COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 14-1 **NSF 13-527** **04/15/14**	FOR NSF USE ONLY NSF PROPOSAL NUMBER **1443497**
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) **PLR - ANTARCTIC INTEGRATED SYS SCI**	

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IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: A systems approach to understanding the Ross Ocean and ice Shelf Environment, and Tectonic setting Through Aerogeophysical surveys and modeling (ROSETTA)**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 155,138	48 months	03/01/15	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________ PHS Animal Welfare Assurance Number ________
- ☒ FUNDING MECHANISM **Research - other than RAPID or EAGER**
- ☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ________ Exemption Subsection ________ or IRB App. Date ________
- ☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
- ☒ COLLABORATIVE STATUS **A collaborative proposal from multiple organizations (GPG II.D.4.b)**

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PROJECT SUMMARY

Overview:

The Ross Ice Shelf (RIS) is formed by merging of ice from the fast-flowing Siple Coast ice streams of West Antarctica and large East Antarctic glaciers that drain catchments holding sufficient ice to significantly raise global sea level. Evidence from sediment cores and ice sheet models suggest that the RIS disappears during some interglacial periods, while satellite and in situ data document thickness and height variability on interannual to century time scales. However, the lack of information about fundamental processes that control RIS mass balance, and the potential role of the RIS in buttressing grounded ice, inhibits the ability to predict ice-sheet mass loss during projected climate warming. The proposed project ("ROSETTA") aims to advance our understanding of the dynamics of the ice-shelf system through acquisition of new high resolution data that will determine RIS thickness and structure, together with bedrock characteristics and seabed bathymetry under the ice shelf. ROSETTA enlists experts in Antarctic geology, geophysics, glaciology and oceanography to identify the critical processes and feedbacks that operate on a wide range of temporal and spatial scales to influence the past, present and future state of the RIS system. The objective is the formulation of accurate models that sharpen the understanding of past, present, and future behavior of the crust - ocean - ice sheet system in West Antarctica, including its boundaries with the Transantarctic Mountains and Marie Byrd Land.

To examine the linkages between ice sheet, ice shelf, ocean and geotectonic structure in the RIS region, the ROSETTA project proposes to acquire aerogeophysical data over RIS (~10 km grid, finer along-track sampling) using the IcePod sensor suite mounted on an LC-130, complemented by ocean measurements using air-deployed expendable profilers. ROSETTA datasets will be augmented by analog data from the 1970s RIGGS program. RIGGS data will be digitized and used to constrain interpretations of the new data, while contributing to preservation and accessibility of a singular dataset. Analysis and modeling of ROSETTA gravity data will yield high-resolution bathymetry, to be combined with magnetics to achieve geologic characterization of bedrock and sediments beneath the RIS. Radar, lidar and imagery will be used to map ice thickness and structure; basal channels, marine ice distribution and variable surface accumulation.

The new high definition models of seabed depth and ice draft will combine to produce a tightly constrained 3D model of sub-ice-shelf cavity geometry to be used in coupled ocean/ice modeling of sub-ice-shelf ocean circulation and basal melting. Ice-sheet dynamical models, informed by the detailed structure of RIS measured by ROSETTA, will be used to explore the sensitivity of RIS extent and thickness distribution to the effect of changes in ocean circulation derived from climate-model projections for the 21st century.

Intellectual Merit :

The ROSETTA aerogeophysical program will generate a comprehensive benchmark data set of geotectonic, ice shelf and ocean structure in the RIS region. New high-resolution models of the RIS sub-ice cavity, including geology-based assessment of bed parameters and permeability, will allow computation of accurate models of ocean/ice-shelf and bed/ice-sheet interactions that determine fine-scale ice-shelf structure and provide predictors for sites of calving, basal mass flux, and variations in flow of adjacent grounded ice streams. New interpretations of the basement structure and sediment distribution beneath RIS will illuminate the interplay between glacial dynamics of Antarctic ice sheets and underlying tectonics in shaping the seabed beneath the RIS.

Broader Impacts :

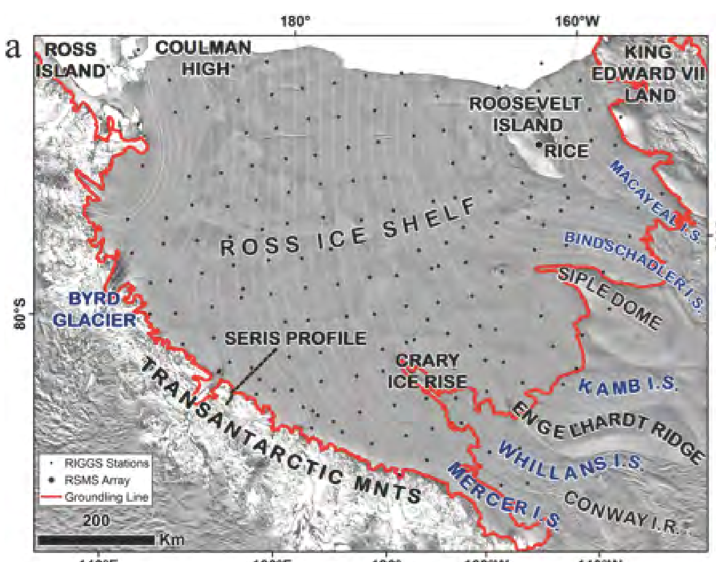
The ROSETTA data set will benefit the broad community interested in past, present and future behavior of the coupled RIS - grounded ice sheet system, and contribute to new understanding of ice-ocean-geotectonic interactions over a wide range of temporal scales. The systems understanding that emerges from this interdisciplinary program of the RIS region will be applicable to other similarly complex settings in Greenland and elsewhere in Antarctica. Education and outreach programs will build on the successful approach of linking data and concepts, targeting high school and undergraduate students with data-centric activities highlighting the importance of the cryosphere in global climate.

This proposal requires fieldwork in the Antarctic.

ROSETTA

A) Motivation, and Introduction to Ross Ice Shelf Region

The Ross Ice Shelf (RIS) region (**Fig. 1**) is a locus of significant interactions between its geotectonic setting, ice sheet, and ocean that have important ramifications across multiple disciplines. Bounded by the Transantarctic Mountains (TAM) to the southwest and Marie Byrd Land to the north, the RIS region (**Fig. 1a**) is the central section of the low-lying Ross Embayment. Tectonically, the RIS region is within the West Antarctic rift province, underlain by thin crust and warm mantle with low seismic velocities. Prominent features in the bed topography are broad, steep-sided, bedrock plateaus at 100 to 350 m below sea level, that are transected by glacial troughs reaching depths of 700 m or more (**Fig. 1d**). Overlying this framework is the massive Antarctic Ice Sheet (AIS) including the floating RIS. AIS catchments that drain into the Ross Sea through glaciers and ice streams feeding RIS (**Fig. 1b**) contain sufficient ice above flotation to significantly increase global sea level, motivating a climate interest in the region. The RIS serves as a buttress to the fast-flowing Siple Coast ice streams from West Antarctica, and to East Antarctic glaciers and ice streams that flow through the TAM. By analogy with observations from other ice-shelf-buttressed systems in both Antarctica and Greenland, we expect that significant changes in the mass budget of RIS will modify rates of ice export from the grounded portion of the ice sheet. Recent studies suggest that a change in the flux of ocean heat into the ocean cavities underlying ice shelves is the most likely trigger for rapid future ice sheet mass loss within the coming decades to centuries [*Joughin et al*., 2012]. On longer time scales, the RIS mass budget may also be sensitive to changes in surface mass balance and ice advection across the grounding line.



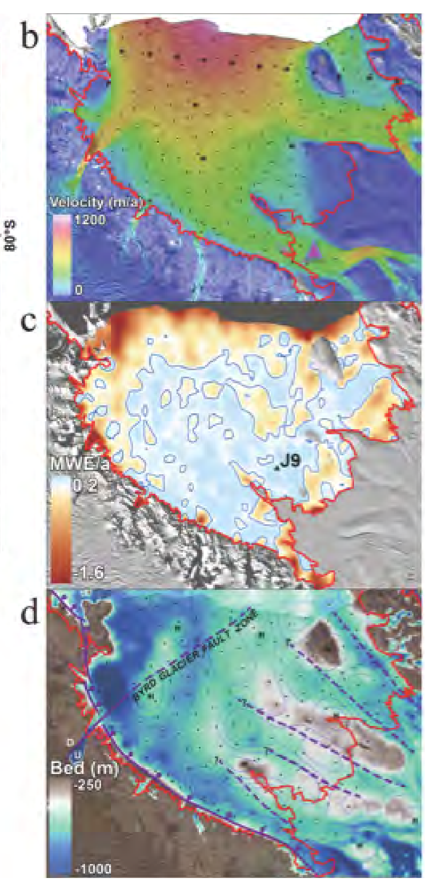


Fig. 1: *Ross Ice Shelf maps, including locations of RIGGS sites. (a) Modis-based MOA image with streamline, grounding lines and location names. (b) Ice velocity [Rignot et al., 2011]; with location of passive seismic study RSMS (stars) and WISSARD (pink triangle). (c) Basal melt rate in water equivalent (m a^{-1}) from Moholdt et al. [submitted]. w_b<0 is melting. Light blue areas inside blue contours are potential areas of marine ice accretion (d) Bedrock topography from Bedmap2 based on RIGGS data, showing extent of submerged basement plateaus with incised troughs, inherited rift structures, and inferred Byrd Glacier tectonic boundary. Contours show free air gravity anomaly from GOCE satellite [Bruinsma et al., 2013].*

