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Bathymetry of the Amundsen Sea continental shelf: Implications for geology, oceanography, and glaciology

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[1] The Amundsen Sea continental shelf is one of the most remote 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. We have combined available multibeam and single-beam bathymetry data from various sources and created a new regional bathymetry of the Amundsen Sea continental shelf and margin. Deep trough systems that dominate the inner shelf 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. This new compilation is a major improvement over previously available regional maps and should aid the numerical modeling of ocean circulation, the reconstructions of paleo-ice streams, and the refinement of ice sheet models.

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1. Introduction

[2] The Amundsen Sea continental shelf is located between 100° and 135°W, south of 71°S, along the margin of the Marie Byrd Land sector of the West Antarctic Ice Sheet (WAIS) (Figures 1 and 4). As one of the more remote Antarctic coastlines, with a nearly perennial sea ice cover and little if any bottom water formation, it remained largely unexplored until the mid 1980s. Interest in the region

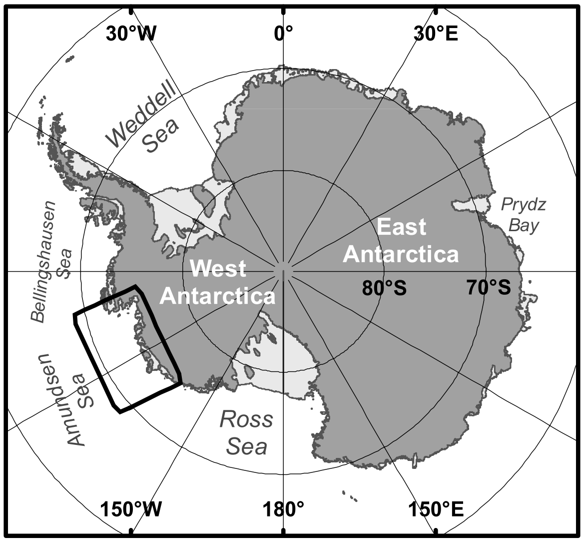

Figure 1. Antarctica with the location of the Amundsen Sea. Outline is based on Antarctic Digital Database 4.1 [*Thomson and Cooper*, 1993] (http://www.add.scar.org/).

increased with the 1994 discovery that the ice shelf at the terminus of the Pine Island Glacier was melting orders of magnitude faster than the Ross and Filchner-Ronne Ice Shelves [*Jacobs et al.*, 1996; *Jenkins et al.*, 1997; *Hellmer et al.*, 1998], accompanied by increased velocity, thinning and grounding line retreat [*Rignot*, 1998; *Rignot and Jacobs*, 2002]. A melt rate exceeding 40 m/yr near its grounding line [*Rignot and Jacobs*, 2002] appears to be driven by "warm" Circumpolar Deep Water (CDW) that floods deeper areas of the Amundsen Sea continental shelf. Subsequent investigations have revealed high melt rates for other Amundsen Sea ice shelves, thinning and increased velocities of tributary glaciers, and decreasing ice surface elevations of the adjacent WAIS drainage basins [*Wingham et al.*, 1998; *Rignot and Thomas*, 2002; *Shepherd et al.*, 2004; *Thomas et al.*, 2004; *Davis et al.*, 2005]. Such findings have revived longstanding concerns about ice sheet stability in this sector [*Hughes*, 1973], particularly as the WAIS is mostly grounded below sea level [*Drewry et al.*, 1982] and the global ocean is warming [*Levitus et al.*, 2005].

[3] Much of the rapid melting occurs within deep troughs on the inner shelf, presumably cut when the ice streams of larger ice sheets were grounded on the present seafloor [*Lowe and Anderson*, 2002; *Evans et al.*, 2006]. As these features now extend beneath the small Amundsen Sea ice shelves, it is important to understand how the troughs facilitate CDW access to the ice, along with their characteristics and connections to the shelf break. A better description of the continental shelf bathymetry could become a key element in improved models of ocean circulation, ocean-ice interactions and ice sheet behavior [*Philippon et al.*, 2006], and in reconstructions of paleo-ice flow [*Kellogg and Kellogg*, 1987; *Lowe and Anderson*, 2002; *Evans et al.*, 2006; *Larter et al.*, 2007].

