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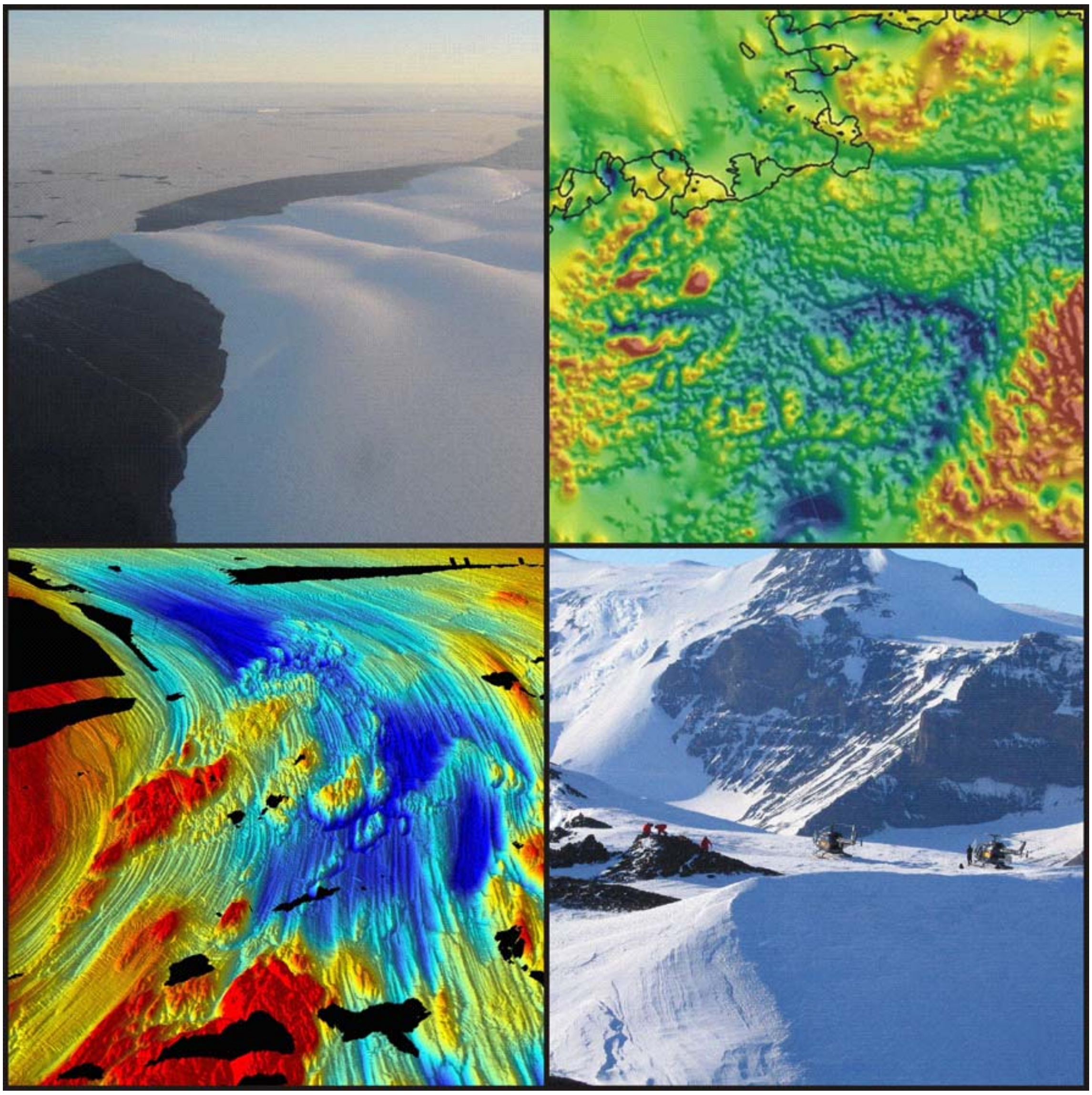
FIRST ANTARCTIC CLIMATE EVOLUTION SYMPOSIUM

Workshop

Amundsen Sea Embayment: Tectonic and Climatic Evolution



Granada, Spain **9th September, 2009**

Programme and Abstracts

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First Antarctic Climate Evolution Symposium Workshop

Amundsen Sea Embayment: Tectonic and Climatic Evolution

9th September, 2009

Conveners: Rob Larter (British Antarctic Survey)
Karsten Gohl (Alfred Wegener Institute for Polar and Marine Research)

Overall Objective

Identify priorities for future geoscience research (terrestrial, marine and airborne) in the Amundsen Sea embayment (ASE) region required to develop a better understanding of the past, present and future behaviour of this sector of the West Antarctic Ice Sheet (WAIS).