The geotectonic, glacial and oceanic components are strongly coupled (**Fig. 2**). Ocean circulation and mixing, by which heat is delivered to the ice base to cause melting, are determined by seabed bathymetry and ice draft under RIS, and the roughness of these surfaces; e.g., whether the seabed is bare crystalline rock or covered with sediments. The bathymetry in the RIS region may have been carved by grounded ice during glacial maxima. The distribution of sediment under the RIS, including ice-flow-stabilizing grounding-zone wedges, depends on the flux of sediment across the grounding line, speed of release by basal melting, and subsequent dispersion by ocean flows. In turn, this sediment flux depends on grounded ice speed that may be controlled by buttressing from RIS and bedrock pinning points on submerged plateaus ("ice rises"). The response of RIS dynamics and its buttressing potential will be modified by variations in ice-shelf properties including “fine structure” such as basal channels, crevasses, basal marine ice, and upper-layer firn properties. The complexity and magnitude of interactions and feedbacks motivates the need for an interdisciplinary approach to understanding the coupled system (**Fig 2).** We have identified three fundamental hypotheses critical to advancing our knowledge of the inherently coupled geotectonic/ice-sheet/ice-shelf/ocean system of the Ross Ice Shelf region.

H.1) *The response of Ross Ice Shelf to changing climate is sensitive to interactions and feedbacks between ice, ocean and bed, the geometry of the sub-ice-shelf cavity and ice-shelf structure derived from ice/bed and ice/ocean interactions.*

H.2) *The prominent bathymetric structures beneath Ross Ice Shelf reveal the history of pre-glacial coastal erosion and glacial erosion of inherited bedrock structures.*

H.3) *Ocean general circulation, tidal currents, hydrography and mixing in the Ross Embayment, including under the ice shelf, are sensitive to seabed geology and changes in ice shelf extent and ice draft.*

These hypotheses are closely linked, motivating ROSETTA’s interdisciplinary systems approach to addressing them through detailed characterization of the entire RIS region, from the RIS grounding line to the calving front and from Marie Byrd Land to the Transantarctic Mountains. We expect that the ROSETTA program will lead to major advances in understanding the geotectonic origin of the Ross Embayment, oceanographic circulation in the sub-ice cavity, and RIS structure and variability under projected climate change.

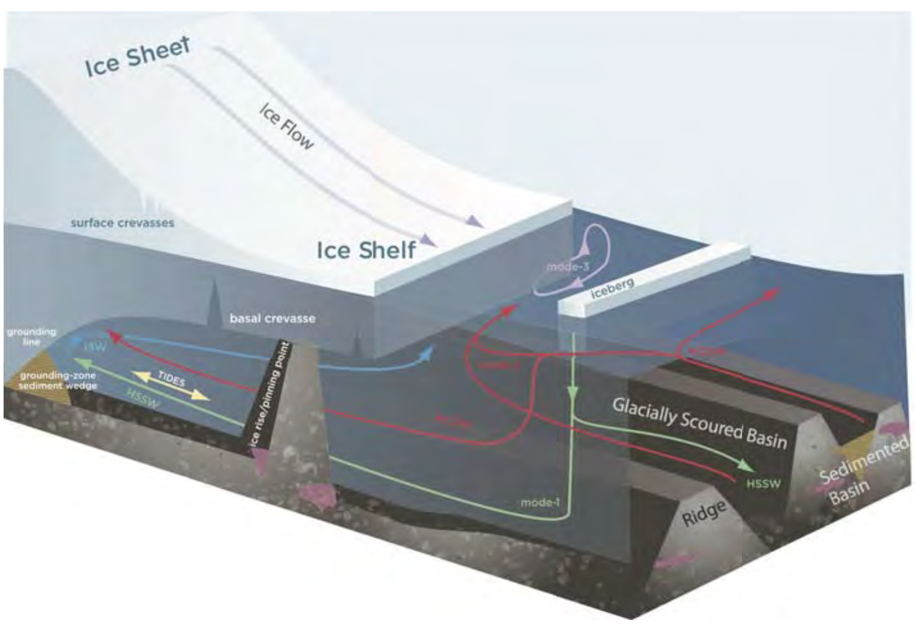


Fig. 2: *Schematic of the Ross Ice Shelf region and the major components of the RIS, an inherently coupled geotectonic/ice-sheet/ice-shelf/ocean system. For explanation of melt modes 1-3, see* **Section B.ii.** *Submarine plateaus and level-topped bedrock ridges influence marine circulation and pathways for fresh meltwater flow.*

B) Background

(i) Ross Ice Shelf (RIS) – Structure, Dynamics and Stability

Ice shelves are the floating extensions of the Antarctic Ice Sheet and are where most of its mass loss occurs, by iceberg calving and basal melting. For a steady-state ice shelf, mass loss balances the mass gained through ice inflow across the grounding line and net surface accumulation from local snowfall. Changes in an ice shelf will occur when any of these mass budget terms change. As ice shelves are already floating, changing their mass does not directly influence sea level. However, ice shelves provide a backstress on the surrounding grounded ice, a process known as "buttressing". Reductions in backstress, through reduced lateral stresses [e.g., *Dupont and Alley*, 2005] or release of a thinning ice shelf from ice rises and other pinning points [e.g., *Dutrieux et al*., 2013], may accelerate flow rates of grounded ice to the ocean [*Rignot et al*., 2004; *Scambos et al*., 2004; *Pritchard et al*., 2012]. The RIS contributes to buttressing of the Siple Coast ice streams, and major East Antarctic outlet glaciers.

The Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) program (1973-1978), led by University of Wisconsin [*Bentley*, 1990], transformed our quantitative knowledge of RIS. The RIGGS program occupied stations on a ~55 km grid (**Fig. 1**). A comprehensive study of the RIS region has not been repeated. The ice shelf is close to 1200 m thick at the deepest grounding lines and thins to <300 m close to the calving front. The ice speed varies from ~200 to 1000 m/yr (**Fig. 1b**) and ice takes ~500-1000 years to travel from the grounding line to the ice front. Some of the early analysis of the RIGGS data pointed towards changes in the ice-shelf flow [*Jezek*, 1984]. Models, satellite observations and sediment cores indicate that the flow and structure of the RIS changes on a wide range of time scales. *Pollard and DeConto* [2009] and *Naish et al*. [2009] noted loss of RIS on glacial-cycle time scales (~40-100 ka). *Hulbe et al.* [2007] and *Catania et al.* [2012] documented slowdown of Whillans Ice Stream on time scales of centuries. *Thomas et al*. [2012] found significant changes in ice-shelf velocity from the RIGGS era to recent InSAR measurements. While analysis of ICESat satellite laser altimetry 2003-2009 indicated the RIS was close to steady-state [*Pritchard et al*., 2012], more recent analyses of the longer satellite radar altimetry record show considerable inter-annual variability in ice-shelf surface elevation (**Fig. 3:** *Fernando Paolo*, pers. comm., 2014). Based on data acquired between 1994 and 2012, these short time scales of observed variability are consistent with sensitivity to atmospheric and/or oceanic variability. We conclude that the RIS has the potential to change dynamically on short time scales.

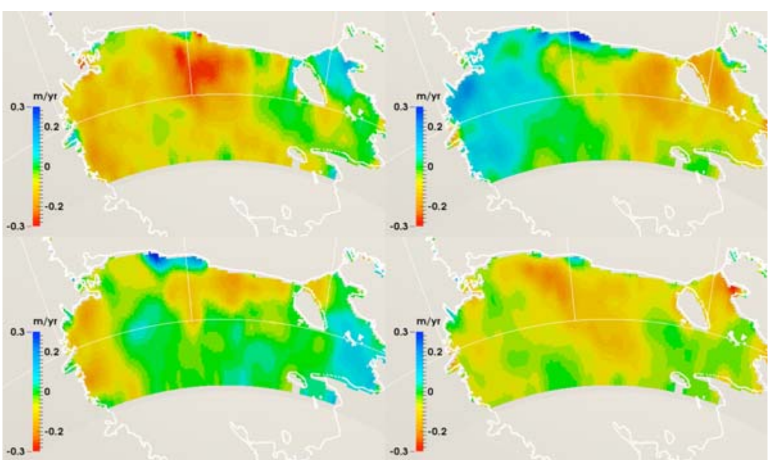


Fig. 3: *4.5-year linear trend dh_i/dt maps for RIS from ESA radar altimetry: (upper left) 1994 to 1998.5; (upper right) 1998.5 to 2003 (lower left); 2003 to 2007.5; (lower right) 2007.5 to 2012. Note large change in magnitudes and spatial patterns between different epochs, especially rapid lowering in western RIS (right side of plot) for epoch 2003-2012, possibly associated with strain thinning following calving of a large iceberg in 2000* [*Lazzara et al., 1999*].