[4] While several previous studies of Amundsen Sea bathymetry provided significant new insights, most have been restricted to local areas covered by single cruises. The aggregated tracks of several expeditions, including recent cruises on the RRS *James Clark Ross* and R/V *Polarstern* in 2006 and the *Nathaniel B. Palmer* in 2007, have now been compiled into a chart that provides an overview of the regional bathymetric setting and its geological, oceanographic and glaciological implications.

2. Setting of the Amundsen Sea Continental Shelf

[5] The tectonic structure of the Amundsen Sea continental shelf results mainly from the Late Cretaceous rifting and breakup between New Zealand and the Marie Byrd Land and Thurston Island blocks, and may also have been affected by the existence of an independent Bellingshausen Plate until the early Tertiary [*Stock and Molnar*, 1987; *Mayes et al.*, 1990; *Larter et al.*, 2002; *Eagles et al.*, 2004; *Gohl et al.*, 2007]. It has been suggested that the southern boundary of the Bellingshausen Plate crossed the continental shelf of the Amundsen Sea embayment [*Larter et al.*, 2002; *Eagles et al.*, 2004; *Gohl et al.*, 2007].

[6] The present continental shelf was sculpted during past glaciations, displaying surface and subsurface features that indicate grounded ice has reached the outer shelf several times [*Kellogg and Kellogg*, 1987; *Nitsche et al.*, 1997; *Lowe and Anderson*, 2002; *Evans et al.*, 2006]. Earlier cruises discovered several deep troughs on the inner shelf [*SPRITE Group*, 1992; T. B. Kellogg et al., Former rock-floored ice-streams on the Amundsen Sea continental shelf, unpublished manuscript, 2000], and subsequent investigations of the trough originating in Pine Island Bay reported exposed crystalline bedrock on the inner shelf, changing to dipping strata with overlying recent sediment cover toward the mid-shelf [*Lowe and Anderson*, 2002; *Uenzelmann-Neben et al.*, 2007]. Mega-scale glacial lineations in this trough indicate that it was occupied by paleo-ice streams. The shallower outer

shelf areas (∼500 m) show widespread iceberg furrows on the seafloor, and broad shelf break depressions that may be related to inner shelf troughs [*Lowe and Anderson*, 2002; *Evans et al.*, 2006; *Walker et al.*, 2007].

3. Data Compilation

[7] Multibeam swath-mapping on several recent expeditions has significantly improved our knowledge of bathymetric features on and along the Amundsen Sea continental shelf. Here we integrate those data and add other available bathymetric and geophysical measurements to create a new regional map of this sector of the continental margin. Our sources include single-beam and multibeam bathymetry available through the NSF-funded Antarctic Multibeam synthesis database [*Carbotte et al.*, 2007], soundings from earlier cruises in the GEODAS database [*National Geophysical Data Center*, 1996], and measurements from James Clark Ross cruises JR84 and JR141, Polarstern cruises ANT-XI/3, ANT-XII/4, ANT-XVIII/5a, and ANT-XXIII/4, and NB Palmer cruise 07-02 (Table 1 and Figure 2).

[8] Usually the shoreline boundary of bathymetry compilations is simply set to 0 m, whereas bathymetric features in West Antarctica often continue below the ice shelves and ice sheet. To accommodate these sub-ice features we integrated ice sheet basement data from the US Airborne Geophysical Survey of the Amundsen Sea Embayment, Antarctica (AGASEA) and the UK Basal Balance And Synthesis (BBAS) projects [*Holt et al.*, 2006; *Vaughan et al.*, 2006] and less detailed topography from the BEDMAP project [*Lythe et al.*, 2000] for areas west and north of the AGASEA/BBAS data sets. Our compilation extends from ∼100°W to 135°W and 68°S to 76°S, reaching from the Abbot, Cosgrove and Pine Island ice fronts in the eastern Amundsen Sea to the western end of the Getz Ice Shelf, and covering the entire continental slope and most of the continental rise.

