Neogene tectonic events in the West Antarctic rift system inferred from comparisons with the East African rift and other analogs

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Summary The West Antarctic rift system (WARS) is largely buried beneath 1-4 km of ice, obscuring vast areas that could provide clues about the potential for active volcanism beneath the ice sheet, and whether significant tectonic extension has taken place in Cenozoic time. This study explores the consequences of viewing the ice as basin fill, and of approximating the mass equivalent of ice as unconsolidated sediment. It then compares the results with active rift systems elsewhere in the world. The results suggest (1) that the interior rift trough is relatively cool and volcanically inactive, (2) that extension and over-deepening of interior basins, like the Bentley Subglacial Trench, has taken place beneath the ice sheet in late Cenozoic time, and (3) that dome uplift and the growth of large central volcanoes along the Marie Byrd Land coast, together with subsidence of interior basins, have significantly increased the relief within the rift system in Neogene time.

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Introduction

The West Antarctic rift system (Fig. 1) appears to have formed initially in response to Gondwanaland breakup, first in the late Jurassic, and then in the late Cretaceous; but it has continued to evolve throughout the Cenozoic. Figure 2 summarizes this 150 m.y. evolution and provides a context for what follows. These comparisons provide perspectives on the tectonics of the rift system that have not been explored previously. Among the most instructive are comparisons of rift topography, and of the relationship between volcanism and uplift, which are the focus of this contribution.

Discussion

Rift topography

Figure 1 represents how the rift system would look ice-free, without considering the possibility that the ice sheet is old enough to substitute for sedimentary fill. Unconsolidated sediment, and hyaloclastites, have densities between

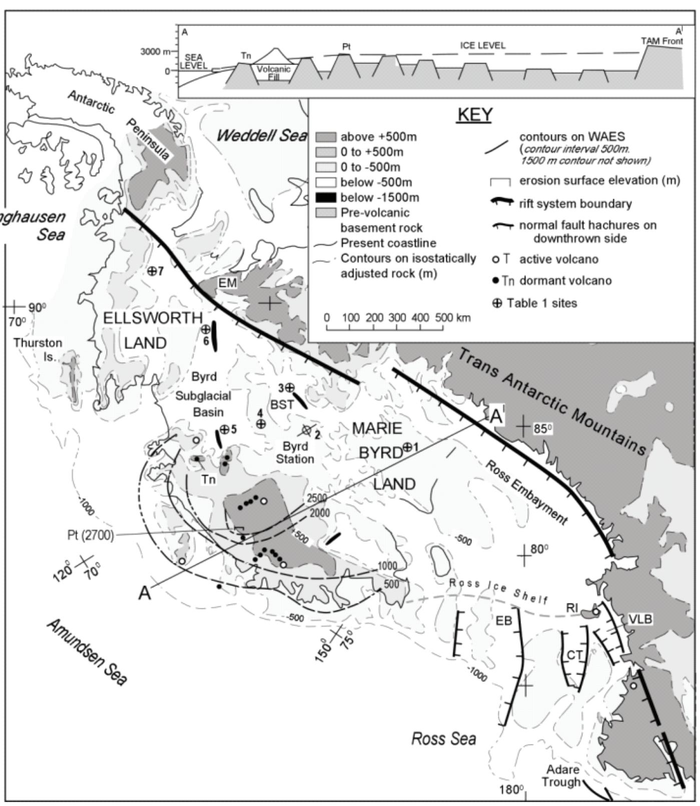

Figure 1. Topography and structure of the West Antarctic rift system showing simplified ice-free isostatically adjusted bedrock topography (Drewry, 1983), MBL dome (LeMasurier, 2006), and Ross Sea basins (Cooper et al., 1991; Cande et al., 2000). The MBL dome is defined by contours on the late Cretaceous West Antarctic erosion surface (WAES) (LeMasurier and Landis, 1996). All four deep basins described in the text extend below -1500m (black). The interior rift trough is the sub-sea-level region that extends from the Ross Sea to the Bellingshausen Sea. Abbreviations: BST, Bentley Subglacial Trench; CT, Central Trough; EB, Eastern Basin; EM, Ellsworth Mountains; MBL, Marie Byrd Land; Pt, Mount Petras, the crest of the MBL dome; RI, Ross Island; Tn, Toney Mountain; VLB, Victoria Land Basin.