Ice shelf retreat is driven by a range of processes from persistent erosion from increased basal melt to catastrophic collapse following surface-melt-enhanced crevasse penetration. The smooth advance of the RIS (~1 km/yr at the ice front (**Fig. 1b**)) is punctuated by sporadic rapid retreat during calving of large tabular icebergs. Occurring every 50-100 years, a single calving event can remove decades of accumulation from the ice shelf [*Lazarra et al*., 1999]. While we regard this process as a quasi-steady-state, processes that might lead to more rapid calving may provide a mechanism for ice-shelf retreat that falls between these two extremes. The calving process is influenced by ice-shelf structure and external forcing. Small-scale structural features of the ice shelf, referred to here as "fine structure", include longitudinal basal channels, rifts and crevasses. These structures influence ice-shelf response to applied forcing, and record the history of processes acting on the ice shelf. Large 1-2 km wide basal channels up to 200–400 m have been found oriented along-flow under Greenlandic and Antarctic ice shelves [e.g., *Rignot and Steffen*, 2008; *Fricker et al.*, 2009; *Vaughan et al.*, 2012]. Under Pine Island Glacier's ice shelf, measured basal melting is higher in a basal channel than under the nearby "ambient" ice shelf [*Stanton et al.*, 2013]. However, the origin of these channels is unclear. Beneath Amery Ice Shelf, channels follow sutures separating ice from individual glaciers [*Fricker et al*., 2009]. Alternative origins include subglacial water discharge at the grounding line [*Le Brocq et al.*, 2013] and lateral shear [*Sergienko*, 2013]. Regardless of ultimate cause, channels may be related to variations in topography and geology of the upstream bedrock, ice-shelf dynamics and ocean circulation and basal melting feedbacks. Increased rifting and calving rates can result from changing the ice debris (mélange) that fills rifts and acts to "glue" ice shelves together [e.g., *Hulbe et al.*, 1998]. Rift propagation may be sensitive to both ocean and atmospheric warming [*Fricker et al.*, 2005]. Model results indicate that increased ocean warming could thin the ice mélange and lead to increased iceberg calving rates [*Larour et al.*, 2004]. Understanding the ice shelf fine structure, rifts and crevasses (**Fig. 4a**) is important because many of these features are diagnostic of the past, present and future state of stress within the ice shelf.

The record is clear that the RIS has disappeared in past interglacials and has changed flow over centuries. Within the ice-ocean-geotectonic framework, we seek to answer the following questions about the RIS: (*1*) What drives the observed interannual and long-term changes in ice thickness on the RIS: atmosphere, ocean, pinning points (sediment wedges, ice rises), or all three? (*2*) How would the RIS evolve if more warm water were to enter the sub-ice-shelf cavity? (*3*) Do fine-scale structures influence the internal ice stresses that determine the response of RIS to changes in ocean/ice and ice/bed interactions? (*4*) Can we use ROSETTA's detailed observations of ice shelf structure to diagnose the current and past state of stress in the ice shelf? (*5*) How will these features evolve under changing ice shelf conditions, and what spatial and time scales are involved?

(ii) Ross Ice Shelf – Oceanography

Ice shelf mass loss affects the ice-shelf's buttressing potential, and will also modify the flux of buoyant, cold freshwater to coastal Antarctica and beyond, including an effect on Antarctic sea ice [*Bintanja et al*., 2013] and Ross Sea ecosystems [*Smith et al.*, 2014]. Mass is lost through iceberg calving and basal melting. Here we focus on basal melting, while noting that thinning near the ice front may increase calving rate. Basal melt rate w_b depends on lateral transport of ocean heat, and mixing of that heat to the ice base [see, e.g., *Holland and Jenkins*, 1999]. The ice-shelf cavity is insulated from direct atmospheric forcing but cavity circulation can be driven by wind stress, ocean densification during sea-ice formation and other processes seaward of the ice front [*Jacobs et al*., 1992], thermohaline flow set up by production of buoyant plumes through melt [*Lewis and Perkin*, 1986], and tides that propagate freely under ice shelves [*MacAyeal*, 1984a,b; *Padman et al*., 2002, 2008]. A characteristic minimum length scale for ocean current variability is the Rossby radius *Ro* which, for weakly stratified high-latitude seas, is ~5 km. The weak stratification also leads to a strong "potential vorticity" constraint on circulation, whereby currents tend to follow lines of constant water column thickness *wct*, which is the vertical distance from the seabed (H_{bed}) to the ice-shelf draft, z_{ice}. This constraint is only broken by small-scale ocean processes that are poorly parameterized in standard climate models. Furthmore, *Mueller et al.* [2012] showed, from their model of Larsen C Ice Shelf, that water column thickness *wct* can have a profound effect on the strength of tidal currents and basal melt rate (w_b) especially in regions like RIS. For RIS, relatively high values of satellite-derived basal melt rates w_b are found in several distinct zones (**Fig. 1c** [from *Moholdt et al*., submitted]). These reflect the three melt modes driven by different processes, first described by *Jacobs et al.* [1992]; see **Fig. 2**. Cold, High Salinity Shelf Water (HSSW) produced by sea-ice formation flows into the cavity along the seabed to the deep grounding lines, producing "mode-1" melting along the deep grounding lines of Siple Coast ice streams and East Antarctic glaciers. The cold (~-1.9°C) HSSW is still much warmer than the *in situ* freezing point $T_f(S,z)$ that is depressed at the high pressure near grounding lines (for typical salinity S, $T_f(z$=1 km)~-2.6°C). This grounding line melting produces a buoyant plume of extremely cold meltwater ("Ice Shelf Water") that rises along the ice base to a depth with higher $T_f(z)$ where it may add "marine ice" to the ice-shelf base [*Jenkins and Bombosch*, 1995]. A thin layer of marine ice was found from an ice core at RIGGS site "J9" [*Zotikov et al.*, 1980]. Recent estimates of basal melt (**Fig. 1c)** suggest that marine ice may be extensive; however, we lack *in situ* data to confirm this. The western RIS melt, and some melt in the northeast RIS, is associated with "mode-2" mid-depth inflows of Modified Circumpolar Deep Water (MCDW) that originates from mixing of CDW with colder upper-ocean waters near the shelf break. These are forced by winds over the Southern Ocean and Ross Embayment. Ice-front melt is a combination of mode-2, plus the effect of short-period processes (e.g., tides and eddies) that bring seasonally warmed upper-ocean water under the ice front (mode-3); the latter process has been observed from through-ice-shelf moorings [*Robinson et al*., 2010; *Stern et al.*, 2013; *Arzeno et al*., 2014] and repeat-track satellite altimetry [*Horgan et al.*, 2011]. All modes are strongly time-dependent, especially at annual periods as winds, sea-ice production, and insolation at the Ross Polynya vary profoundly between winter and summer.

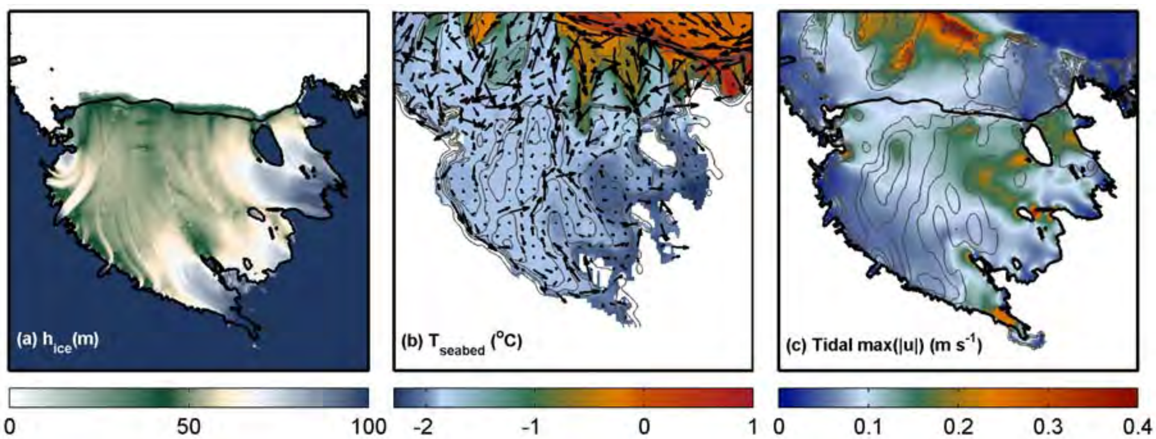


Fig. 4: *(a) RIS surface elevation from Griggs and Bamber [2009], corrected to EGM2008 geoid, showing ice shelf fine structure derived from merging glaciers and ice streams. (b) Seabed ocean temperature from coupled ocean/ice-shelf/sea-ice model with atmospheric and tide forcing. Contours under ice shelf are water column thickness, wct. Vectors indicate depth-integrated annual mean flow. (c) Maximum tidal current (m s^{-1}) from CATS2008b inverse barotropic tide model. Tidal currents greatly exceed mean flow.*

