Multidisciplinary approaches to exploration of the subglacial geology in East Antarctica

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Antarctica is Earth's last continental frontier. Due to extensive ice cover, the lithosphere of East Antarctica remains enigmatic and largely unexplored except for locally well-known coastal geological exposures and from geophysical surveys. Beneath the ice sheet, Precambrian cratonic elements of the composite East Antarctic shield are similar in size to Australia or the contiguous U.S., yet there is virtually no basement outcrop for about a third of its perimeter along the Transantarctic Mountains (TAM) margin. Despite these large gaps, East Antarctic lithosphere is important because: (1) it forms one of the largest coherent Precambrian shields, includes rocks as old as ~3.8 Ga, and represents an important element in the global crustal growth history; (2) it is a key piece in assembly of the Columbia (~2 Ga), Rodinia (~1 Ga) and Gondwana (0.6–0.5 Ga) supercontinents; (3) it is the substrate to Earth's largest ice cap (East Antarctic ice sheet) and influences its thermal state and mechanical stability; and (4) its geotectonic association with formerly adjacent cratons in South Africa, India and Australia suggests that it might harbor important mineral resources.

Uncovering the geology of East Antarctica is critical for understanding its ancient crustal history, its role in supercontinent formation and breakup, and its relationship to development of the Cenozoic ice cap. Outstanding geological problems include recognition of crustal provinces and boundaries; reconstructing the tectonic assembly history; origin of the Gamburtsev Subglacial Mountains; and distribution of heat flow and its role in ice-sheet behavior.

Despite the influence of the East Antarctic shield on these processes and events, there is scant direct evidence concerning its age, composition, internal structure, and petrogenesis. To study a remote continent covered by a thick ice sheet, a variety of innovative and multidisciplinary approaches must be used. Complementary approaches to study of subglacial geology in East Antarctica include: (1) proxy sampling methods (e.g., study of detrital minerals and glacial erratics sourced from beneath the ice sheet); (2) geophysical remote sensing through the ice sheet (ice-penetrating radar, aeromagnetics, gravity, seismology); and (3) direct subglacial access drilling into underlying bedrock in order to obtain samples. Each approach has strengths and limitations. Proxy geologic materials such as detrital zircons and glacial rock clasts provide a means to sample the crust and to acquire precise age and compositional information, but spatial-geographic resolution is poor. Conversely, geophysical data are spatially precise yet limited by uncertainty in geologic interpretation. Subglacial access drilling offers unprecedented opportunity to sample beneath the ice sheet, but it is limited by small number of potential drill sites. Examples of the first and last of these approaches will be explored here, but geophysical methods are intrinsically important to the others for interpretation and targeting.

Crystalline basement outcrops of the Nimrod Complex represent the only known exposure of the East Antarctic shield adjacent to the TAM. This crustal assemblage yields U-Pb zircon ages of ~3.1, 2.5 and 1.7 Ga, but how far it extends into central East Antarctica is unknown. Nonetheless, detrital-zircon provenance and glacial rock-clast studies from the central TAM show that the continental interior was formed by a series of episodic magmatic events between about 2.0–1.1 Ga. Zircon U-Pb ages from a suite of granitoid glacial erratics collected in glacial catchments draining central East Antarctica 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 (Goodge et al., 2008, 2017). Importantly, none of these igneous ages are known from outcrop in the region, indicating that this suite has sampled entirely unique and previously unknown ice-covered crustal provinces.

In addition to its previously unrecognized age history, zircon O and Hf isotopic compositions from this suite 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, the age and isotopic data 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 provenance ties, link East Antarctica with cratonic elements in the Columbia supercontinent. Abundant ~1.2–1.1 Ga igneous and metamorphic clasts may sample crust underlying the Gamburtsev Subglacial Mountains, a possible Mesoproterozoic orogenic belt in the interior of East Antarctica that formed during final assembly of Rodinia.

