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The transition from diffuse to focused extension: Modeled evolution of the West Antarctic Rift system

Audrey D. Huerta [a,*], Dennis L. Harry [b]

[a] Department of Geosciences, Pennsylvania State University, University Park, PA 16801, United States
[b] Department of Geosciences, Colorado State University, Fort Collins, CO 80523-1482, United States

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Abstract

Two distinct stages of extension are recognized in the West Antarctic Rift system (WARS). During the first stage, beginning in the Late Cretaceous, extension was broadly distributed throughout much of West Antarctica. A second stage of extension in the late Paleogene was focused primarily in the Victoria Land Basin, near the boundary with the East Antarctic craton. The transition to focused extension was roughly coeval with volcanic activity and strike–slip faulting in the adjacent Transantarctic Mountains. This spatial and temporal correspondence suggests that the transition in extensional style could be the result of a change in plate motions or impingement of a plume.

Here we use finite element models to study the processes and conditions responsible for the two-stage evolution of rifting in the WARS. Model results indicate that the transition from a prolonged period of broadly distributed extension to a later period of focused rifting did not require a change in the regional stress regime (changes in plate motion), or deep mantle thermal state (impingement of a plume). Instead, we attribute the transition from diffuse to focused extension to an early stage dominated by the initially weak accreted lithosphere of West Antarctica, and a later stage that concentrated around a secondary weakness located at the boundary between the juvenile West Antarctica lithosphere and Precambrian East Antarctic craton. The modeled transition in extension from the initially weak West Antarctica region to the secondary weakness at the West Antarctic–East Antarctic boundary is precipitated by strengthening of the West Antarctica lithosphere during syn-extensional thinning and cooling. The modeled syn-extensional strengthening of the WARS lithosphere promotes a wide-rift mode of extension between 105 and ~65 Ma. By ~65 Ma most of the extending WARS region becomes stronger than the area immediately adjacent to the East Antarctic craton and extension becomes concentrated near the East Antarctic/West Antarctic boundary, forming the Victoria Land Basin region. Mantle necking in this region leads to syn-extensional weakening that promotes a narrow-rift mode of extension that becomes progressively more focused with time, resulting in formation of the Terror Rift in the western Victoria Land Basin.

The geodynamic models demonstrate that the transition from diffuse to focused extension occurs only under a limited set of initial and boundary conditions, and is particularly sensitive to the pre-rift thermal state of the crust and upper mantle. Models that predict diffuse extension in West Antarctica followed by localization of rifting near the boundary between East and West Antarctica require upper mantle temperatures of 730±50 °C and sufficient concentration of heat producing elements in the crust to account for ~50% of the upper mantle temperature. Models with upper mantle temperatures <ca. 680 °C and/or less crustal heat production initially undergo diffuse extension in West Antarctica, and quickly develop a lithospheric neck at the model edge furthest from East

* Corresponding author. Tel.: +1 814 863 3419; fax: +1 814 863 8724.
E-mail addresses: ahuerta@geosc.psu.edu (A.D. Huerta), dharry@cnr.colostate.edu (D.L. Harry).

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Antarctica. Models with upper mantle temperatures >ca. 780 °C do not develop focused rifts, and predict indefinite diffuse extension in West Antarctica.

Keywords: continental extension; rifting; Antarctica

1. Introduction

The Ross Sea region of 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 [1–7]. Geophysical surveys indicate that the early stage of extension in this area accommodated several hundred kilometers of motion across a 750–1000 km-wide region between Marie Byrd Land and the East Antarctic Craton (Fig. 1) [8,9]. In contrast, later extension was primarily accommodated within the Victoria Land Basin located immediately adjacent to East Antarctica [10–12].

This extensional history is significantly different than many other continental rift systems for two reasons. First, most continental rifts (e.g., the East African Rift, Baikal Rift, Rhine Graben, and North American Midcontinent Rift), generally affect a much narrower region (<150 km-wide) than that involved in the early, diffuse phase of extension in the WARS [13–16]. Second, the transition from very broadly distributed extension to focused rifting is unusual. Many narrow rift systems (e.g., the North Atlantic) initially involved deformation over a relatively wide region, but extension in most of these areas became progressively more focused with time. In contrast, in the WARS initial extension was broadly distributed for a prolonged period, and then deformation changed to a distinctly different style of focused extension. The only region of prolonged continental extension over a region of comparable width to the WARS is the Basin and Range province of western North America. However, unlike the WARS, extension in the Basin and Range has not made the transition to focused rifting. In fact, the trend has been the opposite; early (mostly Paleogene) extension in the Basin and Range affected a relatively narrow band of core complexes, whereas later (mostly Neogene) extension was distributed over a much broader region [17–19].

This paper focuses on the transition from prolonged broadly distributed extension to later highly focused rifting in the WARS. In particular, we are interested in determining if intraplate processes can account for the two-stage evolution of the WARS or if extraplate processes (e.g., a change in plate motion directions and/or rates or a change in the mantle thermal state) are required. To this end, we present a series of finite element (FE) simulations that examine how initial and boundary conditions affect the spatial and temporal changes in extensional style. Key variables in the models are the initial geometry and thermal structure of the East and West Antarctic lithosphere. We do not seek to match individual fault bounded rift basin geometries within the WARS. Rather, we seek to reproduce and understand the broad patterns of extension, averaged over length scales of ca. 100 km, and the major temporal changes in the pattern of extension.

