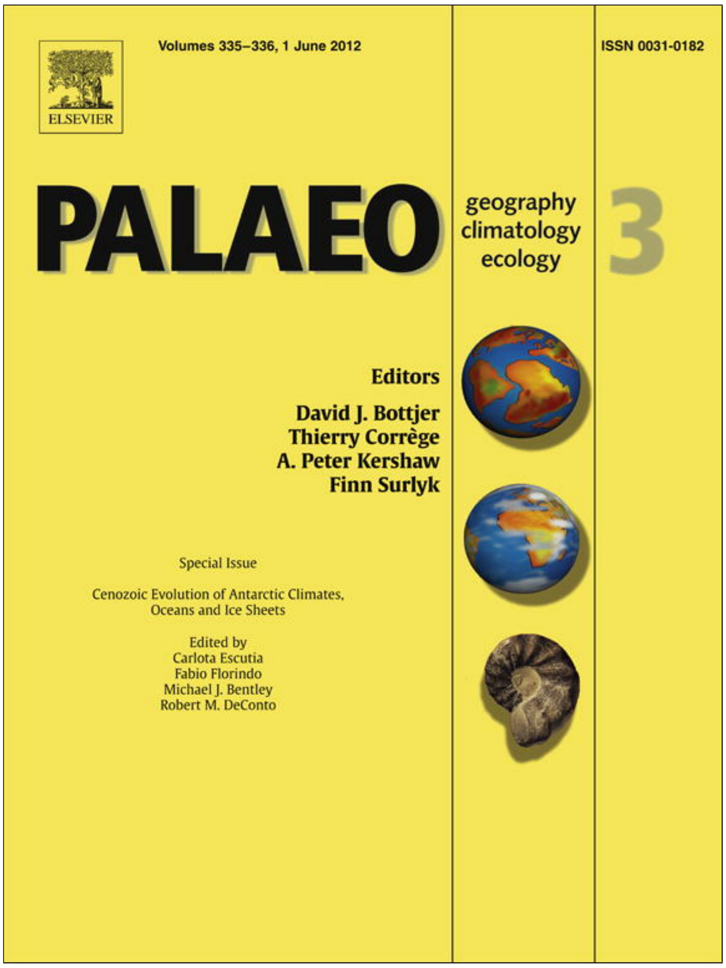
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Basement control on past ice sheet dynamics in the Amundsen Sea Embayment, West Antarctica

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ABSTRACT

The development of landscapes and morphologies follows initially the tectonic displacement structures of the basement and sediments. Such fault zones or lineaments are often exploited by surface erosional processes and play, therefore, an important role in reconstructing past ice sheet dynamics. Observations of bathymetric features of the continental shelf of the Amundsen Sea Embayment and identification of tectonic lineaments from geophysical mapping indicate that the erosional processes of paleo-ice stream flows across the continental shelf followed primarily such lineaments inherited from the tectonic history since the Cretaceous break-up between New Zealand and West Antarctica. Three major ice flow trends correspond to different tectonic phases in east–west, northwest–southeast and north–south directions. East–west oriented basement trends correlate with coastline trends and overlay tectonic lineaments caused by former rift activities. Directional trends with northwest–southeast orientation are observed for the glacial troughs of the western embayment outer shelf, the western Pine Island Bay coastal zones, and the inner Pine Island glacial trough and are associated with a distributed southern plate boundary zone of the former Bellingshausen Plate. The north–south trend of the main Pine Island glacial trough and the north–northeast trend of the Abbot Ice Shelf trough on the outer shelf follow the predicted lineation trend of an eastern branch of the West Antarctic Rift System extending from the Thwaites drainage basin northward into Pine Island Bay. An understanding of this context helps better constrain the geometries and sea-bed substrate conditions for regional paleo-ice sheet models.

1. Introduction

Tectonically induced displacements of crust, basement and sediments are the underlining process controlling the development of landscapes and morphologies which are exploited by surface erosional activities. This context becomes in particular important for reconstructing continental ice sheets at various stages since the beginning of glacial cyclicity. Reconstructing past West Antarctic ice sheet dynamics in the area of the Amundsen Sea Embayment plays an important role as the Pine Island, Thwaites, Smith and Kohler glacier systems of the Amundsen Sea Embayment have thinned at an alarming rate, while flow speed of some of them has dramatically increased (e.g. Rignot et al., 2008; Pritchard et al., 2009). Their catchment area alone has an ice-mass potential for about 1.5 m of sea-level rise (Vaughan, 2008). Modeling results by Pollard and DeConto (2009) suggest that the ice sheet in the Amundsen Sea Embayment has behaved with similar retreat dynamics in earlier epochs, at least since the Pliocene. This paper demonstrates that there is a relationship between the tectonic lineaments inherited from the complex tectonic history of this area since the Cretaceous rifting between New Zealand and West Antarctica, and the flow paths taken by major ice streams. This helps better constrain the geometries and sea-bed substrate conditions for regional paleo-ice sheet models.

