Neogene extension and basin deepening in the West Antarctic rift inferred from comparisons with the East African rift and other analogs

Wesley E. LeMasurier
Institute of Arctic and Alpine Research (INSTAAR), University of Colorado at Boulder, Boulder, Colorado 80309-0450, USA

ABSTRACT

The West Antarctic rift system differs from other volcanically active rift systems in two unusual respects: (1) the rift floor lies 1000–2000 m lower in elevation than others, and (2) four interior ice-filled troughs extend between 1500 m and 2555 m below sea level. Two troughs are more than twice the depth of Lake Baikal, the world's deepest lake. The Marie Byrd Land dome, by contrast, compares closely with the intra-rift Kenyan and Ethiopian domes in the East African rift. Comparisons between these rift systems suggest (1) that the West Antarctic interior is relatively cool and volcanically inactive, (2) that there is likely to have been an episode of extension during Neogene time in the deep interior basins, and (3) that dome uplift and basin subsidence have greatly changed the West Antarctic landscape over the past 25 m.y.

Keywords: West Antarctic rift, ice-filled grabens, dome uplift, tectonic landscape.

INTRODUCTION

The West Antarctic rift system (WARS) is buried beneath 1–4 km of ice over much of its extent, obscuring vast areas that could provide clues about whether Cenozoic extension has been adequate to significantly displace East and West Antarctica from each other (Cande et al., 2000; Steinberger et al., 2004) and whether there is a high potential for subglacial volcanism to destabilize the West Antarctic ice sheet (WAIS) (Blankenship et al., 1993). To address these questions, this study explores the consequences of viewing the ice as basin fill, and of approximating the mass equivalent of ice as unconsolidated sediment. I then compare the results with active rift systems elsewhere in the world. These comparisons reveal large-scale obvious contrasts that have significant implications. (1) Compared with rifts of similar width and crustal thickness, the low elevation of the interior rift trough suggests it is relatively cool and volcanically inactive. (2) The extraordinary depths of four ice-filled interior basins suggest that extension and over-deepening have taken place beneath the ice sheet in Neogene time. (3) Dome uplift and interior basin subsidence have significantly altered the West Antarctic landscape in Neogene time, with implications for ice sheet history.

TOPOGRAPHIC COMPARISONS

The Rift Trough

Perhaps the most conspicuous difference between the WARS and the East African, Basin and Range, and Rio Grande rifts is the low elevation of the West Antarctic rift floor. This is best seen by converting the overlying glacial ice to its mass equivalent in unconsolidated sediment and volcanic debris, to simulate the rift system as it might appear if it had evolved in a temperate region. Table 1 presents the results of a set of such calculations, at stations that extend from near the grounding line of the Ross Ice Shelf, eastward across the main rift trough to Siple Station (Fig. 1). Saturated bulk densities of trachytic and basaltic hyaloclastites in Marie Byrd Land range from 1.64 to 2.48 g/cm^3 (LeMasurier, 2002), those of near-surface sediment from eight marine cores in the Ross Sea range from 1.85 to 2.34 g/cm^3, with an average of 2.13 (Licht, 1999), and saturated bulk densities of Oligocene and Miocene shale from Venezuela increase from 2.17 to 2.52 g/cm^3 from the surface to a depth of 2392 m (Daly et al., 1966). These data are the basis for selecting densities of 1.8 and 2.3 g/cm^3 in Table 1.

Figure 1 shows elevations of ice-free, isostatically adjusted bedrock topography, and 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. For the calculations in Table 1, I use uncorrected bedrock elevations beneath the present ice load, then compute the sedimentary mass equivalent of the ice load for sediment densities of 1.8 and 2.3 g/cm^3, and recalculate the elevations. The resulting elevations range from +500 m to –990 m, with averages of –44 m and –307 m for sediment densities of 1.8 and 2.3 g/cm^3, respectively. This is a gross approximation, but it is adequate to make the point described below. Only site #4 would be above sea level in either case, implying that it is an intra-rift horst that might not have received sedimentary fill under ice-free conditions. In this scenario, the rift floor would still resemble a continuation of the Ross Sea through the interior of West Antarctica to the Bellingshausen Sea, much as it appears in Figure 1.

By contrast, East African rift floors lie mainly between +1000 m and +2000 m, with minima of +400 m to +600 m (Baker et al., 1972). In the Basin and Range province (United States), basin floors are ~+1300 m between Reno and Great Salt Lake, and the floor of the Rio Grande rift is +1619 m at Albuquerque and +2231 m at Santa Fe.

