Crustal structure of the West Antarctic rift system and Marie Byrd Land hotspot

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ABSTRACT

The West Antarctic rift system is one of the largest zones of continental extension on Earth. However, little is known of its crustal structure owing to the vast ice sheet that dominates the region. We report on new insights gained from a recent broadband seismic experiment. The 25-km-thick crust measured on the southern flank of the Marie Byrd Land dome suggests that the high topography there is partially supported by a low-density mantle, possibly a hotspot, whereas the interior of the rift appears to be underlain by average-density mantle, suggesting that active volcanism is not present beneath the interior of the West Antarctic Ice Sheet. The fact that a crustal thickness of only 21 km was measured in the Bentley subglacial trench suggests that the region has undergone locally extreme extension.

Keywords: West Antarctica, hotspot, extension, seismology.

INTRODUCTION

The West Antarctic rift is one the largest regions of extended continental crust on Earth, comparable in size to the western U.S. Basin and Range and the East African rifts (Behrendt et al., 1991; Tessensohn and Worner, 1991). The West Antarctic rift system is one of Antarctica's two major tectonic provinces, the other being the East Antarctic craton (Fig. 1). Unlike the relatively stable East Antarctic craton, the West Antarctic rift system has had a complex history during the past 100 m.y., complicating efforts of plate-circuit reconstructions (Cande et al., 2000). Superimposed on the northern boundary of the West Antarctic rift system is the Marie Byrd Land dome, a region of intraplate volcanism since ca. 30 Ma that is comparable in size to the Yellowstone hotspot (Hole and LeMasurier, 1994). Our current understanding of West Antarctica's history and crustal structure relies heavily on data collected via shipboard geophysics studies in the Ross Sea (e.g., Hamilton et al., 2001; Cooper et al., 1991; Luyendyk et al., 2001; Trey et al., 1999). These data have revealed numerous fault-bounded basins within a thinned continental crust, which has an average thickness of 25 km in the Ross Sea sector of the West Antarctic rift system. However, the onshore part of the rift remains largely unexplored owing to its near-complete coverage by the West Antarctic Ice Sheet and the Ross Ice Shelf, restricting geologic exposures to $<2\%$ of the surface area.

Knowledge of West Antarctic lithospheric structure is important because it forms the cradle of the West Antarctic Ice Sheet and exerts strong influence over its dynamics (Dalziel and Lawver, 2001). The West Antarctic Ice Sheet's mass balance is regulated by several fast-flowing ice streams that drain its interior (Joughin and Tulaczyk, 2002). Critical to the initiation and maintenance of these ice streams is the availability of free water produced as a result of basal melting, a value strongly influenced by geothermal heat flux (Hulbe and MacAyeal, 1999). However, data to constrain the thermal conditions at the bed are difficult to obtain due to the kilometers-thick ice sheet in the region. Detailed knowledge of the West Antarctic lithosphere may provide the best method to constrain this key glaciological parameter by allowing the development of geophysical proxies for geothermal heat flux (Shapiro and Ritzwoller, 2004).

In this paper we provide new insight into the tectonic structure of the continental West Antarctic rift system and Marie Byrd Land from data obtained in a recent broadband seismic deployment on the West Antarctic Ice Sheet (Anandakrishnan et al., 2000; Anandakrishnan and Winberry, 2004), and discuss both the tectonic and glaciological implications of our results.

GEOLOGIC BACKGROUND

The southern boundary of the West Antarctic rift system is marked by the Transantarctic Mountains, often considered a classic example of rift-flank uplift (ten Brink and Stern, 1992). The northern boundary is less well defined but is often inferred to be the Marie Byrd Land region, which is characterized by high elevations. Middle Cretaceous to Cenozoic rifting in West Antarctica produced several hundred kilometers of displacement between Marie Byrd Land and East Antarctica (Luyendyk et al., 1996; Di Venere et al., 1994). Major extension in the region commenced ca. 105 Ma (Bradshaw, 1989; Luyendyk, 1995). Prior to this time the New Zealand microcontinent was still attached to the Antarctic continent, and the Phoenix plate was subducting beneath the region (Weaver et al., 1994). Between 105 and 95 Ma a switch in the magmatic character of the region indicates a change from subduction to extension (Weaver et al., 1994). Estimated amounts of Cenozoic extension vary widely (Trey et al., 1999; Lawver and Gahagan, 1994), but major extension in the West Antarctic rift system is generally agreed to have ceased by the middle Cenozoic (Cande et al., 2000; Hamilton et al., 2001).

