INVEST WHITE PAPER: PROPOSAL FOR FUTURE ANTARCTIC MARGIN PALEOCLIMATE SCIENTIFIC DRILLING UNDER THE IODP.

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Abstract (max 300 words)

We present the core of a multinational, multiplatform scientific drilling strategy to recover key physical evidence constraining past and future Antarctic Ice Sheet behavior, which is aimed at addressing key knowledge gaps about the role of Antarctic ice sheets in climate change as identified by the Intergovernmental Panel on Climate Change (AR4, IPCC, 2007). A Workshop on Developing an Integrated Strategy to Recover Paleoclimate Records from the Antarctic Margin and Southern Ocean, was held on 12-13 of September 2009 in Granada, Spain, following the First SCAR-Antarctic Climate Evolution (ACE) Symposium <www.acegranada2009.com>. Conveners were: Laura De Santis (OGS, Trieste, Italy), Richard Levy (GNS Science, Wellington, New Zealand,), Tim Naish (Victoria Univ., GNS Science, Wellington, New Zealand), and Frank Rack (Univ. of Nebraska-Lincoln, USA). Results of the workshop are summarized in this White Paper. The outcomes of the SCAR-ACE Symposium and workshop provide a broad perspective from the Antarctic community that outlines important scientific questions and strategies for Antarctic scientific drilling as a contribution to the INVEST meeting.

Introduction

Antarctic ice sheet stability, bottom water production and its relation with Southern Ocean circulation influence the Earth's climate. Polar ice is an important component of the climate system, affecting global sea level, ocean circulation and heat transport, marine productivity, and albedo. Drilling around Antarctica in the past decades has revealed regional information about the ice sheets development and stability. Climate models (e.g., DeConto and Pollard, 2003a, 2003b; Huber et al., 2004; DeConto et al., 2007) combined with paleoclimatic proxies (e.g., Pagani et al., 2005; Liu et al., 2009) suggest as the main triggering mechanism for the Antarctic ice sheet stability CO_2 concentration in the atmosphere. Opening of Southern Ocean gateways (Kennett, 1977; DeConto and Pollard, 2003a, 2003b; Huber et al., 2004; Barker and Thomas, 2004) played a secondary, though likely still significant, role. With current increasing atmospheric greenhouse gases concentrations resulting in rapidly rising global temperatures (IPCC, 2007), studies of polar climates have become increasingly prominent on the research agenda. Although progress has been made during the last decades by the ODP, the Cape Roberts and ANDRILL Projects, the short- and long-term paleoceanographic and paleoclimatic history still remains poorly known, because only a few sectors of the Antarctic margin have been sampled and the available technology allows adequate core recovery in only few cases. Eight proposals are currently in the IODP system to drill Antarctic margin and in the Southern Ocean.

The chance to conduct scientific drilling in Antarctic and sub-Antarctic waters has historically averaged about one pair of expeditions about every 10 years. This is due to long vessel transit times, and to the competition with low and mid-latitude proposals of excellent quality (in the frame of IODP). This low number of drilling expeditions in the Polar Regions is in contrast with the crucial needs of a systematic data collection to constrain global models of various types. An urgent and major effort is needed in the next decades to recover sedimentary sections containing the record of Antarctic ice sheet dynamics and stability and its relation to sea level change because, based on IPCC 2007 forecasts, CO_2 doubling or 1.8°–4°C equivalent by the end of this century is expected, and the response of Antarctic ice sheets to this warming remains a major uncertainty. Earth has not experienced these conditions since the early Pliocene. Up to now only few sectors of the Antarctic margin have been sampled by geological drilling (i.e., Antarctic Peninsula, Ross Sea, Prydz Bay and Weddell Sea), and therefore the question of regional vs. global variations remain unclear. For example, the recent successful drilling of the ANDRILL program in Ross Sea identified significant variability and vulnerability of the West Antarctic Ice Sheet, during warmer-than-present early Pliocene climate (3-5 million years ago, Naish et al., 2009).

Drilling around the Antarctic continent is logistically challenging with permanently ice-covered areas, icebergs and low temperatures and high-winds hampering operations. Ship-based drilling (i.e., ODP, IODP, SHALDRIL) brings the technological challenge of recovering continuous sections from glacial deposits on the Antarctic continental shelves, which can likely be improved with the use of a riser system, such as the one used by ANDRILL which is capable of recovering more than 95% strata cored to more than 1000 m bsf. Plans for the construction of the icebreaker *Aurora Borealis* with flexible and *ad-hoc* designed, deep-water drilling capability in thick ice covered areas can be the next technological breakthrough for Antarctic as well as Arctic drilling.

Previous drilling has contributed significantly to knowledge of the development and evolution of the Antarctic ice sheets, their influence on global sea level, paleoceanographic, and biotic changes. It has shown that during episodes of global warmth with likely elevated atmospheric CO_2 conditions, a collapse of the marine based West Antarctic Ice Sheet (Naish et al., 2009; Pollard & De Conto 2009), and loss of sea-ice and ice-sheet retreat of the East Antarctic Ice Sheet (EAIS; Pollard & De Conto 2009; Escutia et al., in press) contributing to rapid increases in global sea level. In the face of rising CO_2 levels (IPCC, 2007) a better understanding of both EAIS and West Antarctic Ice Sheet (WAIS) dynamics is therefore urgently needed from both a scientific as well as a societal point of view. The results from previous drilling and model data comparisons are the bases that guide the future relevant questions to be addressed in the next decades (see below).