Observed crustal thicknesses at seven sites (Fig. 1) in the WARS are 21–31 km (Winberry

TABLE 1. RIFT FLOOR ELEVATIONS (DREWRY, 1983) WITH ICE THICKNESSES CONVERTED TO EQUIVALENT SEDIMENTARY FILL

Site no.	Locality	Bedrock elevation (m)	Ice thickness (m)	Eq. Sed thickness at 1.8 g/cm^3	Eq. Sediment thickness at 2.3 g/cm^3	Elevation with sediment fill 1.8 g/cm^3	Elevation with sediment fill 2.3 g/cm^3
1	135° W, 85° S Ice stream B-C	–500	1000	500	390	0	–110
2	Byrd Station	–1000	2500	1250	978	+250	–22
3	Bentley Trench	–2555	4000	2000	1565	–555	–990
4	Sinuous Ridge	–250	1500	750	587	+500	+337
5	113° W, 78° S Takahe south	–1500	2500	1250	978	–250	–522
6	113° W, 76.5° S Byrd Basin	–2000	3500	1750	1370	–250	–630
7	Siple Station	–1000	2000	1000	783	0	–215
Average						**–44**	**–307**

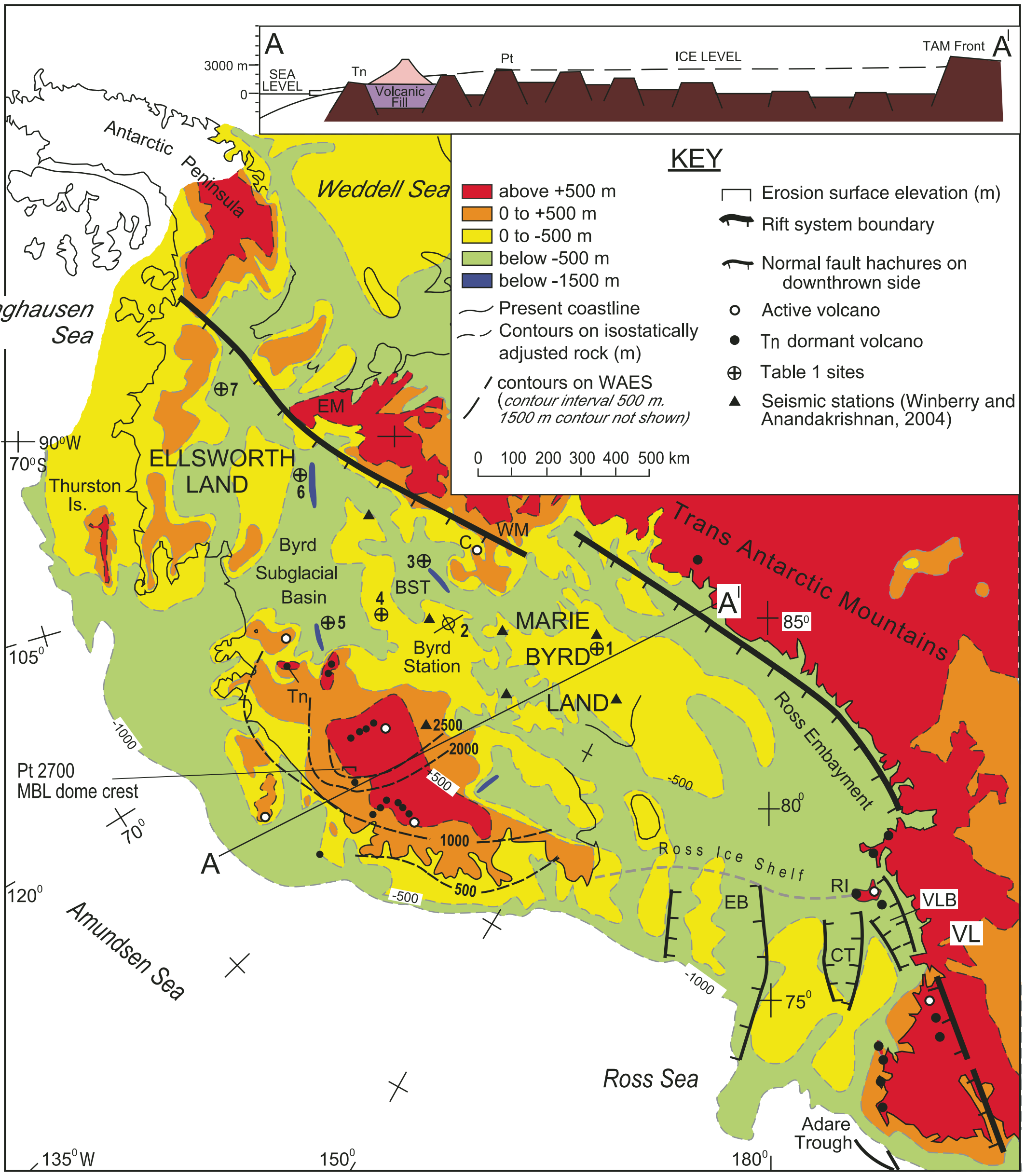

Figure 1. Topography and inferred structure (inset) of the Marie Byrd Land sector of the West Antarctic rift system showing simplified ice-free, isostatically adjusted bedrock topography (Drewry, 1983), Marie Byrd Land dome, and Ross Sea basins (Cooper et al., 1991; Cande et al., 2000). The Marie Byrd Land dome is defined by contours on the late Cretaceous West Antarctic erosion surface (LeMasurier and Landis, 1996). All four deep interior basins described in the text extend below –1500 m (blue). The "rift trough," referred to in the text, is the sub-sea-level region between the Marie Byrd Land dome and Transantarctic Mountains that extends from the Ross Sea to the Bellingshausen Sea. Note that topographic slopes along most of the Transantarctic Mountain front are too steep to represent each contour interval at this scale. Abbreviations: BST—Bentley Subglacial Trench; C—CASERTZ aerogeophysical volcano (Blankenship et al., 1993); CT—Central Trough; EB—Eastern Basin; EM—Ellsworth Mountains; MBL—Marie Byrd Land; Pt—Mount Petras; RI—Ross Island; Tn—Toney Mountain; VL—Victoria Land; VLB—Victoria Land Basin; WAES—West Antarctic erosion surface; WM—Whitmore Mountains.

and Anandakrishnan, 2004). In Kenya, the crust thins from 35 km in the south to 20 km in the north, along the rift axis (KRISP [Kenya Rift International Seismic Project] Working Party, 1991). Average crustal thickness is 30–34 km beneath the Basin and Range (Benz et al., 1990) and 37 km beneath the Rio Grande rift axis (Wilson et al., 2005). Differences in crustal thickness seem unlikely to be a factor in explaining the low elevation of the WARS compared to East Africa, and probably the Basin and Range also, but are likely to be a factor in the greater elevation of the Rio Grande rift.