Background

The ASE is the most rapidly changing sector of the WAIS and contains enough ice to raise global sea level by 1.2 m. Over the past few years considerable efforts have been made to acquire new data to improve knowledge of the geological strucure, subglacial topography, continental shelf bathymetry and glacial history of this remote region. In this workshop we aim to review the current state of knowledge on the tectonic, climatic and glacial evolution of the Amundsen Sea embayment. We also aim to consider the influence of tectonic evolution on ice sheet history, through control of palaeotopography, heat flow, and effects of geological substrate on ice dynamics. The workshop will focus on identifying remaining open questions and future research priorities.

Programme

13.00 – 13.10 Introduction, objectives and work plan (Larter/Gohl)

13.10 – 14.10 Presentations reviewing tectonic history and framework, from perspectives of plate tectonic reconstructions, marine geoscience and airborne investigations

13.10 –13.25 G. Eagles, R.D. Larter & K. Gohl
Constraints on tectonic evolution of the ASE from plate reconstructions

13.25 –13.35 K.Gohl
Insights into tectonic framework of ASE from marine geophysical data, and objectives of 2010 RV *Polarstern* cruise

13.35 – 13.50 D.D. Blankenship, D.A. Young, J.W. Holt & T.M. Diehl
The subglacial ASE: The view from aerogeophysics

13.50 – 15.10 Presentations reviewing glacial history and processes, from perspectives of marine geophysics, marine geology and geomorphology, surface exposure age dating and terrestrial geomorphology, and airborne/oversnow investigations.

13.50 – 14.00 E. Weigelt, K. Gohl, G. Uenzelmann-Neben & R.D. Larter
Seismic stratigraphic evidence for glacial-interglacial cyclicity in the ASE since Neogene time

14.00 – 14.10 M.J. Bentley, J.S. Johnson, C.J. Fogwill, S. Freeman & R.D. Larter
Constraints on ASE glacial history and processes from surface exposure age dating and terrestrial geomorphology

14.10 – 14.20 F.O. Nitsche
Overview of regional bathymetry data and identification of significant data gaps

14.20 – 14.30 A.G.C. Graham, R.D. Larter, K. Gohl, J.B. Anderson, J.S. Wellner, F.O. Nitsche, J. Evans, C.-D. Hillenbrand, J.A. Smith & G. Kuhn
Seabed glacial geomorphology and substrate geology in the ASE: Current understanding and future directions

14.30 – 14.40 J.A Smith, C.-D. Hillenbrand, R.D. Larter, A.G.C. Graham, G. Kuhn & W. Ehrmann
Deglaciation of the WAIS in the western Amundsen Sea

14.40 – 14.50 J.B. Anderson
Objectives of the 2010 RV *Oden* cruise to the Amundsen Sea

14.50 – 15.00	G. Uenzelmann-Neben and K. Gohl Changing currents and climate in the Amundsen Sea
15.00 – 15.10	C.-D. Hillenbrand, G. Kuhn and T. Frederichs Quaternary WAIS (in)stability – implications from deep-sea sediment cores

15.10 – 15.30	Discussion on open questions raised by presentations and opportunities for future research. Organisation of break-out groups
15.30 – 15.45	Coffee break
15.45 – 16.45	Break out groups focussing on tectonic history and glacial history, tasked to identify the most important open questions and priorities for future research.
16.45 – 17.15	Reporting back from breakout groups
17.15 – 18.00	Plenary discussion and formulation of statement about future research opportunities and priorities.

Constraints on tectonic evolution of the Amundsen Sea Embayment from plate reconstructions

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Because of its age, detailed plate tectonic reconstructions based on seafloor data have contributed little to our knowledge of the pre-Cretaceous history of the Amundsen Sea Embayment (ASE). The sparse geological record suggests the ASE was situated at the active margin of Gondwana in Cambrian times, perhaps occupying a back-arc basin setting seaward of the main Ross Orogeny, which was of sinistral convergent origin [Bradshaw, 2007; Bradshaw et al, 2009]. Possibly, a phase of Permian back-arc activity is recorded in New Zealand and the Bounty Trough offshore of the South Island, which may have lain just north of the ASE at the time [Davy, 1993].