Conceivably even more important than the history of the Antarctic glaciations are past lessons from deglaciations. Seismic surveys and pilot studies indicate the existence around Antarctica of sites of ultra-high accumulation rates of sediments recording the Holocene deglaciation. These sections contain high-resolution (i.e., centennial to millennial such as the section recovered in the palmer Deep during ODP Leg 178) to “tree ring” type resolution, annually layered sediments predominantly consisting of phytoplankton remains constituting one of the worlds most expanded archives of recent environmental change is one of the tasks ahead to ensure palaeoenvironmental reconstruction with unprecedented detail. One such ultra-high resolution sedimentary section is targeted for drilling during IODP Expedition 318 to the Wilkes Land margin (Escutia et al., 2008).

Ongoing discussions about the future IODP long-term science plan highlights the importance of societal and science-relevant questions of the carbon cycle, oceanic sequestration and storage mechanisms, extreme climates and abrupt climate changes, geohazards, sub seafloor microbial and abiotic (fluids) activity, permafrost and gas hydrates. All these themes are well addressed by multidisciplinary drilling the Polar Regions where past climate change signals have been recorded in glacial and interglacial sediments.

Scientific drilling in and around Antarctica and the Southern Ocean is undertaken within the framework of the Antarctic Treaty and other international agreements through a wide range of research activities coordinated by the Scientific Committee on Antarctic Research (SCAR) that are supported by the individual national Antarctic Programs. The SCAR-Antarctic Climate Evolution (ACE) initiative, which evolved from the SCAR-Antarctic Offshore Stratigraphy (ANTOSTRAT) project, identifies scientific questions and develops hypotheses and integrated strategies that can be implemented through drilling and other activities in the circum-Antarctic region. ACE projects such as the Circum-Antarctic Seismic Stratigraphy and Paleobathymetry Project (CASP), Antarctic Landscape Evolution Project (ANTScape), the Antarctic Geological Drilling Program (ANDRILL), the Antarctic Seismic Digital Library System (SDLS), among other SCAR activities, serve to inform and guide ongoing discussions about community scientific priorities and long-term planning. These promise to achieve global science outcomes that combine process studies, drilling of critical climate archives and numerical modeling.

Our research strategy is designed to resolve sectoral response of the West and East Antarctic Ice Sheets and margins to climate perturbations over the past 65 million years, as a guide to assessing future climate change more accurately. Of concern is that the future contribution of Antarctic ice to sea level rise over the next 100 years is potentially large (1-2 m by 2100); yet this science was considered “too uncertain” by the IPCC in their 2007 report (AR4; IPCC, 2007), which downgraded its upper limit for sea level rise over the next 100 years from 0.88 m to 0.57 m by leaving the dynamic contribution from polar ice sheets out of the projection. This is motivating the Antarctic research community to rapidly improve our understanding for future IPCC reports (AR5 in 2013, AR6 in 2019).

The international research approach

The uncertainties surrounding future changes to the Antarctic ice sheets are being addressed by three research approaches:
(1) Improved Antarctic ice sheet models are being developed for example, through the US-led Community Ice Sheet Model project for the past 150 years and future centuries led through West Antarctic Ice Sheet Initiative;
(2) Longer and more precise records of satellite mass balance observations from both GRACE and InSAR data, which are reducing uncertainties;
(3) Geological records of past ice sheet behaviour (such as those recovered by ANDRILL, SHALDRIL and IODP) provide the only physical evidence of past ice sheet dynamics when atmospheric CO_2 levels and global temperatures were comparable with those projected for 2100.

The SCAR-ACE community is currently leading an international initiative aimed at redressing the critical lack of high-quality paleoclimate records from the Antarctic continental margin. We are actively working with international drilling programs as well as climate and ice sheet modeling communities to develop a 20 year research strategy that recognizes the fact that Antarctica ice cover has begun to change and time is short. The aim is to produce a blueprint for future international collaboration that makes effective use of the available range of drilling platforms and opportunities. This is driven by the need to quantify the physical boundary conditions (e.g. paleogeography, ice extent, oceanic and atmospheric temperatures) for highly sensitive regions of the Antarctic ice sheets to better constrain and test ice sheet and climate models.

Why more Antarctic drilling?

New results from the ANDRILL Program (Naish et al. 2009; Pollard & DeConto, 2009) provide an important example of how paleoclimate records integrated with climate and ice sheet modeling can help constrain future change. The ANDRILL-1B drill core reflects an unstable West Antarctic Ice Sheet during the Pliocene, 5-2 million years ago during a time when Earth’s average surface temperature were 3-4°C warmer than present, and oceans around Antarctica were 5°C warmer - driving global sea level changes of up to +7 m above present.

ANDRILL-1B supports other studies of the greenhouse world of ~ 50 million years ago, implying a higher 'climate sensitivity 'than currently accepted (e.g. Huber, 2008), suggesting additional positive feed backs (climate amplifiers), perhaps pre-conditioned by CO_2 levels. Moreover, our knowledge of polar regions behavior in a high-CO_2 world (2-4 times pre-industrial levels, levels that may be reached by 2100), still remains one of the greatest uncertainties, althoug CO2 is expected to have major influence on Antarctic ice sheet stability (e.g. DeConto & Pollard, 2003, Pagani et al., 2005). SCAR-ACE community has recommended the acquisition of other records directly influenced by one of the 3 most vulnerable sectors of the WAIS (e.g. Pine Island-Thwaites glacier outlets, the Filchner-Ronne Ice Shelf, and/or the Siple Coast of the Ross Ice Shelf). Key regions of the EAIS margin seaward of sub-glacial basins, (e.g. offshore the Aurora basins) are also yet to be explored. There is also an immediate imperative to recover Antarctic geological records beyond the age-range of ice cores and the current ANDRILL projects back 30 to 50 million years ago when Earth's atmospheric CO_2 was 2 to 4 times higher than present – the high end of IPCC projections for 2100.

