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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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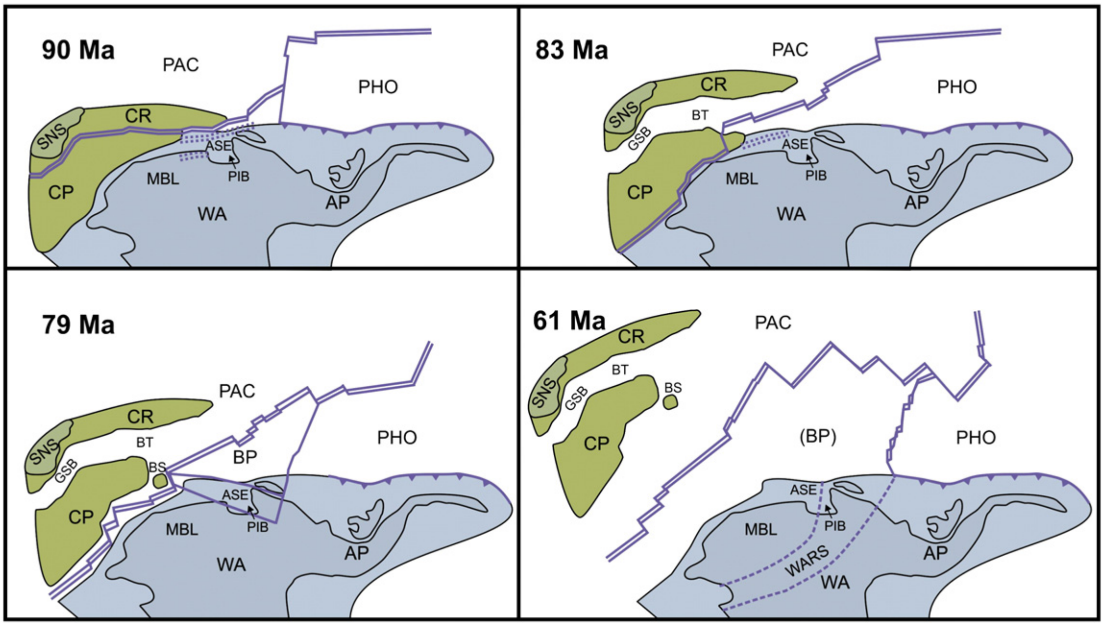

Fig. 1. Plate-kinematic reconstruction of the tectonic development in the Amundsen Sea area from 90 to 61 Ma. The plates are rotated according to rotation parameters compiled and derived by Eagles et al. (2004a). Abbreviations are: PAC Pacific plate, PHO Phoenix Plate, CR Chatham Rise, CP Campbell Plateau, 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