DRAFT FINAL REPORT
RAID Science Planning Workshop

John Goodge and Jeff Severinghaus, conveners

Summary

A RAID Science Planning Workshop was held in La Jolla, California, on March 2-3, 2017. It was supported by an award from the NSF to Scripps Institution of Oceanography. With development of the Rapid Access Ice Drill (RAID) progressing through field testing in Antarctica, the time was ripe for a first in-depth science planning workshop. This two-day workshop brought together scientists with potential interest in using the tool (or the samples and boreholes created by the tool) in order to develop a coherent long-term plan for science deployment. It resulted in a document that systematically maps out the science community's anticipated use of this research facility over a 5-year period. Separate disciplinary reports, currently in draft form, are being assembled by community members representing glaciology, the glacial bed interface zone, and bedrock geology.

Background

Exploration of the interior of the Antarctic ice sheet and its bed has proceeded slowly in the six decades of the US Antarctic program, 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 need for multiple deep boreholes. The search for 1.5 million year-old ice requires fast reconnaissance drilling at low cost without need for long ice cores (Fischer et al., 2013). 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 (NRC, 2015). 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. From this background, the concept was born of a 'rapid-access ice drill' that quickly explores the ice sheet interior in non-coring mode, taking small numbers of short cores of materials with high scientific value.

Briefly, 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 to make multiple long, narrow (3.5 inch diameter) boreholes in a single field season on the ice sheets of Antarctica. It is based on a mineral exploration-type rotary rock-coring system using threaded drill pipe 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 (for a nominal 5 years) with fluid, available 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 less than 200 hours, allowing completion of a borehole and coring in about 10 days at each site. Together, the rapid drilling capability and mobility of the system, along 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 ongoing and repeatable 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. A recent publication describes the RAID system in more detail (Goodge and Severinghaus, 2016).

As of the workshop, RAID has passed important developmental milestones such as design completion; construction, validation, and acceptance; North American testing; shipment to Antarctica; and Antarctic testing of the auger and packer components. These successful milestones demonstrate conceptual feasibility and achievement of design capability. RAID is now at McMurdo Station and is being readied for a second round of field tests in a polar environment, to be conducted at Minna Bluff in December 2017. The RAID Science Planning Workshop was convened in order to build upon our previous informal gatherings of the RAID science community at AGU and other meetings over the past four years.

Workshop Goals

The RAID Science Planning Workshop was intended to:

- provide a venue to bring diverse scientists together to explore new science questions and approaches
- define science goals
- seek synergies between different disciplines for RAID
- develop a coherent community science plan for use of this unique community research facility
- set priorities among the list of science targets
- engage early-career and underrepresented researchers.

The workshop was an opportunity to bring together researchers with scientific interests in glaciology, ice-sheet dynamics, paleoclimate, borehole logging, the ice-bedrock interface, exposure and uplift histories, subglacial bedrock geology, subglacial sediments, microbiology, heat flow, potential-field geophysics, seismology, solid-earth and glacial-rebound geodetics, and ice-penetrating radar. An over-arching goal of the workshop was to identify genuine scientific synergies, enabled by having a very diverse group of specialists and the 'fresh eyes' of early-career researchers, all in the same room.

Setting priorities is often the most difficult part of any community endeavor, and RAID is no exception. Clearly expressed priorities are nonetheless crucial information to provide to the NSF in order to guide difficult decisions on resource allocation. A specific goal of this workshop was therefore to produce a prioritized list of science targets as part of the science planning document that emerges from the meeting.

Participants

The RAID workshop had 37 participants, listed below. These included 7 graduate students, 7 early career scientists, 8 female participants, and 3 from under-represented groups.