The existence of three distinct modes of ocean/ice-shelf interactions that are strongly time-dependent may contribute to the multi-year variability observed in surface elevation (**Fig. 3**). These observations indicate that there are multiple ways for the RIS mass budget to change in a warming climate. Changes in the distribution of basal mass loss will impact the dynamic response of the ice shelf itself. For example, increased melting near the Siple Coast will accelerate loss of grounded ice from West Antarctica. Increased basal melting along the ice front may lead to increased calving as existing fractures, crevasses and rifts expand. Increased calving may result in ice front retreat, with presently uncertain feedbacks on both the ocean circulation and upstream ice dynamical response. Although models [e.g., *Holland et al.*, 2003; *Assmann et al.*, 2003; *Dinniman et al.*, 2007, 2011; *Arzeno et al.*, 2014] produce basal melt rate values averaged for the entire ice shelf w_b that are within a factor of ~2-3 of each other and satellite-derived estimates [*Rignot et al*., 2013; *Depoorter et al.,* 2013; *Moholdt et al*., submitted (see **Fig. 1c**)], the spatial patterns of $w_b(\mathbf{x})$ are poorly correlated. Some of this may be due to errors in atmospheric forcing models, and time-dependence and limitations of melt-rate data (see **Fig. 3**). Model numerical and physics simplifications also contribute to the uncertainties. However, we expect that errors in our knowledge of the ice shelf geometry and underlying bed topography ($H_{bed}(\mathbf{x})$, $z_{ice}(\mathbf{x})$, $wct(\mathbf{x})$)

significantly impact mean circulation pathways, tidal currents and mixing, especially in this region where total currents are dominated by diurnal tides (**Fig. 4c**) [*Padman et al*., 2008; *Mueller et al*., 2012].

To address these issues within an ice/ocean/geotectonic framework, we seek to answer the following questions: (*1*) How sensitive is modeled $w_b(\mathbf{x})$ to errors in H_{bed} at scales not presently resolved by the RIGGS ~50 km grid, and to errors in $z_{ice}(\mathbf{x})$ due to uncertainties in ice/firn density profiles used to infer z_{ice} from satellite-derived ice surface elevation? (*2*) What are the sensitivities of the three melt modes to projected changes in large-scale climate? (*3*) How much ocean heat is delivered to the front of RIS, especially in the undersampled eastern Ross Sea? (*4*) Does small-scale bottom roughness controlled by the underlying distribution of sediments control mixing and w_b? (*5*) What is the glaciological response to different basal-melt modes and calving, and how do these feed back into ocean heat flux into the cavity?

(iii) Geotectonic Framework of Ross West Antarctica

The RIS overlies the West Antarctic rift system, a region of thin crust (20 to 25 km) with uniform Moho depth, and warm mantle that extends from the TAM front to and across Marie Byrd Land (MBL) (**Fig. 1d**) [*Chaput et al*., 2014]. Measured heat flow is in excess of 120 mW/m^2 [*Clow et al*., 2012] and reaches 200 mW/m^2 in places (WISSARD, preliminary result, S. Tulaczyk, pers comm, 2014). Marie Byrd Land corresponds to an active volcanic province [*Lough et al.*, 2013], with recent seismicity including an M5.6 earthquake in 2012 [*Centre Sismologique Euro-Méditerranéen*, 2014]. The RIS region has distinct gravity and bathymetric character from the Ross Sea region [*Wilson and Luyendyk,* 2006]. The two regions are separated by an inherited structure, labeled the Byrd Glacier fault zone in **Fig. 1d** that accommodated ~1 km of south-side-up relative motion [*Foley et al*., 2013].

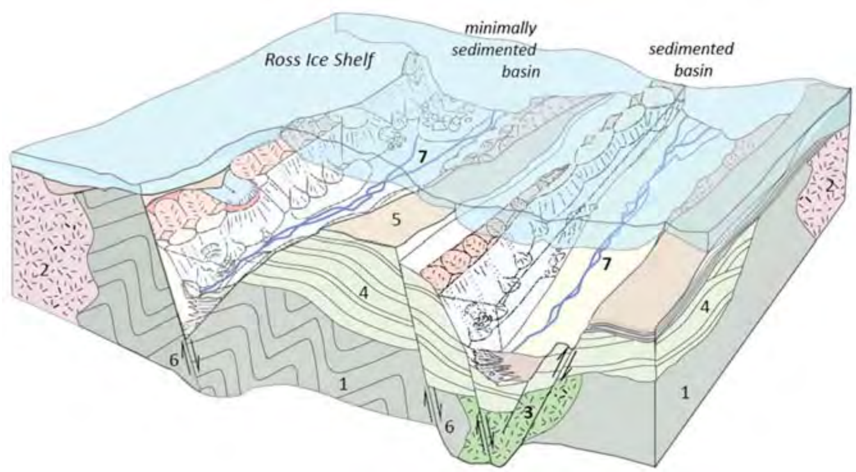


Fig. *5*: *Interpretive block diagram of major bedrock units and bathymetric features of the RIS region, to be distinguished by ROSETTA aero-geophysics data collection and modeling. View is to southeast. Labels are: (1) Thick package of sedimentary rocks, low-grade metamorphosed (metagreywacke), intruded by (2) intermediate to felsic plutons [Yakymchuk et al. 2013]. (3) Mafic igneous rocks, related to WARS development [Davey and Brancolini, 1995]. (4) Tertiary strata deposited after breakup between West Antarctica and New Zealand [e.g. Wilson and Luyendyk, 2011]. (5) Low relief surfaces at 100 to 350 mbsl, remnants of a pre-glacial extensive wavecut platform [Wilson and Luyendyk, 2006]. (6) Inferred high angle normal faults of Mesozoic-Cenozoic origin [Davey and Brancolini,1995]. (7) Linear troughs formed by localized intense glacial erosion [Stern et al., 2005; Wilson and Luyendyk, 2006], ca. 700 mbsl, with moderate to small sediment thickness [Chaput et al. 2014] suggestive of effective removal of detritus or young age of incision (mid-Miocene or younger).*

The indications of active tectonics in the region [*LeMasurier*, 2008] are superimposed upon an older rift architecture and vestigial landforms (**Fig. 5**). The majority of crustal thinning across MBL and the Ross Sea-RIS occurred at ca. 100 Ma during distributed transtension [*Siddoway et al*., 2004; *McFadden et al*., 2010], arising from rapid oblique subduction of young, hydrated oceanic lithosphere [*Sutherland and Hollis*, 2001; *Finn et al*., 2005]. Widespread rapid cooling [*Siddoway*, 2008] led to landscape stabilization and formation of regionally extensive erosion surfaces at two or more elevations [*LeMasurier and Landis*, 1996; *Wilson and Luyendyk*, 2006]. The lower, better-characterized erosion surface formed as a wavecut marine platform, based on the areal extent of the low relief surface that is unaffected by variations in rock type [*Wilson and Luyendyk*, 2006]. This once-continuous platform has been deeply incised by outlet glaciers and ice streams that pass between six or more steep-sided topographic highs at depths of 100 to 350 mbsl along the eastern and southeastern RIS. The flat-topped highs underlie ice rises and promontories in the grounding line, including Engelhardt Ice Ridge, Siple Dome, and Roosevelt Island **(Figs. 1a, 1d)**. The troughs are likely to have localized upon rift structures (**Fig. 5**; e.g., *Siddoway et al*., 2004). Sediment is absent over the bedrock highs and only thin (200-600 m) sediments are found in the glacial troughs [*Chaput et al*., 2013, their Table 1]. The topography in the RIS region resembles that of other rift provinces [e.g., *LeMasurier*, 2008] but also has a strong signature of the two erosion modes. Investigators of the landscape evolution on the margins of the RIS [*Rocchi et al*., 2011; *Lisker and Laufer*, 2013; *Foley et al*., 2013] have recently challenged the established view that the topographic relief between TAM and the West Antarctic rift province is a product of episodic uplift since 55 Ma [*Fitzgerald*, 2002; *Cande et al*., 2000]. The prominent incised troughs of the RIS seabed surrounded by bedrock highs may be a product of intense localized erosion after onset of continental glaciation at ca. 34 Ma [e.g., *Lisker and Laufer*, 2013] or even later, at ca. 14 Ma [e.g., *Stern et al*., 2005].