Science drivers for future Antarctic paleoclimate investigations

The following priorities were identified and recommended by the ACE-SCAR community for a future Antarctic paleoclimate program at the 2009 Granada meeting. In order to address these priorities and questions the proposed program will obtain and utilize geological records integrated with coupled ocean-atmosphere-ice sheet computer models to connect with three major components of the Antarctic cryosphere system:

- The West Antarctic Ice Sheet (including its ice streams and ice shelves) history and behavior;
- The East Antarctic Ice Sheet history and behavior;
- The Southern Ocean history and behavior (including the development of sea-ice and ocean currents)

The Science Priorities

Obtain well-dated, strategically located geological records that directly sample past Antarctic ice sheet dynamics to:

1. Determine the range of temporal and spatial variability of the marine-based West Antarctic Ice Sheet and the low elevation margins of the East Antarctic Ice Sheet (e.g. ice extent, ice volume & contribution to global sea level, thermal condition) that may occur due to changes in Earth's climate (atmospheric greenhouse gas concentrations, sea-surface and land temperatures) projected for coming decades and centuries;
2. Determine the structural, tectonic and geological boundary conditions (e.g. paleogeography) during past ice sheet oscillations;

3. Determine the effect of ice sheet/shelf variability on the regional extent of sea-ice, oceanic conditions (e.g. temperature and salinity), water mass variability and ocean circulation;
4. Determine the broader impacts of ice sheet/shelf and climate variability on ocean circulation processes within the Antarctic Circumpolar Current and its Southern Ocean gyres and investigate the downstream influences on global thermohaline circulation (e.g. as tracked along the Eastern Margin of New Zealand by previous ocean drilling).
5. Determine the relative influence of local insolation-driven atmospheric warming vs. oceanic warming on ice sheet/ice shelf variability.

Integrate climate and ice sheet proxy data (e.g. ice extent, frequency of variability, rate of variability, sea-surface temperature, air temperature, basal hydrology, paleogeography) from well-dated geological records with the latest generation of coupled ice sheet-climate models to:

6. Determine the thresholds and climate sensitivities (e.g., CO_2 concentrations, tectonic, local insulation intensity, positive degree days, ocean temperature) that lead to local, regional and continental scale growth and collapse of the marine-based West Antarctic Ice Sheet and the low elevation margins of the East Antarctic Ice Sheet;
7. Determine the rates of ice-sheet/ice shelf variability at a range of spatial and temporal variations. Can non-linear 'runaway' processes be identified? Can the most vulnerable/sensitive regions be identified? At high resolution does the Antarctic ice margin respond synchronously?
8. Determine Antarctic ice volume contributions to global sea level change at a range of temporal and spatial scales and reconcile with 'far-field' sea level evidence (e.g. oxygen isotope record, sequence stratigraphy and uplifted paleo-shorelines); and,
9. Resolve the relative roles of East and West Antarctic Ice Sheet dynamics in controlling the variability and sensitivity of the Antarctic ice sheet system. Reconcile the contrasting modes of behavior displayed by East and West Antarctic Ice Sheets.

STRATEGIES AND NEEDS

The following strategies, platforms and needs were identified during the Granada workshop. These are considered to be a preliminary assessment of the overall scope of the required effort.

- Integrated inner-shelf-outer shelf to slope-rise-abyssal plain drilling transects are required across key sectors of the Antarctic margin (coordinated by SCAR-ACE) using different platforms like IODP, ANDRILL, SHALDRIL, MeBo, (*Meeresboden* sea-floor drill rig, run by MARUM, University of Bremen, Germany), FASTDRILL.
- Better knowledge, by collecting new geophysical data, about sub-iceshelf basins that trap Neogene sediments is needed to identify drill sites that

can complement the new ANDRILL records and that can be used to validate and test hypotheses explored by the models.

- These drill sites should be coupled with multi-disciplinary marine process studies (e.g. biological ecosystem-scale, physical oceanography, sea ice, etc.) and non-marine studies (subglacial drainage and hydrology)
- We should strive for high recovery of fine-grained, soft sediment (biogenic and fine-grained terrigenous) alternating with overcompacted glacial diamicts that preserve records of glacial advances and retreats in water depths up to 1500 m – which may require a riser system, mud recirculation system for riserless drilling, or a seafloor wireline drill system, or a combination of these approaches.
- The goal should be safe drilling and monitoring (e.g., water mass, sea floor, subsea floor) from ice shelf and sea-ice-covered areas adjacent to the coast, and across the outer shelf, in different places around the margin.

There are still 8 proposals in the IODP system to drill in the Antarctic margin and in the Southern Ocean (see figure and table 1, here below).