2. Tectonic background

The geological history of the Amundsen Sea Embayment and its present geographical outline was controlled by several distinct tectonic phases.

The processes during rifting and break-up of New Zealand from West Antarctica dominate most of the present tectonic nature of the continental margin of the Amundsen Sea (Fig. 1). Eagles et al. (2004a) illustrate that early Pacific–Antarctic separation evolved first as rifting and crustal extension between Chatham Rise and western Thurston Island block and along the present-day Bounty Trough between Chatham Rise and Campbell Plateau (Grobys et al., 2007) as early as 90 Ma. Rifting possibly continued along the present Great South Basin between the Campbell Plateau and the South Island of New Zealand until the rift was abandoned in favor of a new extensional locus to the south, forming the earliest oceanic crust between Campbell Plateau and Marie Byrd Land at 84–83 Ma. The eastern boundary between Chatham Rise and Campbell Plateau at 90 Ma – before the formation of Bounty Trough – was situated off the western Amundsen Sea Embayment at about 120°–125°W.

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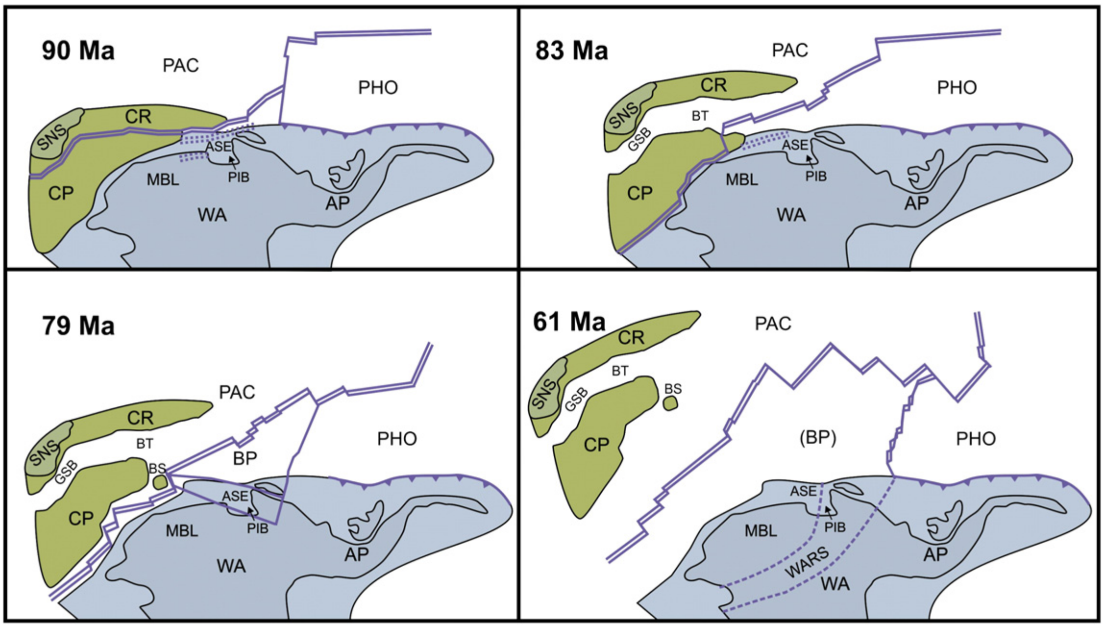

Fig. 1. Plate-kinematic reconstruction of the tectonic development in the Amundsen Sea area from 90 to 61 Ma. The plates are rotated according to rotation parameters compiled and derived by Eagles et al. (2004a). Abbreviations are: PAC Pacific plate, PHO Phoenix Plate, CR Chatham Rise, CP Campbell Plateau, SNS South Island New Zealand, GSB Great South Basin, BT Bounty Trough, BS Bollons Seamount, WA West Antarctica, MBL Marie Byrd Land, AP Antarctic Peninsula, ASE Amundsen Sea Embayment, PIB Pine Island Bay, BP Bellingshausen Plate, and WARS West Antarctic Rift System faults. The development is explained in the main text.

