# Geodynamic models of the tectonomagmatic evolution of the West Antarctic Rift System

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**Summary** Finite element geodynamic models of the West Antarctic Rift System reproduce the transition from prolonged diffuse extension throughout the rift system during the Cretaceous and early Cenozoic to later focused extension in the Victoria Land Basin during the middle Paleogene. The change in the style of rifting is due to intraplate processes, and does not require changes in plate motions or impingement of a mantle plume. The models are consistent with the Paleogene onset of magmatism in the West Antarctic Rift System under normal mantle thermal conditions. However, the preliminary models indicate that spatially widespread magmatism may require mantle temperatures elevated approximately 100 °C above normal, supporting arguments favoring the presence of a plume.

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## Introduction

The West Antarctic Rift System (WARS) underwent a distinctive multi-phase evolution that progressed from an early stage of broadly distributed extension beginning in the Cretaceous Period to a later stage of more focused extension during the Paleogene Period (Cooper and Davey, 1985; Cooper et al., 1991; Davey and Brancolini, 1995; Wilson, 1995; Hamilton et al., 2001). The early stage of extension accommodated several hundred kilometers of motion across a 750-1000 km-wide region in the Ross Sea between Marie Byrd Land and the East Antarctic Craton (EAC) (Figure 1). Later extension was primarily accommodated within the Victoria Land Basin (VLB), immediately adjacent to East Antarctica, and displacements were minor in comparison to Mesozoic extension. (Lawver and Gahagan, 1994; Davey and Brancolini, 1995; Fitzgerald, 2002). Crustal thickness variations determined from seismic data and gravity modeling studies indicate that the crust in the WARS has been variably thinned during extension, resulting in the formation of several basins and basement highs, including the VLB (Cooper et al., 1991; Davey and Brancolini, 1995; Winberry and Anandakrishnan, 2004). The average crustal thickness is ~30 km beneath the WARS (Bannister et al, 2003). But depending on location, the depth to the crust-mantle boundary varies, averaging 19-21 km in the western Ross Sea (reaching a minimum of ~16 km in the Victoria Land Basin) to ~24 km beneath the Central High in the central Ross Sea, (Trey et al. 1999; Busetti et al., 1999; Bannister et al. 2003; Lawrence et al., 2006). Within the Victoria Land Basin late-stage thinning has resulted in the development of the Terror Rift, a deep (up to 12 km thickness of sedimentary rocks) and narrow (<50 km-wide) basin associated with extreme crustal thinning, faults, and mafic intrusions (Davey and Brancolini, 1995). The depth to the moho increases to >39 km under the western part of the Transantarctic Mountains (TAMS) and maintains this thickness into the East Antarctica craton (Ferraccioli, et al., 2001; von Frese, et al., 1999; Bannister, et al., 2003; Lawrence et al., 2006). Crustal thinning and the associated thermal anomaly in the mantle appear to extend ca. 50-100 km inland from the coast beneath the TAMS (Bannister et al., 2003; Winberry and Anandakrishnan, 2004; Lawrence et al., 2006; Watson et al., 2006).

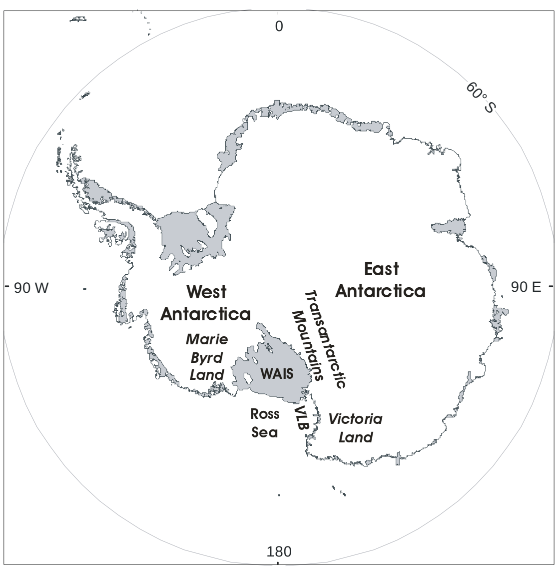


**Figure 1**. Location map. The WARS encompasses the Ross Sea and West Antarctic Ice Sheet (WAIS) and is bounded by (and extends into) Marie Byrd Land and the Transantarctic Mountains. VLB is the Victoria Land Basin.

