Seismic evidence for lithospheric foundering beneath the southern Transantarctic Mountains, Antarctica

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ABSTRACT

The 3000-km-long Transantarctic Mountains (TAMs), which separate cratonic East Antarctica from tectonically active West Antarctica, remain one of the least understood of Earth's major mountain ranges. The tectonic mechanism that generates the high elevation, as well as the processes that produce major differences between various sectors of the TAMs, are still uncertain. Here we present newly constructed seismic images of the crust and uppermost mantle beneath central Antarctica derived from recently acquired seismic data, indicating ongoing lithospheric foundering beneath the southern TAMs. These images reveal an absence of thick, cold cratonic lithosphere beneath the southern TAMs. Instead, an uppermost-mantle slow seismic anomaly extends across the mountain front and 350 km into East Antarctica, beneath a high plateau near the South Pole. Under the slow anomaly, a relatively high-wavespeed root is found at ~200 km depth, connected with the East Antarctic lithosphere, suggesting that sinking lithosphere has been replaced at shallow depths by warm, slow-velocity asthenosphere. A mantle lithosphere foundering model is proposed to interpret these images, which best explains the present large area of high elevation and the uplift of the TAMs, as well as Miocene-age volcanism in the Mount Early region.

INTRODUCTION

The southern Transantarctic Mountains (TAMs), extending from the Ross Ice Shelf front to the Thiel Mountains in Antarctica (Fig. 1), bear different topographic and geologic signatures compared with other sections of the TAMs. Topographically, as the broadest part of the TAMs, they extend more than 300 km into East Antarctica with plateau-like high elevation. In contrast, the northern TAMs are generally narrower. The southern region includes Mount Early and Sheridan Bluff (Stump et al., 1980; LeMasurier et al., 1990; Fig. 2A), which are the only sites where late Cenozoic volcanism is found on the East Antarctic craton side of the TAMs crest. Along other portions of the TAMs, such volcanism is only found within 60–100 km of the boundary along the West Antarctic Rift System (WARS).

The TAMs have been regarded as a rift-shoulder mountain range, perhaps resulting from a combination of (1) asymmetric extension of the WARS, (2) thinning of the mantle lithosphere beneath the WARS, (3) conduction of heat from the WARS to East Antarctica (Stern and ten Brink, 1989), and (4) crustal thickening due to rifting-associated underplating (Fitzgerald, 2002). However, the first three mechanisms do not extend hundreds of kilometers off of the rift axis and so do not account for the broadly distributed high plateau and volcanism extending into East Antarctica well past the mountain crest. For the last mechanism, a complete Airy compensation of the southern TAMs requires a crustal thickness 10–15 km greater than that of surrounding regions. However, seismic data indicate normal crustal thicknesses of 25–38 km beneath the southern TAMs (ten Brink et al., 1993) and an associated Airy crustal isostatic deficit of up to 8 km (An et al., 2015; Chaput et al., 2014). Thus, the fourth mechanism, the crustal thickening model, cannot completely explain the high elevation of southern TAMs.

Several studies in the TAMs (Stern and ten Brink, 1989; Brenn et al., 2017) suggest that tensional stresses resulting from normal faulting could produce additional flexural displacement across a range-parallel master fault. This would require a thick elastic lithosphere beneath the inland plateau. However, we show in this study that thick lithosphere does not exist beneath the southern TAMs, and that normal faulting stresses thus cannot explain the broad high elevation in this region. Another hypothesis is that the TAMs were a plateau before the opening of the WARS (Bialas et al., 2007), although this raises additional difficulties (i.e., the origin of this hypothetical plateau is unknown), and does not explain the persistent low seismic speed that extends 300 km inland of the TAM front. Moreover, these alternative models do not provide magmatic sources for late Cenozoic volcanism such as at Mount Early. This paper provides new tomographic evidence for lithospheric foundering that can explain the high elevation of the southern TAMs, and that is consistent with its uplift history and Cenozoic volcanism.