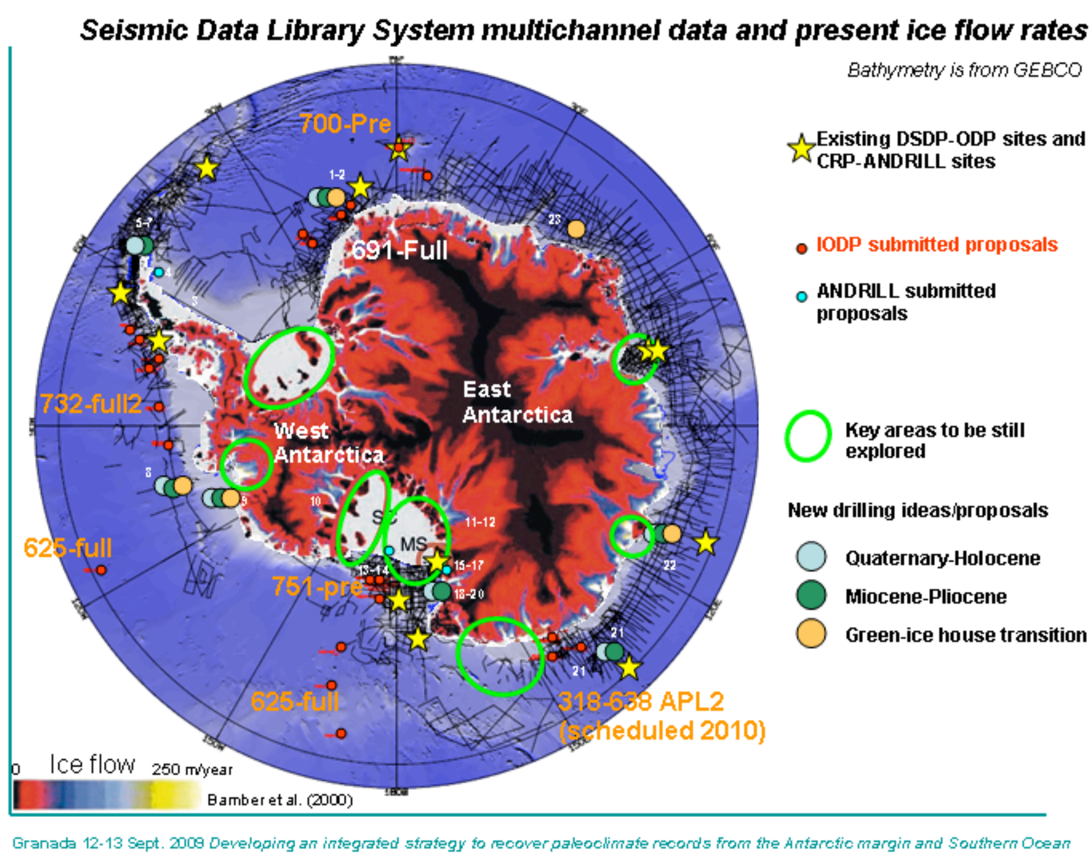

Table 1. existing submitted IODP proposals

Number	Title	P.I.	Country
482-Full3	Cenozoic East Antarctic Ice Sheet History from the Wilkes Land Sediments *DRILLING IS SCHEDULED FOR January-March 2010*	Escutia	Spain
567-Full4	Paleogene South Pacific APC Transect: Heat Transport and Water Column Structure During an Extreme Warm Climate	Thomas	USA
625-Full	Cenozoic Southern Ocean Pacific (CESOP) A proposal for drilling Cenozoic history sites in the Pacific sector of the Southern Ocean	Gersonde	Germany
638-APL2	Annual-to-Centennial Climate Variability along East Antarctica Drilling to Recover a 210 meter laminated Holocene section *DRILLING IS SCHEDULED FOR January-March 2010*	Dunbar	USA
691-Full	The Evolution of the Restricted Mesozoic Basins of the Atlantic sector of Antarctica	Jokat	Germany
700-Pre	Southern Ocean Greenhouse-Icehouse Excursions (SOGIE)	Zachos	USA
732-Full2	Sediment drifts off the Antarctic Peninsula and West Antarctica	Channell	USA
751-Pre	Direct chronologic and environmental-change constraints on the WAIS late Neogene grounding events at the Eastern Basin, Ross Sea, outer continental shelf	Bart	USA

During the workshop held in Granada, in the frame of the 1st ACE symposium, several other ideas or mature proposals for further drilling have been presented and discussed (see table 2, here below). Science questions addressed by each of this new ideas/proposal is illustrated in point 1-11, at the end of table 2.

Table 2. future drilling (IODP, ANDRILL, SHALDRIL, MeBo) proposals

Geographic location (map below)	N. in map	Target (Time period/ nature of record)	Contact persons	Sed thickness Below sea floor (m) /water depth	Site survey status	Type of drilling tool	Science questions addressed*
Western Weddell sea rise drift	1	Quaternary-Pliocene-Miocene, Paleocene, Mesozoic	Wilfried Jokat (AWI, Germany) wilfried.jokat@awi.de	1000 m	MCS lines exist	IODP	1, 2, 3, 5, 6, 10
Weddell Sea rise NE of Crary Fan	2	Quaternary-Pliocene Continuous hi-res record of distal margin sedimentation	Weber, M. E. (AWI, Germany) michael.weber@uni-koeln.de Kuhn, G.	600 m sed; 2400-3000 m water	Few mcs, chirp profiles	IODP to be submitted as ancillary of prop 691-full	2, 9, 10, 11
James Ross Basin (Weddell Sea)	3	Eocene-Pliocene	John Anderson Julia Smith Wellner (Univ. of Houston, Texas USA) jwellner@uh.edu	100-200 m	site survey completed	SHALDRIL	1, 2, 3, 4, 5, 8, 9
Seymour Island	4	Greenhouse-ice house trans.	Alan Vaughan (BAS, UK) apmva@bas.ac.uk Lothar Viereck-Götte (Univ. Jena, Germany), Karsten Gohl (AWI, Germany)	>1000m	Ok	ICDP - ANDRILL	3, 4
Bransfield Strait (Ant. Pensinsula)	5	Quaternary	Julia Smith Wellner (Univ. of Houston, Texas USA) jwellner@uh.edu	500 m	MC Seismic collected (Leg 178 alt. site)	IODP To be submitted in 2010	1,2, 5, 9, 10, 11