To advance our understanding of the intersections between bedrock geology/lithospheric inheritance, oceanography, and glaciology in the RIS region, we will use potential fields data to explore: (*1*) What is the location, rock type, and origin of bathymetric features beneath RIS? (*2*) Do bedrock highs act as RIS-WAIS pinning points, and lows act as pathways for water circulation or escape? (*3*) Have ocean and subglacial meltwater circulation affected the distribution of unconsolidated, permeable sediment? (*4*) Is there evidence of high frequency, high magnetic anomalies corresponding to mafic intrusions, active volcanic centers zones of high heat flow, or structural inheritance, that may influence ocean and ice dynamics? (*5*) Is there evidence of geological fault control on location and orientation of the glacial troughs, or are ocean/meltwater currents responsible for sub-RIS erosion features?

C) Program Objectives

The overarching objective of ROSETTA is to address these fundamental questions of the structure and stability of RIS within the geotectonic framework for the Ross Embayment. We have eight key specific objectives:

(1) Acquire the first comprehensive high resolution aerogeophysical data over RIS to support ice, ocean and geotectonic studies.

(2) Acquire key oceanographic measurements along front of RIS.

(3) Digitize, reanalyze and make more widely accessible the RIGGS seismic and related geophysical data.

(4) Use airborne gravity data with RIGGS seismic constraints to improved models of seabed bathymetry for the Ross Embayment, including under RIS.

(5) Use the new aeromagnetic and gravity data to advance our understanding of the geotectonic framework of the region.

(6) Use airborne radar, LIDAR and imaging to map RIS thickness and ice draft, and constrain RIS structure including basal channels, accumulation history, distribution of crevasses and marine ice.

(7) Improve models of ice/ocean interaction with improved morphology, bathymetry and hydrographic observations, and investigate sensitivity of the RIS to future climate states.

(8) Develop and distribute ROSETTA educational materials using data and human stories as an entry into polar science.

D) Proposed Work

ROSETTA brings together experts in ice, ocean, tectonics and geophysical data collection and analysis in a team that is uniquely suited to pursue an integrated systems approach to understanding the linkages between the Ross Sea, Ice Shelf, and the geotectonics of the Ross Embayment. We will use aerogeophysical surveys, modeling, reanalysis of the RIGGS data, and analyses of satellite-derived data sets. The team will be led by Robin Bell (LDEO), who has extensive experience in Antarctic aerogeophysics. Helen Fricker (SIO), who has worked extensively on ice-shelf stability and remote sensing, will lead the ice-shelf analysis, including mentoring a postdoc dedicated to ice-shelf modeling. Laurie Padman (ESR), who has worked extensively on ice/ocean interactions, will lead the ocean modeling effort. Christine Siddoway (Colorado College), who has worked extensively in West Antarctic tectonics both in the field and with aerogeophysical data, will lead the geotectonic interpretation. Kirsty Tinto (LDEO), who has extensive experience in modeling bathymetry and geology from gravity inversions in her role as instrument team member of Operation IceBridge, will lead the potential field analysis. Indrani Das (LDEO), who has extensively used airborne lidar and radar for surface mass balance estimates, will lead the analysis of the shallow ice radar. Chris Zappa will oversee the addition of AXCTD instrumentation to the IcePod sensor suite. Nick Frearson, lead IcePod engineer, will coordinate the addition of gravity, magnetics and the AXCTD. Stuart Henrys and New Zealand's GNS Science will provide support for the potential field data acquisition and reduction. James Kinsey (WHOI) will also provide gravity field instrumentation. Christina Hulbe (Otago University) will collaborate, contributing to the ice shelf modeling component to the program. The proposed program duration is 4 years.

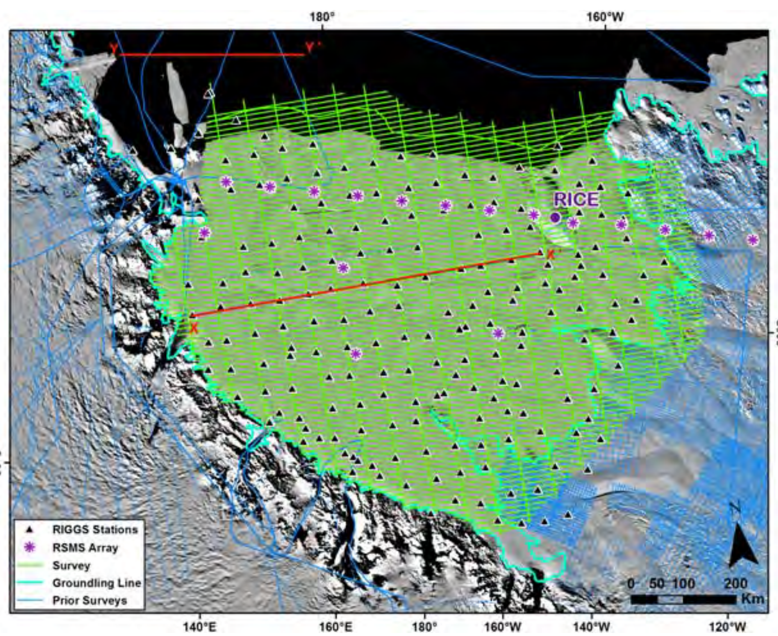


Fig. 6: ROSETTA survey employs 10 km spaced E/W lines with 55 km cross lines. The survey will overfly all RIGGS stations, Roosevelt Island ice cores and the RSMS passive seismic array. Line density will be reduced over the areas of prior surveys along the Siple Coast, but include tie lines that allow integration between ROSETTA and these datasets. x-x': location of **Fig. 9***, y-y': location of* **Fig. 10**.

(1) Aerogeophysical Data Acquisition: The core field program of ROSETTA will be collection of a comprehensive aerogeophysical grid (**Fig. 6**) over RIS during Years 1 and 2, acquired with the IcePod integrated ice sensing system (**Fig. 7**). We propose to fly a gridded survey of the entire Ross Ice Shelf at 10 km, E-W oriented line spacing, with 55 km-spaced, N-S oriented tie lines. Flight elevation will be 1000 m above ground level and flight speed 170 knots. Gravity measurements are central to recovering the RIS bathymetry. The survey line spacing is the same as the along-track, full-amplitude resolution of the gravimeter and will allow a gravity anomaly grid to be produced. Tie-line spacing is determined by the spacing of RIGGS survey stations. The grid is designed to overfly as many RIGGS stations as possible. IcePod's current core instrumentation suite includes a visual and infrared camera, scanning laser, deep and shallow ice radars, a GPS/INS positioning system and a data acquisition system. IcePod has been installed, certified and operated on New York Air National Guard LC-130 aircraft. A total of 36 LC-130 flights (8 hours each) split over the first 2 years of the program will be required to complete the ROSETTA grid. ROSETTA requires the addition of gravity, magnetics and AXCTD capability to the IcePod sensor suite. The Lamont group has flown these instruments on multiple platforms from Twin Otters to P-3s. The gravity, magnetics and AXCTD systems will be tested from Stratton AFB (NY) prior to deployment to Antarctica. Year-1 IcePod flights will overfly the RIGGS sites and survey the ice front, the eastern margin and the grounding line. Year-2 goals will be to complete the

10 km survey lines in the center of the study region and densify the survey in targets of interest.

Fig. 7: *IcePod mounted on NYANG LC-130. Left: on ground. Center: Pod with side panels removed. Sonobuoy tube for launching AXCTDs is visible on the right side Right: Internal instrument rack.*

(2) Hydrographic Data Acquisition: The IcePod system has the capability to launch sensors through a port in the door plug (**Fig. 7**). We have allocated 36 Airborne eXpendable CTD (AXCTD) casts to map undersampled water-mass pathways between the continental slope and RIS in the eastern Ross Sea and collect water column data along the entire ice front. AXCTDs have been routinely used in ONR Arctic programs. The launching system will be commissioned during test flights from Stratton AFB and tested during Year 1. The major deployment will occur during Year 2 (2016-17) to complement a ship-based hydrographic and geochemical tracer program proposed for 2015-2016. Primary targets are modeled pathways of MCDW (**Figs. 2 and 4b**), but sampling is likely to be constrained by sea-ice cover.

(3) Digitize and Review RIGGS Data: Developing an improved model of the water cavity beneath RIS is a major goal for ROSETTA. The Lamont team's efforts to produce bathymetric models in both Greenland and Antarctica from gravity inversions have demonstrated the importance of independent constraints on the water depth. Seismic measurements of water depth at the RIGGS stations will provide these constraints. These values are included in the BEDMAP compilations; however, for developing a new bathymetry of the Ross Region, it is important to revisit these data. The original RIGGS seismic records are presently stored on paper in the Byrd Polar Research Center Archive of the Charles R. Bentley Data Collection (**Fig. 8**). During a series of visits to Byrd Polar, working in collaboration with the Polar Curator, Laura J. Kissel, we will ensure the RIGGS seismic records and logbooks are scanned. We will evaluate the errors in the ice thickness and water depth measurements that are central to the gravity inversion. These scanned records will be served both as part of education activity developed by ROSETTA team members and by the Ohio State University library system. We will also review other RIGGS data including radar, velocity and accumulation data and metadata to identify and scan other data sets relevant to ROSETTA goals.