Later, with extant seafloor available to constrain the region's development more or less indirectly, we can model how New Zealand rifted off Antarctica by stages. An early event was the creation or widening of the Bounty Trough and Great South Basin, following collision, at ~105 Ma, of the Hikurangi Plateau with Chatham Rise [Mortimer and Parkinson, 1996; Eagles et al, 2004a; Grobys et al 2007]. It is possible that rifting related to that in the Bounty Trough continued into the ASE [Gohl et al, 2007]. The next event of whose details we can be confident was the onset of seafloor spreading, at what was to become the Pacific-Antarctic Ridge, at ~83 Ma [Larter et al, 2002], and there are indications that this was preceded by the development of rift basins in the ASE [Gohl et al, 2007]. By 79 Ma, asymmetrical seafloor spreading anomalies show how a small mostly oceanic plate started to rotate independently with respect to the Pacific plate, capturing much of the seafloor bordering the ASE margin [Stock & Molnar, 1987] as well as some of the margin itself. Seismic data reveal an incipient subduction zone originated at this so-called Bellingshausen plate's margin with (west) Antarctica, at the Bellingshausen Gravity Anomaly (BGA) [Gohl et al, 1997]. Motion of the Bellingshausen plate started along with a change in the offset sense and lengthening of the transform arms of the Bellingshausen-Pacific-Farallon triple junction, and may therefore be related to shear stresses raised there, and ceased again by 61 Ma [Eagles et al, 2004b].

Using Joann Stock's unpublished reconstruction parameters for the motion of the Bellingshausen and Pacific plates, Cunningham et al [2002] noticed that Bellingshausen-Antarctic motion was of a magnitude that explains the width and strike of Peacock Sound, which separates Thurston Island from the mainland, and suggested that the Bellingshausen-Antarctic boundary passed through it, then towards and past the nearby stage pole, where it became convergent and emerged from the margin as the BGA. Alternatively, Cande & Stock [2004] show the Bellingshausen-Antarctic boundary passing more-or-less orthogonally into the ASE at 120°W (Carney Island). Either this boundary changed strike to cross the ASE and connect with BGA, or it continued south to meet another intra-Antarctic boundary, for instance a Cretaceous-Paleogene West Antarctic Rift System. Later still, it remains a possibility that the West Antarctic Rift System exited Antarctica via the ASE, which may therefore have seen some Neogene extension. Jordan et al [in press] suggest this may have occurred beneath the Pine Island Glacier. Some of these events are presented here as part of an animated reconstruction of gravity anomalies [Eagles et al, 2004a].

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Insights into tectonic framework of ASE from marine geophysical data, and objectives of 2010 RV *Polarstern* cruise

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An understanding of the glacial history of the Amundsen Sea Embayment (ASE) is essential for developing models on the future development of the West Antarctic Ice Sheet. This requires an understanding of the tectonic history and knowledge of tectonic features such as lineaments, ridges, sills and basins, because basement morphology and inherited erosional features control the flow direction of ice-sheets and the influx of Circum-Polar Deep Water (CDW). This is an attempt to reconstruct the tectonic history with the aim to search for basement features and crustal boundaries which may be correlated to the flow and dynamics of the ice-sheet. The Amundsen Sea Embayment of West Antarctica is in a prominent location for a series of tectonic and magmatic events from Paleozoic to Cenozoic times. Seismic, magnetic and gravity data from the embayment and PIB reveal the crustal thickness and significant tectonic features. NE-SW trending magnetic and gravity anomalies and the thin crust indicate a former rift zone which was active during or in the run-up to the breakup process between Chatham Rise and West Antarctica before or at 90 Ma. NW-SE trending gravity and magnetic anomalies, following a prolongation of Peacock Sound, indicate the extensional southern boundary to the Bellingshausen Plate which was active between 79 and 61 Ma. It is likely that the prominent glacial Pine Island Bay trough follows a structural boundary between the crustal blocks of Ellsworth Land and Marie Byrd Land. Still speculative are possible correlations of this and other tectonic features in the ASE with activities of the West Antarctic Rift System (WARS).