Ice-filled Grabens

There are four basins within the interior rift trough, the deepest portions of which extend more than 1500 m below sea level (Fig. 1). Among these, the Byrd Subglacial Basin and Bentley Subglacial Trench reach maximum depths of –2000 m and –2555 m, respectively (Drewry, 1983). However, the Bentley Subglacial Trench is 500 m higher than predicted by Airy isostatic compensation models (Winberry and Anandakrishnan, 2004); i.e., if isostatically compensated, it would lie at ~–3000 m, which is a common elevation for mid-ocean ridges, yet it is underlain by a 21 km continental crust.

The size of these basins is comparable in scale with Ross Sea basins (Fig. 1), which seismic studies have shown to be asymmetric grabens (Cooper et al., 1991), but seismic studies have also shown that Byrd Subglacial Basin and Bentley Subglacial Trench each have only ~0.5 km of unconsolidated sedimentary fill (Bentley and Clough, 1972; Winberry and Anandakrishnan, 2004), whereas the Victoria Land Basin is filled with up to 14 km of late Mesozoic(?) and younger strata (Cooper et al., 1991). The depths of these interior basins are remarkable when compared with not only Ross Sea basins, but others where geologic evidence suggests that deep basins tend to be rapidly filled with sediment. Lake Baikal, the world's deepest lake (–1190 m below sea level), is perhaps the only intracontinental rift basin in the world that approaches the depths of West Antarctic interior basins. Rifting in Lake Baikal began ca. 27 Ma and has continued episodically to the present, with the accumulation of over 7 km of sediment; but the great depth of the lake is believed to have been produced by a late Pliocene (3.5–2.0 Ma) tectonic pulse (Mats et al., 2000). Another useful comparison is with the Gulf of California rift, which has been filled with 6 km of sediment and lava flows since Miocene time, or possibly within only the last 6 million years (Elders et al., 1972; Oskin and Stock, 2003). The point of these comparisons is to illustrate that intracontinental rift basins tend to be rapidly filled with sediment, and deep unfilled basins are therefore likely to be quite young.

