Tectonic implications for uplift of the Transantarctic Mountains

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Summary The Transantarctic Mountains are a non-compressional mountain belt located on the tectonic boundary between cratonic East Antarctica and non-cratonic West Antarctica. Formation of this mountain belt and a possible relation with the West Antarctic Rift system are still debated. Here we suggest a new explanation for uplift of the mountains, formation of a small crustal root, depression of the hinterland Wilkes Basin and formation of the West Antarctic Rift system. Using thermo-mechanical models to study deformation of the tectonic boundary, we find that convergence of crustal material at the craton edge during extension results in formation of a small crustal root and uplift of the surface. Crustal material accumulates at the craton edge during extension because the cratonic lithosphere is too strong to deform. This explains the location of the mountains. We further suggest that the West Antarctic Rift system formed at the side of the craton because this is the weakest location in the region. The hinterland Wilkes Subglacial Basin is a flexural depression; thermo-mechanical models show that rifting does not occur in the hinterland as the craton is simply too strong. Our models thus suggest that uplift of the Transantarctic Mountains is related to formation of the West Antarctic Rift system and flexural depression of the Wilkes Basin.

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Introduction

The Transantarctic Mountains form the morphological and geological boundary between East and West Antarctica. They are the largest non-compressional mountain belt in the world (Figure 1), and are characterized by the absence of compressional deformation within sediments, folding and thrust faulting. The range is located on the tectonic boundary between cratonic East- and non-cratonic West Antarctica. How the Transantarctic Mountains were formed, why they are located on the tectonic boundary, and whether uplift of the mountains is related to the West Antarctic Rift system (Figure 1) are still debated.

In this study, we address the dynamic evolution of the tectonic boundary between West and East Antarctica with a thermo-mechanical modeling approach. This tectonic boundary is likely an inherited laterally varying lithosphere structure from earlier tectonic events (Kalamarides et al., 1987) that preceded the Cretaceous to Cenozoic extension phase that formed the West Antarctic Rift system. Such an inhomogeneous, asymmetric lithosphere structure likely caused lateral strength variations that may have influenced the localization of lithosphere deformation during the Cretaceous/Cenozoic extensional phase. Here, we develop models of lithosphere extension to study how the craton edge evolves during extension, and suggest a new explanation for uplift of the Transantarctic Mountains.

Existing explanations for uplift of the Transantarctic Mountains

The cause of uplift of the Transantarctic Mountains (TAM), and a possible relation between the uplift and the formation of the West Antarctic Rift (WAR) are still debated. Existing explanations can be divided into thermally driven uplift, mechanically driven uplift, or a combination of the two. Several sources have been suggested for thermally driven uplift. Smith and Drewry (1984) for example attribute uplift of the TAM to heating of the lithosphere by anomalously warm asthenosphere temperatures underneath the area, induced by rifting processes. Berg et al. (1989) suggest that magma injections into the middle and lower crust of the rift zone increased temperatures which resulted in thermal expansion of the mountain belt. Rifting is inferred to have been focused by a mantle plume according to Behrendt (1999). In this model, lateral heat transfer from the warm, thin lithosphere beneath the rifted areas affected the cold lithosphere from East Antarctica resulting in the high elevated mountain range.

ten Brink and Stern (1992) have proposed a mechanical source for formation of the TAM. In these flexural models, uplift of the end of a broken-plate occurs, whereby the plate has been broken by a deeply penetrating normal fault. Uplift then results from a combination of processes, such as lateral variations in temperature or density structure, erosion, and footwall uplift. Fitzgerald et al. (1986) suggest a lateral and depth dependent asymmetric rifting model for formation of the TAM/WAR region, in which the TAM is underlain by a shallow lithosphere/asthenosphere boundary, created by a detachment zone dipping beneath the mountain belt. Lawrence et al. (2006) conclude that uplift can best be explained by a combination of a buoyant thermal load and flexural uplift. Alternatively, ten Brink et al. (1997) propose that uplift of the TAM is not related to the main phase of extension of WAR formation, but to a more recent transtensional event.