The upcoming RV *Polarstern* expedition ANT-XXVI/3 (30 Jan - 5 April 2010) has the general objectives to decipher the tectonic, sedimentary and glacial development of the West Antarctic margin from the NZ-MBL breakup to glacial cycles in the Quaternary. Main study areas cover the southern Amundsen Sea and the ASE. Planned methods include high-resolution to deep crustal seismics, magnetics, gravity, multibeam bathymetry, subbottom profiling, heat-flow probing, sediment coring/sampling, rock sampling for cosmogenic nuclide and fission-track analyses, GPS measurements, and oceanographic CTD casts.

The subglacial ASE: The view from aerogeophysics

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In 2004/05, the subglacial regime of the Amundsen Sea Embayment was mapped out for the first time by the joint AGASEA/BBAS aerogeophysical project. A University of Texas team focused on Thwaites Glacier, while a British Antarctic Survey group focused on Pine Island Glacier.

Each aircraft used coherent ice penetrating radar, gravimeters and magnetometers to provide a geological context for the large ice streams of the region. These surveys unveiled a sector of the WAIS differing in important ways from the previously studied Siple Coast.

Ice penetrating radar measurements of ice thickness allowed a comparison of the gross bed rock topography between the two glaciers, revealing that Thwaites Glacier occupies a broad transverse trench, perpendicular to flow, while Pine Island Glacier is confined in a narrow, longitudinal trough.

Morphology, gravity and magnetic data, combined with the results of basal shear stress inversions of ice flow, indicate that sediments are restricted to these troughs, leading to a strongly segmented glaciological regime in Thwaites Glacier. In addition, abundant evidence of subaerial volcanism is complemented with observation of subglacial volcanism, which may influence the style and distribution of subglacial water systems. This work is now being followed up by detailed ground studies on both glaciers.

Seismic stratigraphic evidence for glacial-interglacial cyclicity in the ASE since Neogene time

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Multichannel seismic reflection profiles provide a record of the glacial development in the western Amundsen Sea Embayment during the Neogene. We identified a northwest-dipping reflector series of more than 1 s TWT thickness (> 800 m) on the middle continental shelf indicating well-layered sedimentary units. The dipping strata reveal a striking alternation of reflection-poor, almost transparent units and sequences of closely spaced, continuous reflectors. We suggest that the distinct changes in reflection character represent episodes of ice sheet advance and retreat forced by climate changes. The similarity to seismo-stratigraphic records from the Ross Sea suggests that dipping strata have accumulated since the Miocene. A major problem is to define the age of the dipping strata and with it the episodes of ice sheet extension because drill sites do not exist within the Amundsen Basin. Therefore a future research priority will be the collection of a series of core samples. The outcrop of layers along large parts of the shelf and the shallow water depth provide a favorable base for shallow drilling.

Constraints on ASE glacial history and processes from surface exposure age dating and terrestrial geomorphology

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The glacial history of the Amundsen Sea embayment is poorly known, and based almost exclusively on a relatively sparse marine geological dataset. Here, we present new onshore constraints on past ice sheet thinning from cosmogenic surface exposure dating of glacially-transported erratic boulders. The dataset consists of exposure ages for granitic boulders deposited on nunataks in the Hudson Mountains, immediately adjacent to the true right side of the Pine Island Glacier. Samples from a number of nunataks have been dated: preliminary data suggest that those from Mt Moses appear to have a low recycling ratio, and show an internally-consistent thinning history for the ice sheet. Geomorphological mapping of the area shows that a prominent lateral moraine garlanding the upper parts of Mt Moses may mark the Last Glacial Maximum (LGM) position of the ice sheet surface. A minimum of 400 m of thinning has occurred since the LGM and the data imply that most of that thinning occurred during the Late Holocene. This is in contrast to both published and newly emerging marine geological data which suggest relatively early (pre-Early Holocene) grounding line retreat across the Amundsen Sea continental shelf. Possible explanations for this mismatch between records of ice sheet thinning and grounding line retreat will be explored.

Our mapping, combined with previous work has shown that a longer-term glacial history is preserved in the Hudson Mountains, and nearby Jones Mountains. This includes evidence of sub-glacial eruptions in the Hudson Mountains, and a major subaerial eruption over a glaciated surface in the Jones Mountains in the Late Miocene. Possible future directions for further study of the long-term glacial history and landscape evolution will be suggested.

