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Proterozoic crustal evolution of central East Antarctica: Age and isotopic evidence from glacial igneous clasts, and links with Australia and Laurentia

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ABSTRACT

Rock clasts entrained in glacial deposits sourced from the continental interior of Antarctica provide an innovative means to determine the age and composition of ice-covered crust. Zircon U-Pb ages from a suite of granitoid clasts collected in glacial catchments draining central East Antarctica through the Transantarctic Mountains show that crust in this region was formed by a series of magmatic events at ~2.01, 1.88–1.85, ~1.79, ~1.57, 1.50–1.41, and 1.20–1.06 Ga. The dominant granitoid populations are ca. 1.85, 1.45 and 1.20–1.06 Ga. None of these igneous ages are known from limited outcrop in the region. In addition to defining a previously unrecognized geologic history, zircon O and Hf isotopic compositions from this suite have: (1) mantle-like $\delta^{18}O$ signatures (4.0–4.5‰) and near-chondritic Hf-isotope compositions ($\varepsilon_{Hf} \sim +1.5$) for granitoids of ~2.0 Ga age; (2) mostly crustal $\delta^{18}O$ (6.0–8.5‰) and variable Hf-isotope compositions ($\varepsilon_{Hf} = -6$ to $+5$) in rocks with ages of ~1.88–1.85, ~1.79 and ~1.57 Ga, in which the ~1.88–1.79 Ga granitoids require involvement of older crust; (3) mostly juvenile isotopic signatures with low, mantle-like $\delta^{18}O$ (~4–5‰) and radiogenic Hf-isotope signatures ($\varepsilon_{Hf} = +6$ to $+10$) in rocks of 1.50–1.41 Ga age, with some showing crustal sources or evidence of alteration; and (4) mixed crustal and mantle $\delta^{18}O$ signatures (6.0–7.5‰) and radiogenic Hf isotopes ($\varepsilon_{Hf} = +3$ to $+4$) in rocks of ~1.2 Ga age. Together, these age and isotopic data indicate the presence in cratonic East Antarctica of a large, composite igneous province that formed through a punctuated sequence of relatively juvenile Proterozoic magmatic events. Further, they provide direct support for geological correlation of crust in East Antarctica with both the Gawler Craton of present-day Australia and Proterozoic provinces in western Laurentia. Prominent clast ages of ~2.0, 1.85, 1.57 and 1.45 Ga, together with sediment source linkages, provide evidence for the temporal and spatial association of these cratonic elements in the Columbia supercontinent. Abundant ~1.2–1.1 Ga igneous and metamorphic clasts may sample crust underlying the Gamburtsev Subglacial Mountains, indicating the presence of a Mesoproterozoic orogenic belt in the interior of East Antarctica that formed during final assembly of Rodinia.

1. Introduction

The nature of Antarctic continental lithosphere is Earth's last geological frontier. The Precambrian cratonic elements of the East Antarctic shield are of similar size as Australia or the contiguous U.S., yet, because of extensive ice cover and sparse remote-sensing data, this composite shield remains largely unexplored except for locally well-known coastal geological exposures (Harley and Kelly, 2007). Further, there is virtually no basement outcrop for about a third of its perimeter along the Transantarctic Mountains (TAM) margin, which are underlain mainly by Phanerozoic rock assemblages. Despite large gaps in our understanding, however, the East Antarctic lithosphere is globally important because: (1) as one of the largest coherent Precambrian shields, including rocks as old as ~3.8 Ga, it represents an important component in the global crustal growth history (Condie and Aster, 2010; Hawkesworth et al., 2016); (2) it is a key piece in assembly of the Columbia (~2 Ga), Rodinia (~1 Ga) and Gondwana (0.6–0.5 Ga) supercontinents (e.g., Fitzsimons, 2003; Boger, 2011; Ferraccioli et al., 2011; Harley et al., 2013; Goodge and Fanning, 2016), the assembly and breakup of which are associated with major changes in paleogeographic, sediment dispersal, geochemical, and biotic patterns (e.g., Lindsay and Brasier, 2002; Moores, 2002; Nance et al., 2014; Gernon et al., 2016); (3) it is the substrate to Earth's largest ice cap