Sridhar Anandakrishnan	Penn State University
Monica Arienzo	Desert Research Institution
Greg Balco	Berkeley Geochronology Center
Suzanne Baldwin	Syracuse University

Ryan Bay	UC Berkeley
Carolyn Branecky	UC Santa Cruz
Knut Christianson	University of Washington
Jason Coenen	Northern Illinois University
Kurt Cuffey	UC Berkeley
Anders Damsgaard	Scripps Institution of Oceanography
Scott DeWolf	Clemson University
Cooper Elsworth	Stanford University
Elizabeth Erickson	UC Santa Barbara
Fausto Ferraccioli	NERC/BAS (UK)
Paul Fitzgerald	Syracuse University
John Goodge	University of Minnesota Duluth
Michael Jackson	NSF
Merlin Mah	University of Minnesota Twin Cities
Glen Mattioli	UNAVCO
Jessica Ng	Scripps Institution of Oceanography
Erin Pettit	University of Alaska Fairbanks
Joseph Pettit	UNAVCO
Eric Salzmann	NSF
Joerg Schaefer	Lamont/Columbia University
Reed Scherer	Northern Illinois University
Helene Seroussi	Jet Propulsion Laboratory
Jeff Severinghaus	Scripps Institution of Oceanography
Matthew Siegfried	Scripps Institution of Oceanography
Emilie Sinkler	University of Alaska Fairbanks
John Stone	University of Washington
Randy Stotler	University of Kansas
Joey Talghader	University of Minnesota Twin Cities
Doug Wiens	Washington University in St Louis
Thom Wilch	NSF
Paul Winberry	Central Washington University
Duncan Young	University of Texas Institute for Geophysics
Mark Zumberge	Scripps Institution of Oceanography

RAID organization

Based on discussion among the whole group, a previously designated Site Selection Committee was reformulated more simply as the RAID Steering Committee. This group will help to guide operational use of RAID based on scientific goals articulated by the research community and as made possible by funded science projects.

RAID 5-year priority science plan

The workshop successfully resulted in a set of disciplinary reports that outline the major goals, priorities, and locations of future drilling targets. Discipline areas include glaciology, paleoclimate, glacial bed interface, and solid earth. In order to identify both scientific synergies and geographical overlaps, the whole group outlined a sequence of traverses operating in East Antarctica from a logistical hub at South Pole for a series of boreholes to be completed during a 5-year drilling campaign (Y1 to Y5). The order of targets is organized by overall science priority balanced by consideration of logistical support requirements. Principal goals and objectives for this effort are outlined in Table 1 and illustrated graphically in Figure 1.

Principal science drivers and questions to be addressed for each year of the 5-year program are as listed below. All boreholes will be considered targets of opportunity for a combination of borehole logging, observation and sampling of glacial bed materials, microbiology, bedrock core recovery, exposure age determination, temperature gradient and heat flow, and borehole instrumentation (as borehole characteristics and suitability allow).

Y1 (4 holes, 2019-20):

- traverse from McMurdo to South Pole region
- proving of drill operations at high elevation on the polar plateau
- drill 2 closely-spaced holes at Hercules Dome to evaluate the presence of Eemian ice, and to set up an experiment for assessing borehole logging replication and validation of geophysical survey
- drill at Titan Dome to assess for oldest ice, bedrock geology exploration, and heat flow
- drill at South Pole to assess ice dynamics via borehole deformation, bedrock geology samples, and to provide a conduit to ground scientific equipment at South Pole station

Y2 (5 holes, 2020-21):

- traverse along a corridor between South Pole and Dome A
- bedrock sampling profile across crustal provinces and tectonic boundaries
- assess glacial dynamics along an ice flow line with a series of boreholes
- reconnaissance search for oldest ice
- ice-sheet exposure age history near rock promontories

Y3 (6 holes, 2021-22):

- network of boreholes over the western part of the Gamburtsev Subglacial Mountains
- reconnaissance search for oldest ice
- direct rock sampling of enigmatic Gamburtsev Mountains geology
- expose age history to date onset of ice sheet
- targeted short ice cores in enigmatic ice 'plumes' seen in AGAP radar profiles

Y4 (6 holes, 2022-23):

- traverse following downstream profile of major ice stream draining East Antarctica (Support Force Ice Stream)
- series of 3 boreholes (without bed intersection) along downstream flow line of the Support Force Glacier to assess glacial dynamics in different segments and regimes
- boreholes over Recovery Subglacial Highlands and west of South Pole for oldest ice reconnaissance and testing of Rodinia supercontinent assembly models