Overview of regional bathymetry data and identification of significant data gaps

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Good bathymetry data are essential for understanding tectonic settings, modeling ocean circulation, reconstructing paleo-ice streams, refining ice sheet models, and for planning expeditions. The Amundsen Sea is one of the remotest areas of coastal Antarctica, and was relatively unexplored until the late 1980s. Over the last two decades, increased oceanographic and geological interest has led to several cruises that resulted in sufficient bathymetric data to compile a fairly detailed regional map of the Amundsen continental shelf and margin. This includes the location of cross-shelf trough systems that are aligned with present glaciers and separated by shallower ridges. Shaped by paleo-ice streams, these features merge into a small number of broader troughs on the middle shelf and shoal seaward. They now serve as conduits and reservoirs for relatively warm Circumpolar Deep Water. Since the publication of the first Amundsen Sea bathymetry map in 2007 additional data have been collected as expeditions continue to visit this area. I will provide an overview of the data coverage to date, but also indicate gaps in the present coverage that include areas which might be critical for understanding the processes on the continental margin and its glacial history. These areas include an outer shelf trough north-west of Thurston Island, the connection of a outer shelf depression in central Amundsen Sea with one of the main trough systems, details of the trough in front of Thwaites Glacier, and details of the geometry of the continental slope and smaller troughs in the western embayment.

Sea-bed glacial morphology and substrate geology in the Amundsen Sea Embayment: current understanding and future directions

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The Late Quaternary glacial evolution of the Amundsen Sea Embayment (ASE) is captured within the rocks and sediments, and in the geomorphic expression of the sea floor, on the West Antarctic continental shelf and margin. Landforms and sediments created or deposited by ice streams, which account for most ice discharge from the modern West Antarctic Ice Sheet (WAIS), are particularly important in this area for: (i) understanding the configuration of palaeo-ice sheet flow, (ii) establishing the dynamics of any changes in the ice sheet through time (e.g. during deglaciation), and (iii) providing insights into processes occurring at the ice-bed interface.

Here, we review present understanding of subglacial landforms formed by palaeo-ice streams in the ASE, and outline the geological framework which acted as a substrate for formerly more-extensive ice sheets. We review the development of landform models, from initial recognition of general down-flow progressions to more recent interpretation of complex, multi-temporal bedform assemblages. We highlight the potential of several methods for analysing these bedform imprints, including bedform geometry and bed roughness analyses: tools that have been used widely in similar studies from the northern hemisphere, and in glaciological studies of modern ice-sheet beds. We also show new evidence from recent marine geophysical surveys for palaeo-grounding-line features on the shelf, formed during the last deglaciation, and highlight their importance for understanding of regional ice-sheet changes. We review existing seismic profiles in the embayment, and show our latest interpretation of the distribution and character of the main geological units. Lastly, we identify some possible future directions for geomorphological and geophysical research in the ASE, including: (i) further regional flow-pattern mapping and analysis, (ii) detailed outcrop-scale bedform mapping, (iii) continued focus on ice-marginal geomorphic indicators, and (iv) linkages between the offshore geology and recent sub-ice sheet geological mapping.

Deglaciation of the WAIS in the western Amundsen Sea

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The Amundsen Sea sector of the West Antarctic Ice Sheet (WAIS) contains enough ice to raise global sea level by ~1.5m. During the past two decades glaciers in this region have undergone grounding line retreat, flow acceleration, and a substantial decrease in surface elevation which may have been driven by oceanic melting of the fringing ice shelves due to intrusions of Circumpolar Deep Water onto the continental shelf. In order to put these recent changes in perspective and to determine whether they form part of an ongoing retreat from the Last Glacial Maximum (LGM) or represent recent dynamical changes it is necessary to establish the maximum extent of the ice sheet at the LGM and its subsequent retreat history. So far, only the deglacial history in the southeastern Amundsen Sea (Pine Island Bay) has been reconstructed, and its chronology is limited to a few radiocarbon dates. Here we present the first LGM deglacial chronology for the Dotson-Getz area of the western Amundsen Sea which is based on extensive marine geophysical and geological data collected during cruises of the RRS *James Clark Ross* (JR141) and RV *Polarstern* (ANT-XXIII/4) in early 2006. Cores are characterised by three main facies: (i) subglacial, (ii) pro-glacial (proximal to the grounding line) and (iii) open marine (distal from the grounding line). We have dated the proglacial sediments deposited during the transition from subglacial to open marine sedimentation to obtain a minimum age for deglaciation. Our deglacial chronology is constrained by over 50 radiocarbon ages derived from both the acid-insoluble organic (AIO) fraction and calcareous foraminifera. Surface ages obtained range from 2768 to 6429 ^{14}C years BP and illustrate problems associated with the input of old carbon from the hinterland and current-induced reworking of sediments on the outer shelf. Our dating strategy is also augmented by ^{210}Pb data from surface sediments as well as relative palaeomagnetic intensity (RPI) dating of selected cores. We discuss the problems associated with obtaining reliable deglacial chronologies from continental shelf sediments before finally placing the deglaciation of this sector of the WAIS into a wider regional context.