DATA

During the past 15 yr, a succession of passive seismographic deployments has been carried out across Antarctica, with the most important for this study being the Polar Earth Observing Network–Antarctica Network (POLENET-ANET; 2007–present) stations (Fig. 1). Surface wave analysis of seismic data, using ambient noise and teleseismic earthquake methods, shows low Rayleigh wave phase speeds at periods between 30 to ~120 s, providing direct evidence that seismic wave speeds in the uppermost mantle are substantially lower than beneath East Antarctica. To quantify the spatial distribution of these slow upper mantle seismic speeds, we have combined the Rayleigh wave maps derived from ambient noise with those from teleseismic earthquakes

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Figure 1. Sub-ice topography of Antarctica (Fretwell et al., 2013) and bathymetry of surrounding oceans relative to sea level, showing study region (black box) and seismic stations utilized (circles). Major mountain ranges between East Antarctica (EANT) West Antarctica (WANT) include the northern and southern Transantarctic Mountains (N. TAMs and S. TAMs, respectively); Ellsworth Mountains (EM); Whitmore Mountains (WM); and Thiel Mountains (TM). Northern Victoria Land (NVL), the Ross Ice Shelf (RIS), West Antarctic Rift system (WARS), Adare Trough (AT), and Terror Rift (TR) are also marked by abbreviations. Two red dashed lines mark rift-shoulder (western) and inland (eastern) flanks of high-elevation region that separates the continent into stable, cratonic EANT and more tectonically active WANT. POLENET-ANET— Polar Earth Observing Network–Antarctica Network; GNS—Global Seismographic Network; temp.—temporary.
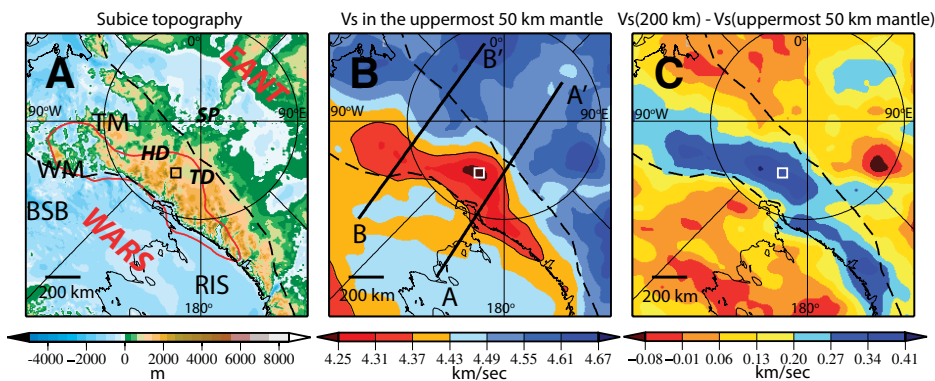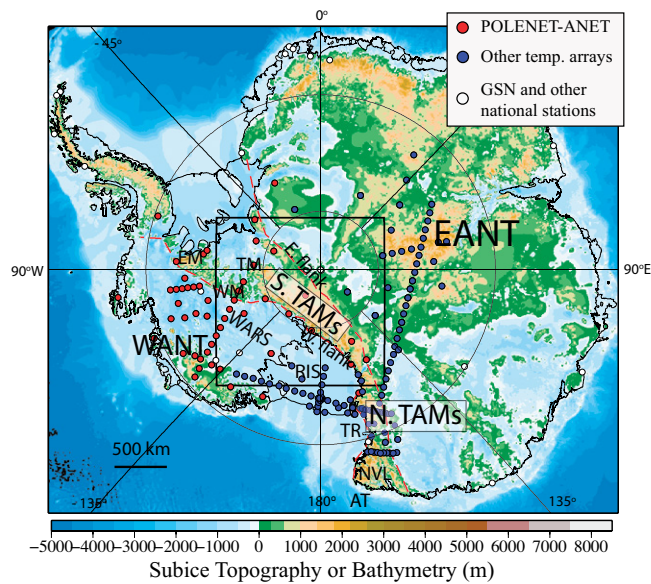