Fig. 8: RIGGS Data *(left) Bentley collection at Byrd Polar. (center) Seismogram Station Record K11. (right) Published seismogram - K11.*

(4) Develop an improved bathymetric model for the RIS region: We will use our aerogravity data, acquired at ~10 km along-track resolution, 10 km line spacing and ~2 mGal accuracy to derive a 10-km resolution, 50-100 m accuracy bathymetry model for RIS. The potential improvement in resolution from current constraints is demonstrated by the bathymetry modeled from preliminary Operation IceBridge gravity data from the Ross Ice Shelf in 2013 (**Fig. 9**). The modeling approach will be based on our experience of developing bathymetry models from gravity surveys of Antarctic ice shelves and tongues (Thwaites, Abbot, Larsen C and others) and Greenlandic fjords (Petermann and >40 others) [*Tinto and Bell*, 2011; *Cochran and Bell*, 2012; *Cochran et al.*, 2014]. The free air gravity anomaly is primarily driven by topography when measured over land, and bathymetry when measured over water. Gravitational attraction varies with the square of distance, and the interface between rock and water is both the nearest and the greatest density contrast below sea level (1.64 g/cm^3). This relationship is seen in the large-scale correlation between high free air satellite gravity and shallow bathymetry over the RIS (**Fig. 1d**). The gravitational effect of floating ice can be discounted as it is in hydrostatic equilibrium. We will invert gravity anomalies using GMSys software in profiles *[Talwani et al., 1959]* and in grids [*Parker, 1973]* in order to establish a detailed, self-consistent model of bathymetry variations. Gravity inversions can accurately predict the shape of the seafloor, but must be tied to known constraints in order to produce reliable absolute depths. The seismically derived sea floor depths of the RIGGS survey provide ideal constraints for gravity inversion, allowing the bathymetry model to be tested and constrained every 55 km, ensuring that the effects of long-wavelength density variations from geological variations, such as those described to the north of the Byrd Glacier fault [*Karner et al*., 2005], are identified and corrected. These density variations then form the framework for a geological model of the RIS. The ROSETTA magnetic survey will provide further constraints for the geological model, and so allow us to fine-tune the bathymetry model.

(5) Advance our understanding of the geotectonic framework of the Ross Region: Our analysis of the geotectonic history of the RIS will be founded on the new aeromagnetic dataset and informed by aerogravity, RIGGS seismic results and presently funded studies of the mantle structure under RIS (RSMS). We will employ multiple analysis techniques based on both profiles and grids to investigate shallow and deep sources of magnetic anomalies. We will produce a tectonic map of the region by taking the horizontal and vertical gradients of the gridded total field anomaly to enhance the structural trends in magnetic data [e.g., *Behrendt and Grim*, 1983; *Grauch and Cordell*, 1987]. This regional framework will allow us to delineate structural patterns and trends in the shallow geology, identify faults and regions of magmatic intrusions and mark the transition between scoured basement and sedimentary basins.

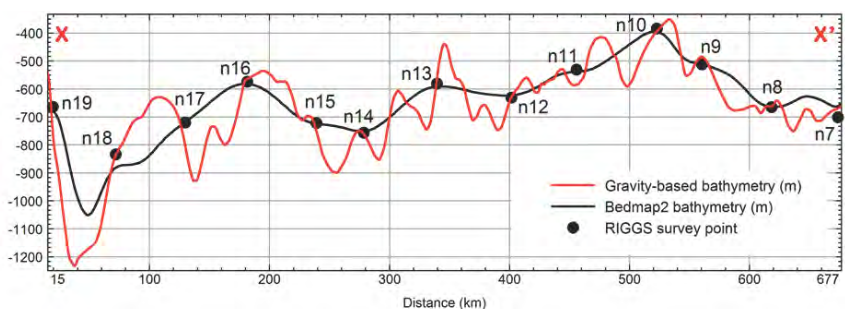


Fig. 9: *New bathymetry from 10 km filtered IceBridge data profile across RIS. Illustrates improved resolution from gravity-based bathymetry (red line) compared with available RIGGS bathymetry (black dots). Profile location* **Fig. 6**.

We will investigate the variable depth of sediment cover within the region by estimating the depth to magnetic basement using Werner deconvolution [*Werner*, 1953; *Jain*, 1976; *Hansen and Simmonds*, 1993]. Werner deconvolution assumes that the sediments within a basin have weak magnetic susceptibilities compared to the underlying crystalline basement, and so the depth to magnetic source is the depth to crystalline basement. The magnetic field is analyzed in a series of overlapping windows at a range of window lengths. The source of the anomaly is taken as a contact or a dyke, in the presence of a regional field, and calculated depths to source are plotted along the profile [*Werner*, 1953]. Where solutions cluster in a vertical streak, the shallowest solution identifies the magnetic basement (**Fig. 10**). This approach has been employed in the Ronne Ice Shelf and Weddell Sea [*Maslanyj et al*., 1991], and *Jain* [1976] concluded that the technique could return depths accurate to 10%.

Deep sources of magnetic anomalies, such as magmatic underplating of the lithosphere, can be identified by isolating the long-wavelength components of the magnetic anomalies by upward continuation. Long-wavelength magnetic anomalies most likely reflect the pattern of crustal magnetization down to the level of the Curie isotherm (~580^{o}C) at 30-60 km in continental regions. In regions of high heat flow, the Curie isotherm is elevated to shallower levels of the crust and the frequency spectrum of observed magnetic anomalies has reduced power at the lowest frequencies. We will perform spectral analysis of the measured magnetic anomalies in order to assess the variability of the depth to the Curie isotherm across the RIS.

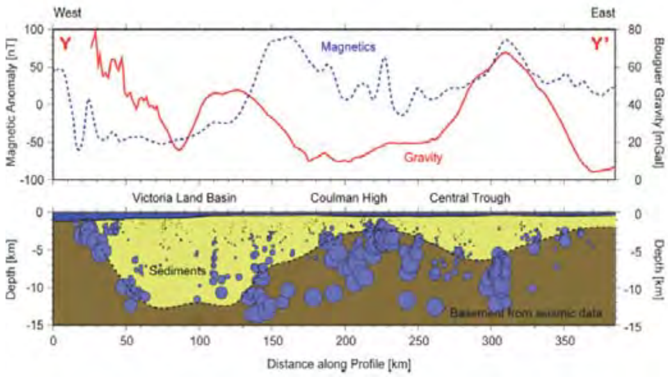


Fig. 10: *Werner depth-to-magnetic basement estimates along a Ross Sea profile superimposed onto seismic reflection basement. Circles are individual Werner solutions for depth–to-magnetic basement. Circle size scaled to the magnetic susceptibility of the solution. Werner solutions cluster along the seismically defined basement depths (dashed line). Profile location* ***Fig. 6****.*

(6) Mapping the Ross Ice Shelf Structure : The ROSETTA team will use the IcePod airborne radar, LIDAR and imaging systems to map RIS thickness and ice draft and constrain the RIS structure including accumulation history and distribution of marine ice, basal channels and crevasses. IcePod's shallow- and deep-ice radar systems will provide information to constrain the ice-shelf structure. The first step will be to generate an ice thickness map of the RIS using the IcePod radar data. The travel time from the radar will be corrected for the observed firn depth over RIS from both the Roosevelt Island RICE core and RIGGS stations. Combined with the coincident ice surface measurements from the LIDAR, we will be able to produce a map of the RIS ice draft. We will compare our ice thickness results with the RIGGS ice thickness measurements to identify any changes in the structure of the ice shelf since the 1970s; see *Thomas et al*. [2013] for evidence that ice velocities have changed, suggesting possible associated thickness changes through strain thinning. The RIGGS program found extensive bands of basal debris, evidence of basal crevasses and, in some places, abrupt 80 m steps in the ice thickness. We will document these features as a means of constraining the flow history, possible changes in the grounding line and the boundaries between distinct bodies of ice. We will also map the basal reflectivity, which may identify regions where marine ice forms. If the interface between the meteoric ice and marine ice is imaged, we will estimate the distribution of marine ice by combining elevations from satellite radar altimetry with ice thicknesses from radio-echo sounding data based on methodology applied to the Amery Ice Shelf [*Fricker et al.*, 2001]. We will compare our map of the marine ice distribution to satellite-derived estimates (along-flowline integration of basal mass balance in **Fig. 1c**) and predictions from our ocean/ice-shelf models.