The Marie Byrd Land intraplate volcanic province is a largely basaltic region that has been active since ca. 30 Ma (Hole and LeMasurier, 1994). The extent of the province is defined by a 1000 km by 550 km dome that rises to >2700 m in elevation. The abundant volcanic rocks in the region have been attributed to a mantle hotspot now thought to underlie the region (Hole and LeMasurier, 1994; Weaver et al., 1994). Some suggest that the hotspot is local in scale, centered on the topographic expression of the dome (Weaver et al., 1994), whereas others have suggested a continental-scale feature underlying

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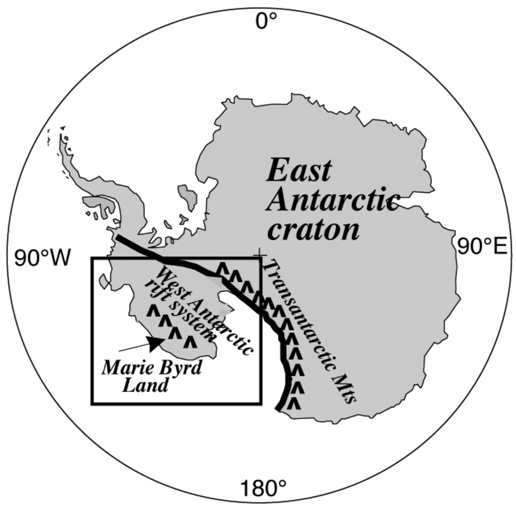

Figure 1. Antarctic region; study area is outlined. Southern extent of West Antarctic rift system is defined by topographic boundary of Transantarctic Mountains, thick black line.

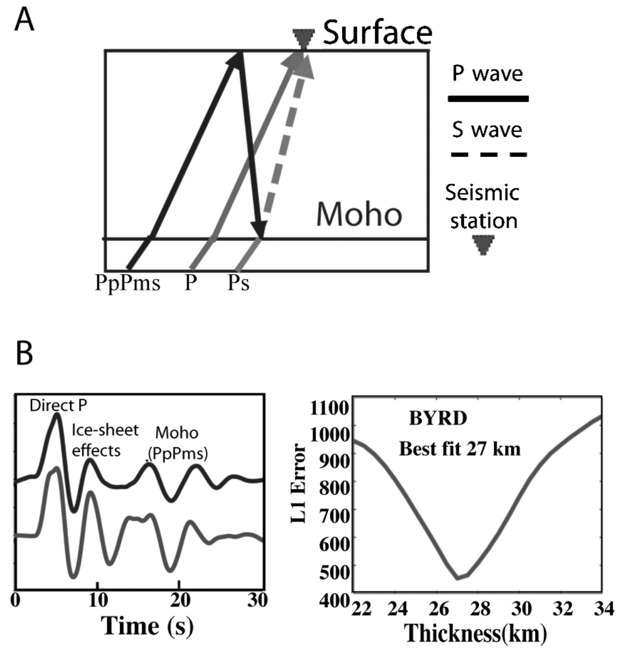

Figure 2. A: Summary of receiver-function method. Significant velocity contrast at crust-mantle boundary results in portioning of energy into P and S waves. Relative travel-times of these phases are used to model depth to interface. B: Example receiver function. In left panel, top receiver function is data, whereas lower receiver function is best model fit. Right panel shows minimization of error.

the entire West Antarctic region (Hole and LeMasurier, 1994; Behrendt et al., 1994). The mechanisms responsible for Marie Byrd Land's topography also remain elusive; its high elevations have been explained by both thin crust passively uplifted by the hotspot (LeMasurier and Landis, 1996) and as a region of isostatically compensated thick crust (e.g., Groushinsky and Sazhina, 1982).