Figure 2. Map view images of shear wave structure. A: Elevation of study region, with tectonic locations marked by abbreviations: East Antarctic (EANT) craton; West Antarctic Rift System (WARS); Ross Ice Shelf (RIS); Byrd Subglacial Basin (BSB); Whitmore Mountains (WM); and Thiel Mountains (TM). Small open box marks approximate location of Mount Early and Sheridan Bluff volcanism. Red contour highlights area with the slow (<4.37 km/s) uppermost mantle speed beneath southern Transantarctic Mountains (TAMs) shown in B. Geographic locations including South Pole (SP), Titan Dome (TD), and Hercules Dome (HD) are indicated. B: Average V_s in uppermost 50 km of mantle, showing absence of cold, fast mantle lithosphere beneath TAMs. Black lines indicate locations of two vertical profiles shown in Figure 3. C: Difference between V_s at 200 km and average V_s in uppermost 50 km of mantle. Regions with large positive differences indicate cold lithosphere below warm asthenosphere.

constructed by Heeszel et al. (2016) to construct a new three-dimensional (3-D) shear speed (V_S) model for the crust and upper mantle beneath western and central Antarctica encompassing the southern TAMs. To provide better constraints on shallower structure, P to S receiver functions are also incorporated at seismic station locales. Compared with the methods of Heeszel et al. (2016), the incorporation of the ambient noise data and receiver functions helps us impose better constraints on crustal and Moho structures, decrease the tradeoff between Moho depth and the velocity of the adjacent crust and

mantle, and better understand the contribution of mantle support to the high elevation in addition to simple Airy compensation. Notably, the rigorous Monte Carlo error estimates for the resulting 3-D seismic model confirm a seismically low-velocity zone (LVZ) beneath the southern TAMs.

RESULTS

Key features of the new 3-D model are shown in Figures 2 and 3. An LVZ is observed in the upper 50–80 km beneath the southern TAM front, extending into East Antarctica (Fig. 2B). The widest portion of the LVZ extends to

the inland (eastern) flank of the southern TAMs, suggesting that the LVZ covers a broad region of >200,000 km². The slowest V_S of the LVZ is ~4.12 ± 0.04 km/s at ~80 km depth (see the GSA Data Repository[1]) and is underlain by a relatively fast (4.65 ± 0.06 km/s) deeper mantle compared to the WARS. Figure 2C presents the difference between V_S at ~200 km depth and for averaged uppermost mantle (averaged across the uppermost 50 km). Beneath the LVZ, this difference is especially large (~0.3–0.4 km/s), while in contrast, it is −0.1 to 0.1 km/s across the rest of the study region, and the global average is ~0.02 km/s. Error analysis shows that this velocity increase is required by the seismic data, regardless of the Moho uncertainties, prior models, and other assumptions incorporated into the inversion, thus it is unlikely generated by the depth tradeoff of surface wave inversion. Vertical cross sections (Figs. 3A and 3B) confirm a slow-above-fast structure beneath the high southern TAMs. The fast structure dips toward the WARS, and its inland end is continuous with East Antarctic lithosphere. We interpret this as foundering cold and fast lithosphere, and the wedge-shaped slow anomaly in the uppermost mantle is interpreted as the warm and slow asthenosphere that has flowed into the region formerly occupied by the lithosphere.