We will map the spatial variations in surface accumulation over the RIS using the internal layers in the shallow ice radar. The RACMO climate model [*Lenaerts et al.,* 2012] estimates present-day annual accumulation rate averaged over RIS of 12 cm/yr. We will study the difference in thickness between the near-surface isochrones normalized with respect to their depths along the ice shelf to identify if there has been spatial variability of accumulation rate on a decadal timescale. We will be able to determine whether the observed time-dependent variability of satellite-derived *dh/dt* (**Fig. 3**) is caused by surface accumulation. Spatial variability of accumulation rates can be quantified from shallow ice radar by tracking the leading edge of horizons within the reflection profile which, from their depth, can also be identified and thus dated in an ice core [*Arcone et al.*, 2005; *Medley et al.*, 2013; *Sinisalo et al.*, 2013]. We will overfly the Roosevelt Island ice core dataset (RICE) with the shallow ice radar for this purpose. The depth-density and dielectric profiles from this core will be available to the community [*Nancy Bertler*, pers. comm., 2014]. Standard models, such as *Herron and Langway* [1980] for the depth-density relationship and *Kovacs et al.* [1995] for firn dielectric calibration, are often used in combination with ice core parameters for quantifying accumulation rates from snow radars [*Medley et al.*, 2013; *Arcone et al.*, 2005; *Eisen et al.*, 2008]. The surface mass balance estimates can be obtained from these isochronous layers using shallow ice approximation [*Sinisalo et al.,* 2013]. To determine with certainty whether the observed isochrones are annual (rather than interannual or subannual) layers, it is necessary to compare and correlate to ice core annual layers [*Medley et al.*, 2013]. We will quantify accumulation rates over RIS. Comparing with the RIGGS snow accumulation map will provide insights to any changes in accumulation since RIGGS.

(7) Ice/Ocean Modeling: For our 3-D ocean model, coupled to a thermodynamically-active ice shelf, ESR proposes to use the Regional Ocean Modeling System (ROMS; *Shchepetkin and McWilliams* [2005]) that we have used in prior studies [e.g., *Marcott et al*., 2011; *Mueller et al*., 2012]. However, we have also begun to run MITgcm for other purposes, and will investigate its use in Year 1. Both models evaluate basal melt rate w_b using thermodynamics based on *Holland and Jenkins* [1999]. Models will be forced by ERA-Interim Reanalysis atmospheric state (see *Dinniman et al*. [2007, 2011] for details) and include a coupled dynamic/thermodynamic sea-ice model. Models will include tidal forcing applied as open boundary conditions obtained from our "CATS" barotropic inverse tide model [*Padman et al*., 2002, 2008]. For ice modeling, we propose to use the model described by *Hulbe and MacAyeal* [1999] as modified by Christina Hulbe [see *Hulbe and Fahnestock*, 2004]. (Dr. Hulbe is a collaborator on this proposal; see Letter of Collaboration). This model is a plane-fitting finite element model that includes buttressing, basal drag, and compression upstream of ice rises. Velocity responds to changes in forcings nearly instantaneously, while thickness responds on advective time scales. This work will be carried out by the SIO postdoc, who will look at ice-shelf response to changing ocean state and calving, and the role of ice-shelf fine structure derived from the ROSETTA survey.

The ocean-focused modeling has several targets. (1) We will investigate sensitivity of ocean circulation and hydrography to uncertainties in cavity geometry due to errors in H_{bed} at scales not presently resolved by the RIGGS ~55 km grid, and errors in z_{ice} arising from uncertainties in ice/firn density profiles used to infer z_{ice} from satellite-derived ice surface elevation. The change in H_{bed} suggested by **Fig. 9** is, from a model perspective, profound: we expect the short-wavelength topography to significantly alter circulation, tides, eddies, and the generation of baroclinic flows such as internal waves that can maintain a significant heat transport to the ice base. Our initial modeling studies will follow the general procedure in *Mueller et al.* [2012]; i.e., develop plausible alternative geometries (both H_{bed} and z_{ice}) and run a moderate-resolution model (~3 km) using real atmospheric forcing from the ERA-Interim reanalysis model plus tides. We will use three metrics for comparing model runs: (i) comparison of $w_b(\mathbf{x})$ with the satellite-derived values reported by *Moholdt et al*. [submitted; see **Fig. 1c**]; (ii) comparison of tidal elevations with CATS and with tidal data (tide gauges, GPS, altimetry; see *King and Padman*, 2005; *Padman et al*. [2008]); and (iii) comparison with hydrographic distributions along the ice front, from *Orsi and Wiederwohl* [2009] and *Smethie and Jacobs* [2005]. Once ROSETTA data acquisition and analyses are completed (end of Year 2), we will rerun the model with updated geometry. (2) We will identify which of the three modes of melting are most sensitive to projected changes in large-scale climate. Following the general procedure described by *Hellmer et al*. [2012], we will determine $w_b(\mathbf{x})$ for models forced with projected climate states in mid- and late-21st century. Under separate (NASA) funding, we are already evaluating the best CMIP5 climate models for Antarctic studies. As with (*1*), our primary effort here will be on a moderate-resolution model, forced by projected climate from ~3-4 CMIP5 models. We will analyze these runs, focusing on: (*a*) atmospherically-forced MCDW incursions; (*b*) ice-front melting due to intermittent subduction of upper-ocean heat from both advection and summer insolation; and (*c*) melting near the grounding line in relation to HSSW production over the continental shelf. (3) We will investigate whether bottom roughness (e.g., sedimented basins vs exposed bedrock) influences mixing and w_b. Generation of tidal and higher-frequency internal waves by current interactions with steep and/or rough topography, and eddy generation at abrupt changes in topography, are effective mechanisms for generating ocean mixing. While these processes are not excluded in current models, smooth geometry grids reduce their likelihood so that, in practice, most mixing affecting basal melt comes from parameterized friction between ocean currents and the ice base. The new ROSETTA bathymetry will be incorporated into our model to investigate the potential for these additional sources of mixing. We will also impose additional topographic roughness with characteristics motivated by the improved geotectonic model. While most models will be run at ~3 km, one or more runs at ~1 km will be used to fully resolve ocean processes at close to the Rossby radius (*Ro*~5 km).

We will use the ice-sheet/ice-shelf model to test how changes in basal melting, calving events, and internal weaknesses in ice (crevasses, rifts, basal channels) affect ice flow. Processes of interest include sensitivity of ice flow to release from, or attachment to potential pinning points identified by the improved sub-ice cavity model, and grounding-line migration due to ice thinning or development of sediment wedges. We do not, at this time, plan a fully coupled integration where changing ice-shelf draft and fine structure distribution feed back, in real-time, to ocean circulation and tides. However, some runs will be "quasi-coupled", where the effect of modified ice draft predicted by our ice-model runs is tested in restarted runs of the ocean-focused models.

(8) ROSETTA Broader Impacts: The rich history of human exploration of the RIS, combined with the evidence for changing flow, offers a unique entry point for education at both the high school and undergraduate level. Few other places in Antarctica have been explored with horses, dogs, skis, snowmobiles, tractors, explosives, satellites and airplanes. Leveraging these stories of evolving science techniques and changing ice, we will develop a series of activities based in the data sets collected by ROSETTA and the 1970s RIGGS program. The core concept of the ROSETTA education program will be to connect students to fundamental concepts in physics and earth science informed by multiple datasets. The LDEO Polar Geophysics Group (PGG) online data visualization tool (http://pgg.ldeo.columbia.edu/projects/antarctica/) will be used to introduce students to the basic structure of the RIS and the surrounding West and East Antarctic ice sheets (see Data Management Plan). The open-access PGG data portal is filled with layers of data which students can load and explore including flowlines, velocity, ice thickness and surface elevations and other relevant data about the region. We will populate the portal with new datasets that highlight the dynamic changing nature of the ice shelf and surrounding Siple Coast ice streams. As ROSETTA data become available, we will serve these data sets on the portal and develop educational material to accompany them. We aim to engage students in the nature of science, with real ice shelf data including the newly scanned RIGGS seismograms and ROSETTA data. We will enlist science classes to work through the data to identify the ice, water and bottom surfaces in the seismograms and calculate thicknesses and depths from the seismic travel times. Students can then compare their calculations to the measurements collected from the ROSETTA project. These activities will be geared towards high-school students and undergraduate science students (physics, environmental sciences and geoscience). We will distribute these materials through our network of teachers, NSTA, Ohio State University and the undergraduate programs at the ROSETTA team members' institutions at UCSD, Colorado College, Columbia University and through events at Geologic Society of America. We will reach out to high school environmental, physics and earth science educators through our active education programs at STANYS (Science Teacher's Association of NYS), ESPRIT, the Oneonta State Earth Science teacher's listserve and the Geophysical Information for Teachers session at AGU. Siddoway will design interpretation exercises of ROSETTA survey data in her upper level classes, including GY400 Digital Mapping and GY250 Introduction to Geodesign, and contribute ROSETTA based activities to the Colorado Science Festival that annually offers a week-long Antarctic Discovery program (http://cssciencefestival.org/).

E) Linkages with Other Programs

The ROSETTA team will work closely with the ongoing ice, ocean and tectonic programs in the region. D. Wiens of Washington University is leading the Ross Sea Mantle Structure (RSMS) passive seismic experiment that will support a new seismic velocity tomographic model, which will improve our understanding of the tectonics of the regions. The seismic array, consisting of 18 stations, will be installed for 2 years beginning in 2014 across the RIS (**Fig. 1b**). P. Bromirski of SIO and R. Stephens of WHOI will use the passive seismic array to determine the spatial and temporal distribution of ocean wave-induced signal sources along a the high-density array to monitor and localize fracture (icequake) activity.