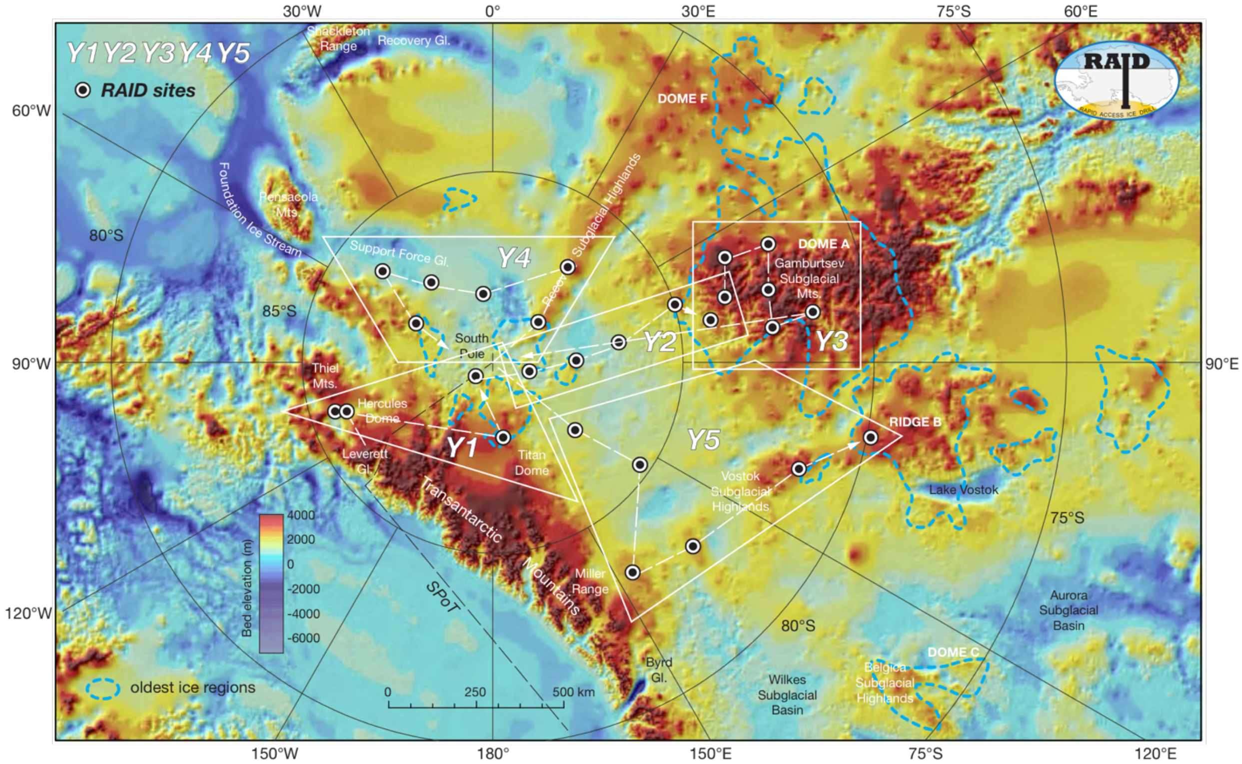

Figure 1. Map of subglacial topography (from Bedmap2) in central East Antarctica showing proposed locations and sequence of multi-disciplinary RAID boreholes. Areas predicted to harbor oldest ice (≥1.5 my) outlined by dashed blue lines. Y1-Y5 indicate principal areas of interest as outlined by white polygons.

Y5 (2023-24):

- traverse grid southeast of South Pole for access to ice streams, Wilkes Subglacial Basin, and sampling profile across bedrock crustal provinces
- sampling profile (counterpart to Dome A corridor in Y2) from near Nimrod Glacier to Ridge B for bedrock geology, to test Rodinia supercontinent assembly models
- intersect upper Wilkes basin for ancient paleoclimate records
- oldest ice reconnaissance on flank of Ridge B
- in-route coring at sites suitable for study of ice-stream dynamics, sedimentary basins, and bedrock geology
- possible return to McMurdo via Dry Valleys traverse route to bring RAID modules back to original station (could be completed at beginning of following season)

Table 1. Proposed RAID 5-year priority science plan.