DISCUSSION

Given their remote location and thick ice sheet, the southern TAMs, especially their extensive inland plateau, have sparse geological constraints on tectonic history. The seismic model, showing an absence of a crustal root and strong slow-velocity anomalies, along with the episodic uplift history, Cenozoic volcanism, absence of compressional faulting, and extension along the adjacent WARS, all provide strong support for a mantle source of the high elevation. Cross section A-A′ (Fig. 3A) shows a slow speed anomaly with an amplitude of ~−6% relative to both the regional average and the global reference V_{SV} (vertically polarized shear-wave velocity), and up to ~−10% relative to the East Antarctic lithosphere beneath the elevated regions. The abnormally slow speed may have elements that are compositional (Lee, 2003), but it is most likely predominantly thermal (Cammarano et al., 2003), indicating a much higher temperature relative to both the East Antarctic craton and the average mantle at these depths. Calculations using experimentally derived relations between shear velocity and mantle temperature (e.g., Goes et al., 2000) suggest temperatures of ~300–500 K above the mantle temperatures beneath East Antarctica.
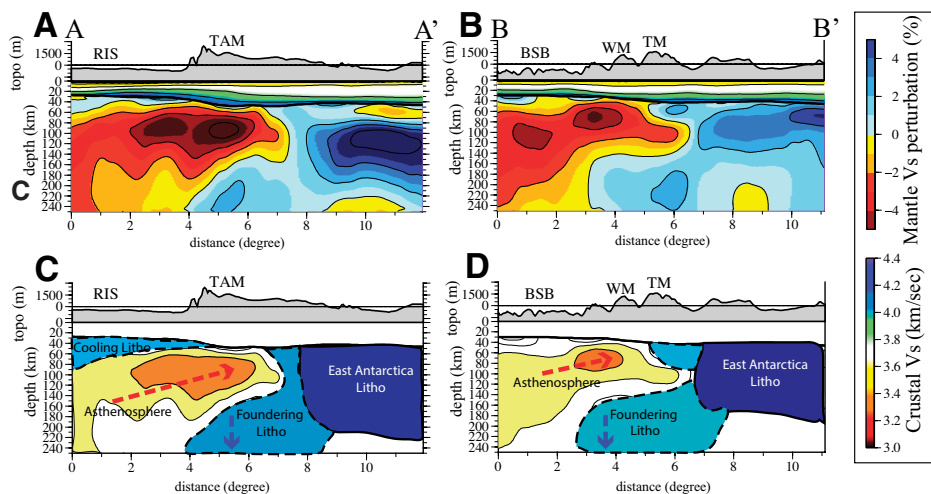
Figure 3. Vertical profiles and interpretation. A,B: Vertical V_s cross sections along A-A′ and B-B′ (locations shown in Fig. 2). V_s in crust is plotted as absolute value, and V_s in mantle is plotted as percent perturbation relative to averaged one-dimensional V_s structure of study region. Geographic features are marked by abbreviations: Byrd Subglacial Basin (BSB); Ross Ice Shelf (RIS); Transantarctic Mountains (TAM); Whitmore Mountains (WM); and Thiel Mountains (TM). C,D: Interpretation of seismic images in A and B. topo—topography; litho—lithosphere.

This elevated temperature reduces the density of the uppermost 60–100 km of the mantle by ~1%–1.5%, providing an extra buoyancy force that is capable of supporting an additional ~1.5–2 km of surface elevation. Near the southern TAMs, the slow anomaly beneath the high plateau extends ~350 km inland, mirroring the distribution of high elevations. Additionally, cross section B-B′ (Fig. 3B) also shows that an uppermost-mantle LVZ extends beneath the Thiel Mountains, which are ~300 km inland from the WARS.

The southern TAMs have uplifted episodically from the Late Cretaceous through to the present (Behrendt and Cooper, 1991; Barrett, 2013). Fission-track and geological data suggest, however, a particularly dominant period of exhumation and uplift from 50 Ma to 20 Ma (Fitzgerald, 2002; Fitzgerald and Stump, 1997; Miller et al., 2010). Uplift at this time scale can be explained by the adiabatic upwelling of asthenosphere mantle due to lithosphere foundering (Göğüş and Pysklywec, 2008). Mount Early and Sheridan Bluff, located on the East Antarctic flank, erupted at ca. 15–19 Ma (Stump et al., 1980; K. Panter, 2017, personal commun.), and glacially deposited boulders dated at ca. 17 Ma with a likely source region farther inland (K. Licht, 2017, personal commun.) indicate an extensive region of Miocene volcanism. These volcanic deposits are ~200–300 km inland from the TAM front and lie above the slowest uppermost mantle region (Fig. 2B), indicating that mantle temperature beneath the high-elevation region was high enough to serve as a magmatic source.