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(East Antarctic ice sheet), including numerous subglacial lakes, and influences its thermal state and mechanical stability (Pollard et al., 2005; Jamieson and Sugden, 2008; Van Liefferinge and Pattyn, 2013; Schroeder et al., 2014); and (4) its geotectonic association with formerly adjacent cratons in South Africa, India and Australia suggests that it might harbor important mineral resources. Despite the influence of the East Antarctic shield on these processes and events, however, there is scant direct evidence concerning its age, composition, internal structure, and petrogenesis.

Uncovering the ice-covered geology of East Antarctica is therefore critical for understanding its ancient crustal history, its role in supercontinent formation, and its relationship to development of the Cenozoic ice cap. For example, despite seismological evidence for thick, cold lithosphere across much of East Antarctica (e.g., An et al., 2015), we have little explicit knowledge about its age and composition except from limited coastal and mountain rock exposures. Likewise, hypotheses for crustal provinces and boundaries related to assembly of the East Antarctic shield (e.g., Fitzsimons, 2003; Boger, 2011) are based mainly on extrapolation of coastal geology toward the interior, yet these models are largely unconstrained very far inland. Also, ideas concerning the origin and evolution of the completely buried Gamburtsev Subglacial Mountains, some including hypotheses of orogenic activity (e.g., Ferraccioli et al., 2011), are permissive based on interpretation of potential-field geophysical data but lack direct evidence of geologic age and composition. Despite the ambiguities inherent in studying a continent covered by a thick ice sheet, it is clear that multiple approaches—including detrital-mineral provenance study, analysis of glacial clasts, airborne and ground-based geophysics, and future sub-glacial drilling—are improving our view of the remote continental interior. Proxy geologic materials such as detrital zircons and glacial clasts provide a means to sample the ice-covered crust, although spatial-geographic resolution is poor; conversely, geophysical data are spatially precise yet limited by uncertainty in geologic interpretation. In addition to U-Pb zircon ages of ~3.1, 2.5 and 1.7 Ga from outcrops of the Nimrod Complex (e.g., Goodge and Fanning, 2016), an isolated basement assemblage adjacent to central East Antarctica, detrital-zircon provenance and glacial clast studies from the central Transantarctic Mountains show that the continental interior was formed by a series of episodic magmatic events between about 2.0–1.1 Ga (Goodge et al., 2004, 2008, 2010). Whereas geophysical data provide insight into lithospheric properties and internal structure (e.g., Aitken et al., 2014; An et al., 2015), and the geology circumscribing East Antarctica provides specific age constraints that outline a long-lived Mesoarchean to Mesoproterozoic history (Harley and Kelly, 2007; Harley et al., 2013), much can be gained from rock samples recovered from the continental interior.

Our main goal in this study is to illuminate the geology of the ice-covered East Antarctic shield, document its crustal history, and evaluate correlations with other cratons in order to test and develop supercontinent growth models. The approach we adopted is to sample igneous and metamorphic rock clasts from glacial moraines sourced within central East Antarctica (Fig. 1). Our focus is on analysis of accessory minerals such as zircon to determine their U-Pb ages, and Hf and O isotopic compositions. Because of its robust nature and host to different trace elements, zircon is a rich repository of age and isotopic information that can be used to assess crustal composition and process as a function of time (Hawkesworth and Kemp, 2006; Kemp et al., 2006; Harley and Kelly, 2007; Scherer et al., 2007; Condie et al., 2009). Zircons are abundant in many rock types, often occur as composite grains with complex internal structure, contain valuable isotopic and trace-element information, are refractory and resistant to high-*T* chemical change, and provide arguably the best geochronometer available (via the U-Pb system) to address a wide range of geological processes. Long used as an age tool, continuing advances in analytical approaches (in particular: SIMS; LA-MC-ICPMS; and LASS[2]) allow for the *in situ* measurement of many elements and isotopes, making it possible to associate age and isotopic tracer information to specific growth stages and conditions. A focus in this study on zircon from glacial igneous rock clasts can therefore provide critical data about age and inheritance (U-Pb), the involvement of hydrated crustal or mantle source materials (O isotopes), and mantle vs. crustal sources during their evolution (Hf isotopes). Together with whole-rock geochemical analyses, new zircon age and isotopic data can help to refine models of crustal assembly in East Antarctica, provide constraints on models of Columbia and Rodinia supercontinent assembly, provide new details of the cratonic substrate to the East Antarctic ice sheet, and help guide future subglacial bedrock coring in the interior of East Antarctica.