			John Anderson Charlotte Sjunneskog				
Maxwell Bay (King George Is., Ant. Pensinsula) Admiralty Bay (Ant. Pensinsula))	6	Quaternary-Pliocene?	John Anderson (Rice Univ., Texas USA)	100-1000 m	1 core drilled by SHALDRIL already	IODP Editing work in progress	1,2, 5, 9, 10, 11
Eastern Ant. Penins. shelf; Vega Drift	7	Holocene	Domack - Leventer (USA)	80	Mcs and scs, short cores, multibeam	IMAGES, SHALDRIL	10, 11
Amundsen Sea-deep water drifts	8	Quaternary-Pliocene	Claus Hillenbrand (BAS, UK) hilc@bas.ac.uk Gabi Uenzelmann-Neben	500m	Some mcs lines; needs: more mcs for connecting data sets	IODP work in progress	2, 9, 10, 11
Amundsen Sea – shelf Pine Is. Bay	9	Quaternary-Miocene	Karsten Gohl (AWI, Germany) Karsten.Gohl@awi.de Torsten Bickert (Univ Bremen, Germany) Rob Larter (BAS, UK)	100-800 m	Some mcs lines; needs: more mcs for connecting data sets	MeBo strategy; SHALDRIL	1,2, 5, 9, 10, 11
Ross Ice Shelf/ Siple Coast near Roosevelt Island	10	Plio-Pleistocene	Tim Naish Tim.naish@vuw.ac.nz	100-1000m	Needs aeromagnetics, mcs seismic surveys	ANDRILL	1,2,3,8,9
Ross Ice shelf Byrd Glacier/ Discovery Deep	11	Greenhouse-ice house trans. WAIS–EAIS Interaction Cenozoic-Pleistocene	Richard Levy (GNS Science, New Zealand) r.levy@gns.cri.nz	100m	Some seismic lines; needs: more mcs	ANDRILL	1,3,4,5,7
Ross Ice Shelf off Beardmore /Shackleton Gl AND Ross Ice Shelf	12	Holocene-Quaternary and ?Paleogene records from 85ºS	Peter Barrett (VUW) Terry Wilson (OSU) twilson@mps.ohio-state.edu Stefan Vogel	Sed 1000 m Ice ~500m Water ~500m	Seismic line (ten Brink&Stern 1993). RISP seismic data Science-needs more data	ANDRILL, FASTDRILL	1,3,4,5,6, 7, 10
Bay of Whales (east Ross Sea)	13	Cretaceous-Eocene (?); Oligocene- early Miocene	Bruce Luyendyk, (Univ. of California, Santa Barbara, USA) luyendyk@geol.ucsb.edu Doug Wilson, Christopher Sorlien, Louis Bartek, Frank Rack, Sherwood Wise, James Kennett, Rob DeConto, David Pollard, Amelia Shevenell	Sed ≤ 100 m cores; Ice 0; Water ~500-700 m	Mcs exist	SHALDRIL Pending NSF approval; Scheduled for 2011-2012	1,3,5, 7, 8,
Coulman High	14	Greenhouse-ice house trans. WAIS history.	Frank Rack (University of Nebraska – NE,	>1200 m core; Ice ~250 m;	Hot water drilling and ocean current	ANDRILL Submitted; Phase I	1,3,4,5, 8

		WARS tectonics	USA) frack2@unl.edu Bruce Luyendyk, Richard Levy, Doug Wilson, Steven A Fischbein, David M Harwood, Terry Wilson, Fabio Florindo	Water ~ 840-870 m	measurements, some over snow MCS tie lines	approved by NSF	
Ross Sea Mackay Sea valley	15	Holocene-late Pleistocene	Ross Powell (Univ. of Illinois, USA) rpowell@niu.edu Robert B. Dunbar	80-200 m	good Holocene seismic but we'd need some more mcs for the deeper sections	SHALDRIL ANDRILL submitted proposal	11
Ross Sea Offshore New Harbor	16	Eocene, E/O bdy, Mid Oligocene, basement, late Miocene	Stephen Pekar, Stephen.pekar@qc.cuny.edu Marvin Speece, David Harwood, Fabio Florindo, Gary Wilson	1200	Mcs exist	ANDRILL	1,3,4,5, 8
Southern McMurdo Ice Shelf	17	Greenhouse-ice house trans.	Gary Wilson gary.wilson@stonebow.otago.ac.nz	400	Hot water drilling and current measurements	ANDRILL (prelim proposal submitted	1, 3, 4, 7, 8.
West Ross Sea, South-Eastern Crary Bank (OGS Explora Mounds)	18	Quaternary biogenic carbonate? mounds. Multiple BSRs related to gas hydrate. Cenozoic stratigraphy of Central Victoria Land Basin	Martina Busetti (OGS, Italy) musetti@ogs.trieste.it Riccardo Geletti	50-100 m for the mounds 700-1000 m for multiples BSRs and Cenozoic stratigraphy of central VLB	Existing MCS and Multibeam data	IODP-SHALDRIL MeBo Editing work in progress	1, 2, 5, 9 10,11
Ross Sea Northern Basin North Drygalski basin Victoria Land basin	19	Pliocene-Miocene	Terry Wilson (Ohio-state Univ., USA) twilson@mps.ohio-state.edu Stuart Henrys Martina Busetti Riccardo Geletti Chiara Sauli Carlo Baroni	100, 1000 m	Mcs and scs, short cores	SHALDRIL IODP ANDRILL work in progress	1, 2, 3, 5, 7, 8, 9
Ross Sea, North Basin	20	Plio-Pleistocene-Miocene Correlation with ANDRILL	Phil Bart (Univ. of Loiusiana, USA) pbart@lsu.edu Laura De Santis (OGS, Italy)	300 m	Mcs and scs, short cores	SHALDRIL proposal submitted, possible schedule 2011-2012	1, 2, 3, 5, 7, 8, 9
Wilkes Land Sediment drift-rise	21	Quaternary-Pliocene bottom current	Laura De Santis (OGS, Italy) ldesantis@ogs.trieste.it Andrea Caburlotto	30-100 m	Few mcs, chirp profiles Needs: mcs Multibeam-physical oceanogr	IMAGES (submitted) IODP work in progress	2, 6, 9, 10, 11