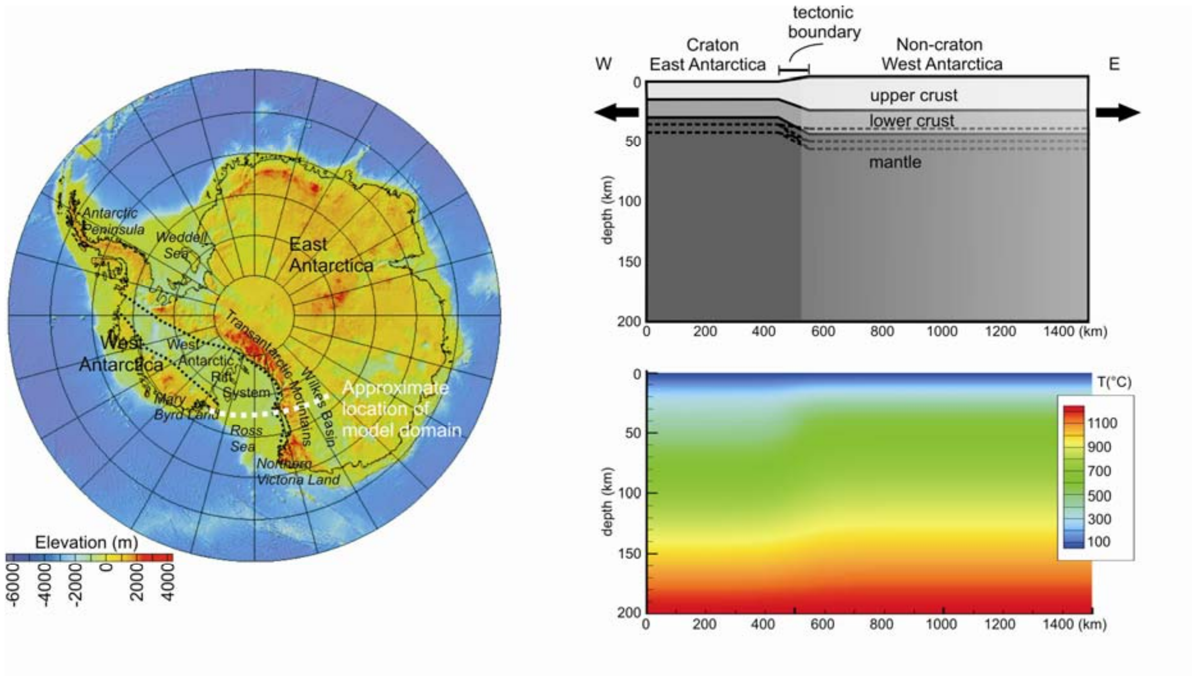

Figure 1. Subglacial topography and bathymetry map of Antarctica (Lytte et al., 2000). The black dotted lines are the inferred boundary of the West Antarctic Rift System from Rocchi et al. (2002). Right panels show the lithosphere structure prior to the extensional phase used in the thermo-mechanical model, with the cold craton of East Antartcia and warmer non-cratonic lithosphere of West Antarctica.

Models of lithosphere deformation; extension of the continent

We use numerical models to study deformation of the tectonic boundary between West and East Antarctica. In these models, the lithosphere is extended for a finite duration between Late Cretaceous and present day. We used a 2-D finite element model based on the Lagrangian approach (van Wijk and Cloetingh, 2002) that solves for visco-elastic deformation of the lithosphere with a parameterization for plastic behavior, and the heat flow equation. The model domain (Figure 1) is divided into upper crust, lower crust and mantle parts, and includes the craton of East Antarctica, the craton edge, and West Antarctica. Extension of the lithosphere is modeled by pulling the left and right sides of the domain outward.

What is the cause of extension of the Antarctic continent? Antarctica is almost completely surrounded by mid-ocean spreading ridges that have continuously added oceanic lithosphere to the plate. Consequently, the proportion of old oceanic Antarctic lithosphere has increased over time (Sandiford and Coblentz, 1994), changing the potential energy of the plate and creating deviatoric tension. Other authors have attributed rifting in Antarctica to mantle plume processes (Weaver et al., 1994), citing domal uplift and hotspot-like volcanic rocks in Marie Byrd Land (LeMasurier and Landis, 1996), and geochemical similarity between WAR volcanic rocks and hot spot volcanism as evidence. We adopt the passive rifting model in this study because the region lacks a hot spot track and there is a clear relation between magmatism, rifting, and plate tectonic processes.