Based on analysis of aeromagnetic data, the volume of syn-extension magmatism in the WARS has been estimated to be ca. $10^6$ $km^3$, making it comparable to other well-known Large Igneous Provinces (Behrendt et al., 1994, 2006). Dating of exposed rocks in Marie Byrd Land and the Transantarctic Mountains suggest most of the magmatism is Eocene or later in age (Hole and LeMasurier, 1994; Tonarini et al., 1997; Rocchi et al., 2002). This seems consistent with a passive rifting model in that magmatism post-dates the onset of rifting, but there are complicating factors. Most importantly, the major episode of extension is thought to have ended in Late Cretaceous. Cenozoic extension, although possibly ongoing, has been minor and episodic (Cooper and Davey, 1985; Cooper et al., 1991; Lawver and Gahagan, 1994; Wilson, 1995; Karner et al., 2005). It is difficult to reconcile the late onset of magmatism with the waning of extension. One argument has been that transtensional deformation after Late Cenozoic led to deep lithosphere thinning that could account for ongoing decompression melting in the asthenosphere (Davey and Brancolini, 1995; Behrendt, 1999). Alternatively, impingement of a mantle plume or multiple plumes during the Middle or Late Cenozoic has been suggested (Hole and LeMasurier, 1994; LeMasurier and Landis, 1996; Hart et al., 1997; Sieminski et al., 2003). Models have also been proposed that attribute the melt source to a metasomatised lithospheric mantle (Molzahn et al., 1996; Rocchi et al., 2002). Alternative models invoke a stratified mantle that has fossil plume (HIMU) sources, depleted mantle (asthenosphere MORB) sources, and enriched lithospheric mantle (EM) sources (Rocholl et al., 1995; Worner, 1999). Lastly, it has been suggested that the magmatism is only coincidentally related to rifting and requires no plume, but is instead a result of subduction-related metasomatism and induced overturn in the mantle that is related on a hemispheric scale to the breakup of Gondwana (Finn et al., 2005).

The purpose of this paper is to present preliminary geodynamic modeling studies of the tectonic evolution of the WARS, and to assess their magmatic implications. The ultimate goal is to develop geodynamic models that can be used to test the various hypotheses that have been presented to explain magmatism in the WARS by combining both the tectonic and magmatic processes into an integrated quantitative model.

## Prior model results

Huerta and Harry (2007) developed a 2-D geodynamic model of extension in the WARS using a finite element modeling method. Those results demonstrated that intraplate processes could lead to an abrupt change from a period of prolonged diffuse extension to a later period of much more focused extension, without requiring a change in plate motion directions or impingement of a mantle plume. The model matches the large temporal- and spatial- scale aspects of evolution of the WARS (Figures 2 and 3). The model requires a relatively hot lower crust and high heat production in the lower crust in comparison to the East Antarctic craton. In such a scenario, the lower crust and upper mantle in the WARS cools rapidly in zones of extension, promoting a shift of extension into neighboring regions in the WARS. This is similar to the argument presented by Buck (1991) to explain what he called a wide-rift mode of extension. The difference between the Buck model and the model of Huerta and Harry is that the latter includes lateral changes in crust and lithosphere structure. In the model of Huerta and Harry, the portion of the WARS lithosphere adjacent to East Antarctic is not involved in the early stages of extension because of a refrigeration effect; East Antarctica keeps this part of the lithosphere relatively cool, and therefore strong. West Antarctica cools during extension (a result of thinning of the heat generating crust), and becomes stronger (as per the argument of Buck). Eventually, the WARS region becomes sufficiently cool to cause deformation to shift to the area