[9] Data processing and integration followed the scheme in Figure 3. All single-beam soundings were converted into a common format and then imported into ArcGIS software (ESRI). Most of the swath-bathymetry data sets were initially ping edited and processed aboard ship. We reduced the swath-bathymetry data to manageable size by creating grids of 200–250 m resolution using MB-system [*Caress and Chayes*, 1996] or Fledermaus IVS [*Mayer et al.*, 2000], depending on the original format, and imported those grids into ArcGIS, reconverting raster to point data. These point data were the basis for generating new grids. Positional accuracy of the data sets varies, but most data used for this compilation (1988 and younger) were obtained with GPS systems that reached an accuracy of <100 m. Navigation data from earlier cruises, which represent a small fraction of the whole compilation and were used to fill gaps in sparsely covered parts of the continental rise, were collected using the older US Navy TRANSIT satellite navigation system, accurate to ∼2 km or better, or celestial navigation. To accommodate positional inaccuracies and the varying density of available data we chose a 2 km grid resolution. After testing several interpolation schemes we settled on a "natural neighbor" algorithm [*Sibson*, 1981] as implemented by ArcGIS for grid formation. This algorithm exactly recovers reference points and can handle highly irregular data distributions [*Sambridge et al.*, 1995], suitable for the present Amundsen Sea where areas covered by high-density swath-bathymetry data are typically separated by large gaps (Figure 2). As data quality varies between individual surveys, several iterations were required to identify and remove disparate measurements. This included single or small groups of measurements that created obvious artifacts in the grid including local, unrealistically deep holes and edge effects resulting from less reliable outer beams of multibeam swaths.

4. New Amundsen Sea Bathymetric Map

[10] The resulting compilation outlines for the first time the full extent and shape of the Amundsen Sea continental shelf, defining its shelf break along most of its length (Figure 4). Seaward of the coastline, the continental shelf narrows westward from >400 km north of Pine Island Bay to 100–200 km west of Siple Island. The outstanding features on the continental shelf are its deep and rugged inner shelf troughs that typically merge and shoal seaward of the ice shelf fronts. Individual troughs often merge into single features by mid-shelf, with the eastern shelf dominated by two trough systems. The one in Pine Island Bay combines troughs that originate from the Pine Island, Thwaites, and Smith Glaciers. A second system includes troughs from the Dotson and eastern Getz ice shelves. Maximum depths in both systems exceed 1600 m, but are not always near the present-day ice fronts. These dendritic trough sys-

Table 1. Survey ID, Data Type, Navigation Equipment, Date, and Sources Used for Compilation, With Selected References Describing or Utilizing These Data