In addition to age and compositional information, the glacial erratics can inform about subglacial thermal conditions. Terrestrial heat flow is a critical first-order factor governing the thermal condition and, therefore, mechanical stability of Antarctic ice sheets, yet heat flow across Antarctica is poorly known. Estimates of terrestrial heat flow in East Antarctica come from inversion of seismic and magnetic geophysical data, by modeling temperature profiles in ice boreholes, and by calculation from heat production values reported for exposed bedrock. Although accurate estimates of surface heat flow are important as an input parameter for ice-sheet growth and stability models, there are no direct measurements of terrestrial heat flow in East Antarctica coupled to either subglacial sediment or bedrock. First-order estimates of heat flow in central East Antarctica can be extrapolated from heat production determined by the geochemical composition of glacial rock clasts eroded from the continental interior.

U, Th, and K concentrations in the Proterozoic granitoids sourced from central East Antarctica indicate average upper crustal heat production of about 2.6 ± 1.9 μW m^{-3} (Goodge, 2018). Assuming typical mantle and lower crustal heat flux, the heat production values yield estimates of surface heat flow ranging from 33 to 84 mW m^{-2} and an average of 48.0 ± 13.6 mW m^{-2}. This suite of glacially sourced granitoids therefore indicates that the interior of the East Antarctic ice sheet is underlain in part by Proterozoic continental lithosphere with an average surface heat flow, providing constraints on both geodynamic history and ice-sheet stability. Although not of uniform age, they indicate only minor variations in thermal contribution to the overlying ice sheet from upper crustal heat production.

Exploration of the interior of the Antarctic ice sheet and its bed has proceeded slowly over the past several decades, motivating a rapid alternative to traditional methods of ice coring and rock drilling. At the same time, new technologies such as borehole optical logging have lessened the need for traditional continuous ice cores and increased the desire for multiple deep boreholes. The search for 1.5 million year-old ice requires fast reconnaissance drilling at low cost without taking long ice cores. Pressing questions about future sea level rise also create an urgent need for direct borehole-based observations in Antarctica, such as geothermal heat flow and basal material properties. Furthermore, most of the Antarctic geological map is still blank, hampering understanding of how the Antarctic continent was assembled, a need best addressed by a survey program of short rock cores taken quickly from multiple sites beneath the ice. To this end, the concept was born of a 'rapid-access ice drill' (RAID) that quickly explores the ice sheet interior in non-coring mode, taking small numbers of short cores of materials with high scientific value (Goodge and Severinghaus, 2016).

RAID was designed to quickly penetrate the Antarctic ice sheets in order to create borehole observatories and take cores in deep ice, the glacial bed, and bedrock below. It is unlike any other ice-penetrating tool. RAID is a sled-mounted mobile drilling system capable of making multiple long, narrow (3.5 inch diameter) boreholes in a single field season. It is based on a mineral exploration-type rotary rock-coring system to cut through ice, with reverse circulation of a non-freezing fluid for removal of ice cuttings and pressure-compensation. Near the bottom of the ice sheet, a wireline latching assembly will enable the taking of rapid short cores of ice, the glacial bed, and bedrock below. Once complete, boreholes will be kept open with fluid for future down-hole measurements of ice chronology, ice deformation, temperature gradient, heat flow, and subglacial geodetics, crustal stress, and seismology. RAID is designed to penetrate up to 3,300 meters of ice and take cores in about 10 days at each site. The rapid drilling capability and mobility of the system, together with ice-penetrating imaging methods, will provide a unique 3D picture of interior and subglacial features of the Antarctic ice sheets. Both the samples returned from coring and the creation of a legacy borehole array for repeat observation make RAID a uniquely powerful research tool that is highly interdisciplinary, with applications in ice-sheet dynamics, paleoclimate, glaciology, ice-sheet history, geology, crustal history, microbiology, heat flow, potential-field geophysics, seismology, and geodetics. RAID is now at McMurdo Station and is being field-tested in the Antarctic environment.

References

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