From about 79 Ma or earlier, the Bellingshausen Plate (Fig. 1) moved as a micro-plate independently on the southern flank of the mid-Pacific spreading ridge until about 61 Ma when a major plate reorganization occurred in the South Pacific (e.g. Larter et al., 2002; Eagles et al., 2004a,b). The small plate's western boundary was situated in the area of the Marie Byrd Seamounts; its eastern transpressional boundary lies along the Bellingshausen Gravity Anomaly lineament in the western Bellingshausen Sea (Gohl et al., 1997; Eagles et al., 2004a). Although its southern plate boundary has been projected to extend from the Marie Byrd Seamount area onto the shelf and mainland for reasons of completeness (Eagles et al., 2004a,b), it is not clearly identified and it may be of a distributed boundary type.

The plan shape of Pine Island Bay has stimulated several researchers to suggest that the bay is the location of a major crustal boundary between the Marie Byrd Land block to the west and the Thurston Island/Ellsworth Land blocks to the east (e.g. Dalziel and Elliot, 1982; Grunow et al., 1991; Storey, 1991) which may have been active during the Late Cretaceous New Zealand–Antarctic break-up or even before in the early Mesozoic or Paleozoic. However, direct evidence is still missing. Conceptual models suggest that Pine Island Bay was affected by the West Antarctic Rift System, which may have played a deformational role in the onshore and offshore eastern Amundsen Sea Embayment at some stage (Fig. 1). Jordan et al. (2010) invert airborne gravity data for crustal thickness revealing extremely thin crust and low lithospheric rigidity for the onshore Pine Island Rift and interpret this as a result of West Antarctic Rift activity. Müller et al. (2007) suggest that from chron 21 (48 Ma) to chron 8 (26 Ma) the West Antarctic Rift System was characterized by the extension in the Ross Sea embayment and dextral strike-slip in the east, where it was connected to the Pacific–Phoenix–East Antarctic triple junction (Fig. 1) via the Byrd Subglacial Basin and the Bentley Subglacial Trench, interpreted as pull-apart basins. Müller et al. (2007) infer that transtensional tectonic reactivation may have occurred along a zone from the Thurston Island/Ellsworth Land block into the western Bellingshausen Sea in the Eocene/Oligocene as part of the eastern tectonic activity of the West Antarctic Rift System. It is also possible that such transtensional activity also occurred earlier farther west in Pine Island Bay along a north–south striking zone (Dalziel, 2006; Ferraccioli et al., 2007; Gohl et al., 2007; Jordan et al., 2010), either as a reactivation of a former crustal block boundary or an initial deformation forming the paleogeographic outline of Pine Island Bay.

A further aspect of the tectonically induced geomorphological development of the Amundsen Sea Embayment is the as yet little-quantified effect of the Marie Byrd Land dome uplift. The erosion surface across the dome is uplifted to elevations of 400–600 m along the coast and rises to 2700 m inland at the crest (LeMasurier, 2008). Crustal thickness estimates are derived from receiver function analysis and show that the crust beneath the central dome is about 25 km thick and that it is supported by a low-density mantle, which may indicate a hot spot (Winberry and Anandakrishnan, 2004). This thickness is consistent with the measured crustal thickness of 22–24 km at the adjacent western Amundsen Sea Embayment shelf (Gohl et al., 2007). The Marie Byrd Land dome is not considered a northern flank of the West Antarctic Rift System, as earlier studies suggested, but it is an integrated feature within the rift system and has risen since about 29–25 Ma (LeMasurier, 2008).

3. Geophysically observed lineaments

Grids of geophysical potential field data of the Amundsen Sea Embayment reveal distinct trends of lineaments, which can be linked to tectonic phases. Linear trends in the satellite-derived gravity anomaly grid of McAdoo and Laxon (1997) (Fig. 2) as well as magnetic anomalies (Gohl et al., 2007) of the western Amundsen Sea embayment, running sub-parallel to each other, are interpreted as indicating an intrusive crustal origin. Their NE–SW trend parallels the initial spreading center's azimuth between Chatham Rise and West Antarctica and can thus be related to rift processes occurring during breakup or just beforehand. The only 22–24 km thick crust beneath the inner shelf, as derived from seismic refraction data (Gohl et al., 2007), suggests a crustal thinning process. These observations infer tectonic and magmatic processes leading to a failed initial rift or distributed crustal extension in the Amundsen Sea Embayment. Such rifting must have been active before 90 Ma or accompanied the rifting in Bounty Trough and its northward translation of Chatham Rise at