ASSOCIATION OF VOLCANISM WITH UPLIFT

There are two volcano-tectonic domes in the East African rift system that compare closely with the Marie Byrd Land dome, and provide additional perspective on the evolution of the West Antarctic landscape and its influence on ice sheet history. The Kenya dome is roughly 700 × 300 km in area and rises to ~3000 m elevation, or ~1000 m above the adjacent rift floor. The Ethiopian dome is ~1000 × 500 km in area and also rises to ~3000 m elevation, or ~1000 m above adjacent rift floors. Both have risen in three pulses since ca. 35 Ma, accompanied by volcanism, which is focused on the two domes (Baker et al., 1972). The basalts are alkaline, similar to oceanic island basalt (Rogers, 2006). The associated felsic rocks span the range from phonolite to trachyte to peralkaline rhyolite.

The Marie Byrd Land dome is ~700 × 500 km in area. Pre-volcanic basement, beveled throughout Marie Byrd Land by the very low relief West Antarctic erosion surface, is exposed at 2700 m on the dome crest (Fig. 1), but unlike East Africa, the dome rises from an adjacent rift floor 500–1000 m below sea level, or ~−44 m to −307 m on a sediment-filled basis (Table 1). The dome stands 1 km higher than the elevation predicted by Airy isostasy, and this has been explained by low-density mantle support and Pratt-type compensation (Winberry and Anandakrishnan, 2004). Uplift began ca. 28–30 Ma and has been accompanied by basaltic and felsic volcanism that is similar in nearly all respects to the African volcanic activity (LeMasurier and Landis, 1996; LeMasurier, 1990).

DISCUSSION

The Rift Trough

The low elevation of the rift trough, coupled with crustal thicknesses that are similar to those in the much higher East African and Basin and Range provinces, suggests that the rift interior is relatively cool and magmatically inactive, and that the volcanism and high heat flow of today are focused on the Marie Byrd Land dome (Fig. 1). This is consistent with teleseismic studies which show that hot, low-density mantle lies beneath the Marie Byrd Land dome, but does not extend to the rift interior (Winberry and Anandakrishnan, 2004). Similarly, several other studies have found faster mantle velocities and evidence for lower heat flux in the rift interior (Sieminski et al., 2003; Shapiro and Ritzwoller, 2004), as well as high electrical resistivity within the upper 100 km of the Byrd Subglacial Basin, suggesting an absence of igneous melts (Wannamaker et al., 1996). These studies are all consistent with normal, magmatically inactive mantle beneath the rift interior, but are difficult to reconcile with aerogeophysical studies that suggest recent, perhaps widespread volcanism on the rift floor (Blankenship et al., 1993; Behrendt et al., 1994). In the East African and Rio Grande rifts the high rift floor elevations are associated with abundant, well-exposed, Plio-Pleistocene volcanic rock (Baker et al., 1972; Baldridge, 1979). The possibility of young and widespread volcanism associated with the low elevation of the West Antarctic rift trough would present a geodynamic paradox, unless this volcanism is mainly older and much more spatially restricted than has been proposed. On balance, the geologic and much of the geophysical character of the rift interior suggest that there is not a high risk of subglacial volcanism destabilizing the WAIS.

Ice-filled Grabens

The Byrd Subglacial Basin and Bentley Subglacial Trench lie adjacent to the Transantarctic Mountains and Ellsworth Mountains, with peaks of 4000–5000+ m, an environment much like that of western Ross Sea basins (Fig. 1). Why are they so very different from one another in terms of depth and sediment fill? From a geologic perspective, the unusual depth of the interior basins, coupled with evidence that such features become rapidly filled with sediment in temperate regions, suggests that glacial ice should indeed be thought of as basin fill, and hence, that the great depths of these basins were created after the WAIS was in place. This is analogous to the great depth of Lake Baikal forming within the past 2–3 m.y., but under ice in West Antarctica rather than water. These basins may, therefore, represent an episode of extension and subsidence since the inception of the WAIS, which hydrovolcanic deposits, seismic stratigraphy, and geomorphic evidence, suggest took place ca. 28–15 Ma (Bart, 2003; Rocchi et al., 2006). By the same reasoning, the dearth of sediment beneath the ice in the Byrd Subglacial Basin and Bentley Subglacial Trench, compared with Ross Sea basins, suggests that the interior basins experienced much longer periods of glacial cover, during which sediment accumulation was not possible. The Bentley Subglacial Trench has been interpreted as a region of "highly concentrated extension" that predates the ice sheet (Winberry and Anandakrishnan, 2004). In light of the comparisons just discussed, the great depth and lack of isostatic equilibrium both suggest extension so recent that there has not been time for the basin to subside to an equilibrium position.