Survey ID	Data Type	Navigation	Year	Source	Reference
ELT11	single-beam PDR 12 kHz	sextant	1964	GEODAS[a]	
ELT17	single-beam PDR 12 kHz	sextant	1965	GEODAS[a]	
ELT33	single-beam PDR 12 kHz	TRANSIT/sextant	1968	GEODAS[a]	
DSDP35GC	single-beam 12 kHz/GIFFT	TRANSIT	1974	GEODAS[a]	*Tucholke and Houtz* [1976]
THB80	single-beam unknown	unknown	1981	GEODAS[a]	*Yamaguchi et al.* [1988]
DF85	single-beam SeaBeam 12 kHz	TRANSIT	1985	GEODAS[a]	*Kellogg and Kellogg* [1987]
PD190L02	single-beam EDO depth tracker	GPS	1990	GEODAS[a]	
NBP92-08	single-beam Simrad:EK500	GPS	1992	GEODAS[a]	
PS92	single-beam	GPS	1992	GEODAS[a]	*SPRITE Group* [1992]
RITS94B	multibeam SeaBeam	GPS	1993	NGDC[b]	
NBP94-02	single-beam Simrad:EK500	GPS	1994	GEODAS[a]	*Jacobs et al.* [1996]
ANT-XI/3	multibeam Hydrosweep DS-1	GPS	1994	AWI[c]	*Nitsche et al.* [2000]
ANT-XII/4	multibeam Hydrosweep DS-1	GPS	1995	AWI[c]	*Nitsche et al.* [2000]
NBP96-02	multibeam SeaBeam:2112	GPS	1996	AMBS[d]	
NBP99-02	multibeam SeaBeam:2112	GPS	1999	AMBS[d]	*Lowe and Anderson* [2002]
NBP99-09	multibeam SeaBeam:2112	GPS	1999	AMBS[d]	
NBP00-01	multibeam SeaBeam:2112	GPS	2000	AMBS[d]	
BEDMAP	various	various/GPS	2000	BEDMAP	*Lythe et al.* [2000]
ANT-XVIII/5a	multibeam Hydrosweep DS-2	GPS	2001	AWI[c]	*Scheuer et al.* [2006]
JR84	multibeam Simrad EM120	GPS	2003	SPRI[e]	*Dowdeswell et al.* [2006a]; *Evans et al.* [2006]
ANT-XXIII/4	multibeam Hydrosweep DS-2	GPS	2006	AWI[c]	*Larter et al.* [2007]; *Gohl et al.* [2007]; *Uenzelmann-Neben et al.* [2007]
JR141	multibeam Simrad EM120	GPS	2006	BAS[f]	*Larter et al.* [2007]
AGASEA/BBAS	radar	GPS	2006	AGASEA/BBAS	*Vaughan et al.* [2006]; *Holt et al.* [2006]
NBP07-02	multibeam Simrad EM120	GPS	2007	AMBS[d]	

[a] GEODAS Web site: http://www.ngdc.noaa.gov/mgg/geodas/geodas.html.
[b] National Geophysical Data Center http://www.ngdc.noaa.gov/.
[c] Alfred Wegener Institute for Polar and Marine Research.
[d] Antarctic Multibeam Bathymetry and Geophysical Data Synthesis Web site: http://www.marine-geo.org/antarctic/.
[e] Scott Polar Research Institute.
[f] British Antarctic Survey.

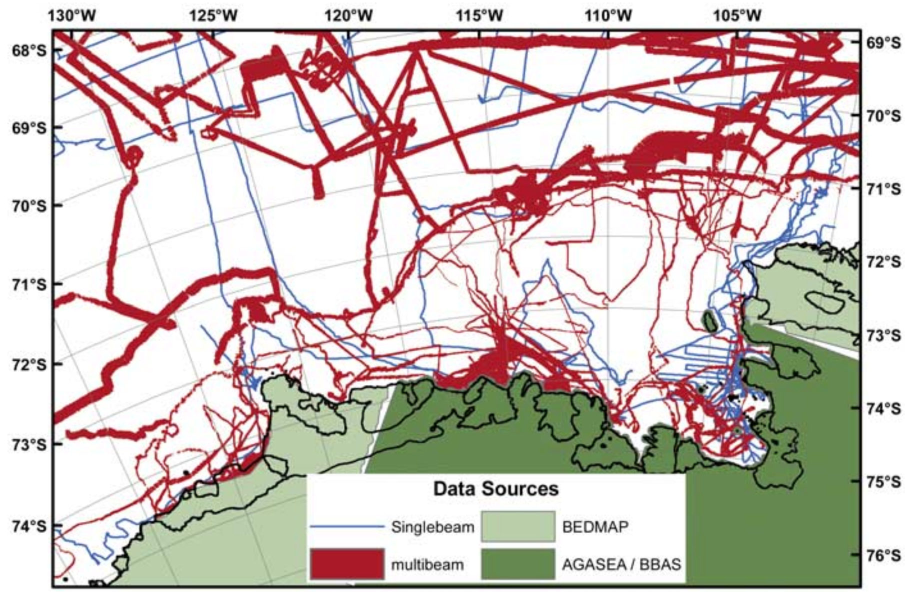

Figure 2. Distribution of the various data sources that form the basis for the new bathymetric grid. Red areas show the coverage of the multibeam bathymetry data, blue lines represent tracks of individual soundings, and green areas represent additional data sets that we used for areas covered by continental ice. Table 1 provides details.