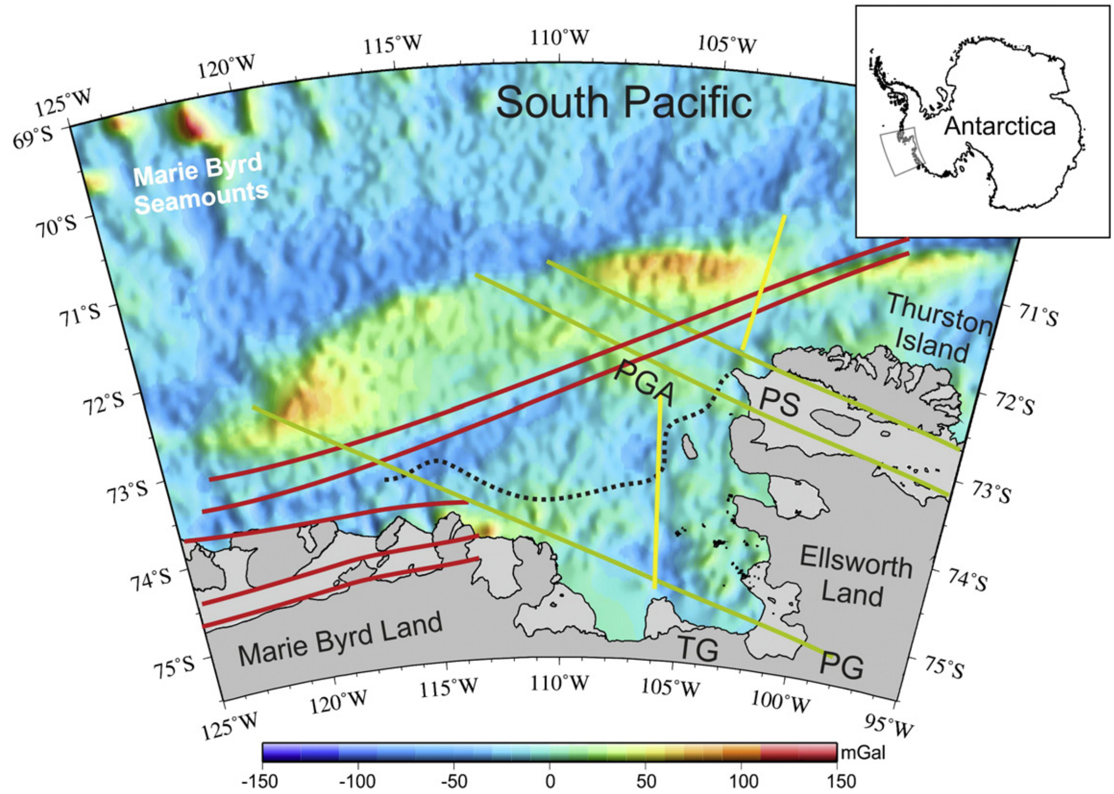

Fig. 2. Satellite-derived gravity anomaly map of the Amundsen Sea Embayment (McAdoo and Laxon, 1997) with interpreted tectonic lineaments. Red lines mark lineaments generated during pre-breakup rifting between New Zealand and West Antarctica; green lines represent lineaments caused by a distributed system of a shifting southern Bellingshausen Plate boundary; yellow lines indicate possible traces of a northward trending branch of the eastern West Antarctic Rift System. The black dotted line shows the boundary between outcropping basement to the south and the sediment basin on the shelf as identified by seismics (Graham et al., 2009; Weigelt et al., 2009). Abbreviations are: PS Peacock Sound, PGA Peacock Gravity Anomaly, PG Pine Island Glacier, and TG Thwaites Glacier.

this time. Although earlier reconstructions demonstrate a reasonable break-up fit of the shelf-break lines of the conjugate New Zealand eastern plateau and West Antarctic margins (e.g. Larter et al., 2002), recent geophysical data indicate that the crust of the outer Amundsen Sea Embayment thinned or fragmented extremely before break-up, leaving the continent–ocean boundary several tens of kilometers oceanward of the shelf-break (Gohl, 2008, 2010).

The gravity anomaly grid (Fig. 2) also shows a distinct linear, WNW–ESE striking positive anomaly across the outer continental shelf of the Amundsen Sea Embayment in northwestward extension from Peacock Sound between Thurston Island and the mainland (Larter et al., 2002; Eagles et al., 2004a,b). This so-called Peacock Gravity Anomaly is modeled with an underlying high-density body (Gohl et al., 2007) and is interpreted as a magmatic zone, which overprinted the NE–SW trending rift structure. Magnetic data show that magmatic intrusions were emplaced in some places along this boundary (Gohl et al., 2007). Consistent with the plate-kinematic process described for the Bellingshausen Plate (Eagles et al., 2004a), one can infer that this feature acted as an active southern Bellingshausen Plate boundary of relatively minor extensional and translational movements.