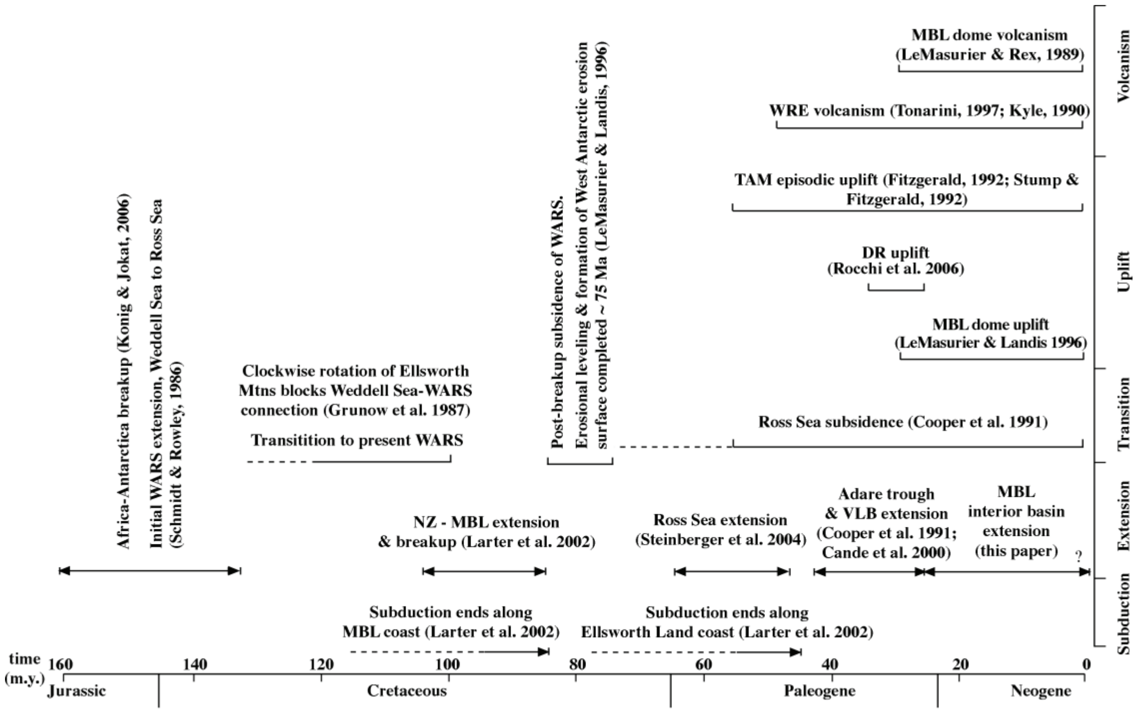

Figure 2. Summary of major tectonic and volcanic events in the history of the West Antarctic rift system. Abbreviations: DR, Dorrel Rock; MBL Marie Byrd Land; NZ, New Zealand; TAM, Transantarctic Mountains; VLB, Victoria Land Basin; WARS, West Antarctic rift system; WRE, Western Ross embayment.

1.8 -2.3 g/cm^3 (Daly et al., 1966; Licht, 1999; LeMasurier, 2002). Using uncorrected bedrock elevations beneath the present ice load, these densities have been used to compute the sedimentary mass equivalent of the ice, and recalculate elevations on this hypothetical basin fill at seven locations from Ice Stream B, along the rift trough to Siple Station (Fig. 1). The resulting elevations range from +500m to -990m, with averages of -44m and -307m for sediment densities of 1.8 and 2.3 g.cm^3, respectively (LeMasurier, in preparation). By contrast, rift floors in the East African, Basin and Range, and Rio Grande rifts, with crustal thicknesses similar to the WARS, stand 1000m to 2000m higher than this. Furthermore, they have all been volcanically active within the past 10,000 years (Simkin and Siebert, 1994), and hence their elevations can reasonably be attributed to elevated mantle temperatures. The much lower elevations of the West Antarctic rift interior suggest that this region is underlain by cool and magmatically inactive mantle. This is consistent with several geophysical studies (Wannamaker, et al., 1996; Sieminski, et al., 2003; Shapiro and Ritzwoller, 2004; Winberry and Anandakrishnan, 2004), but conflicts with others that suggest widespread late Cenozoic subglacial volcanism in the rift interior, and a high risk that volcanism could destabilize the ice sheet (Blankenship et al., 1993; Behrendt et al., 1994). This study adds to the evidence that the risk of subglacial volcanism destabilizing the ice sheet is low.