DATA AND RESULTS

Because of the remoteness and harsh climate, the Antarctic is one of the most sparsely instrumented areas on the planet. Permanent broadband seismic stations are confined to the coast (the South Pole being the exception). The Antarctic Network of Unattended Broadband Seismometers (ANUBIS) Project was designed to expand the amount of broadband seismic data available for Antarctica (Anandakrishnan et al., 2000). Data from this experiment as well as data from the Global Seismic Network station at the South Pole (SPA) are used in this study to expand our knowledge of the continental structure of Antarctica.

We estimate crustal thickness by using teleseismic earthquakes and the receiver-function technique of Langston (1979; Ammon, 1991). This technique uses the conversions and reflections of seismic energy at distinct boundaries within Earth (e.g., the Moho discontinuity) in order to model the depth to these interfaces. As has been discussed elsewhere, the presence of an ice sheet adds significant high-frequency signal to the early part of the receiver function (Anandakrishnan and Winberry, 2004). This signal is due to reverberations of seismic energy within the ice sheet because of the large acoustic-impedance contrast between the ice and the rocks beneath. These reverberations make observation of the compressional (P) to shear-wave (s) conversion at the Moho (Ps) difficult, so we use a Moho multiple (PpPms) to model the crustal thickness (Fig. 2A). Our assumptions of a P-wave velocity of 6.5 km/s and an S-wave velocity of 3.75 km/s, the global average for continental crust (Christensen and Mooney, 1995), result in an uncertainty of ± 1 km in our crustal-thickness estimates. At all stations the ice thicknesses are known and the thickness of low-velocity sedimentary layers have been determined by modeling P to s conversions from the base of the sedimentary unit in order to fit the early part of the receiver function (Anandakrishnan and Winberry, 2004) (Fig. 2B).

We use only events of magnitude $M > 6.0$ and within the great circle range of 60°–90° to construct our receiver functions. Most of the events are subduction-zone events from the Kermadec Trench. Our use of a simple grid-search technique to determine crustal thickness minimizes the error between modeled and recorded receiver functions. In addition, we determined the isostatic compensation at each station by using the appropriate crustal-thickness values and adjusted bedrock elevations (Drewry, 1983). The stations can be divided into two groups, those approximately compensated in an Airy isostatic manner (ISDE, OND, SDM, BYRD, STC, SPA) and those out of Airy isostasy, whose elevations are greater than expected (MBL, MTM). Results are summarized in Figure 3, in which crustal thickness is measured from the base of the ice sheet.

Most of the results are consistent with previous models of the West Antarctic rift system structure. The data show a thin extended continental crust (21–31 km) (Clarke et al., 1997; Studinger et al., 2002) bounded by a thicker East Antarctic craton (34 km), although this thickness is lower than the average of >40 km from previous studies of East Antarctica (Groushinsky and Sazhina, 1982; Ritzwoller et al., 2001). The thin crust of station MTM in the Bentley subglacial trench (21 km) and the relatively thin crust (25 km) observed at station MBL on the flank of the Marie Byrd Land dome require further discussion.

DISCUSSION

The 21 km crustal thickness observed beneath the Bentley subglacial trench is the thinnest crust ever observed in the West Antarctic Ice Sheet region of Antarctica. The trench is a subglacial basin 100 km wide by 500 km long, filled with more than 500 m of unconsolidated sediment (Anandakrishnan and Winberry, 2004) and maximum depths >3000 m below sea level (Drewry, 1983). The elevation at MTM, however, is still 500 m greater than predicted by a model assuming Airy isostasy. The narrow wavelength of the basin's topography (<100 km) and the high upper-mantle velocities observed beneath the region, suggesting a cold upper mantle (Sieminski et al., 2003), point to flexural support of the topography (Watts, 2001). The basin's