A geophysical signature of a major crustal block boundary in Pine Island Bay, separating the Marie Byrd Land and Thurston Island blocks, is not obvious from potential field data (Gohl et al., 2007; Gohl, 2010). If such a crustal boundary exists, its signature is possibly overprinted by the effects of Cenozoic magmatic intrusions and recent volcanism (e.g. LeMasurier, 1990; Corr and Vaughan, 2008). The deeply incised inner and middle shelf of Pine Island Bay with glacial troughs and channels reaching 1000–1500 m depth (Lowe and Anderson, 2002; Larter et al., 2007; Graham et al., 2010) may in addition obscure interpretations of the magnetic anomaly field. It seems likely that the surface-erosional processes exploited such a crustal boundary zone, as originally suggested by the SPRITE Group (1992), and/or further eroded a major fault system generated by West Antarctic Rift System activity. This may have laid the base for the formation of the main Pine Island Trough, stretching from the mouth of the Pine Island Glacier to the middle shelf in NW and NNW orientations.

4. Basement relief and sediments

The compiled bathymetry of the Amundsen Sea Embayment by Nitsche et al. (2007) illustrates a continental shelf, which is divided into two bathymetric provinces, the eastern and western Amundsen Sea Embayment, each heavily incised by a deeply eroded glacial trough system (Fig. 3). The provinces are separated by a northwest trending ridge of less than 500 m water-depth. The deepest troughs reach 1600 to 1200 m water-depth near the glacier mouths from where they converge onto the middle shelf (Larter et al., 2007; Graham et al., 2009). The glacial troughs shallow to about 700–500 m depth on the middle to outer shelf. Multi-beam data from both provinces reveal streamlined subglacial bedforms which change spatially in substrate characteristics (Graham et al., 2009, 2010; Larter et al., 2009). On the inner shelf, some troughs are incised by narrow channels which, in the case of the Getz B Ice Shelf trough, strike in east–west direction parallel to the main trough, before a transition to a northeast-trend occurs farther offshore (Larter et al., 2009). This divergence of the erosional path from the direct outflow to the outer shelf can best be explained by the blockage of the flow path by highly resistive basement rock units such as high-grade magmatic dikes, striking in an east–west direction.

Geophysical surveys in the last decade have revealed some insight into the structure of the basement and sediments of the Amundsen