Results show that the transition to focused extension occurs only under a narrow range of initial conditions, while the early stage of diffuse extension in the WARS can be produced under a wide range of initial and boundary conditions. The initial thermal structure of the lithosphere is the primary factor that controls whether the model develops a two-stage extensional history that involves a transition from diffuse to focused extension. Specifically, an initial upper mantle temperature of 730 ± 50 °C is required, and heat production in the crust must account for 40–50% of that temperature. The simulations match the geological and geophysical constraints on WARS evolution using constant thermal and mechanical boundary conditions and do not require a change in the tectonic regime (i.e., a change from extension to transtension or impingement of a mantle plume) to recreate the transition from diffuse Mesozoic extension to focused Cenozoic rifting in the WARS [4,20,21].

2. Geologic setting

The WARS is a low-lying region 750 to 1000 km wide situated between Marie Byrd Land and the East Antarctic craton (Fig. 1a). The majority of the WARS lies below sea level. This includes the Ross Sea region, where several N–S striking sedimentary basins (Eastern Basin, Central Trough, and Victoria Land Basin and its extension into the Northern Basin) and basement highs (Coulman High and Central High) provide a record of extension and crustal thinning during the early Late Cretaceous and Paleogene Periods (Fig. 1b) [1–5]. Seismic reflection data shows that a regional Paleogene

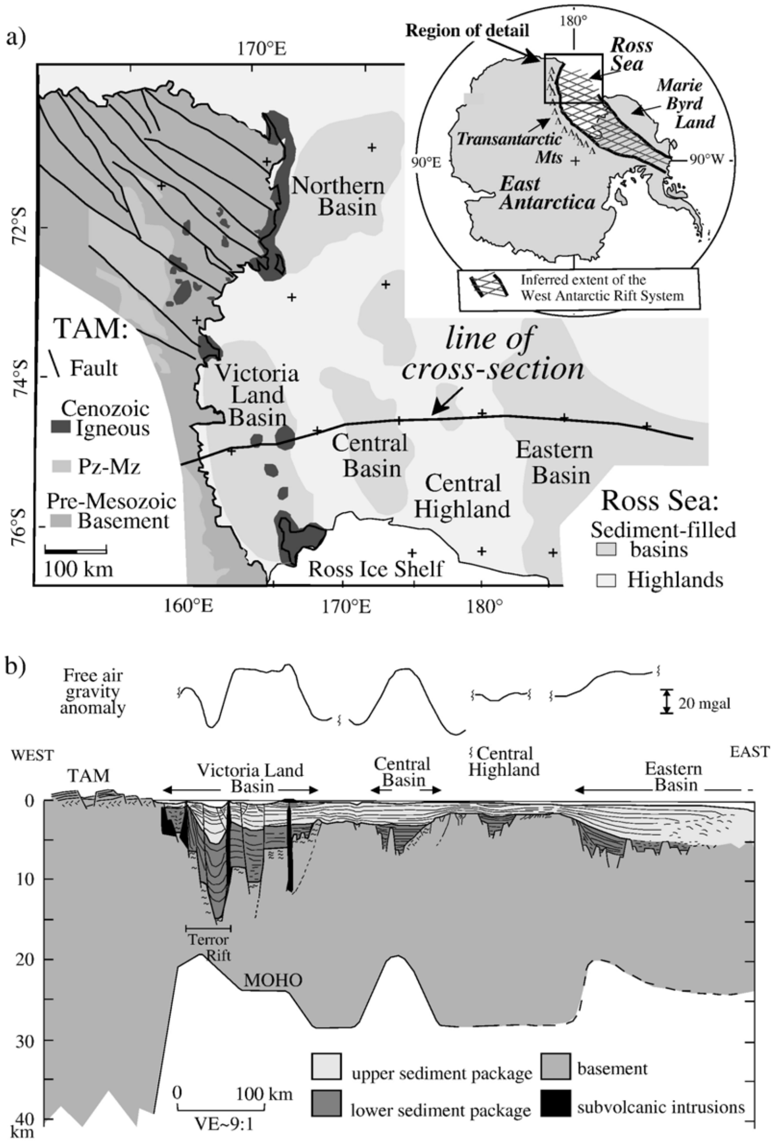

Fig. 1. Antarctic location map and West Antarctic Rift System [22]. a): Map of Ross Sea region of WARS delineating major basins and geology of adjacent East Antarctica and Transantarctic Mountains (TAM). b) Generalized profile across Ross Sea showing early basins and sediment fill ("lower sediment package") overlain by regional unconformity and second ("upper") sedimentary package. Late faults and intrusives deform both sedimentary packages within Victoria Land Basin where pre-rift crust has thinned to ~5 km. Note that in this projection, East Antarctica is to the left of West Antarctica.

unconformity (the U6 unconformity) separates two packages of sediments that infill and overlay the fault-bound basins in the Ross Sea [5,15]. Across much of the Ross Sea, sedimentary rocks below the unconformity are cut by basement-penetrating normal faults, whereas sediments above the unconformity are relatively flat-laying and show only minor faulting [3,5,16,17]. This suggests an early stage of regional extension and infilling followed by a later stage of tectonic inactivity throughout most of the Ross Sea. In contrast, basement penetrating normal faults and syn-rift igneous intrusions in the Victoria Land Basin at the western edge of the Ross Sea cut through the entire sedimentary sequence [16,17]. The stratigraphic data of the Ross Sea therefore is interpreted as representing two stages of extension [5,11,16–18]. Prior to formation of the U6 unconformity extension was broadly distributed throughout the Ross Sea, whereas later extension was focused primarily in the Victoria Land Basin.

