zircon as an optic wave guide [8], the development of nuclear waste forms for excess weapons plutonium [9] and fission track dating and thermochronology [10, 11]. For all of these applications, the early work by Holland and Gottfried remains the fundamental foundation.

[1] Holland & Gottfried (1955) *Acta. Cryst.* **8**, 291-300. [2] Murakami *et al.*. (1991) *Amer. Mineral.* **76**, 1510-1532. [3] Weber *et al.*. (1994) *J Mater. Res.* **9**, 688-698. [4] Exarhos (1984) *Nucl. Instr. Method Phys. Res.* **B1**, 538-541. [5] Wang & Ewing (1992) *Nucl. Inst. Method Phys. Res.* **B59**, 395-400. [6] Bursill and Braunshausen (1990) *Phil Mag.* **A62**, 395-420. [7] Glasmacher *et al.*. (2006) *Phys. Rev. Lett.* **96** 195701-195705. [8] Babsail *et al.*. (1991) *Nucl. Instr. Method Phys Res.* **B59**, 1219-1222. [9] Ewing *et al.*. (1995) *J. Mater. Res.* **10**, 243-246. [10] Lang *et al.*. (2008) *EPSL* **274**, 355-358. [11] Li *et al.*. (2011) *EPSL* **302**, 227-235; Li *et al.*. (2012) *EPSL* **321**, 121-127.

Formation and geochemistry of rutile from garnet gabbros of the Jijal Complex, Kohistan island arc

T.A. EWING* AND O. MÜNTENER

Institut de Sciences de la Terre, UNIL, CH-1015 Lausanne, Switzerland (*correspondence: tanya.ewing@unil.ch; othmar.muntener@unil.ch)

The Kohistan paleo-island arc preserves a ~50 km-thick section of Jurassic–Cretaceous arc crust renowned as one of the best exposures of an exhumed island arc. The lowermost Jijal Complex comprises an ultramafic and a mafic section. The latter is dominated by garnet gabbros, the origin of which is controversial. Formation of garnet in these rocks has been ascribed to dehydration melting of hornblende-bearing precursors [e.g. 1], prograde metamorphic reactions [e.g. 2] or fractional crystallisation at high pressures followed by isobaric cooling [3, 4].

Rutile (TiO_2) is an accessory phase in garnet-hornblende pyroxenites, garnet gabbros, paragonite gabbros and epidote-bearing pegmatites. In some samples garnet cores preserve ulvöspinel inclusions while garnet rims host rutile, suggesting formation of rutile at the expense of ulvöspinel. In paragonite gabbros rutile is associated with epidote–quartz intergrowths and may have formed as a result of the breakdown of clinopyroxene and garnet to form epidote and amphibole. Both reactions are consistent with isobaric cooling.

Garnet gabbros, paragonite gabbros and epidote-bearing pegmatites give Zr-in-rutile temperatures of 650–700°C. A few analysed rutiles are in contact with quartz and have indistinguishable Zr from other rutiles. These lithologies are largely zircon-free and Zr-in-rutile thus gives minimum temperatures. The Zr-in-rutile temperatures are lower than ~800–1000°C Fe–Mg temperatures for the same lithologies, and it is unlikely that this difference can be explained entirely by the lack of equilibrium with zircon. Zr content within individual grains displays little variation, arguing against diffusive re-equilibration, but it remains to rule out complete recrystallisation. Rutile from the Jijal Complex samples has Zr/Hf distinct from that of rutile from lower continental crustal metapelites, pointing to different controls on these geochemical tracers in rutile from different settings.

[1] Garrido *et al.* (2006) *J. Petrology* **47**, 1873–1914. [2] Yamamoto & Yoshino (1998) *Lithos* **43**, 219–234. [3] Ringuette *et al.* (1999) *Geology* **27**, 139–142. [4] Jagoutz *et al.* (2011) *EPSL* **303**, 25–36.