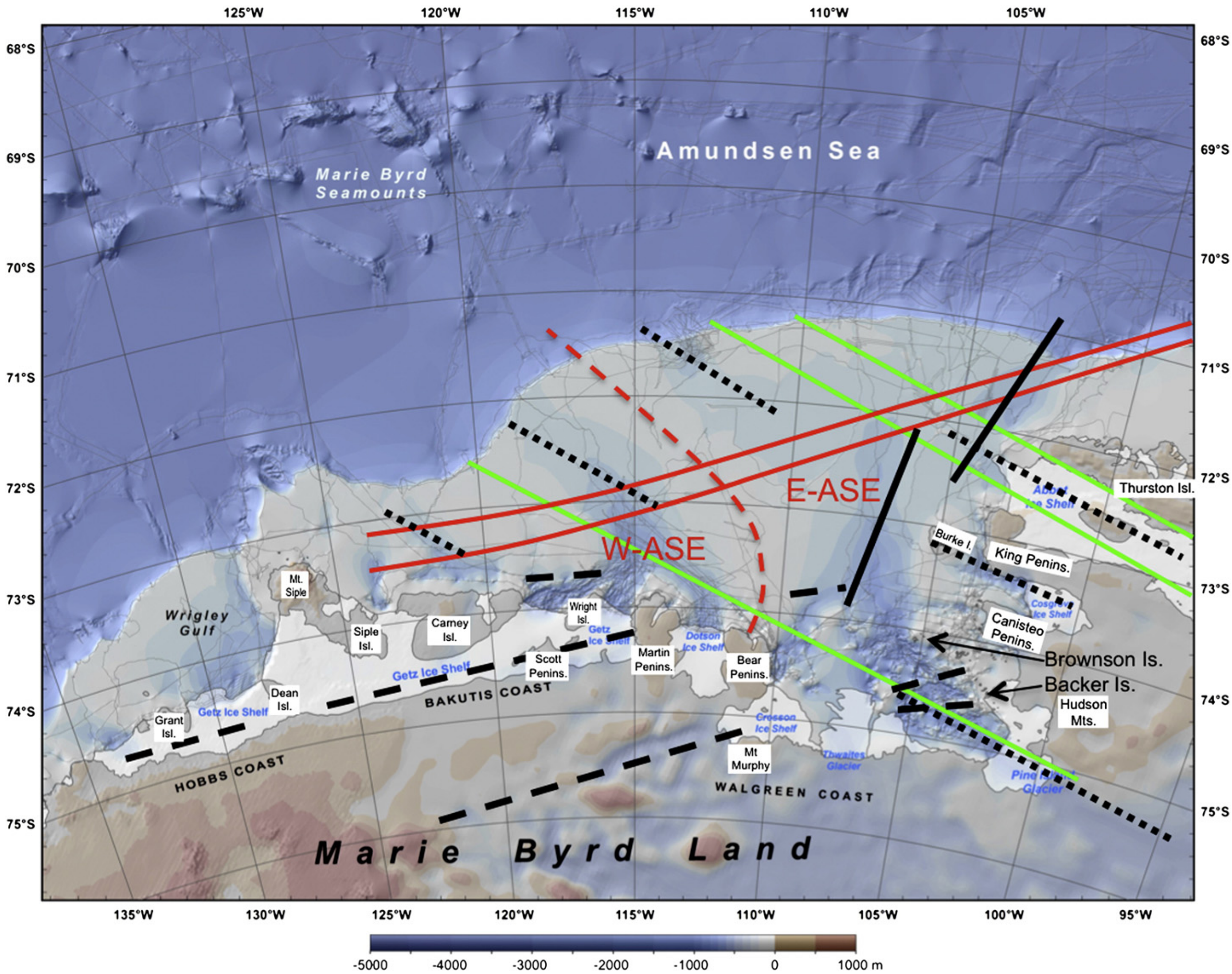

Fig. 3. Bathymetric pattern of the Amundsen Sea Embayment, compiled by Nitsche et al. (2007) from single and multibeam data along indicated ship-tracks until 2006, and with the following interpreted underlying tectonic lineaments: black hashed lines are lineaments from distributed parallel rift axes before the New Zealand–West Antarctic breakup, black dotted lines represent a shifting southern Bellingshausen Plate boundary, black solid lines indicate a projected West Antarctic Rift System lineament. Solid red and green lines are tectonic lineaments interpreted from the gravity anomaly field of Fig. 2 for comparison. The red hashed line indicates the topographic and basement ridge which acts as boundary between western (W–ASE) and eastern embayment (E–ASE).

Sea Embayment shelf. A distinct boundary between outcropping crystalline basement of relatively rough morphology to the south and the sedimentary shelf basin of oceanward dipping strata to the north is clearly imaged in seismic profiles (Lowe and Anderson, 2002; Larter et al., 2007; Graham et al., 2009; Weigelt et al., 2009; Gohl, 2010) and can be mapped across the embayment (Fig. 2). The sediments north of the boundary increase in thickness to at least 800 m, possibly much thicker.

Seismic data from RV *Polarstern* cruise ANT-XXIII/4 and RRS *James Clark Ross* cruise JR141 in 2006 indicate that the bathymetric ridge, separating the eastern from the western embayment (Fig. 3), is underlain by elevated older sediments which dip westward towards the main glacial trough (Graham et al., 2009; Weigelt et al., 2009). New, as yet unprocessed seismic data from the RV *Polarstern* cruise ANT-XXVI/3 in early 2010 (Gohl, 2010) also indicate a similar declining pattern to the east of the ridge crest towards the eastern embayment trough. It can therefore be assumed that this ridge is underlain by elevated crystalline basement extending north of Bear Peninsula.

Basement crops out or is scarcely covered by sediments with a few narrow pockets and troughs of thicker sediments along the eastern side of Pine Island Bay between the Pine Island Glacier Trough, Canisteo Peninsula, Burke Island and northward to the Abbot Ice Shelf mouth (Uenzelmann-Neben et al., 2007). This also includes a narrow trough south of King Peninsula connecting to the Cosgrove Ice Shelf. Groups of tiny granitoid and gneissic islands, some cut by mafic dikes, line up mostly in northwest trending clusters, such as the Brownson Islands and Backer Islands southwest and south of Canisteo Peninsula (Fig. 3). This directional trend coincides with the general strike directions of the bathymetric ridge between the eastern and western embayments and the main glacial troughs of the middle to outer shelf of the western embayment (Fig. 3). The bathymetry and seismic records of inner Pine Island Bay show numerous distributed basement ridges and domes within the main glacial Pine Island Trough. Some are aligned in an east–west orientation, others do not show any preferred aligned orientation. Lacking samples from the submarine basement, it can only be assumed that they consist of rock material similar to that of the adjacent small islands. These edifices have probably served as pinning points at times when the ice shelf covered the inner shelf and, therefore, affected its retreat mechanism and rates.