Major structural fabrics in the Ross Sea generally trend sub-parallel to the East Antarctica coastline, roughly perpendicular to the extension direction inferred from the basin trends. Consequently, the major features associated with extension can be reasonably represented in two-dimensional cross-section (Fig. 1b). Crustal thickness variations determined from seismic data and gravity modeling studies indicate that the crust has been variably thinned during extension, resulting in the basins and basement highs mentioned above. Depth to the crust–mantle boundary varies from ~16 km within the Victoria Land Basin in the eastern Ross Sea to ~24 km beneath the Central High in the central Ross Sea (Fig. 1b) [22–24]. 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 [1]. The depth to the moho increases to ~39 km under the adjacent Transantarctic Mountains [24–26].

The total amount of extension in the WARS is difficult to determine, but most estimates suggest several hundred kilometers of relative motion between East Antarctica and Marie Byrd Land. Plate reconstructions require in excess of 300 km of extension [6,27–30]. Comparisons of present-day crustal thickness to an assumed original thickness of ~40 km (comparable to the present thickness of East Antarctic crust) suggest 200–500 km of extension within the Ross Sea [1,23,30]. Corresponding extension factors range from $\beta \sim 2$ across much of the WARS to $\beta > 4.0$ in the Terror Rift (β=original crustal thickness/new crustal thickness).

The timing of extension in the WARS is controversial, but is known in broad terms. Prior to ~105 Ma Marie Byrd Land was the overriding plate of a convergent margin [31–33]. There is little evidence for major extension in the Ross Sea region prior to this time [31,33]. An earlier Jurassic phase of transtensional deformation and magmatism in the Transantarctic Mountains may have been associated with strike–slip motion in the Ross Sea [4,34,35], but the main phase of extension in the WARS is generally interpreted to have begun after cessation of subduction at ca. 105 Ma [6,7,9,36–39]. Stratigraphic, thermobarometric, and magmatic data as well as plate reconstruction models indicate that much of the extension in the eastern Ross Sea occurred prior to separation of the Campbell Plateau from West Antarctica at 84–79 Ma [33,38,40,41]. In the western Ross Sea, additional extension occurred in the Paleogene, primarily in the Victoria Land Basin [3–5,11,16]. North of the Ross sea, magnetic lineations within the Adare trough indicate approximately 180 km of extension some time before chron 20 and ending by chron 8 [10]. This represents a period from 46 Ma to 25 Ma [42]. The Adare trough aligns with basins of the western Ross Sea, suggesting that this sea floor spreading was accompanied by continental extension in the western region of the Ross Sea. The timing of extension in the Adare trough compares well with results of the Cape Roberts Drilling Project, where seismic and core data suggest that much of the disrupted sediments (and by association, extension) in the nearby Victoria Land Basin are Eocene through Oligocene [5,11].

The evidence above suggests a tectonic history involving an initial stage of extension across the entire Ross Sea between Marie Byrd Land and East Antarctica between ~105 Ma to ~80 Ma. Oblique transtension may have occurred prior to this, but probably was not part of the major extensional phase [9]. The 105 to 80 Ma stage of diffuse extension resulted in the development of fault-bound basins and uplifts across the northern Ross Sea region. A second stage of extension occurred in Paleogene time and ended by ~26 Ma. This stage of extension was focused primarily within the Victoria Land Basin near the boundary with East Antarctica, and ultimately led to development of the Terror Rift. It is possible that there was an extensional hiatus between 80 Ma and early Paleogene time, but thermomechanical models of subsidence in the large basins of the northern Ross Sea suggest that extension in this area continued throughout the Late Cretaceous [43]. Thus, the simplest model of extension in the Ross Sea is one of continuous extension between 105 Ma and 26 Ma, separated into two distinct stages based on extensional styles. The first stage involved diffuse extension throughout the Ross Sea beginning at 105 Ma and continuing into early Paleogene time. The second stage of extension was more strongly focused, primarily within the Victoria Land Basin, and ended by ca. 26 Ma.