			Massimo Presti				
Totten Glacier system-Mawson Sea (East Antarctica)	22	Cenozoic	German Leitchenkov (VNIIOKEANOLOGIA, S. Pietroburgo, Russia) german_leitchenkov@hotmail.com Federica Donda	1000 m	Some mcs lines; needs more High resolution mcs for connecting data sets	IODP work in progress	2,3,4,5,6,9, 10
Enderby Land margin-Cosmonaut Sea (East Antarctica)	23	Greenhouse-ice house trans.	German Leitchenkov (VNIIOKEANOLOGIA, S. Pietroburgo, Russia) german_leitchenkov@hotmail.com	1000 m	Some mcs lines; needs more High resolution mcs for connecting data sets	IODP work in progress	3,4,6

***Science questions addressed by future drilling**

1. *What is the contribution of Antarctic ice to past and future sea level changes in terms of rate and magnitude? Will sectors of the marine-based Antarctic ice sheets experience "runaway collapse" as climate warms?*
   Models hypothesise unpredictable and rapid deglaciation of marine terminating ice sheets as they retreat into deep basins below sea level (e.g. Schoof et al., 2006). Three meters equivalent sea level of ice within the WAIS (Bamber et al., 2009) is potentially susceptible to "runaway retreat" capable of producing sea level rise of 1-3m per century. A numerical ice sheet modelling approach calibrated with drill core evidence of past WAIS collapses is required to address this issue. The threat of abrupt collapse of WAIS sectors is one of the largest unknowns identified by IPCC in terms of future sea level rise estimates. To address this question, drill core records adjacent to the Siple Coast, Pine Island Bay and the Ronne-Filchner Ice Shelf are recommended. These may require ANDRILL technology from fast ice or ice shelves, , shallow drilling systems (e.g., MeBo, SHALDRIL), or the *Aurora Borealis* new technology, possibly employing a mud-recirculating, drilling riser system. IODP riserless drilling technology would be useful on the rise and continental slope.

2. *How did paleo-Antarctic ice sheets respond when Earth's atmosphere had 400 ppm CO_2?*
   The early Pliocene Epoch represents the last time Earth's climate was as warm as it is likely to be by 2100 (~3ºC). However this warmth was achieved when atmospheric pCO2 was known to be 400ppm and other climatic boundary conditions (e.g. continental and polar ice sheet configurations) were the same. The reasons why such a substantial increase in temperature was achieved over time with such a modest forcing are still speculative (eg. Federov et al., 2008). It also raises the question as to why the earth is not warming faster in response to the present forcing, and whether the climate system is close to a response threshold to rapidly accelerated warming. ANDRILL-1B core (Naish et al., 2009) record of ice sheet variability in western Ross Sea was not directly deposited but physically influenced by west Antarctic ice, and has provided some critical insights suggesting a dynamic WAIS collapsing during past warmer-than-present interglacials. This record needs confirmation with a more WAIS-proximal record as discussed above (e.g. Pine Island Bay, Ross Ice Shelf, Weddell Sea).

3. *How did the Antarctic ice sheets respond the last time Earth's atmosphere was between 600-1000ppm CO_2?*

The Oligocene Epoch is characterised by dynamic ice sheets on both East and West Antarctica (e.g. Naish et al., 2001; Zachos et al., 2001) when atmospheric pCO_2 was between 600-1000 ppm. This period known as the “hothouse world”, is the last time EAIS oscillated in response to orbitally-forced surface melting and is an important geological analogue for evaluating Antarctic response to IPCC A1 and A2 emission scenarios. A major question that can only be addressed only through a combined modelling and geological validation approach, is an understanding of the hysteresis of EAIS. We know the ice sheet forms when pCO2 concentrations are below 2-3 times pre-industrial levels (DeConto and Pollard, 2003), but removing significant sectors of EAIS may require significantly more greenhouse gas-induced warming (e.g. DeConto et al., 2008). IODP Expedition Leg 318 to Wilkes Margin will address this question, but more spatial coverage elsewhere is required.

4. *What did a “greenhouse Earth” look like in Antarctica? Can Antarctica sustain any ice sheets when the atmosphere is above 1000 ppm CO_2?*
   The Eocene-Oligocene climate transition in Antarctica is poorly known from proximal geological evidence, yet models (DeConto and Pollard, 2003) and far-field paleoceanographic proxy data (Liu et al., 2009) suggest that the Earth cooled by 3-4°C and the first large permanent ice sheets formed on Antarctica, when atmospheric pCO2 concentrations dropped to about 1000 ppm during a cooling trend in the late Eocene. ANDRILL Coulman High Project, IODP Wilkes Land Leg 318, and Eastern Ross Sea SHALDRIL are focussed on recovering this geologic interval. Other sites in strata expected to record Greenhouse to ice house transition were identified for future drilling along the Antarctic margins (see figure and table) during the Granada workshop.