Objectives of the 2010 RV *Oden* cruise to the Amundsen Sea

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An upcoming (2010) cruise aboard the Swedish Icebreaker *Oden* is aimed at acquiring swath bathymetry data from the largely unmapped central and outer continental shelf in and offshore of Pine Island Bay and at acquiring sediment cores from the area. The objective is to search for grounding zone wedges and other features that can be used to reconstruct the retreat history of the ice sheet. Sediment cores will be used for sedimentological and paleontological evidence for the mechanisms associated with grounding line retreat and to further constrain the timing of retreat. This is a joint effort between the University of Stockholm, Lamont Doherty and Rice University.

Changing currents and climate in the Amundsen Sea

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Little has been published on the oceanographic and climatic development of the Amundsen Sea during the Tertiary. The study of seismic reflection data has revealed that, in general, the continental margin is characterised by channel-levee complexes indicating episodic material input from the continent probably in close interconnection with the waxing and waning of the West Antarctic Ice Sheet. Still, several areas can be identified where the interplay of bottom currents with the turbiditic activity has led to the formation of so called levee-drift systems. A detailed analysis of those levee-drifts would lead to a better understanding of the oceanographic and climatic development in this region an age-depth model provided.

Quaternary WAIS (in)stability – implications from deep-sea sediment cores

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Modern global warming may trigger a collapse of the WAIS, which would raise global sea level by up to 3.3-5 meters. Despite the importance of the WAIS for sea-level changes, its response to the Quaternary climatic cycles is poorly constrained. The geological evidence for a WAIS melt-down within the last 800 ka, probably during Marine Isotope Stage (MIS) 11, is mainly based on the findings of marine diatoms of Quaternary age in the till bed underlying a modern West Antarctic ice stream, and of beach and coastal deposits on the Bahamas, the Bermudas and in Alaska, which indicate a Mid-Pleistocene sea-level highstand of up to 20m above the modern sea level. However, these finding may not necessarily indicate a WAIS collapse during the last 800 ka, and, so far, clear marine sedimentary evidence for the postulated collapse during that time is missing.

The Amundsen Sea embayment is considered to be one of the main exit gates for icebergs calved by the WAIS during a collapse. Therefore, it is reasonable to assume that a WAIS melt-down is recorded in offshore sediments from the continental margin in the Amundsen Sea. Here we present sedimentological data of two sediment cores recovered from the continental slope and rise. The age models of the cores are based on a combination of magnetostratigraphy, lithostratigraphy and/or benthic foraminiferal oxygen isotope stratigraphy and document that the two sequences span >800 ka. Within the sediment cores proxies for biological productivity and the supply of lithogenic detritus from the West Antarctic hinterland exhibit cyclic fluctuations in accordance with the glacial-interglacial cycles. Minor discrepancies in these fluctuations between the two core sites are attributed to regional and/or local environmental impacts on sediment deposition. Neither of the two records exhibits a prominent anomaly that unequivocally documents a WAIS collapse (e.g. a pronounced maximum in the abundance of iceberg-rafted debris). However, a depositional anomaly spanning MIS 15 to MIS 13 is observed at both sites. Proxies for productivity and lithogenic sediment supply suggest that on the West Antarctic continental margin the interval MIS 15-13 has the characteristics of one, prolonged interglacial period. No proxy suggests environmental conditions much different from today, but if the WAIS collapsed during the last 800 ka, then MIS 15-13 seems to be the most likely time period. Here, we discuss the relevance of our findings and different WAIS collapse scenarios, which may make it difficult to identify the “smoking gun” for such a collapse in continental margin sediments.