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Introduction

Versatile monazite: Resolving geological records and solving challenges in materials science†

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Monazite is ubiquitous in the geological realm (Overstreet 1967). Its compositional and isotopic response to changes in intensive and extensive rock parameters has made it an increasingly important component of integrated pressure-temperature-deformation-composition-time (*P-T-D-X-t*) studies, particularly in complex poly-metamorphic terranes (Janots et al. 2012; Kelly et al. 2012; Langille et al. 2012). The utility of monazite also includes its role in understanding igneous, sedimentary, and hydrothermal systems (Dumond et al. 2008; Mahan et al. 2010; Aleinikoff et al. 2012), and more recently, as a means for examining repositories of radioactive waste (Oelkers and Montel 2008).

Since the broader potential applications of monazite as a geochronometer were described by Parrish (1990), several significant developments have since occurred that allow for the routine compositional and isotopic analysis of monazite by a variety of techniques. These include technological advances in electron-probe microanalysis (EPMA: Suzuki and Adachi 1991; Montel et al. 1996; Pyle et al. 2005; Williams et al. 2007; Jercinovic et al. 2008), secondary ion mass spectrometry (SIMS: Zhu et al. 1997; Bosch et al. 2002), laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS: Machado and Gauthier 1996; Košler 2001; Horstwood et al. 2003), isotope dilution-thermal ionization mass spectrometry (ID-TIMS: Hawkins and Bowring 1997; Crowley et al. 2009), and micro-XRF (Cheburkin et al. 1997; Engi et al. 2002). While U-(Th)-Pb dating of monazite is well established, in situ isotopic analytical techniques (SIMS, LA-ICP-MS) are now being applied to the Sm-Nd system in monazite (McFarlane and McCulloch 2007; Gregory et al. 2009; Fisher et al. 2011; Iizuka et al. 2011; Liu et al. 2012). Advances in laser and multi-collector detector technology also enable accurate measurement of isotopic abundances from exceptionally small sample volumes of monazite (Cottle et al. 2012), while developments in chemical abrasion-TIMS techniques (without high-temperature annealing) may provide even more high-precision data for monazite (Peterman et al. 2012).

In addition to more traditional aspects of high-temperature geochronology and the integration of monazite into constraining deformation histories (e.g., Williams and Jercinovic 2012), new techniques are continually being developed that have expanded the numbers of geological problems to which monazite may be applied. These applications include: low temperature (U-Th)/He thermochronology for constraining cooling ages (Boyce et al. 2009), detrital monazite geochronology (Hietpas et al. 2011), understanding mechanisms for alteration via dissolution-reprecipitation (Harlov et al. 2011; Williams et al. 2011; Wawrzenitz et al. 2012), and incorporating monazite phase relations into thermodynamic phase equilibria (Kelsey et al. 2008; Spear 2010).

The value of monazite is not restricted to the Earth sciences. The ability of monazite to accommodate significant quantities of naturally occurring actinides (Th and U) makes it an attractive natural analog for studying the long-term effects of radioactive decay on the structural and crystallographic properties of phosphate-based materials that have been proposed for isolation and storage of radioactive waste (Oelkers and Montel 2008). Other applications in materials science include studying the proton-conductivity of rare earth element phosphates for applications in hydrogen-based clean energy technologies (Amezawa et al. 1998; Norby and Christiansen 1995). Last, monazite is mined or quarried at various localities around the world as a source of light rare earth elements that are increasingly important commodities for high-technology industries (Chakhmouradian and Wall 2012).

The papers assembled for the launch of this special issue result from presentations made at a special theme session convened at the 2011 Geological Society of America Annual Meeting in Minneapolis, entitled "Monazite: The ultimate geologic record." Oral contributions and posters were presented in two well-attended sessions, and we thank all the participants for making them such a success. During the development of this special collection for *American Mineralogist*, the title was changed to reflect the diversity of contributions received, which covered a broad spectrum of mineralogy, geochronology, geochemistry, petrology, tectonics, as well as materials science. We thank the authors who have contributed manuscripts for the launch of this special collection and the reviewers for their careful and valued comments. We hope more contributions will be added as

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† Special Collection: Versatile Monazite: Resolving Geological Records and Solving Challenges in Materials Science is a thematic collection of papers based on a session at GSA in 2011. The special associate editors are Gregory Dumond and Callum Hetherington. Special collection papers can be found on GSW at http://ammin.geoscienceworld.org/site/misc/specialissuelist.xhtml. Additionally the GSW site has a classification tag found on the right-hand side of the article that is a link to all the collection papers. The MSA website has complete information at http://www.minsocam.org/MSA/AmMin/AmMineral.html

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time goes by, and we sincerely thank the staff and the editors of *American Mineralogist* for the invitation to work with them in publishing a series of papers that truly demonstrate the diversity and versatility of monazite-related science.

References cited

Aleinikoff, J.N., Hayes, T.S., Evans, K.V., Mazdab, F.K., Pillers, R.M., and Fanning, C.M. (2012) SHRIMP U-Pb ages of xenotime and monazite from the Spar Lake Red Bed-Associated Cu-Ag Deposit, Western Montana: Implications for ore genesis. Economic Geology, 107(6), 1251–1274.