5. *Can Antarctic ice volume/sea level records be reconciled with far-field deep ocean oxygen isotope and temperature proxy records?*
   Recent studies calibrating the ice volume/sea level component (e.g. Pekar et al., 2008; DeConto et al., 2008) of the Cenozoic oxygen isotope record require the existence of 20% more polar ice on Antarctica and/or the northern hemisphere continents during major glacials (e.g. Mi and Oi glacial events) than is considered possible by both models (DeConto et al., 2008) and geological evidence (Naish et al., 2008). The apparent over estimation of ice volume in the models may lie in our present lack of knowledge of past Antarctic continental configurations (paleogeography). The ANTscape project has been developed to prepare a series of paleotopographic maps for 6 time periods over the last 100 Ma (www.ANTscape.org). A recent paleogeographic reconstruction for West Antarctica (Wilson and Luyendyk, 2009) represents a pilot study that shows significantly more land in West Antarctica at the end of the Eocene. This effectively enlarges the whole of Antarctica by 10-20% at this time, and provides an explanation for this apparent discrepancy. Ground truth for the reconstructions currently comprises a single site, DSDP site 270, drilled in 1972. Proposed drilling in the Ross Sea by SHALDRIL (eastern Ross Sea) and ANDRILL (Coulman High) and by using other systems like MeBo (*Meeresboden* sea-floor drill rig, run by MARUM, University of Bremen, Germany) in the inner shelf of the Amundsen Sea Embayment all target strata ranging in age from Paleocene to Pliocene, and will provide further critical ground truth for these reconstructions.

6. *How much of EAIS is vulnerable to marine melting?*
   Significant new advances are being made in imaging the bedrock topography under the EAIS using airborne radio echo-sounding by programs such as AGAP and ICECAP. These data identify deep basins in the Wilkes, Amery and Weddell sectors susceptible to collapse as ocean temperatures continue to warm. While the data provide important new boundary constraints for ice sheet modelling, a high priority must be the recovery of drill core records on the continental margin adjacent to these regions that directly samples past ice sheet variability. This is one of the goals of the IODP Expedition 318 to the Wilkes Land Margin, but more spatial coverage needs to be a priority of future IODP. The

compilation of seismic-stratigraphic thickness maps from the East Antarctic margin (Close et al., 2007; Leitchenkov et al., 2007) in the frame of the ACE/CASP project has identifed at least two key areas for future drilling, where huge sediment delivery from the continent occurred after the onset of glaciations. Other areas, that received low sediment supply from the interior, instead preserve a clear imprint of Circum-Antarctic Bottom water recorded in thick sediment drift in the continental rise.

7. *What are the relative sensitivities of EAIS and WAIS to marine vs. atmospheric ablation?*
   Ice sheet modelling studies (e.g. Pollard and DeConto, 2009) show that the marine terminating portions of both ice sheets are most sensitive to oceanic melt rates near ice shelves and grounding lines, whereas it remains unclear what atmospheric and greenhouse gas levels and temperatures are required to ablate terrestrial portions of ice sheets and particularly the high-altitude EAIS (e.g. Hill et al., 2008). A major issue in answering this question lies in understanding the degree of hysteresis of the EAIS (discussed above). Modelling studies need to be informed by direct geological evidence from drill core recovery around the continental margin of EAIS, which can be used to reconstruct past ice extent, ocean and atmospheric temperatures. One of the goals of IODP Expedition 318 is to address this issue. The contrasting controls on the mass balance of EAIS vs. WAIS have highlighted a critical need to reconcile data sets which show a dynamic late Neogene ice sheet in south-western Ross Sea (post 14 Ma; Naish et al., 2009), whereas the high-elevation eastern margin of the EAIS in the Transantarctic Mountains appears to have experienced stable polar conditions (e.g. Lewis et al., 2008). Other sites for future drilling to address this question along the coast of the north Victoria Land, have been identified during the Granada ACE workshop. Here outlet glaciers draining the EAIS across the TAM left a clear imprint of their past advances and retreats as marine glacial valleys-levees since the mid-Miocene. Their environmental record will contribute to understand the age and variability of the Neogene glacial regime.

8. *What were the thermal characteristics of Antarctic ice sheets during past warmer-than-present climates?*
   A major source of uncertainty in modelling ice sheet behaviour in response to warmer-than-present climates is that the thermal characteristics of the ice sheets are not known. The nature of the basal geology (bedrock and till) and the sub-glacial hydrology are 1st order constraints on slipperiness and basal flow of an ice sheet. The sedimentological characteristics of subglacial and grounding-line proximal drill core sediments can provide important information on these thermal conditions (e.g. McKay et al. 2009).