The transition from diffuse to focused extension may be a consequence of other coeval geologic processes recognized in and near the Terror Rift and the adjacent Transantarctic Mountains [5,44,45]. For example, strike–slip faults within the Transantarctic Mountains that post-date normal faulting and associated extensional structures have been used to argue that more focused tectonism during the Paleogene resulted from a transition from an extensional regime to oblique transtension [4,41]. Alternatively, Eocene and younger alkali basalts near and within the Terror Rift [46–48] have been interpreted to suggest impingement of a mantle plume [49,50]. Impingement of this plume on the base of an already thinning lithosphere could have focused extension within the Terror Rift. Here, we test the simpler hypothesis that the transition from diffuse to focused extension is a consequence of the thermal

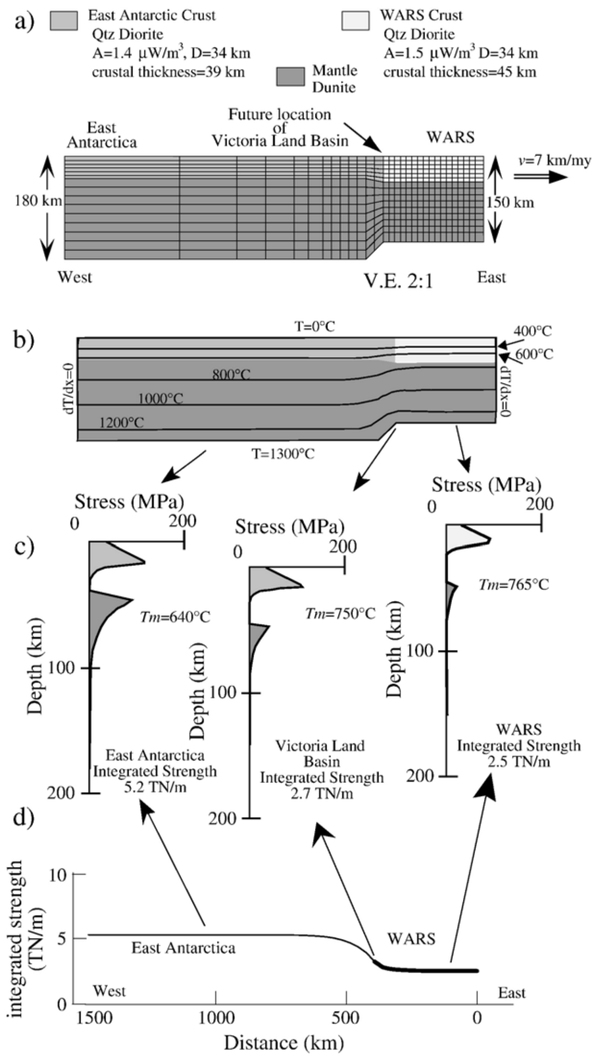

Fig. 2. Finite element model initial and boundary conditions. a) Initial geometry of lithosphere and crust of East and West Antarctica. b) Initial thermal structure. c) Initial vertical strength profiles calculated at a strain rate of 1×10^{-15} s^{-1} of the lithosphere in the East Antarctic craton, near the boundary between East and West Antarctica, and in central West Antarctica. d) Integrated strength of the lithosphere across the model. *Tm* is the temperature at the crust–mantle boundary.

evolution of the lithosphere during extension and does not require changes in plate motion directions or rates or changes in asthenosphere thermal conditions.

3. Numerical model

In this paper we explore the processes and conditions responsible for the transition from diffuse extension to focused extension. Specifically we ask the question "does this transition require changing boundary conditions (i.e. change to oblique extension, impingement of a plume), or is there a set of initial and constant boundary conditions that inherently result in the transition from diffuse to focused extension?" To answer this question, we use a finite element modeling method to dynamically simulate the extensional evolution of the Antarctic lithosphere. Since the model is dynamic, the strength, strain field, and thermal structure of the model evolve naturally in response to the initial and boundary conditions. The models examined here are similar in design and behavior to those examined by Bassi et al. [51], however, we explicitly address the question of transition from diffuse to focused extension as observed in the West Antarctic Rift system.

3.1. Modeling method

The FE model represents a simple two-layer lithosphere composed of quadrilateral elements (Fig. 2a). Elements within the crust are assigned rheologic properties of a diorite composition, while elements within the lithospheric mantle are assigned properties of a dunite composition (Table 1). The FE algorithm uses an iterative time-stepping technique that first solves for the strain rate and the effective viscosity in the model according to the Navier–Stokes equation for a nonlinear visco-plastic medium [52,53]. At each time step the mode of deformation of each element is determined dynamically such that each element fails by the weaker of either a pressure dependent brittle failure criterion (typically under conditions of high stress and low temperature) [54], or by power-law ductile creep (at higher temperature conditions) [55]. After the calculated strain is applied to each element, the transient heat equation is solved to determine temperatures throughout the model at the new time step.

The model is started in thermal steady state with a constant temperature boundary condition of 0 °C at the surface. On the sides, an insulator boundary condition is applied ($\mathrm{d}T/\mathrm{d}x=0$). Most models use a 1300 °C constant temperature boundary condition at the base of

Table 1
Rheologic parameters

	Crust	Mantle
Viscous rheology [a]		
A, s^{-1} Pa^{-n}	5×10^{-18}	4×10^{-25}
Q, kJ mol^{-1}	219	498
n	2.4	4.5
ρ, kg m^{-3}	2850	3300
Plastic rheology [b]		
S, MPa	60	60
B, MPa km^{-1}	11	11

[a] $\sigma=[\dot{\varepsilon}/A]^{1/n}e^{Q/nRT}$ [48].
[b] $\sigma=S+Bz$ [47].

the lithosphere (Fig. 2b). The importance of this boundary condition and alternative conditions are discussed in Section 6. In all simulations a constant velocity of 7 km/Myr is applied to the right (West Antarctica) side of the model for 80 m.y. This leads to a total of 560 km of extension between Marie Byrd Land and East Antarctica, consistent with estimates of the duration and total amount of extension.

