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Invited research article

Tectonomorphic evolution of Marie Byrd Land – Implications for Cenozoic rifting activity and onset of West Antarctic glaciation

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ABSTRACT

The West Antarctic Rift System is one of the largest continental rifts on Earth. Because it is obscured by the West Antarctic Ice Sheet, its evolution is still poorly understood. Here we present the first low-temperature thermochronology data from eastern Marie Byrd Land, an area that stretches ~1000 km along the rift system, in order to shed light on its development. Furthermore, we petrographically analysed glacially transported detritus deposited in the marine realm, offshore Marie Byrd Land, to augment the data available from the limited terrestrial exposures. Our data provide information about the subglacial geology, and the tectonic and morphologic history of the rift system. Dominant lithologies of coastal Marie Byrd Land are igneous rocks that intruded (presumably early Paleozoic) low-grade meta-sedimentary rocks. No evidence was found for un-metamorphosed sedimentary rocks exposed beneath the ice. According to the thermochronology data, rifting occurred in two episodes. The earlier occurred between ~100 and 60 Ma and led to widespread tectonic denudation and block faulting over large areas of Marie Byrd Land. The later episode started during the Early Oligocene and was confined to western Pine Island Bay area. This Oligocene tectonic activity may be linked kinematically to previously described rift structures reaching into Bellingshausen Sea and beneath Pine Island Glacier, all assumed to be of Cenozoic age. However, our data provide the first direct evidence for Cenozoic tectonic activity along the rift system outside the Ross Sea area. Furthermore, we tentatively suggest that uplift of the Marie Byrd Land dome only started at ~20 Ma; that is, nearly 10 Ma later than previously assumed. The Marie Byrd Land dome is the only extensive part of continental West Antarctica elevated above sea level. Since the formation of a continental ice sheet requires a significant area of emergent land, our data, although only based on few samples, imply that extensive glaciation of this part of West Antarctica may have only started since the early Miocene.

1. Introduction

The West Antarctic Rift System (WARS) transects the entire Antarctic continent. Its southern shoulder, formed by the Transantarctic Mountains, rises to >4500 m, while its bottom reaches down to ~2500 m below sea level along the deeply incised valleys of Bentley Subglacial Trench and the Byrd Subglacial Basin. Traces of the WARS separate several West Antarctic crustal blocks, including Marie Byrd Land, Thurston Island, Ellsworth-Whitmore Mountains, and Antarctic Peninsula (Dalziel, 2006; Fig. 1). Tectonic activity within the WARS started during the Cretaceous and may have lasted through to the present. Unlike most other continental rifts that are better exposed, development of the WARS structure is poorly understood.

Unanswered questions remain about WARS concerning amounts of extension and crustal displacement, exact timing of rifting activity, positions of rift branches, the relationship between rifting and magmatism, and topographic evolution of the rift. For example, published amounts of total crustal extension range between 120 and 1800 km (DiVenere et al., 1994; Busetti et al., 1999; see Storti et al., 2008 for a more detailed discussion). While it is generally assumed (although not really proven) that the majority of crustal extension took place during the Cretaceous (e.g., Siddoway, 2008), about 180 km of Cenozoic crustal extension was proposed for the Ross Sea sector of the rift (Cande et al., 2000; Cande and Stock, 2004). However, while Cenozoic rifting is relatively well documented for the Ross Sea area, no direct evidence for Cenozoic rift activity exists for the interior of Marie Byrd Land (Dalziel, 2006). Also, it is still unknown how the WARS continues from the Ross Sea sector to inner parts and other coastal areas of West Antarctica. On the basis of plate kinematic reconstructions (Larter

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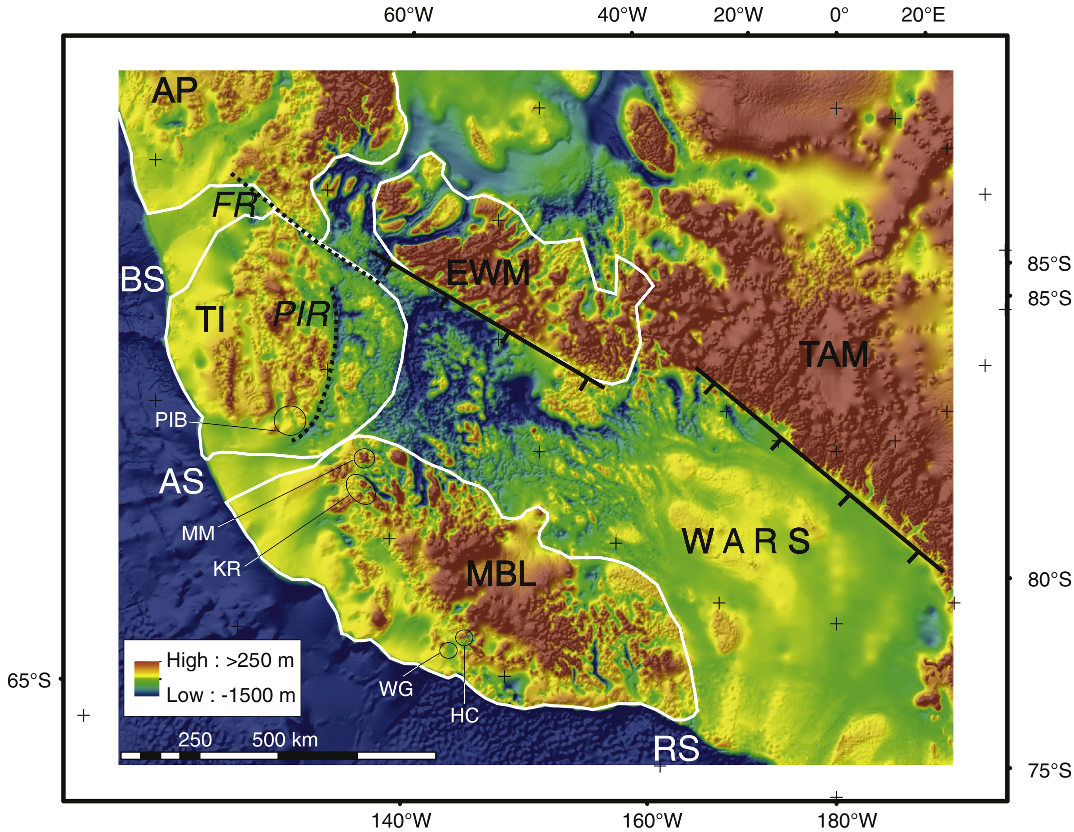