Mantle lithosphere foundering by delamination (Bird, 1979) or viscous downwelling (Conrad and Molnar, 1997), resulting from the gravitational instability of cold and thus negatively buoyant lithosphere, is a promising candidate for interpretation of our seismic images and other observations in this area. Given a reasonable difference between ambient mantle (assumed to be ~3.3 g/cm³) and sub-TAM lithosphere (~1% higher, at ~3.33 g/cm³) and an initial thickness of sub-TAM lithosphere of ~150–250 km, such foundering can initiate within 10–20 m.y. after the lithosphere perturbation and can run to completion in ~80 m.y., given an intermediate upper-mantle lithospheric viscosity (~10^{22} Pa). Replacement of cold lithosphere by warmer asthenosphere, on a time scale that is dependent on upper-mantle viscosity, is the key consequence of this foundering. Other consequences include (1) zones of differential uplift due to the replacement of the lithosphere by asthenosphere (Göğüş and Pysklywec, 2008; Stern et al., 2013), (2) volcanism due to decompression melting, and (3) crustal extension near the plateau uplift, of which all are observed near the southern TAMs area. Figures 3C and 3D highlight this proposed mechanism. Please note that the width and characteristics of the TAMs change significantly along strike, so it is currently unclear whether the foundering model can be successfully applied to the entire TAMs range.

Seismic and geological evidence for lithosphere foundering has been found in many other continental locales (e.g., Zandt et al.,2004; Levander et al., 2011; Stern et al., 2013). Its onset requires two conditions: (1) a cold and heavy subcontinental lithospheric mantle lid; and (2) a trigger that thermally disrupts the mantle lid, or a simple deformation on a non-Newtonian rheology (Billen and Houseman, 2004). Ancient refractory cratonic mantle lithosphere is usually neutrally or positively buoyant (Jordan, 1988) and has a dry peridotite rheology (Karato

and Wu, 1993; Peslier et al., 2010), preventing it from foundering. However, early tectonic events (i.e., the early Paleozoic Ross orogeny [Goodge, 2007] and Late Jurassic rifting evidenced by tholeiitic magmas [Schmidt and Rowley, 1986]) may have replaced the original lithosphere with fertile mantle or refertilized the older mantle through metasomatism in this region. Following a cooling process of >100 m.y., a thick, cold and heavy lithospheric lid would form, leaving the continental lithosphere vulnerable to foundering under suitable subsequent tectonic conditions.

In an extensional environment, lithosphere foundering may proceed following the formation of a step or edge in the mantle lithosphere (Buck, 1986; Stern et al., 2013). For the southern TAMs, we suggest that Cretaceous and later rifting in the WARS would have created the step. Active volcanism in the Mount Early region at 15–20 Ma (Stump et al., 1980) suggests that foundering had progressed significantly by that time. This age is similar to that of the rifting episodes at the Adare Trough at 24 and 17 Ma (Granot et al., 2010) and the Terror rift (Hall et al., 2007), suggesting that Miocene rifting might be the trigger. Another possibility is that the foundering was triggered at an earlier time during Paleogene rifting (ca. 60–80 Ma) at the TAM front, when initial destabilization of the lithosphere could have caused a set of significant exhumation episodes in this region between 80 and 20 Ma (Fitzgerald, 2002). In the second case, the lithospheric foundering may have migrated inboard to generate the Mount Early volcanism and the broad plateau uplift at ca. 17 Ma. In either case, the foundering was triggered by the rifting of the WARS, perhaps through edge-driven convection of the uppermost mantle (e.g., van Wijk et al., 2008).

A broader implication is that the presence of warm asthenosphere at shallow depth would greatly alter glacial isostatic adjustment (GIA) in this region. Previous GIA calculations using typical global average lithospheric thickness and mantle viscosity estimates predict a much higher uplift rate than observed by continuous GPS receivers in this area, and the data cannot be fit by any reasonable ice mass change model (Whitehouse et al., 2012; Wilson et al., 2016). Much thinner elastic lithosphere and low-viscosity mantle resulting from the lithospheric foundering and asthenospheric upwelling would cause faster GIA such that the observed uplift is only sensitive to very recent ice mass changes. These anomalous mechanical properties of the uppermost mantle in southern TAMs should be considered in future GIA interpretation and modeling.

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