3.2. Parameter testing

To understand the extensional history of West Antarctica we explore the evolution of a range of initial mesh geometries and model parameters (Table 2). Our intent is to identify the parameter space compatible with the two-stage extensional history of West Antarctica. In all simulations, the East Antarctic craton is modeled with a relatively thick lithosphere (varying between 180 and 280 km in different simulations) consistent with teleseismic studies [56–58], a crustal thickness of 39 km [24] and a range of crustal heat production rates consistent with continental crust (varying between 1.1 to 1.4 μW/m^3 in different simulations; [59]). For the initial structure of West Antarctica we explore a range of geometries consistent with lithospheres of accreted regions. These include a range of relatively small (in comparison to East Antarctica) lithospheric thicknesses (varying between 120 and 220 km), relatively large crustal thicknesses (either 39 or 45 km), and crustal heat production rates varying from .75 to 2.0 μW/m^3 [59]. Since the thermal structure plays such a critical role in the evolution of the models, we specifically explore the impact of varying the thermal parameters. In particular, we investigate the impact of the distribution of heat production in the crust and the thermal boundary condition at the base of the lithosphere. For simplicity, we prescribe a uniform distribution of heat production within a layer of finite thickness in the crust in most of the models because this allows us to i) easily specify the upper mantle temperature in the model, which is a key variable, and ii) directly compare the effects of models in which heat production is confined to shallow portions of the crust vs. models that include deep crust heat production. A few models were also investigated in which heat production decreases exponentially with depth (e.g., 50 km) to assess the extent to which model behavior is dependent on the details of how heat producing elements are distributed.

Within the parameter space tested, all simulations predict diffuse extension throughout West Antarctica during the initial phase of extension. However, the Paleogene transition from diffuse to focused extension is replicated in only a limited subset of the parameter space. Simulations that capture the transition from diffuse to focused extension near the boundary with East Antarctica are all characterized by an initial upper mantle temperature of ~730±50 °C beneath West Antarctica. The general form of model behavior is relatively insensitive to details of how heat producing elements are distributed in the crust as long as the upper mantle falls within this temperature range and crustal heat production accounts for ca. 40–50% of the temperature at the base of the crust (the remaining contribution to the temperature at the base of the crust comes from heat conducted from the asthenosphere). Under these conditions, all models predict a transition from diffuse to focused extension. However, within this class of simulations there are significant variations in the timing and location of extension focusing. All simulations that predict focusing of extension at the location of the Terror Rift during the Eocene require only moderate heat flux from the asthenosphere underlying the WARS (<ca. 20 mW m^{-2}) [60].

3.3. The best-fit model for West Antarctica

The model that best matches the geologic evolution of the Ross Sea region of West Antarctica begins with an East Antarctica structure of 180 km thick lithosphere, 39 km thick crust, and a crustal heat production rate of 1.4 μW/m^3 distributed evenly in a 34 km thick layer (resulting in a surface heat flow of 62 mW/m^2, consistent with estimated heat flow values of East Antarctica) [61]. The pre-extension thickness of the model lithosphere in

Table 2
Thermal parameters and mesh geometry[a]

Thermal parameters	WARS	EA
Crust		
H_0, Crust heat production, μW m^{-3}	.75 to 2.0	1.1 to 1.4
D, Thickness of heat producing layer, km	10–45	10–40
Thermal Conductivity, W m^{-1} °C^{-1}	2.5	2.5
Specific heat, J kg^{-1} °C^{-1}	875	875
Coefficient of thermal expansion, °C^{-1}	3.1×10^{-5}	3.1×10^{-5}
Mantle		
Heat production, μW/m^3	0	0
Thermal Conductivity, W m^{-1} °C^{-1}	3.4	3.4
Specific heat, J kg^{-1} °C^{-1}	1250	1250
Coefficient of thermal expansion, °C^{-1}	3.1×10^{-5}	3.1×10^{-5}
Initial layer thickness		
Crust, km	39 to 45	39
Lithosphere, km	120 to 220	150 to 280

[a] Surface heat production and crust and lithosphere thickness were varied in different models between the ranges given.

West Antarctica is 150 km, and the crust thickness is 45 km. These are consistent with the accretionary history of the region, restorations of crustal thickness, and evidence of elevated topography and thicker than normal crust [30,62,63]. The upper 34 km of the West Antarctica crust has a heat production rate of 1.5 μW/m^3, which is within the range of intermediate composition magmatic rocks that are typical of both upper continental crust and volcanic arc andesites and diorites [59]. This results in a surface heat flow of 71 mW/m^2 prior to extension, which is similar to global average heat flow values for Phanerozoic continental crust [64].

