

MICROSTRUCTURE AND U-Pb DATES OF MARTIAN BADDELEYITE RIMMED BY ZIRCON INDICATE A 'YOUNG' IGNEOUS AND METAMORPHIC HISTORY FOR SHERGOTTITE NWA 5298

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Introduction

A current paradox in martian geochronology is that basaltic shergottites yield whole rock and unradiogenic mineral isotopic Pb-Pb compositions consistent with a primary Noachian (>4 Ga) age for crystallization (e.g. [1]) whereas mineral isochrons consistently return 'young' post-Amazonian (<0.6 Ga) ages [2,3]. Resolution of the shergottite geochronology debate by U-Pb dating microcrystals of the accessory phase baddeleyite (ZrO₂) has been suggested [4] although the small size of the targets poses technical challenges. LA-MC-ICPMS U-Pb analyses of baddeleyite in subsequent studies have yielded a range of dates between 0.1 and 1.2 Ga [4,5] yet questions remain as to whether the 'young' dates reflect shergottite crystallization, martian metamorphism or disturbance by shock metamorphism.

Part of the conundrum in interpreting U-Pb baddeleyite dates stems from the experimental prediction that shock and attendant heating do not cause Pb loss in baddeleyite [6] although these workers note that their experimental baddeleyites are as much as 100 times larger than martian grains. We note that similar experiment-based predictions were made early for the mineral zircon, but were falsified following investigation of natural samples where shock heating was significant [7,8]. Here we pair single-grain isotopic SIMS U-Pb analyses by the relatively new technique of SIMS microbaddeleyite dating [9,10] with chemical and deformation microstructure data obtained with electron nanobeam techniques in order to resolve baddeleyite paragenesis and degree of alteration by shock processes. We have focused on microbaddeleyites from shergottite NWA 5298 [11]-M53387 from the Royal Ontario Museum's meteorite collection, an enriched basaltic shergottite exhibiting a primary phaneritic igneous texture which, apart from its enrichment and relatively oxidized state, is similar to other basaltic shergottites [12].

Materials and methods:

The recent detailed petrogenetic study by [12] establishes that NWA 5298 has compositional similarities to other shergottites including Shergotty, Zagami and Los Angeles in aspects such as plagioclase composition. These authors conclude that NWA 5298 is an unbrecciated, highly shocked basaltic meteorite that likely crystallized from a thick lava flow on Mars. Partial breakdown of pyroxferroite to fayalite suggests

reheating by a later event such as overlying lava flow or shock heating. Pervasive maskelynite indicates shock pressures of at least 30 GPa, and the presence of included vapourization pockets suggests much higher pressures of 60 to 80 GPa. In our study microbaddeleyite grains were located in a petrographic thin section of NWA 5298 by EPMA mapping. A subsection containing more than 15 targets was isolated and cast in epoxy along with the Phalaborwa baddeleyite standard (2060 Ma; [13]). SIMS analyses on the UCLA CAMECA ims1270 were acquired using protocols previously described [10]. Isotopic U-Pb ratios were corrected for martian common Pb composition [2], except for one grain which had high common Pb, and for which surface contamination with terrestrial Pb was assumed. Electron nanobeam analyses (Fig.1) were performed at the University of Western Ontario Zircon and Accessory Phase Laboratory (ZAPLab) using a Hitachi SU-6600 variable pressure FEG-SEM according to protocols described in [8].

Results:

The baddeleyite grains range in size from 20 to 2 μm in the longest dimension. They exhibit a range of forms, but generally occur as subhedral to euhedral blocky to bladed grains, often in multi-crystal clusters at the boundaries of larger main phase minerals. SE and BSE imaging of grain interiors showed that grains are often composed of equant microdomains that give the appearance of a granular texture. Grains are often surrounded by rims of zircon a few microns wide as identified by EDS and EBSD (Fig. 1), and are sometimes cross-cut by fractures in-filled with secondary minerals such as zircon. CL imaging was used to map submicron variations in trace element chemistry. Several CL zoning types were observed within baddeleyite grains including simple bright, narrow rims of variable thickness surrounding dark cores, and patchy to diffuse and mottled CL domains at the margins of grains or in areas of crystal disruption and apparent granular texture. A subset of grains exhibits oscillatory planar growth banding that is parallel to the euhedral grain margins and also defines triangular sector zoning. These patterns are similar to igneous growth banding we have observed in terrestrial baddeleyite crystallized from basaltic magmas. Zircon luminesces in the UV range and often forms a discontinuous polycrystalline rind several microns

wide that can replace baddeleyite or grow outward from the baddeleyite grain margin.