Multiple examples of Cenozoic extension have been cited in the Ross Sea region; but thick ice cover has made it difficult to determine whether this activity continues into the deep interior. Plate circuit studies suggest that ~300 km of rifting took place in the Ross Sea between 65 and 47 Ma (Steinberger et al., 2004). Marine seismic work provides evidence for extension in the Victoria Land Basin (Fig. 1) beginning in the Eocene (Cooper et al., 1991), and for ~180 km of E-W seafloor spreading in the Adare trough between 43 and 26 Ma, perhaps representing larger scale motion between East and West Antarctica (Cande et al., 2000). The Neogene episode proposed here extends the duration of these earlier episodes, but unlike them, it is focused on the deep interior of the rift system. It therefore strengthens proposals of Cenozoic motion between East and West Antarctica.

Marie Byrd Land Dome

The Marie Byrd Land dome has, in the past, been interpreted as the northern flank of the WARS, largely on the basis of topography (LeMasurier, 1990; Behrendt et al., 1991). This view has subsequently been revised, because it has been recognized that the attenuated crust, block faulting, and alkaline volcanism that define the rift extend northward to the sea, where Cretaceous oceanic crust represents the locus of most extreme extension during Marie Byrd Land-New Zealand breakup (LeMasurier and Landis, 1996). It is now clear that the dome has risen within the rift, much as the Kenyan and Ethiopian domes have risen within the East African rift, and to roughly the same elevation.

Mantle plume support has been proposed to explain the elevation of the Marie Byrd Land dome (LeMasurier and Landis, 1996), 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 elevations and volcanic activity of the Kenyan and Ethiopian domes (Rogers, 2006). It is noteworthy that all three domes rise to roughly the same elevation, irrespective of the elevations of surrounding lowlands. The net vertical displacements to be expected in continental rifts due to thinning of the lithosphere, plus the thermal effects of mantle plume activity, have been calculated (White and McKenzie, 1989). The resulting curves show that thinning of the lithosphere by a factor of 2, above asthenosphere at 1480 °C, will produce alkali basalt and a net uplift of ~500 m, although the uplift may be greater above the plume center. This suggests that the elevations of the three domes represent the buoyancy of sub-lithospheric plumes that are just hot enough to yield alkali basalt, that the lithosphere in Africa and Marie Byrd Land have been thinned to a comparable degree, and that the elevation of surrounding lowlands seems to be controlled independently of the mechanism that causes dome uplift. This offers a reasonable explanation of why Marie Byrd Land dome uplift and volcanism seem to be uncoupled from the dynamics of the rift interior.

The combination of dome uplift on the coast, extension and subsidence in the rift interior, all in Neogene time, implies that the WAIS formed in an environment of significantly lower coastal elevations and shallower inland seas than those represented by the ice-free topography of today. This evolution is an important consideration in attempting to interpret the history of the WAIS.

CONCLUSIONS

1. The floor of the WARS is 1000–2000 m lower in elevation than the East African, and Basin and Range rifts, even after approximating the mass equivalent of ice as sedimentary basin fill. Because crustal thicknesses are similar among these three, the elevation difference implies that the interior of the WARS is relatively cool, and that the risk of a subglacial volcanic eruption destabilizing the ice sheet is low.

2. The unusual depths of ice-filled basins in the rift interior can be reasonably explained by extension and subsidence beneath the ice sheet. This implies an episode of Neogene extension in that region which, together with Ross Sea geophysical results, strengthens the case for Cenozoic motion between East and West Antarctica.

3. The Marie Byrd Land volcano-tectonic dome is an intra-rift dome, similar to the Kenyan and Ethiopian domes, that has risen contemporaneously with extension and subsidence in the rift interior, greatly increasing topographic relief of the landscape over the past 25–30 m.y. The WAIS is the only continental-scale ice sheet on Earth today, or in the recent past, that rests on a tectonically active landscape. The effect of this activity on ice sheet history has not been adequately evaluated.

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