tems are separated by a bank extending northward from the Bear Peninsula, with water depths of ~250–400 m, where deep-draft icebergs go aground. Recently collected swath bathymetry data that have been included in the new bathymetric compilation show that geomorphic features interpreted as subglacial meltwater features [*Lowe and Anderson*, 2003] are widespread throughout the inner shelf troughs.

[11] Several smaller troughs and trough systems are found near Cosgrove Ice Shelf, and off Carney Island and the central and western Getz Ice Shelf fronts. These inner shelf troughs commonly display rugged relief, to >200 m in Pine Island Bay, and a host of smaller features including striations, grooves, drumlins, and mega-scale lineations indicative of glacial erosion [*Wellner et al.*, 2001; *Lowe and Anderson*, 2002]. Similar troughs also appear along other parts of the Antarctic continental margin [*Pudsey et al.*, 1994; *Canals et al.*, 2000, 2002; *Ó Cofaigh et al.*, 2002, 2005] and previously glaciated margins in the northern hemisphere [e.g., *Stokes and Clark*, 2001; *Ottesen et al.*, 2005; *Dowdeswell et al.*, 2006b; *Shaw et al.*, 2006].

[12] Depths along the continental shelf break average ~500 m, but vary from ~400 to >600 m (auxiliary material[1] Figure S2). An outer shelf depression near 114°W has been charted in some detail [*Dowdeswell et al.*, 2006a; *Walker et al.*, 2007], but persistent sea ice has limited mapping of other shelf break depressions NW of Thurston and Siple Islands. Connections between these depressions and inner-shelf troughs remain to be confirmed by more detailed mapping of mid-shelf areas usually covered by perennial ice. West of Siple Island a trough near ~128°W can more clearly be followed from the ice edge to the shelf break.

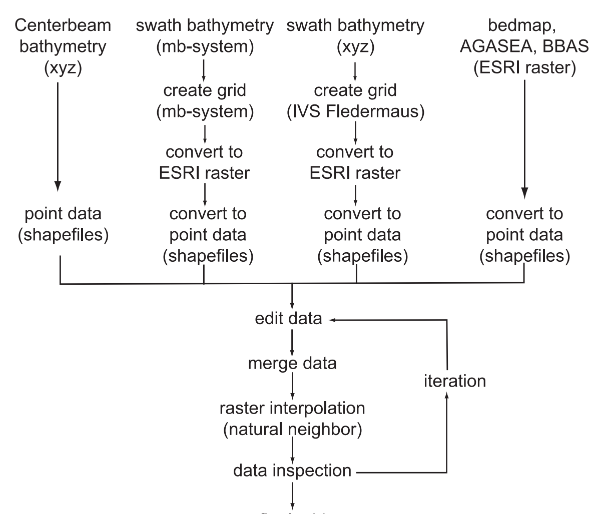

Figure 3. Processing scheme used to integrate the different data sets and create the final grid.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GC001694.