9. *How do the Antarctic ice sheets respond to orbital forcing?*
   Remarkably, 30 years after Milankovitch's orbital theory of the ice ages was confirmed for Northern Hemisphere glaciations (e.g. Hays et al., 1976), we do not understand how Antarctic ice sheets respond to orbitally-induced climate variations. Nor do we know what changes in the Southern Ocean accompanied ice sheet responses? "Milankovitch theory" implies that long-term variations in the northern hemisphere (NH) summer insolation control synchronous glaciations on both hemispheres. A key problem, however, is that the intensity of summer is controlled by the globally "out of phase" ~20,000 year-long precession cycle, whereas the glacial cycles revealed by $\delta^{18}O$ profiles and sea level records occur every 41,000 years, corresponding to the globally-symmetrical influence of Earth's obliquity. Historically, the lack of precession in the geological record has been attributed to the importance of annual insolation that is controlled by obliquity, with more influence on polar temperatures than seasonal insolation modulated by precession (Young and Bradley, 1984). Recently, two additional competing hypotheses have been proposed. (1) Because Earth's orbital precession is out of phase between hemispheres, 20,000 year changes in ice volume in each hemisphere cancel in globally integrated proxies such as $\delta^{18}O$ records leaving the "in-phase" obliquity to dominate the geologic record (Raymo et al., 2006). (2) Alternatively on long timescales insolation integrated over the length of summer (summer energy) which according to Kepler's 2nd law is

inversely proportion to the Earth's distance from the Sun, has been shown in models to control surface melting of ice sheets at both the precession and obliquity periods (Huybers, 2006), providing that the ablating margin is at high latitude and surface temperature remains above freezing for significant part of the season (Huybers & Tziperman, 2008). Although the latter condition is not currently met by the Antarctic ice sheet, its melt threshold may have been exceeded when atmospheric CO_2 levels were higher (e.g. 5-3 Ma). Geological evidence from Antarctic margin drill cores to date (Naish et al., 2001; 2009; Scherer et al., 2008) and numerical ice sheet models (Hill et al., 2008; Pollard and DeConto, 2009) show that orbital control on the Antarctic ice sheet is complex responding variously to both orbital frequencies and to the duration and intensity of insolation. Well-dated drill core records that recover direct evidence of ice sheet variability are critical in testing these hypotheses.

10. *How does the Antarctic Circumpolar Current and Circumpolar Deep Water incursions onto the continental shelf control the stability of marine-based ice margins?*
Incursions of warm, CO_2-rich Circumpolar Deep Water (CWD) on to the Antarctic continental shelf has been implicated in regulating Antarctic climate and marine ice sheet behaviour on short (Toggweiller et al., 2007) and millennial (Naish et al., 2009) timescales. Evidence of Southern Ocean-sourced, CO_2 influencing polar atmospheric temperatures is also provided from ice core records (Monnin et al., 2001). Strategically-located palaeoceanographic records of the three major oceanic gyres (Wilkes, Ross and Weddell) and their influence of on (i) the transfer of water between the Antarctic Circumpolar Current and the Antarctic margin, (ii) the vigour of the westward coastal currents along the margin and (iii) the production and transfer of deep and bottom water are critically needed to understand the interrelationships between ice sheet variability and ocean circulation. Producing temperature proxy records of past CWD incursions from drill cores is still a challenge. With recent observations of present deep water incursions into the deep troughs of the Pine Island and Thwaites glacier systems, shallow drilling in the Amundsen Sea Embayment can produce material for testing and improving proxy techniques that lead to reconstructing the effects of CDW on past ice-sheet dynamics

11. *Did the dramatic millennial-scale, D-O climate cycles of the Northern Hemisphere manifest themselves in the Southern Hemisphere (SH)? If so, what was the amplitude of the response, and was the SH in-phase or out-of-phase with the D-O cycles?*
There are few studies from inner shelf ultra-high resolution sections that recorded seasonal sea ice changes in the Holocene suggesting astronomical forcing for sea ice and glacier dynamics and bottom current changes (e.g. Domack et al., 2001, Leventer et al., 2002; 2006, Denis et al.,2009; Harris et al., 2001). Regional differences in sea-ice concentration variability have been reported with a sea-ice concentrations decrease in Bellingshausen and Amundsen Seas and an increase in part of East Antarctica and the Ross Sea (Rayner et al., 2003). A freshening trend of the Antarctic bottom water, also produced in the western Ross Sea, and the Oates Land-George V-Adelie Land coastal polynyas, was observed during the last decades, likely caused by increased melting of glacial ice (Rignot & Jacobs, 2002; Aoki et al., 2005). However, the direct (instrumental) climate records available for the Southern Hemisphere limited both in time and space and only few proxy-based reconstructions of the Holocene climate are available for the Southern Hemisphere high latitudes compared to those for the Northern Hemisphere. The mechanisms responsible for the observed changes in sea-ice and temperature and modern changes in the Antarctic cryosphere, are not well understood and if we want to improve our understanding of the global climate system we must drill continuous sequences in shelf basins beneath ice shelves and sea ice for physical evidence of Holocene climate trends around the Antarctic margin. These cores will provide datable material well-dated material for paleoclimate proxies to provide constraints and tests on ice-ocean-climate models. More basins that are still trapping continuous sequences are likely to be discovered beneath the ice shelves and thick sea ice, so new geophysical data are needed to detect and characterize these basins and to expand the current list of drilling targets.

Expanded Quaternary sections have been retrieved from sediment drifts of the continental rise in the George V Land margin and from the SE Weddell Sea, where High Salinity Shelf Waters (HSSW) which forming on the shelf and periodically over-spilling the shelf edge, deliver sediments to the deeper environment feeding the bottom nepheloid layer within channels. High sedimentation rates within the slope and rise channels derive from sediment settling from the nepheloid layer and/or direct input by the HSSW. This process was also active also during the last glacial allowing the survival of the biological productivity (e.g. Caburlotto et al., 2009). Further studies on these kinds of deposits will allow a test of bottom water production during past glacial times.

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