5. Glacial pathways

Seismic reflection data in the Pine Island Bay region show that the outer shelf and slope have undergone both progradational and aggradational deposition of sediments since the mid-Miocene. Erosional unconformities are present on the outer shelf, implying the former presence of a grounded ice sheet (e.g. Nitsche et al., 2000; Lowe and Anderson, 2002). The presence of mega-scale glacial lineations and grounding zone wedges on the outer shelf indicates that the ice sheet extended to, or near, the shelf edge during the last glacial maximum (Lowe and Anderson, 2002; Evans et al., 2006; Graham et al., 2010) and possibly during glacial periods prior to the last one. Ice stream advances would have followed low-lying morphologies such as pre-existing troughs. Three main groups of directional trends can be observed in the compiled bathymetric and topographic grid of the Amundsen Sea Embayment (Fig. 3). In superposing the bathymetric impression of the main glacial troughs and intra-trough channels onto an interpreted map of tectonic features in the embayment, it can be inferred that past ice streams followed primarily tectonically inherited lineaments.

(1) The east–west oriented basement features and deviated glacial trough morphology of the inner shelf of the western embayment align with general trends in the Bakutis Coast coastline and the elongated inner Getz Ice Shelf. This east–west trend also correlates with the dominant trends in basement ridges crossing the main Pine Island Trough of inner Pine Island Bay and with the ESE-trending onshore subglacial topography of the Crosson Ice Shelf drainage basin. This trend field coincides with the distributed series of rift axes during the New Zealand–Marie Byrd Land separation process before break-up in the Late Cretaceous, as derived from plate-kinematic reconstructions (Figs. 1 and 2).

(2) A remarkable coinciding NW–SE to WNW–ESE directed trend can be observed for the glacial troughs of the western embayment outer shelf, the Peacock Sound (Abbott Ice Shelf), the Cosgrove Ice Shelf and glacial trough, and the Pine Island glacial trough of the inner Pine Island Bay shelf and onshore. Plate-kinematic models predict that the southern boundary of the Bellingshausen Plate existed in the same directional trend. This observation of parallel trending morphological expressions suggests that this plate boundary must have acted as a distributed plate boundary system crossing oceanic and continental crust with a shifting boundary axis.

(3) The north–south trend of the main Pine Island glacial trough on the middle shelf and the NNE-trend of the outer Abbot Ice Shelf trough on the outer shelf follow the predicted lineation trend of an eastern branch of the West Antarctic Rift System extending from the Thwaites drainage basin northward into Pine Island Bay (Dalziel, 2006; Ferraccioli et al., 2007; Gohl et al., 2007; Jordan et al., 2010). Graham et al. (2010) describe that the extended Pine Island–Thwaites paleo-ice stream possibly took the westerly path on the outer shelf and switched to the northerly path at a later time. The timing of such a switch cannot be established at this stage, but it cannot be excluded that younger tectonic processes changed the bathymetry on the shelf.

Much of the shelf and the near-shelf continental basins of the Amundsen Sea Embayment would have been below sea-level (Holt et al., 2006; Vaughan et al., 2006), making significant pre-glacial erosion less likely. By the time major glacial cycles occurred in the coastal and shelf areas in the early to middle Miocene, almost all tectonic basement features and faults had already existed and were exploited by glacial erosional processes of periodically advancing grounded ice streams. It seems obvious that erosional and ice-flow processes are largely controlled by outcropping basement lineaments. It is less obvious how tectonic lineaments under a thick sediment cover, as observed for the middle and outer shelf (Weigelt et al., 2009), control ice stream flows. An explanation is that the sediment morphologies along these major tectonic lineaments became never entirely leveled before glacial onset and during interglacial times due to continuous oceanward flowing bottom currents.

Regarding the uncertainty of the timing of any West Antarctic Rift activity in this region, it is not impossible that continued tectonic movements occurred in Pine Island Bay and altered the early flow paths of the Pine Island and Thwaites ice stream systems. However, a better understanding of the processes, extent and timing of the West Antarctic Rift System tectonics is urgently needed.

As the retreat history of glacial cycles before the last glacial period cannot be reconstructed for the Amundsen Sea Embayment at this stage, due to an yet uncompleted stratigraphic model and missing age constraints for the shelf, an attempt is made to illustrate the retreat of grounded ice sheet since the last glacial maximum in a schematic sketch (Fig. 4). The Holocene age constraints come from cosmogenic exposure dating results from rock samples on the mainland and islands (Johnson et al., 2008), from carbon isotope dates of foraminifera samples in shelf