Strength of the lithosphere: location of rifting

Lateral variations in the strength of the lithosphere control the location of rift basin formation in extensional environments, by focusing deformation into the weakest zones. The tectonic boundary between the weak West Antarctic lithosphere and strong East Antarctic lithosphere induces this sort of focusing. All the models that we tested predict the formation of a rift basin (WAR) on the non-craton side of the tectonic discontinuity. Calculations of the total lithospheric strength show that this is indeed the weakest zone in the model domain. Thickening of the crust and uplift of the TAM (Figure 2, 3) is predicted to occur above the tectonic boundary where the strength of the lithosphere increases rapidly toward East Antarctica.

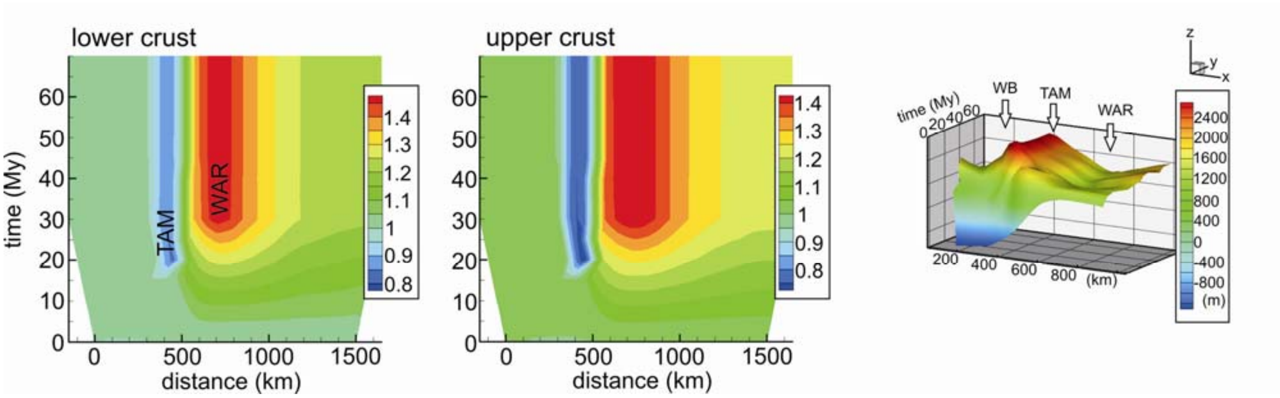

Figure 2. Left panels: model predicted thinning (thinning factors) of upper and lower crust through time. Thinning factors are the ration between initial layer thickness and present thickness. The WAR is formed on the side of the tectonic boundary between West and East Antarctica (red colors, thinning factors >1). The TAM are formed on the edge of the craton (blue colors, thinning factors <1, denoting crustal thickening). The crust thickens here by convergence of crustal material as the adjacent craton is too strong to deform. This results in uplift (right panel) adjacent to the WAR. WB=Wilkes Basin, TAM=Transantarctic Mountains, WAR=West Antarctic Rift.

Formation of the WAR

The West Antarctic Rift system is formed adjacent to the craton edge as this is the weakest location. The crust is thinned most in the area closest to the TAM and decreasingly so to the east, however, a very wide zone (500-1000 km) is affected by the rifting process. The crust is predicted to thin to about 20 km in our models, which is in agreement with observations. Further, the models show that also the mantle part of the lithosphere is thinned beneath the rift zone, and that the lithosphere/asthenosphere boundary may be at a depth as shallow as 50 km. The surface of the rift zone is depressed (Figure 2). Warm mantle material wells up beneath the rift system in our models, in agreement with observations from seismic studies (Lawrence et al., 2006).

Formation of the Wilkes Basin

Below the Wilkes Basin, no crustal thinning is predicted in our models. Our models do predict a surface depression (Figure 2) in the hinterland, which is caused by flexure of the lithosphere.