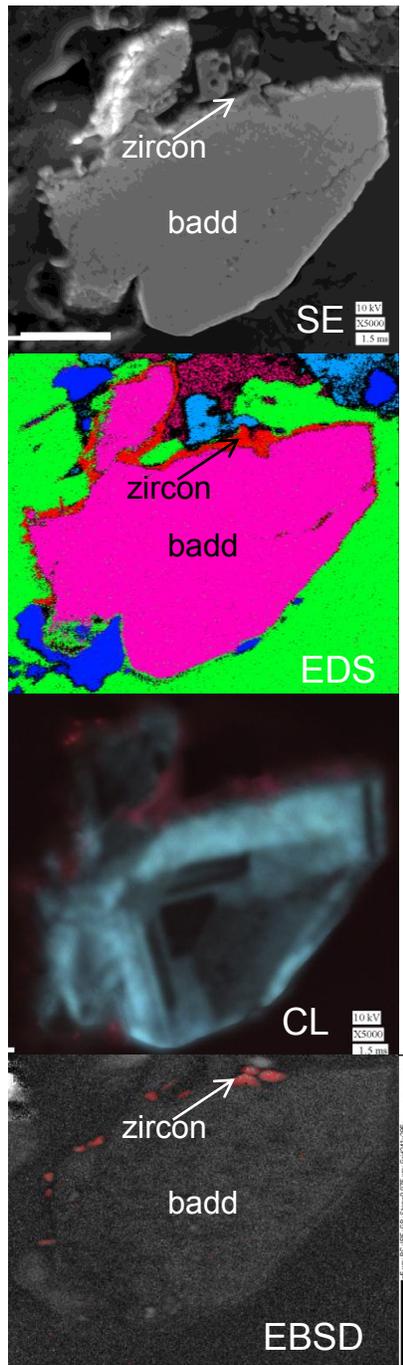


Figure 1: SE image of euhedral microbaddeleyite (badd). Note microgranular texture. Scale bar = 5 microns; EDS phase map showing baddeleyite, zircon rim and host plagioclase/ maskelynite (green); CL image revealing planar sector zoning typical of igneous crystallization plus zircon rim (magenta); EBSD band contrast map indicating that all phases are now amorphized due to shock except for zircon rim crystallites.

Our EBSD mapping indicates clearly that the baddeleyite is now quasi-amorphous and is hosted by amorphous maskelynite, whereas zircon is crystalline. Individual zircon crystallites appear unshocked, although an investigation at higher resolution for the high pressure polymorph, reidite, is ongoing. SIMS analysis of 12 grains yielded $^{206}\text{Pb}/^{238}\text{U}$ dates ranging from 209 ± 22 Ma (2σ) to 26 ± 2 Ma. An unforced discordia line has an upper intercept with concordia at $0.9 +1.2/-0.7$ Ga and a zero age lower intercept.

Discussion and Conclusions: Our SIMS data together with microtextural data for the baddeleyites are consistent with U-Pb disturbance of primary igneous grains during relatively recent shock heating. The unshocked zircon rims are evidence of metamorphic reaction during or immediately following the shock event. We hypothesize that zircon rims are a reaction product of shock-induced Si release from matrix mafic minerals [14], possibly during the martian impact ejection event. This is the event that facilitated Pb-loss and resetting of the primary baddeleyite age. Based on CL zoning the baddeleyites are original crystallization products of a martian igneous body, and the upper concordia intercept of $0.9 +1.2/-0.7$ Ga establishes that igneous activity occurred in the latter half of martian evolution. A scenario is favoured wherein bulk melting of ancient 4 Ga parent material produced the NWA 5298 magma through volcanic or impact melting. This would reconcile ‘young’ mineral dates and isochrons with the unradiogenic and whole rock Pb-Pb age data inform basaltic shergottites. We propose a two-stage sequence for NWA 5298 mineralogy:

- 1) Crystallization of baddeleyite from a martian basalt as evidenced by oscillatory CL zoning at some point between 2.1 and 0.2 Ga.
- 2) Shock deformation and heating of the shergottite (likely during the ejection event) caused amorphization of baddeleyite, loss of radiogenic Pb isotopes, Si release from mafic phases and growth of zircon around baddeleyite.

It is possible that this history is shared by a number of basaltic shergottites.

References: [1] Bouvier et al., 2005 *EPSL* 240:221–233; [2] Borg and Drake, 2005 *JGR* 110:E12S03; [3] Nyquist et al., 2009 *GCA* 73:4288–4309; [4] Herd et al. (2007) *LPSC XXXVIII*, Abstract #1664; [5] Hays et al. 2011 *LPSC XXXXII*, Abstract #1243; [6] Niihara T. et al. 2009 *LPSC XXXIX*, Abstract #1562; [7] Krogh et al., 1996 *Geophysical Monograph*, 95, pp. 343–353; [8] Moser D.E et al., 2011 *Can. J. Earth Sci.* 48:117–139; [9] Chamberlain et al. 2010 *Precambrian Res* 183:379–387; [10] Schmitt et al. 2010 *Chem Geol* 269:386–395; [11] Irving and Kuehner 2008 *Met Soc Abstract*#5332 [12] Hui et al. 2011 *MAPS* 46: 1313–1328; [13] Heaman 2008 *Chem Geol* 261 43–52; [14] Miyahara et al. 2011 *Japanese Geoscience Union Abstract* # PPS003-01.