Vertical strength profiles illustrate the combined effects of the initial model geometry and thermal structure on the strength of the lithosphere (Fig. 2). In East Antarctica the combination of a thick lithosphere and cool upper mantle (642 °C) result in a strong lithosphere (5.2 TN/m) in comparison to the relatively warmer and weaker West Antarctica (762 °C, and 2.5 TN/m). The strength of the lithosphere decreases monotonically across the transition from East to West Antarctica due to both the higher temperature of the upper mantle and the decreased thickness of the lithosphere in West Antarctica (Fig. 2d). The relatively warm temperature at the top of the modeled mantle in West Antarctica in comparison to East Antarctica is the result of greater heat generation in the crust and thinner lithospheric mantle assigned to West Antarctica.

4. Model results

Figs. 3 and 4 display the results of the simulation of the two-phase extensional evolution of the WARS over a 80 m.y. period from ~105 to 25 Ma (we use m.y. to signify time, and Ma to signify age). During the first 20 m.y., extension is distributed throughout the WARS (Figs. 3a–b and 4a–b). After 20 m.y. (***t***=85 Ma) 140 km of extension is accommodated, primarily in West Antarctica (−140<×<410 km in model coordinates) where the crust has thinned from an initial thickness of 45 km to 32 km (β~1.4). The amount of crustal thinning decreases abruptly near the boundary with East Antarctica, where the crust has thinned only slightly (β~1.0).

As the model evolves, extension continues within the WARS region, and by ***t***=65 Ma the WARS is 677 km wide (Fig. 3c). The thickness of the crust throughout the WARS region has decreased to ~25 km (β~1.8), and crustal thickness increases smoothly toward the East Antarctic boundary. Extension is beginning to become localized in the Victoria Land Basin near the West Antarctic/East Antarctic boundary at this time (Fig. 4c).

By ***t***=45 Ma the locus of maximum crustal extension is mostly confined to the Victoria Land Basin region

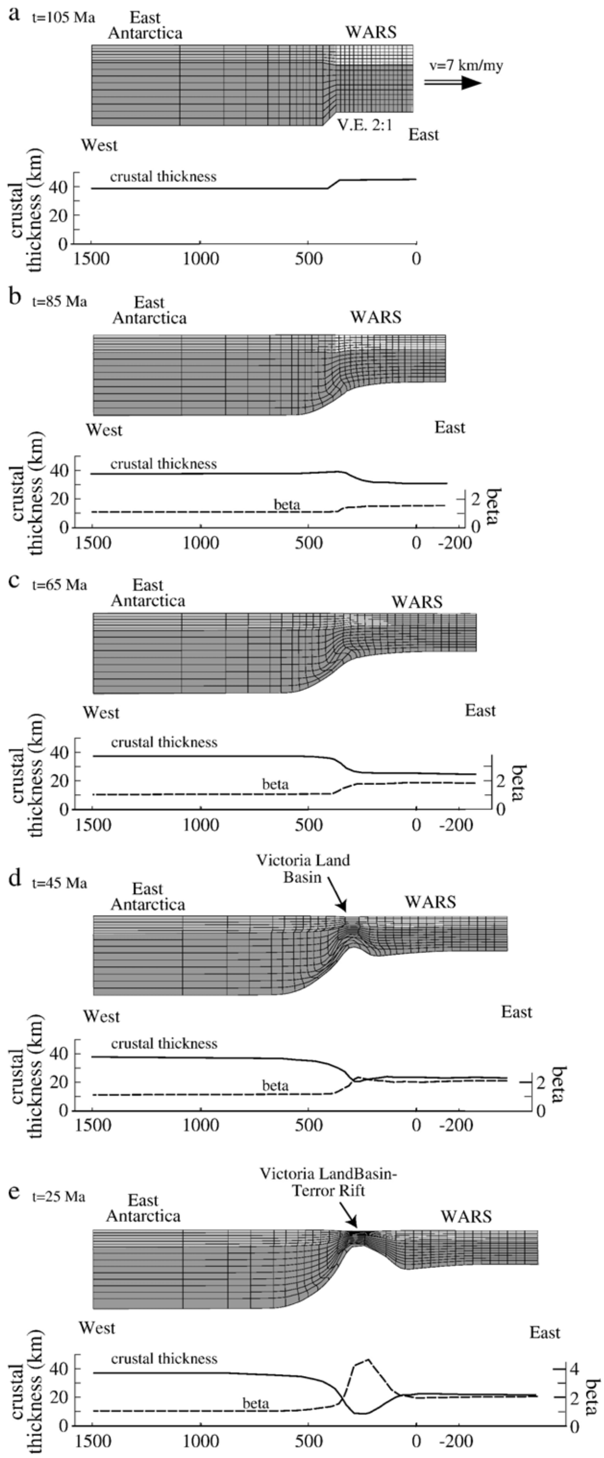

Fig. 3. Evolution of model geometry, crustal thickness and extension factor β during 80 m.y. of extension. Note diffuse extension throughout WARS region during first 40 m.y. and focused extension near boundary with East Antarctica afterward.