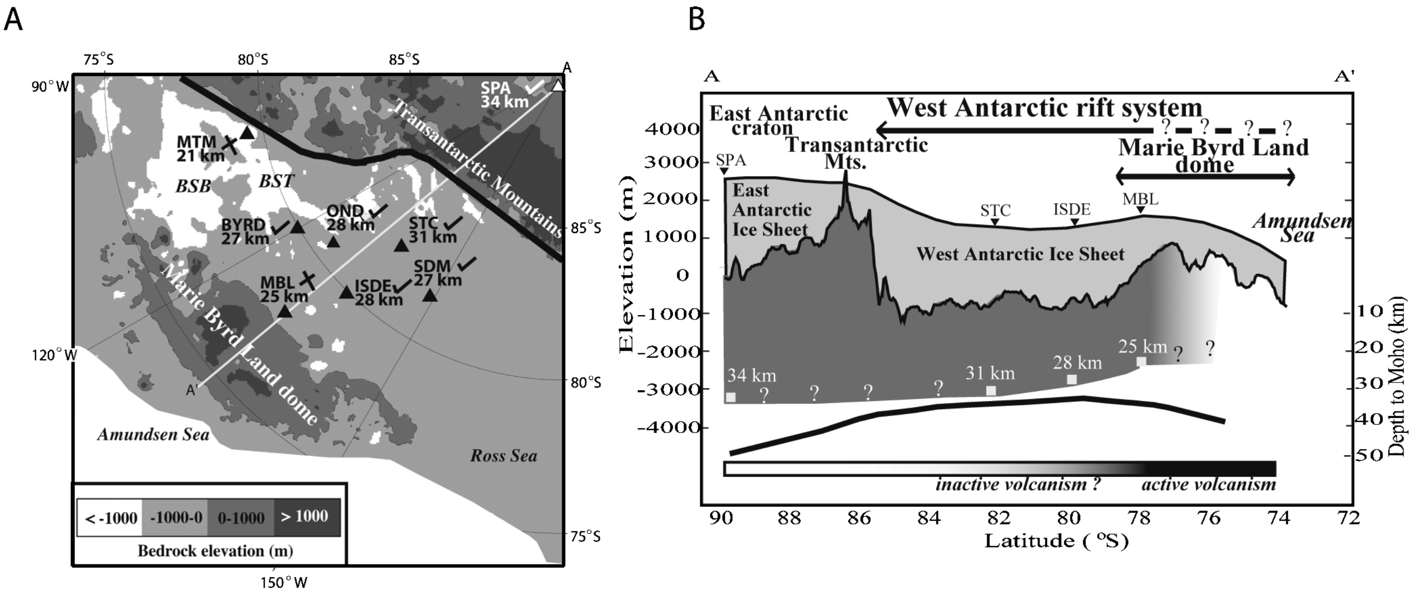

Figure 3. A: Bed-elevation map of study region. Abbreviations: BSB—Byrd subglacial basin, BST—Bentley subglacial trench; others are seismic stations (marked by black triangles). Solid black line shows approximate location of southern boundary of West Antarctic rift system. Crustal-thickness estimates are given as measured from base of ice sheet. Checkmarks denote crust that is out of Airy isostatic equilibrium; crosses denote stations compensated or undercompensated in Airy manner. White line shows location of cross section in B. B: Cross section through West Antarctic rift system at 130°W showing bedrock elevations and possible crustal models. Shaded gray model is from this study; solid black line at bottom of figure shows crustal models derived from gravity measurements by assuming Airy-type compensation (Groushinsky and Sazhina, 1982). Data from stations STC and ISDE are projected onto cross section.

extreme topography and thin crust most likely represent a region of highly concentrated extension not previously imaged; although timing of any extension is not known, it most likely predates the onset of major glaciation in West Antarctica, as major sediment deposition is not expected beneath a large ice sheet.