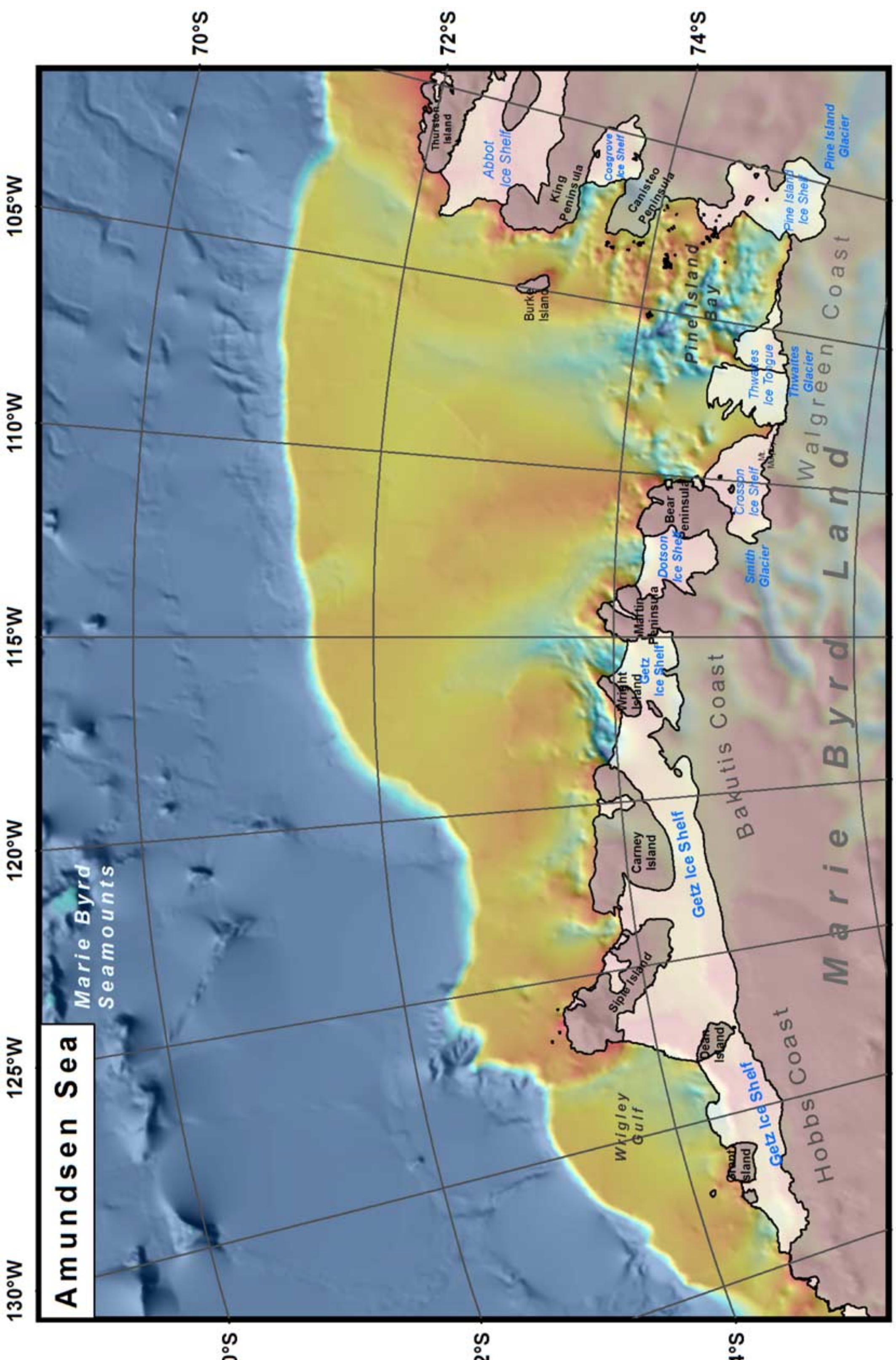

Figure 4. Bathymetry of the Amundsen Sea based on data available through March 2007 (Table 1). Grid control is based on the ship tracks shown in Figure 2. The coastline, ice shelves, and grounding lines are based on the Antarctic Digital Database 4.1 but have been modified to fit more accurate MODIS satellite image [see also *Swithinbank et al.*, 2003, 2004]. The sub-ice topography is based on AGASEA/BBAS and BEDMAP data sets.