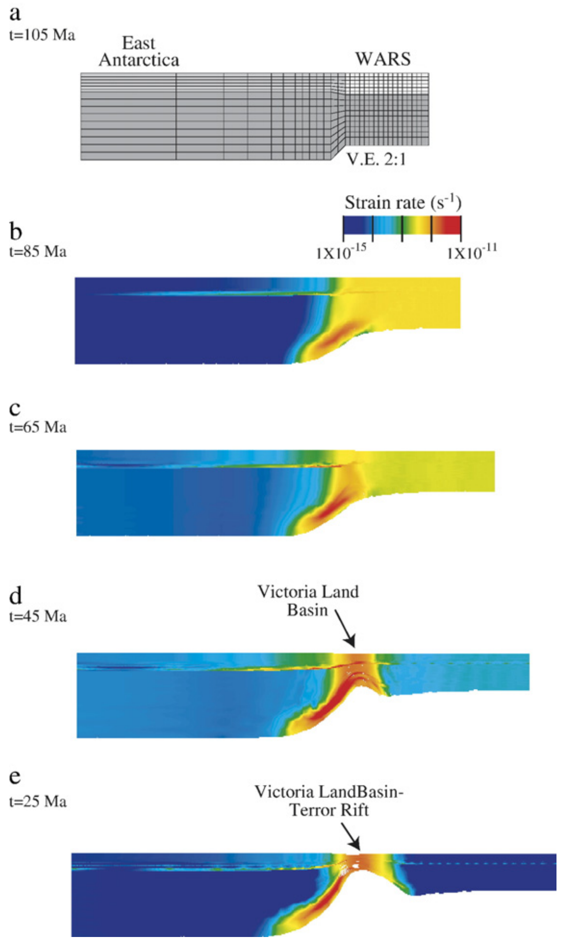

Fig. 4. Second invariant of strain rate in the model. Warm colors indicate rapid strain rate, cool colors slow strain rate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 4d). The crust in this region has thinned to ~20 km (β~2.3) and incipient lithospheric necking has raised the bottom of the lithosphere to a depth of ~80 km (Fig. 3d). The eastern and central region of the WARS have not experienced any significant extension since ~65 Ma, and the thickness of the crust in these regions has remained at ~24 km (β~1.9).

By t=25 Ma, crustal thinning has strongly focused in a narrow region near the boundary with East Antarctica (Fig. 4e), and the lithosphere shows pronounced necking (Fig. 3e). The crust here has thinned to ~9 km (β~4.5), and the thickness increases smoothly toward the central WARS, where it has remained relatively unchanged since 65 Ma. A total of 487 km of extension has been accommodated within the WARS, which is now 897 km wide.

This modeled extensional evolution generally matches the geology of the WARS both spatially and temporally (Table 3). In particular the model predictions match the spatial constraints of the regionally averaged crustal thickness across the WARS, the crustal thickness in the Terror Rift, the width of the Victoria Land Basin, and the location of maximum thinning near the boundary with East Antarctica (Fig. 5). The modeled temporal evolution matches the observed evolution of Cretaceous diffuse extension in West Antarctica followed by Paleogene focused extension in Victoria Land Basin and late Paleogene formation of the Terror Rift. The modeled upwelling asthenosphere in the Victoria Land Basin/Terror Rift would begin to undergo decompression melting once it ascends to ca. 80 km depth [65]. In the model this occurs at approximately 35 Ma, consistent with the onset of rift-related magmatism in the Terror Rift region [39–43].

5. Processes controlling location and modes of extension

The modeled extensional history evolves in regards to both the location of extension (migrating from the WARS to the Terror Rift), and the mode of rifting (changing from diffuse to focused). We first address the controls on location of extension, and then we address the controls on the mode of rifting.

5.1. Location of extension

Consideration of the initial temperatures within the model leads to a straightforward understanding of the reasons that extension is initially distributed throughout West Antarctica. Temperatures throughout the West Antarctic crust and lithospheric mantle prior to extension are higher than in East Antarctica, making the West Antarctic region the weakest part of the model (Fig. 2). As discussed earlier, these higher temperatures are a result of greater heat generation in the thicker crust, and thinner lithospheric mantle of West Antarctica.

To better understand the processes that lead to the transition to focused extension near the East Antarctic boundary, we look in detail at the strength of the model

Table 3
Comparison of model and observations

	Model	Observed
Period of extension, Ma	105–25	105–26
Onset of focused rifting	~65 Ma	Paleogene
Width of WARS, km	900	700–1000
Width of Victoria Land Basin, km	~250	~180
Thickness of WARS crust, km	23–25	16–21
Thickness crust in Terror Rift, km	9	4
WARS extension factor β	1.9–2.0	~2
Terror rift extension factor β	4.5	>4.0