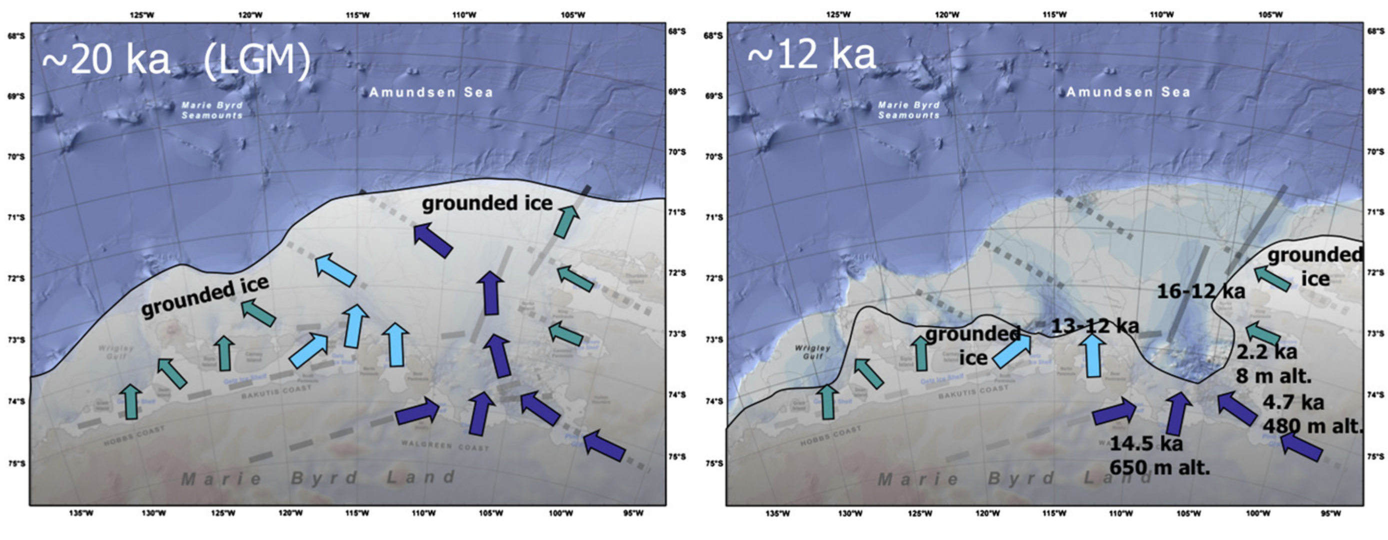

Fig. 4. Models of ice sheet extent and retreat paths in the Amundsen Sea Embayment at the last glacial maximum (LGM) at about 20 ka and at 12 ka. Retreat ages are from cosmogenic exposure dates by Johnson et al. (2008) and microfossil analyses by Lowe and Anderson (2002) and Hillenbrand et al. (2009). Arrows indicate major ice stream flow directions and are colored according to drainage basin groups. Tectonic lineaments in the background (gray solid, dotted and hashed lines) are according to Fig. 3. The bathymetric/topographic compilation is from Nitsche et al. (2007).

sediments of Pine Island Bay (Lowe and Anderson, 2002), and from diatomaceous ooze and mud cored at the inner shelf of the western embayment (Hillenbrand et al., 2009). It must be noted that the individual retreat ages suffer from large uncertainties. However, the fact that the different methods of different areas converge to similar ages for retreat to the inner shelf in the early Holocene places some degree of confidence in the general retreat trend. The retreating ice limits along the shelf are estimated by interpolating between the benchmark locations of age control. Independent of the processes causing ice sheet retreats (e.g. warm Circum-Polar Deep Water incursions), it is valid to assume that the retreat paths of the main ice streams follow the present glacial troughs due to the loss of ground control in their deeper bathymetry (Fig. 4), while pinning points of shallow banks and ridges continued to hold back the retreat for a little longer until continued melting thinned the grounded ice enough for farther retreat.

6. Conclusions

Observations of the bathymetric pattern of the Amundsen Sea Embayment shelf and identification of tectonic structures from geophysical mapping indicate that the erosional processes of paleo-ice stream flow across the continental shelf followed primarily tectonic lineaments inherited from the complex tectonic history since the Cretaceous break-up between New Zealand and West Antarctica. East–west oriented basement features of the embayment and glacial trough morphology of the inner shelf of the western embayment correlate with coastline trends and overlay tectonic lineaments interpreted as rifting axis active at pre-breakup times. Directional trends in NW–SE to WNW–ESE orientation are observed for the glacial troughs of the western embayment outer shelf, the Peacock Sound, the Cosgrove Ice Shelf and trough, and the inner Pine Island glacial trough and are superposed on lineaments of a distributed southern plate boundary zone of the former Bellingshausen Plate. The dominant north–south trend of the main Pine Island glacial trough on the middle shelf and the NNE-trend of the outer Abbot Ice Shelf trough on the outer shelf follow the predicted lineation trend of an eastern branch of the West Antarctic Rift System extending from the Thwaites drainage basin northward into Pine Island Bay.

These results help better constrain the geometries and sea-bed substrate conditions for regional paleo-ice sheet models.

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