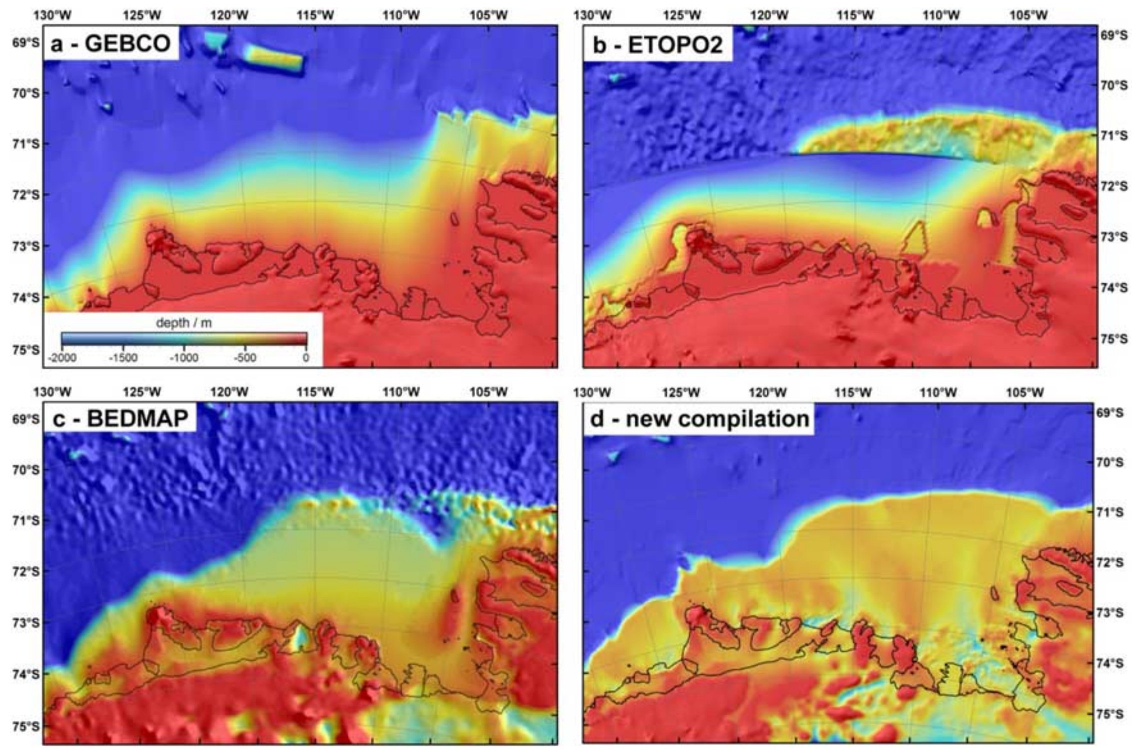

Figure 5. Other representations of Amundsen Sea bathymetry: (a) GEBCO [*Mammerix and Cande*, 1982], (b) ETOPO-2 [*Smith and Sandwell*, 1994, 1997], and (c) BEDMAP [*Lythe et al.*, 2000], compared to (d) the new bathymetry grid. The largest differences appear in the outline of the shelf break and in the trough and ridge structures.

[13] The general morphology of the continental slope and rise is comparable to other parts of the Antarctic continental margins. The slope ranges from 2°–5° with parts of the upper slope being dissected by gullies that in some areas converge downslope and feed into large channels that cross the continental rise [*Dowdeswell et al.*, 2006a; *Lowe and Anderson*, 2002]. More detailed multibeam coverage of both the slope and shelf is needed to definitively relate gullies, depressions, lineations, troughs and paleo-ice streams. In addition to sedimentary features previously reported on the continental slope [*Dowdeswell et al.*, 2006a] a series of mounds radiate away from the slope between 105°W and 110°W. These mounds connect to known features on the lower continental rise [*Yamaguchi et al.*, 1988; *Nitsche et al.*, 2000; *Scheuer et al.*, 2006]. North of Siple Island (125°W–127°W) the slope is interrupted by a large SE-NW oriented ridge at depths of 1–3 km, incised by steep canyons. Its shape and water depth preclude glacial links, but its proximity to the Mt. Siple volcano and Marie Byrd Seamounts suggests a tectonic origin.