Several groups are developing oceanographic programs in the Ross Sea including the PIPER polynya program led by S. Ackley and a proposed study of tracers along the front of the ice shelf led by P. Schlosser. The new insights into the structure of the RIS and the underlying topography will be important to providing a framework for interpreting these new data. Co-PI Siddoway will serve on the core characterization team for the 2018 ANDRILL project that will drill in to basement rock at Coulman High, allowing for integration of ROSETTA perspectives to the ANDRILL program.

F) Results of Prior NSF Awards

Kirsteen Tinto and Indrani Das have had no prior NSF support.

Robin E. Bell, Michael Studinger Lamont-Doherty Earth Observatory, Collaborative Research: IPY: ERA: Gamburtsev Aerogeophysical Mapping of Ice and Bedrock Targets Award: ANT-0632292, 9/24/2007-9/01/2014 (active), $2,281,088. Intellectual Merit: During the International Polar Year 2007-9, the seven-nation AGAP expedition sought to comprehensively image the ice sheet bed, deep in the interior of Antarctica. This study used airborne and ground-based geophysical methods to understand the fundamental structure of Dome A, the top of the East Antarctic ice sheet and the underlying Gamburtsev Mountains, which were a major nucleation point for growth of the Antarctic ice sheet during the Cenozoic. Presently, ice at Dome A drains into all the major ice shelves of Antarctica. The results from this program include major shifts in our understanding of basal process beneath thick ice sheets, the fundamental structure of East Antarctica and novel insight into how topography can be preserved beneath thick ice sheets. Results from the program include: The discovery of widespread persistent basal freeze-on [*Bell et al.*, 2011]; The insight that East Antarctica has been cut by a large rift system similar in scale to the East Africa Rift system [*Ferraccioli et al*., 2011]*;* First predictive model of how persistent wind scour modifies surface accumulation based on AGAP Lidar and radar data. [*Das et al*., 2013]. *Broader Impacts*: The broader impact includes the education of three doctoral students and outreach programs in the New York area and nationally that reached over 6000 students and teachers. 7 publications, 40 presentations, and 3 students resulted from this award. 3 Peer-reviewed publications are listed in the reference section, indicated by **®**.

Christine Siddoway; OPP-0944600; Collaborative research: Polyphase orogenesis and crustal differentiation in West Antarctica, 09/15/2010- 09/14/2014, $145,260. OPP-0944777, Research at Undergraduate Institutions: Development of an on-line GIS repository of geological data from the Ford Ranges, Marie Byrd Land, 06/10-05/13, $49,545.

Intellectual Merit: OPP-0944600 used petrology, geochemistry, and structural approaches to assess chemical differentiation/stabilization of the continental crust of West Antarctica within the context of Gondwana and once-contiguous sectors of Zealandia and Australia. The understanding of Paleozoic accretion has direct bearing on the subsequent stage of vast intracontinental extension across the West Antarctic rift system in Cretaceous time. OPP-0944777 trained undergraduates in use of geospatial methods for development of a comprehensive online GIS, accompanied by tectonic investigation of a large ice covered region of West Antarctica. Structural and geochemical data from 9 seasons' research comprise the GIS that is being made available through PGC and Esri web services (Esri-open source, soon to be released). *Broader Impacts:* OPP-0944600 involved new investigators in Antarctic research, trained 2 graduate students, and involved Australian colleagues as a means to strengthen international scientific cooperation. OPP-0944777 supported 8 undergraduate interns who became proficient in use of geospatial software and/or computation of DEMs using stereographic imagery, presenting results at national [e.g., *Contreras et al.*, 2012; *Robertson et al*., 2012] or international [*Emery et al*., 2012] meetings. Siddoway offered undergraduate GIS-based courses and educated additional undergraduates about Antarctic earth science. Four peer-reviewed publications and 9 conference presentations are listed in the reference section, indicated by **¢**.

Laurie Padman and Scott Springer: Collaborative Research: Upper ocean heat flux in the Eurasian Basin: Oceanic thermodynamic forcing contributing to Arctic ice loss, ARC-1249182, 8/5/2012-7/31/2015 (active), $544,222. Intellectual Merit: This grant supports analyses of hydrographic and microstructure data in the eastern Arctic Ocean, to quantify the relative contributions of shear-driven mixing and double-diffusive convection (DDC), and nonlinear interactions of these, to the upward flux of Atlantic Water (AW) heat to the surface mixed layer (SML). *Polyakov et al*. [2012] described DDC over the eastern Arctic continental slope and identified remarkable persistence of DDC steps in a region where large-scale ocean dynamics should be conducive to step disruption. *Polyakov et al.* [2013] quantified the seasonal variability of upper-ocean heat fluxes over the deep basins, finding strong seasonality in the release of AW heat to the upper pycnocline, followed by seasonal release of that heat to the surface mixed layer. *Broader Impacts*: (*1*) We develop, and provide user support of polar tide models and Matlab tidal prediction software, used by 100's of researchers worldwide [*Padman*, 2014 (web product)]. (*2*) We give talks to school kids, teacher workshops, and the public (~4 per year), participate in science fairs, and comment on climate science in Opinion Pages of the Corvallis, OR newspaper. (3) L. Padman co-convened the *Untersteiner Workshop: On the Role and Consequences of Ocean Heat Flux in Sea Ice Melt* at UAF Fairbanks in March 2013 and is workshop co-convener *Observations of upper-ocean and sea-ice interactions in the eastern Arctic Ocean*, to be held Washington DC in April 2014. (*4*) The grant supports a new PhD student Allison Einolf, at Oregon State University. Two publications, 2 presentations, 1 web product, and 1 student presently funded by this award. Peer-reviewed publications and web products are listed in the reference section, indicated by ∞.

H.A. Fricker, NSF-0838885, 9/1/2009-8/31/2014, $633,455: Collaborative Research: Integrative Study of Marine Ice Sheet Stability & Subglacial Life Habitats in W Antarctica - Lake & Ice Stream Subglacial Access Research Drilling (LISSARD). LISSARD provided the surface geophysical context for the larger WISSARD project, including the continuous monitoring of the subglacial lakes network via a 23-unit GPS array, satellite remote sensing, and hydrologic modeling. *Intellectual Merit (SIO group):* (1) ICESat laser altimeter data showed that SLW had drained a second time between 2008 and 2009 [*Fricker et al.*, 2011] allowing hydrological flow paths from SLW to the grounding line to be mapped, and subglacial water flux across the GL to be estimated [*Carter and Fricker*, 2012]. (2) Modeling work, coupled with reanalysis of ICESat data revealed a significant subglacial water piracy event that redirected water away from SLW after its second discharge event [*Carter et al.*, 2013]. (3) By combining ICESat, GPS & CryoSat-2 data we detected a flood of SLM in 2012 [Siegfried et al., 2014] and using GPS data, tracked both the movement of subglacial drainage water downstream and the resulting dynamic ice velocity response. *Broader Impacts:* WISSARD Education and Outreach program thus far has produced numerous milestones including: an education partnership with Native American students; a teacher professional development partnership with the National Science Teachers Association (NSTA); web seminars; teacher professional development symposia; staffing an OPP exhibit at NSTA; numerous discrete outreach activities targeting K-12 or public audience; extensive global media coverage from last season; $225,000 in additional funds were leveraged from other sources to support these efforts. SIO undergraduate student M. Roberts, PhD Candidate M. Siegfried, and Post-Doc S. Carter have all been supported by this funding. *Publications (SIO Group):* Research from this project has been presented >12 times at international conferences; four publications resulting from this project are listed in the references (indicated by τ).

Robin E. Bell, Nicholas P. Frearson, Christopher J. Zappa, Lamont-Doherty Earth Observatory, Major Research Instrumentation: Developing an Ice Imaging System for Monitoring Changing Ice Sheets Mounted on the NYANG LC-1302010-2015 (05/01/2010-04/30/2015) Award: ANT-0958658, $4,140,323. Intellectual Merit: The Lamont-Doherty Earth Observatory of Columbia University developed an ice imaging system, or "IcePod," for use in measuring the surface and subsurface topography of ice sheets in Greenland and Antarctica. IcePod consists of a modular Common Science Support Pod containing the following remote sensors: deep-ice and shallow-ice radars, visible wave and infrared cameras, laser scanner, inertial measurement unit and GPS. *Broader Impacts:* The IcePod airborne sensor system commissioning will be to provide the polar community including students, postdoctoral scientists and experienced scientists with new capacity to image the ice sheets and surrounding polar oceans. The IcePod enables other science instruments to be installed on LC-130s that conform to pod specifications and will enable the IcePod to be used as an NSF long-term research facility. 23 presentations, and 4 students resulted from this award.

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