Because so little of the Precambrian shield of East Antarctica is exposed in either the Transantarctic Mountains or coastal areas, bedrock erosion by glacial flow can provide natural proxy samples of the continental interior (e.g., Peucat et al., 2002; Goodge et al., 2008, 2010). Major ice streams in East Antarctica are marked by nearly radial flow away from central ice divides and domes toward the continental margin (Fig.1a). Unique among the major ice-stream systems, glacial ice in the Byrd Glacier and related smaller drainages moves laterally from the main ice divides and is obstructed by the high-standing Transantarctic Mountains (peak elevations > 4000 m). Ice flows through the mountains via channelized outlet glaciers, but it also ablates in areas where it ramps up against the mountain range (Whillans and Cassidy, 1983). Glacial moraines are formed both along the margins of the outlet glaciers and where ice is ablating, forming lag deposits adjacent to the mountains. For this study, we targeted about a dozen sites extending > 1500 km along the length of the Transantarctic Mountains where glacial moraines are exposed, from the Convoy Range in southern Victoria Land to Strickland Nunatak near Reedy Glacier (Fig. 2). Ice velocity fields show that material transported in the greater Byrd Glacier system may have been eroded from a broad area of central East Antarctica, potentially from near the upstream boundary along the major ice divide connecting Dome A and Dome C (Fig. 1).

This study reports findings from geochemical, geochronological, and isotopic analysis of a subset of igneous rock clasts collected from glacial deposits flanking the Transantarctic Mountains. The rocks considered here consist mainly of intermediate to felsic igneous rocks, mostly of granitoid composition, representing magmatic components of the ice-covered East Antarctic craton. Many of the samples are meta-igneous rocks with deformation fabrics and/or metamorphic mineralogies that reflect a multi-stage history of initial crystallization and overprinting. Here we report new whole-rock major- and trace-element compositions, U-Pb zircon ages, and O- and Hf-isotopic compositions for a suite of 22 igneous clasts. Populations with ages between about 2.0–1.0 Ga provide new constraints on the Proterozoic crustal history of central East Antarctica, including magma sources, crustal inheritance, and periods of deformation. Age and isotopic correlations between these samples and rocks in both Australia and Laurentia strengthen paleogeographic ties during the Proterozoic assembly of the supercontinents Columbia (or Nuna; see Meert, 2012) and Rodinia.

2. Approach and analytical methods

This study focused on five sites in the general area of the Byrd Glacier drainage—Argo Glacier, Lonewolf Nunataks, Milan Ridge, Mt. Sirius, and Turret Nunatak—that yielded pre-Ross igneous clasts, thereby providing evidence regarding composition and age of the Precambrian East Antarctic shield (Figs. 1 and 2; Table 1). One of the most productive sites at Lonewolf Nunataks consists of elongate bands of distributed moraine and ice-matrix debris along narrow flow lines related to ice movement along the southern margin of Byrd Glacier (Fig.3a). Sites at Milan Ridge and Argo Glacier, directly adjacent to exposed Precambrian basement in the Miller Range, comprise thin, distributed morainal deposits dominated by a rich variety of crystalline rock types. Sites at Turret Nunatak and Mt. Sirius are dominated by clasts of Jurassic Ferrar-type tholeiitic dolerites or sedimentary rocks of the Beacon Supergroup (Devonian to Triassic Gondwana strata), but

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[2] SIMS, secondary-ion mass spectroscopy; LA-MC-ICPMS, laser-ablation multi-collector inductively-coupled plasma mass spectroscopy; LASS, laser-ablation split stream.