Ice-filled grabens

Although the rift interior appears to be cool and magmatically inactive, there is still reason to suspect that amagmatic Cenozoic extension has taken place there. Figure 1 shows the locations of four ice-filled interior basins that extend more than 1500m below sea level. Among these, the Byrd Subglacial Basin (BSB) and Bentley Subglacial Trench (BST) reach maximum depths of -2000m and -2555m, respectively. They are comparable in scale with Ross Sea basins (Fig. 1), which seismic studies have shown to be asymmetric grabens (Cooper et al., 1991), but differ in that BSB has only 0.5 km of sedimentary fill (Jankowski et al., 1983) while Victoria Land Basin has up to 14 km of fill (Cooper et al., 1991). They are truly anomalous features and may be unique. Lake Baikal, the world's deepest lake (1190m below sea level), is less than half the depth of the BST. Over 7 km of sediment has accumulated in the lake since ~27 Ma, but the great depth of Lake Baikal was produced by rifting within the past 2 m.y. (Mats et al., 2000). This illustrates that deep, unfilled basins are likely to be quite young. It also suggests that glacial ice should indeed be thought of as basin fill in the West Antarctic basins, and hence, that the great depths of these basins was created after the ice sheet was in place. They may, therefore, represent an episode of extension and subsidence within the past 28-15 m.y. (Rocchi et al., 2006), which extends the duration of Cenozoic extension through the Neogene, and extends its locus from the Ross Sea into the deep interior. This interpretation supports proposals of Cenozoic motion between East and West Antarctica (Cande et al., 2000; Steinberger et al., 2004).

Marie Byrd Land dome uncoupled from the rift interior

The volcanically active MBL dome appears to be uncoupled from the rift interior, and further comparisons suggest why this may be so. The Kenyan and Ethiopian domes are similar in many ways to the MBL dome. In all three, volcanism and uplift have been focused on these domes since mid-Cenozoic time (Baker et al., 1972; LeMasurier and Rex, 1989), they each rise to ~3km above sea level, each is ~700x500km in area, and volcanism in each has produced alkaline basalts, and felsic rocks that range from phonolite to trachyte to peralkaline rhyolite (Rogers, 2006; LeMasurier and Rex, 1989). Unlike the East African domes, however, the MBL dome rises from a rift floor that is below sea level.

Mantle plume support has been proposed to explain the uplift and volcanism of the MBL dome (LeMasurier and Landis, 1996; LeMasurier, 2006), and this is consistent with seismic studies (Sieminski et al., 2003; Winberry and Anandakrishnan, 2004). Dynamic support by two separate plumes has also been proposed to explain the Kenyan and Ethiopian domes (Rogers, 2006). It is noteworthy that all three domes rise to similar elevations, irrespective of the elevations of surrounding lowlands. White and McKenzie (1989) have calculated the amount of vertical displacement that would result from varying degrees of lithospheric thinning, at different mantle temperatures, in rift environments. Their results suggest (1) that the similar elevations of the three domes could represent the buoyancy of sub-lithospheric plumes that are just hot enough to yield alkali basalt, (2) that the lithosphere in Africa and MBL have been thinned to a comparable degree, and (3) that the elevation of surrounding lowlands is controlled independently of the mechanism that causes dome uplift (LeMasurier, in preparation).

Landscape evolution

Neogene tectonic activity in the MBL sector of the WARS has included tectonic uplift of the MBL dome, from near sea level to +2700m (LeMasurier and Landis, 1996), the growth of 18 large central volcanoes since ~19 Ma, 10 of which exceed 3000m elevation (LeMasurier, 1990), and the extension and subsidence of four interior basins. The West Antarctic ice sheet is the only continental ice sheet on earth today, or in the recent past, that rests on a tectonically active landscape, and one that has changed so dramatically in the lifetime of the ice sheet. This must have had a significant influence on ice sheet history.

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