[14] Earlier depictions of the Amundsen Sea region (BEDMAP/ETOPO/GEBCO in Figure 5) predated the marine multibeam data utilized here, and so are deficient in several important respects. However, control for the current bathymetry is still uneven, with many large gaps between ship tracks (Figure 2), some resulting from the typical distribution of perennial sea ice. The depth accuracy varies accordingly, being highest in areas with modern multibeam cover, but containing significant uncertainties in the large interpolated areas. Seams between detailed multibeam bathymetry and interpolated areas can cause artifacts such as sudden changes in seafloor roughness and the outward bulge of the lower continental slope between 121°W and 125°W. The seafloor bathymetry is still unknown beneath the ice shelves, although recent airborne radar missions suggest the continuation of some troughs below the Smith, Thwaites and Pine Island Glaciers [*Holt et al.*, 2006; *Vaughan et al.*, 2006].

5. Implications

[15] Concerns about ice sheet mass balance and sea level change have recently focused on the Amundsen Sea because high basal melt rates of its small ice shelves are positively correlated with acceler-

ating ice streams and apparent draw-down of the adjacent ice sheet [*Shepherd and Wingham*, 2007]. The shelf bathymetry is thought to play a substantial role in this process, both as a gateway facilitating CDW intrusions near the shelf break and a link to deep ice shelf grounding lines. There are indications from observations and models that warm deep water may preferentially move onto continental shelves via shelf break curvatures and depressions [*Dinniman et al.*, 2003; *Walker et al.*, 2007]. However, CDW rises well above the Amundsen shelf break across a wide area [*Jacobs et al.*, 2002], and as yet little is known about the temporal variability of its penetration onto the shelf. Once in the troughs, the saltiest and therefore densest deep water sinks and flows into the ice shelf cavities, its melting potential enhanced by the seawater freezing point depression with increasing pressure [*Jacobs et al.*, 1996].

[16] One consequence of recent work in the Amundsen Sea is that models of ice sheet behavior must now be updated to include the effects of an evolving ocean and its ice shelves. Similarly, models of the ocean circulation must properly account for this remarkable continental shelf, its fringing ice shelves and persistent sea ice cover. Quite different results may be obtained from models based on the bathymetry reported here, compared to that shown on prior maps (Figure 5). The new bathymetry could impact estimates of ice shelf melting, WAIS mass balance, and ocean freshening. The locations and depths of the trough systems are also important for reconstructions of paleo-ice flow and deglaciation. This compilation of Amundsen Sea bathymetry represents a major improvement over previously available regional data sets, which involved far more interpolation between sparser, less accurate observations. A larger-scale version of the map is available in the auxiliary material (Figure S1), and the grid may be obtained from http://www.marine-geo.org/link/entry.php?id=Amundsen_Sea_Nitsche.

Acknowledgments

[17] We thank the personnel aboard the several ships, especially the *NB Palmer*, R/V *Polarstern*, and RRS *James Clark Ross*, who have been responsible for obtaining bathymetric data in the Amundsen Sea, often under difficult conditions. Multibeam data on cruises ANT-XXIII/4 and JR141 were collected and processed by S. Gauger and T. Deen, respectively. T. Kellogg digitized bathymetry from DF85, J. Dowdeswell made data available from JR84, H.-W. Schenke provided access to *Polarstern* data, and J. Anderson, S. Cande, and others contributed observations through the Antarctic Multibeam Bathymetry Synthesis database. S. Carbotte, S. O'Hara, and the database team at Lamont provided key assistance. The manuscript benefited from the comments by two anonymous reviewers. This work was supported in part by U.S. National Science Foundation through a supplement to U.S. National Science Foundation ANT 04-40655 and by ANT 02-33303 and ANT 04-40775. It also forms part of the BAS Glacial Retreat in Antarctica and Deglaciation of the Earth System (GRADES) Program as well as the MARCOPOLI Work Packages MAR2 and POL6 of AWI. This is Lamont contribution 7068.

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