RAID 5-YEAR PRIORITY SCIENCE PLAN							
Year	**Season**	**General area**	**Principal goals**	**No. of holes**		**Sites of interest**	**Primary Objectives**
Y1	2019-20	South Pole region	Plateau proving	4	1	Hercules Dome (2 holes)	Eemian ice recon, borehole validation
					2	Titan Dome	oldest ice recon, bedrock access, heat flow
					3	South Pole	bedrock access, ice dynamics, instrument ground
Y2	2020-21	Gamburtsev region	Dome A corridor	5	1	'Saddle'	oldest ice recon, ice dynamics, bedrock access
					2	Ridge site 1	oldest ice recon, ice dynamics, bedrock access
					3	Ridge site 2	oldest ice recon, ice dynamics, bedrock access
					4	Ridge site 3	oldest ice recon, ice dynamics, bedrock access
					5	Ridge site 4	oldest ice recon, ice dynamics, bedrock access
Y3	2021-22	Gamburtsev massif	Dome A and GSM	6	1	GSM highlands 1	oldest ice recon, GSM bedrock, exposure ages
					2	GSM highlands 2	oldest ice recon, GSM bedrock, exposure ages
					3	GSM margin	ice plumes, ice dynamics
					4	GSM highlands 3	oldest ice recon, GSM bedrock, exposure ages
					5	GSM highlands 4	oldest ice recon, GSM bedrock, exposure ages
					6	GSM highlands 5	oldest ice recon, GSM bedrock, exposure ages
Y4	2022-23	Recovery Highlands	Ice stream profile	6	1	Recovery Highlands 1	Recovery Highlands bedrock, oldest ice recon
					2	Recovery Highlands 2	Recovery Highlands bedrock, exposure ages
					3	Ice stream 1	Support Force Ice Stream dynamics 1
					4	Ice stream 2	Support Force Ice Stream dynamics 2
					5	Ice stream 3	Support Force Ice Stream dynamics 3
					6	Pensacola Highlands	oldest ice recon, bedrock access, exposure ages
Y5	2023-24	Beardmore-Byrd sector	Byrd sector corridor	6	1	Titan Dome E	bedrock access, exposure ages
					2	Beardmore E	bedrock/Wilkes basin, Byrd ice stream 1
					3	Nimrod province	crustal profile 1, oldest ice recon, exposure ages
					4	Upper Wilkes basin	crustal profile 2, Byrd ice stream 2, Wilkes basin
					5	Vostok Highlands	crustal profile 3, oldest ice recon
					6	Ridge B	crustal profile 4, oldest ice recon
Total				**27**			

Recognized synergies of RAID

RAID was designed as both a multi-disciplinary and an interdisciplinary tool. Although RAID clearly benefits from the logistical advantage of making an ice borehole at the same time as sampling the glacial bed and taking bedrock cores, there are also genuine opportunities for scientific synergy. From the broad research areas represented by the workshop participants, a set of critical synergies were identified that can be uniquely addressed by RAID, but that also serve to bring together members of the scientific community who typically do not work directly with one another. The highlighted synergies include:

- heat flow as a contributor from the solid earth to ice-sheet stability
- basal materials and properties as a control on ice-sheet dynamics
- bedrock exposure ages as a window into ice-sheet growth history
- borehole instrumentation as a long-term observatory for crustal and ice-sheet dynamics
- geodesy (Glacial-Isostatic Adjustment) in regions far from outcrops via borehole strain

A consensus among workshop participants is that heat flow is foremost among these synergies. It is clear that heat flow is the most crucial variable in determining whether ancient ice has been preserved or melted away near the bed, and in constraining the current potential for basal ice-sheet instability, and yet heat flow is one of the most poorly known parameters in the Antarctic system (Fischer et al., 2013). Heat flow depends on the bedrock concentrations of heat-producing radioactive elements (uranium, thorium, and potassium), so the emerging knowledge of bedrock geology from RAID will guide the search for 1.5 million-yr old ice and provide constraints on input parameters for future ice-sheet models.

References

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