Fig. 1. Subglacial topography of the West Antarctic Rift System (data from Bedmap2, Fretwell et al., 2013). Thick white lines delineate crustal blocks that constitute West Antarctica (after Dalziel and Elliot, 1982). Dotted lines show location of proposed rift branches, open circles refer to sample locations. Abbreviations: AP – Antarctic Peninsula, AS – Amundsen Sea, BS – Bellingshausen Sea, EWM – Ellsworth Whitmore Mountains, FR – Ferrigno Rift (Bingham et al., 2012), HC – Hobbs Coast, KR – Kohler Range, MBL – Marie Byrd Land, MM – Mount Murphy, PIB – Pine Island Bay (location of samples studied by Lindow, 2014), PIR – Pine Island Rift (Jordan et al., 2010), RS – Ross Sea, TAM – Transantarctic Mountains, TI – Thurston Island, WARS – West Antarctic Rift System, WG – Wrigley Gulf.

et al., 2002; Eagles et al., 2004), crustal thickness and geomorphic features, it has been suggested that the WARS branches into the Amundsen Sea, following the trough beneath Pine Island Glacier (Dalziel, 2006; Gohl et al., 2007; Jordan et al., 2010; Fig. 1); that it reaches into the Bellingshausen Sea (Müller et al., 2007; Eagles et al., 2009; Bingham et al., 2012), or that it connects the Ross Sea with the Weddell Sea (Dalziel, 2006). Another peculiar feature of the WARS is that while most of the crustal extension is thought to have taken place during the Cretaceous, volcanic activity mostly occurred during the late Cenozoic. The majority of volcanoes are situated in the area of the Marie Byrd Land Dome, a large (~1000 × 500 km) domal structure rising to ~2700 m above sea level (Fig. 1). Its uplift is thought to have started at ~29 to 25 Ma. This date is derived from the oldest known volcanism from this area (Mt. Petras volcano), assuming that volcanic activity and uplift of the dome were contemporaneous (LeMasurier, 2006). However, no direct evidence exists about the timing of the exhumation of the Marie Byrd Land dome.

The reason for the many unknowns is that the WARS is overlain by the West Antarctic Ice Sheet, which covers >98% of the outcrops. Presently, rapid thinning and retreat characterize the West Antarctic Ice Sheet, particularly in the Amundsen Sea sector, and its glaciers show the highest mass losses of ice across the entire Antarctic continent. The glacial cover hampers direct geological investigations, but it also makes studying the WARS particularly interesting, since it provides insights to interactions between lithospheric and glacial dynamics. In the first place, the basic reason for the instability of the West Antarctic Ice Sheet is the tectonic setting of the underlying crust. Rifting and associated crustal extension results in a subdued, low-lying topography, such that most of the West Antarctic Ice Sheet is grounded below sea level (Fretwell et al., 2013). This, together with the inward dipping bedrock (i.e., towards the continental interior) allows warm circumpolar deep water to penetrate beneath the glaciers, melting them from below, causing grounding line retreat (Payne et al., 2004; Jenkins et al., 2010; Ross et al., 2011). Deep-reaching rift valleys provide subglacial pathways for warm ocean water, which is why their locations are of particular interest (Jordan et al., 2010; Bingham et al., 2012). Furthermore, bedrock geology is an important parameter for glacial dynamics, influencing basal boundary conditions for ice movement. The nature of the bedrock "almost certainly plays a fundamental role in determining many large-scale dynamic aspects of ice-sheet behaviour" (Boulton, 2006). Also, tectonic evolution influences crustal heat flow and thus the thermal regime at the bases of glaciers (e.g., Van der Veen et al., 2007). It also influences topography, which in turn is influenced by (glacial) erosion, illustrating interplay complexity. Topography provides important boundary conditions for the onset of continental glaciation. For West Antarctic Ice Sheet evolution, topographic evolution of Marie Byrd Land dome is particularly important, as it is the only large area of West Antarctica significantly elevated above sea level (excluding the Antarctic Peninsula). Continental glaciation of West Antarctica is assumed to have initiated either during late Paleogene or early Neogene (Barker et al., 2007; Wilson et al., 2013). At that time, the ocean temperatures were presumably too warm to allow for formation of a marine-based ice sheet, and for the formation of a terrestrially grounded ice sheet, a certain amount of topography above sea level was required (e.g., Wilson et al., 2013).

The aim of this paper is to (i) describe the bedrock geology exposed beneath the glacial cover of central Marie Byrd Land (Hobbs Coast area), (ii) outline the tectono-thermal history of the Amundsen Sea sector of the WARS (eastern Marie Byrd Land), particularly with respect to its Cenozoic rifting history and exhumation of the Marie Byrd Land dome. To