Amezawa, K., Kjelstrup, S., Norby, T., and Ito, Y. (1998) Protonic and native conduction in Sr-substituted $LaPO_4$ studied by thermoelectric power measurements. Journal of the Electrochemical Society, 145(10), 3313–3319.

Bosch, D., Hammor, D., Bruguier, O., Caby, R., and Luck, J.-M. (2002) Monazite "in situ" $^{207}Pb/^{206}Pb$ geochronology using a small geometry high-resolution ion probe. Application to Archaean and Proterozoic rocks. Chemical Geology, 184(1–2), 151–165.

Boyce, J.W., Hodeges, K.V., King, D., Crowley, J.L., Jercinovic, M.J., Chatterjee, N., Bowring, S.A., and Searle, M. (2009) Improved confidence in (U-Th)/He thermochronology using the laser microprobe: An example from a Pleistocene leucogranite, Nanga Parbat, Pakistan. Geochemistry, Geophysics, Geosystems, 10, Q0AA01, DOI:10.1029/2009GC002497.

Chakhmouradian, A.R. and Wall, F. (2012) Rare earth elements: Minerals, Mines, magnets (and more). Elements, 8(5), 333–340.

Cheburkin, A.K., Frei, R., and Shotyk, W. (1997) An energy-dispersive miniprobe multielement analyzer (EMMA) for direct analysis of trace elements and chemical age dating of single mineral grains. Chemical Geology, 135(1–2), 75–87.

Cottle, J.M., Kylander-Clark, A.R., and Vrijmoed, J.C. (2012) U-Th-Pb geochronology of detrital zircon and monazite by single shot laser ablation inductively coupled plasma mass spectrometry (SS-LA-ICPMS). Chemical Geology, 332–333, 136–147.

Crowley, J.L., Waters, D.J., Searle, M.P., and Bowring, S.A. (2009) Pleistocene melting and rapid exhumation of the Nanga Parbat massif, Pakistan: Age and *P-T* conditions of accessory mineral growth in migmatite and leucogranite: Earth & Planetary Science Letters, 288, 408–420.

Dumond, G., McLean, N., Williams, M.L., Jercinovic, M.J., and Bowring, S.A. (2008) High-resolution dating of granite petrogenesis and deformation in a lower crustal shear zone: Athabasca granulite terrane, western Canadian Shield.: Chemical Geology, 254, 175–196.

Engi, M., Cheburkin, A.K., and Koppel, V. (2002) Nondestructive chemical dating of young monazite using XRF: 1. Design of a mini-probe, age data for samples from the Central Alps, and comparison to U-Pb (TIMS) data. Chemical Geology, 191(1–3), 225.

Fisher, C.M., McFarlane, C.R.M., Hanchar, J.M., Schmitz, M.D., Sylvester, P.J., Lam, R., and Longerich, H.P. (2011) Sm-Nd isotope systematics by laser ablation-multicollector-inductively coupled plasma mass spectrometry: Methods and potential natural and synthetic reference materials. Chemical Geology, 284(1–2), 1–20.

Gregory, C.J., McFarlane, C.R.M., Hermann, J., and Rubatto, D. (2009) Tracing the evolution of calc-alkaline magmas: In-situ Sm-Nd isotope studies of accessory minerals in the Bergell Igneous Complex, Italy. Chemical Geology, 260, 73–86.

Harlov, D.E., Wirth, R., and Hetherington, C.J. (2011) Fluid-mediated partial alteration in monazite: the role of coupled dissolution-reprecipitation in element redistribution and mass transfer. Contributions to Mineralogy and Petrology, 162(2), 329–348.

Hawkins, D.P. and Bowring, S.A. (1997) U-Pb systematics of monazite and xenotime: case studies from the Paleoproterozoic of the Grand Canyon, Arizona. Contributions to Mineralogy and Petrology, 127(1–2), 87–103.

Hietpas, J., Samson, S., and Moecher, D. (2011) A direct comparison of the ages of detrital monazite versus detrital zircon in Appalachian foreland basin sandstones: Searching for the record of Phanerozoic orogenic events. Earth and Planetary Science Letters, 310(3–4), 488–497.

Horstwood, M.S.A., Foster, G.L., Parrish, R.R., Noble, S.R., and Nowell, G.M. (2003) Common-Pb corrected in situ U-Pb accessory mineral geochronology by LA-MC-ICP-MS. Journal of Analytical and Atomic Spectroscopy, 18, 837–846.

Iizuka, T., Eggins, S.M., McCulloch, M.T., Kinsley, L.P.J., and Mortimer, G.E. (2011) Precise and accurate determination of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ in monazite using laser ablation-MC-ICPMS. Chemical Geology, 282(1–2), 45–57.

Janots, E., Berger, A., Gnos, E., Whitehouse, M., Lewin, E., and Pettke, T. (2012) Constraints on fluid evolution during metamorphism from U-Th-Pb systematics in Alpine hydrothermal monazite. Chemical Geology, 326–327, 61–71.