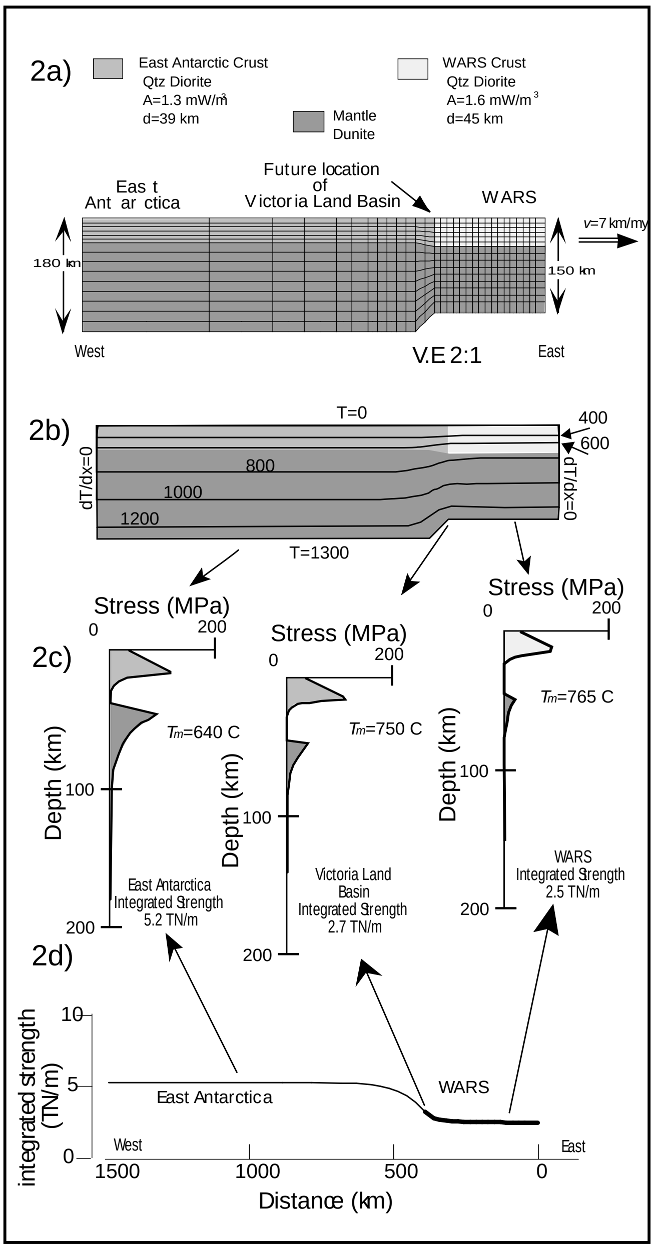


**Figure 2.** Starting FE model of Huerta and Harry (2007). a) Initial mesh geometry (surface heat production rate and thickness of heat producing layer indicated at top). b) Pre-rift geotherms. c) Yield strength vs. depth. d) Integrated strength of model lithosphere.

immediately adjacent to the East Antarctica craton, leading to a change from diffuse to focused extension.

In addition to a warm lower crust, the Huerta and Harry (2007) model also required relatively low heat flux from the mantle (<25 mW m$^{-2}$). This seems to preclude the presence of a modern mantle plume beneath the WARS. Here, we examine whether this model can produce an appropriate volume of melt during the Cenozoic, and if the low mantle heat flux is a robust aspect of the model (that is, is it required?).

## New (preliminary) model results

We evaluated the melt production predicted by the Huerta and Harry (2007) model using the algorithm described by McKenzie and Bickle (1988). This algorithm assumes melt is produced by decompression melting of asthenospheric mantle, with the mantle potential temperature being the primary variable parameter. In the context of our finite element models, the decompression rate is controlled by lithospheric thinning, with the melt being predicted a posteriori by assuming a mantle potential temperature. We seek models that match the melt production history of the WARS while being consistent with the finite element models. In particular, the mantle potential temperature in the melt production model should agree with the basal boundary condition used in the lithosphere-scale finite element models used to simulate the tectonic evolution of the WARS.

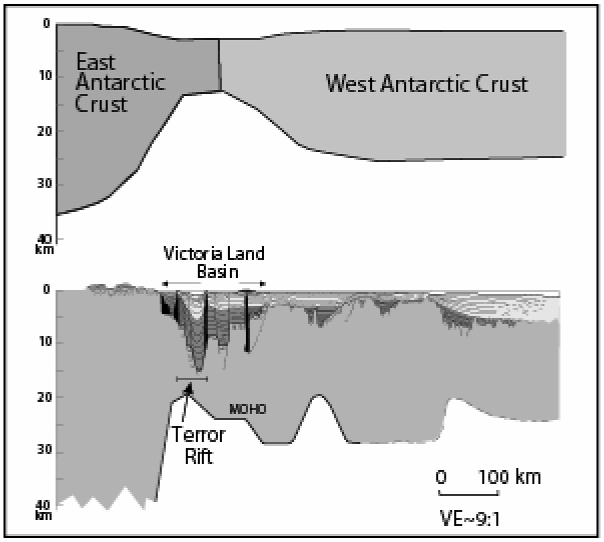


**Figure 3.** Comparison of final results of Huerta and Harry (2007) model and cross section of the WARS (after Busetti et al. (1999). Note general agreement of WARS crustal thinning and late-stage necking in Victoria land Basin.

Our preliminary models show that the model presented by Huerta and Harry (2007) is incapable of producing sufficient melt at the proper time. We have, however, been able to refine the Huerta and Harry model to achieve a reasonable melt production history. We have identified two key alternatives, both of which are consistent with a prolonged period of diffuse extension followed by a rapid transition to focused rifting. 1) By assuming a modestly thinner lithosphere in both East and West Antarctica prior to extension (145 km vs. 180 km and 115 vs. 150 km, respectively) and a slightly higher (but still acceptable) extension rate (9.6 vs. 7.0 mm/yr), the revised model predicts melting to begin after ca. 60 m.y. of extension. This model invokes a mantle potential temperature of 1300 °C, and so does not require the presence of a plume, but most of the melt is confined to the Victoria Land Basin region. 2) The thickness of the East and West Antarctic lithospheres may be similar to those in the Huerta and Harry model, but a modestly higher extension rate (8.3 mm/yr) and significantly higher mantle potential temperature (1380 °C) is required to account for Cenozoic melt production. In this model, melting begins ca. 40 m.y. after the onset of extension and is more widespread than in the previous model. This model is consistent with the presence of a mantle plume, but does not require changes in plate motions to explain the change from diffuse to focused extension that is observed in the WARS.

## Discussion

The preliminary models presented here indicate that a plume is not required to account for the either the change in tectonic style in the WARS, from diffuse to focused extension, or the timing of the onset of magmatism. The models do not, however, rule out the possibility that a plume played a major role, nor do they speak to the possibility that a change from extensional to transtensional motion is important. Our models test a simple hypothesis: can the changes in tectonic style be accounted for without invoking extra-plate processes? The models affirm this hypothesis. Within the range of thermal conditions and extension rates examined, it is plausible that other hypotheses remain viable. Further geodynamic modeling can help to address this issue.

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