Formation of the TAM

Crustal thickening occurs in an ~250 km wide zone, resulting in a total of ±8 km of thickening in the models. The total crustal thickening is dependent on the strength difference across the tectonic boundary between West and East Antarctica, and the amount of extension. During the extensional phase, the upper crust in the TAM area is not under compression, so it is counterintuitive that thickening should occur here. However, during the formation of the localized rift zone, crustal material is transported away from the rift zone center, but converges at the edge of the craton, due to the great cratonic strength. Analysis of the horizontal component of the velocity field shows a negative velocity gradient in the TAM region meaning that this is a region of convergence. In this area the crust thickens; a crustal root is formed and the surface is uplifted as seismically observed (Lawrence et al., 2006).

Discussion

Previous studies have pointed toward two main causes for uplift of the TAM: 1) thermal uplift due to high temperatures at shallow depths, and 2) flexural uplift along a broken plate. Our models suggest another major cause for uplift of the TAM: convergence of crustal material that results in thickening of the crust and a small crustal root. This is the result of rift localization adjacent to a craton province. Accumulation of crustal material results in local thickening of the crust some time after the extensional phase has started, but prior to the main phase of rifting and localization. Accumulation forms a small crustal root that may explain the 3 to 5 km crustal thickening beneath the TAM, found in the TAMSEIS experiment (Lawrence et al., 2006).

Prior studies have posited that the Wilkes Subglacial Basin is either a depression caused by rifting or a flexural trough. Our models support the latter explanation. None of our models predict crustal thinning or extension in the TAM hinterland because the strong cratonic lithosphere resists deformation there. Some of the tested models formed surface depressions in the hinterland of the TAM as a result of lithospheric flexure. The magnitude of the predicted surface depression depends on the tectonic evolution of the rift zone and mountain range; it varies in the tested models between ~1 km below sea level to a local depression.

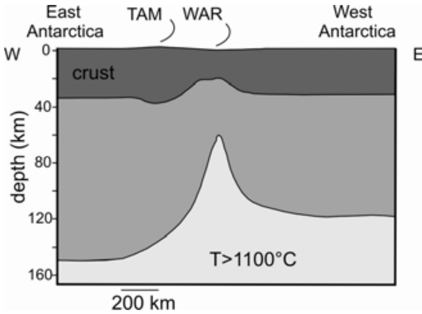

Figure 3. Present day lithosphere structure as predicted by our model.

Timing and duration of the rift phase(s) that formed the WAR are not well constrained, and models in which we varied the duration and timing of extension show a wide range in tectonic evolution. A common feature of the models is however that the rift zone is always formed at the edge of the craton, with strongest localization close to the craton and wide, distributed rifting further eastward. The craton boundary is the weakest location and therefore the preferred place of rift formation. The cratonic lithosphere remains unaffected by the extensional event.

Uplift of the Transantarctic Mountains: result of asymmetric rifting?

Figure 3 shows the predicted present day lithosphere structure based on our models. The asymmetric pre-rift lithosphere structure has resulted, upon extension, in the formation of an asymmetric rift zone. The cratonic lithosphere is not affected by the rifting event, causing the western side of the rift to end abruptly against the strong lithosphere. Below the eastern flank of the TAM, lithosphere temperatures are elevated, and the thermal expansion related to these elevated temperatures may have contributed to uplift of the TAM. Relative timing of uplift in relation to the stretching is still debated; our models suggest that upon initial, moderate extension, the main uplift phase precedes the major rift phase. All models that we tested suggest that uplift of the TAM, extension of West Antarctica and formation of the Wilkes Basin can be tectonically related. Crucial for this finding and for the development of the area is the role played by inherited structures. The inherited tectonic boundary between East and West Antarctica focuses extensional deformation (whether induced by the arrival of a mantle plume head or by plate-boundary forces) at the tectonic boundary. Rift related deformation then includes uplift of the Transantarctic Mountains and formation of the flexural Wilkes Basin in the hinterland. Along strike, both the rifted system and TAM show large variations in the amount of extension and orientation of extensional structures, and uplift rate and timing. The different setup conditions that were tested in the modeling indicate that if such variations would exist along strike of the tectonic boundary, they could account for the variation in character and uplift of the WAR and TAM.

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