Jercinovic, M.J., Williams, M.L., and Lane, E.D. (2008) In-situ trace element analysis of monazite and other fine-grained accessory minerals by EPMA. Chemical Geology, 254, 197–215.

Kelly, N.M., Harley, S.L., and Moeller, A. (2012) Complexity in the behavior and recrystallization of monazite during high-T metamorphism and fluid infiltration. Chemical Geology, 322, 192–208.

Kelsey, D.E., Clark, C., and Hand, M. (2008) Thermodynamic modeling of zircon and monazite growth in melt-bearing systems: examples using model metapelitic and metapsammitic granulites. Journal of Metamorphic Geology, 26, 199–212.

Košler, J. (2001) Laser-ablation ICPMS study of metmaorphic minerals and processes. In P. Sylvester, Ed., Laser Ablation-ICPMS in the Earth Sciences: Principles and Applications, 29, 185. Mineralogical Association of Canada, Quebec.

Langille, J.M., Jessup, M.J., Cottle, J.M., Lederer, G., and Ahmad, T. (2012) Timing of metamorphism, melting, and exhumation of the Leo Pargil dome, northwest India. Journal of Metamorphic Geology, 30(8), 769–791.

Liu, Z.-C., Wu, F.-Y., Yang, Y.-H., Yang, J.-H., and Wilde, S. A. (2012) Neodymium isotopic compositions of the standard monazites used in U-Th-Pb geochronology. Chemical Geology, 334, 221–239.

Machado, N. and Gauthier, G. (1996) Determination of $^{207}Pb/^{206}Pb$ ages on zircon and monazite by laser-ablation ICPMS and application to a study of sedimentary provenance and metamorphism in southeastern Brazil. Geochimica et Cosmochimica Acta, 60, 5063–5073.

Mahan, K.H., Wernicke, B.P., and Jercinovic, M.J. (2010) Th-U-total Pb geochronology of authigenic monazite in the Adelaide rift complex, South Australia, and implications for the age of the type Sturtian and Marinoan glacial deposits. Earth and Planetary Science Letters, 289, 76–86.

McFarlane, C.R.M. and McCulloch, M.T. (2007) Coupling of in-situ Sm-Nd systematics and U-Pb dating of monazite and allanite with applications to crustal evolution studies. Chemical Geology, 245, 45–60.

Montel, J.-M., Foret, S., Veschambre, M., Nicollet, C., and Provost, A. (1996) Electron microprobe dating of monazite. Chemical Geology, 131, 37–53.

Norby, T. and Christiansen, N. (1995) Proton conduction in Ca- and Sr-substituted $LaPO_4$. Solid State Ionics, 77(C), 240–243.

Oelkers, E.H. and Montel, J.-M. (2008) Phosphates and nuclear waste storage. Elements, 4(2), 113–116.

Overstreet, W.C. (1967) The geological occurrence of monazite. United States Geological Survey, Professional Paper 530.

Parrish, R.R. (1990) U-Pb dating of monazite and its application to geological problems. Canadian Journal of Earth Sciences, 27, 1431–1450.

Peterman, E.M., Mattinson, J.M., and Hacker, B.R. (2012) Multi-step TIMS and CA-TIMS monazite U-Pb geochronology. Chemical Geology, 312, 58–73.

Pyle, J.M., Spear, F.S., Wark, D.A., Daniel, C.G., and Storm, L.C. (2005) Contributions to precision and accuracy of monazite microprobe ages. American Mineralogist, 90(4), 547–577.

Spear, F.S. (2010) Monazite-allanite phase relations in metapelites. Chemical Geology, 279, 55–62.

Suzuki, K. and Adachi, M. (1991) The chemical Th-U-total lead isochron ages of zircon and monazite from the gray granite of the Hida terrance, Japan. Journal of Earth Sciences, Nagoya University, 38, 11–37.

Wawrzenitz, N., Krohe, A., Rhede, D., and Romer, R.L. (2012) Dating rock deformation with monazite: The impact of dissolution precipitation creep. Lithos, 134–135, 52–74.

Williams, M.L. and Jercinovic, M.J. (2012) Tectonic interpretation of metamorphic tectonites: integrating compositional mapping, microstructural analysis, and in situ monazite dating. Journal of Metamorphic Geology, 30(7), 739–752.

Williams, M.L., Jercinovic, M.J., and Hetherington, C.J. (2007) Microprobe monazite geochronology: Understanding geologic processes by integrating composition and chronology. Annual Review of Earth and Planetary Sciences, 35(1), 137–175.

Williams, M.L., Jercinovic, M.J., Harlov, D.E., Budzyń, B., and Hetherington, C.J. (2011) Resetting monazite ages during fluid-related alteration. Chemical Geology, 283, 218–225.

Zhu, X.K., O'Nions, R.K., Belshaw, N.S., and Gibb, A.J. (1997) Significance of in situ SIMS chronometry of zoned monazite from the Lewisian granulites, northwest Scotland. Chemical Geology, 135, 35–53.

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