Station MBL is located on the southern flank of the Marie Byrd Land dome and provides preliminary insight into the region's structure. Marie Byrd Land is often interpreted as a region of thicker crust, 30 km (Luyendyk et al., 2003) up to 40 km (Groushinsky and Sazhina, 1982), relative to that found farther south. However, the observed 25-km-thick crust is significantly thinner than those estimates. The bedrock elevation at station MBL is 1 km higher than that predicted by Airy isostasy. If this result is typical for the entire Marie Byrd Land region, the high elevations observed throughout the region may reflect extended continental crust whose topography is supported by a combination of low-density upper mantle and Pratt-type compensation rather than a thick Airy-type compensated crust (LeMasurier and Landis, 1996). This interpretation is consistent with a surface-wave tomography study that imaged a significant low-velocity zone confined beneath the Marie Byrd Land dome (Sieminski et al., 2003).

The hotspot volcanism of Marie Byrd Land has been proposed to extend beneath the interior of the West Antarctic Ice Sheet, several hundred kilometers away from the observed volcanic outcrops. This theory is largely based on aerogeophysical observations, including the presence of numerous circular magnetic anomalies (Behrendt et al., 1994; Blankenship et al., 1993). The presence of active volcanism beneath the West Antarctic Ice Sheet could possibly trigger its collapse due to enhanced basal melting (Blankenship et al., 1993), resulting in as much as 6 m of sea-level rise. However, several lines of evidence suggest that the hypothesized low-density upper mantle beneath Marie Byrd Land may not extend to the interior of the West Antarctic rift system. Stations within the interior of the rift (excluding MTM) and in East Antarctica (SPA) are all compensated or slightly undercompensated in an Airy manner, suggesting a normal mantle beneath the interior of the rift. This interpretation is consistent with (1) magnetotelluric soundings in the region that suggest no melt within the upper part of the lithosphere (Wannamaker et al., 1996), (2) faster mantle velocities found within the rift's interior relative to the Marie Byrd Land dome (Sieminski et al., 2003; Ritzwoller et al., 2001), and (3) a recent geophysical study estimating heat flux indicates values are likely lower within the rift's interior (Shapiro and Ritzwoller, 2004). Implicit in this interpretation is a strong lateral thermal gradient between the lithosphere of Marie Byrd Land dome (hot lithosphere) and the interior of the West Antarctic rift system (normal lithosphere), suggesting that the interior of the West Antarctic rift system is not volcanically active at present. This is in agreement with a recent ice-sheet modeling study that requires a relatively low geothermal heat flux (60 mW/m^2) to explain the recent behavior of the West Antarctic Ice Sheet, the shutdown of ice stream C–Kamb Ice Stream (Parizek et al., 2003). If our interpretation of a volcanically dormant West Antarctic rift system interior is correct, magnetic anomalies that have been previously interpreted as late Cenozoic in origin may be relict features of a previous phase of extension (Behrendt, 1999).

CONCLUSIONS

The thin, isostatically compensated crust observed throughout much of the West Antarctic rift system is consistent with previous interpretations that West Antarctica underwent a prominent phase of extension from the Cretaceous to middle Cenozoic. However, several important features have been documented in the present study: (1) The thin crust and extreme topography associated with the Bentley subglacial trench suggest that this region (possibly including the Byrd subglacial basin to the north) represents a distinct tectonic regime that has undergone locally extreme extension. (2) The thin crust observed on the flank of the Marie Byrd Land dome suggests that the region has undergone significant crustal thinning and is a continuation of the West Antarctic rift system province, not the northern boundary (Fig. 3B). If this is the case, the high topography observed in the region most likely reflects thin, extended crust currently underlain by a low-density upper mantle, consistent with the interpretation of a large intraplate hotspot.

(3) The active hotspot volcanism observed in Marie Byrd Land likely does not extend beneath the interior of the West Antarctic Ice Sheet.

The data presented have illuminated several complexities in the West Antarctic rift system–Marie Byrd Land hotspot system. Future geophysical studies that can produce detailed images of crust and upper-mantle structure are critical to better understanding of the regional tectonics, in particular the Bentley subglacial trench–Byrd subglacial basin system and Marie Byrd Land hotspot.

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