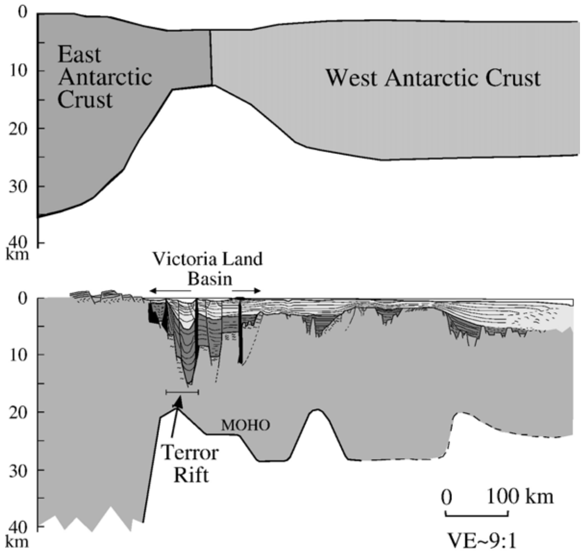

Fig. 5. Detail of modeled crustal geometry after 80 m.y. of extension (top) compared to current crustal geometry of Ross Sea and adjoining East Antarctica (bottom; after [22]). (TAM = Transantarctic Mountains).

lithosphere at $t=65$ Ma, just as extension moves to the Victoria Land Basin region (Fig. 6). At this time the vertically integrated strength of the lithosphere across much of the WARS has increased from an initial strength of 2.5 TN/m to 2.6 TN/m (Fig. 6b, c). The strength of the Victoria Land Basin region adjacent to East Antarctica has decreased slightly from 2.7 to 2.4 TN/m. Thus, by 65 Ma the weakest lithosphere is near the boundary with East Antarctica and thinning moves to this region.

What causes the lithosphere to strengthen across the eastern and central WARS region as extension progresses? Inspection of the strength profiles at $t=65$ Ma reveals that much of the strength of the lithosphere is in the upper portion of the mantle, and by 65 Ma this region is relatively strong across the WARS (Fig. 6b). This increase in strength is due to the cooling of the upper mantle. In central WARS the temperature at the top of the mantle is now <650 °C, much cooler than the initial temperature of ~765 °C (Fig. 6b, d). Cooling of the upper mantle across the WARS region primarily results from thinning of the crust and the corresponding reduction of the total amount of radiogenic heat generated by the crust. Thus, during the early stage of diffuse extension, cooling of the upper mantle across the West Antarctic region progressively strengthens the lithosphere.

Why does the strength of the lithosphere near East Antarctica remain relatively constant? The initial strength of lithosphere near East Antarctica is slightly higher than the strength across the rest of WARS (2.6 TN/m versus 2.5 TN/m; Fig. 6c). This is because the strength profile in this region is transitional between the initially warm and thin West Antarctic lithosphere and the initially cooler and thicker East Antarctic lithosphere. Since this region is relatively strong in comparison to most of the WARS, there is minimal extension here during the early stages of rifting. Consequently, there is little lithospheric (or crustal) thinning, and the thermal structure and strength in this

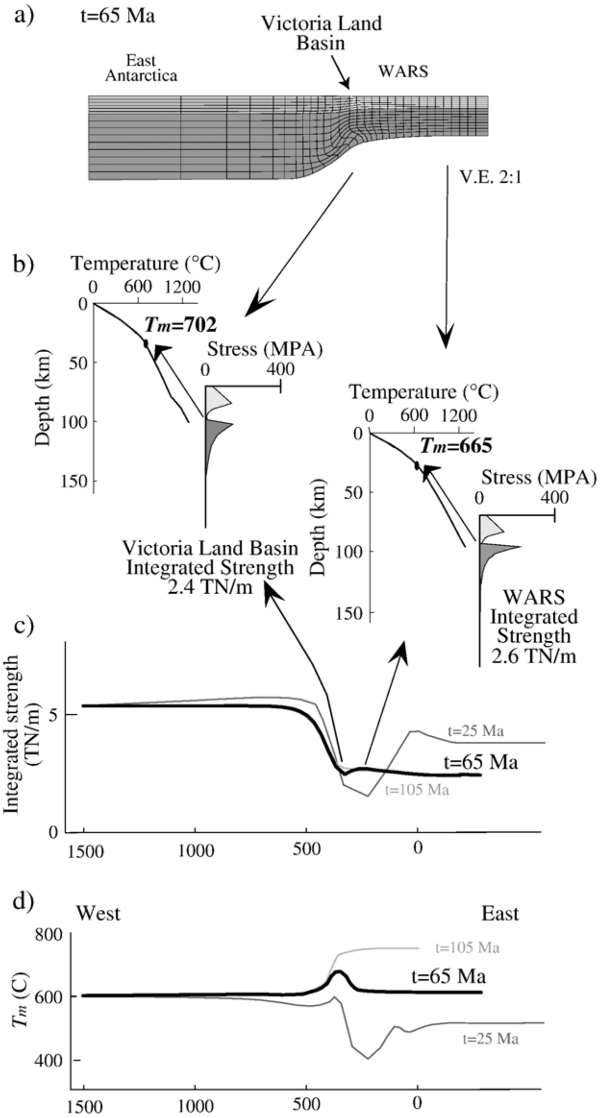

Fig. 6. Modeled thermal structure and strength of lithosphere at 65 Ma, during transition from diffuse extension to focused extension. a) Model geometry b) vertical strength profiles and thermal structure of lithosphere near boundary between East and West Antarctica and in WARS c) integrated strength across East Antarctica and WARS at 105 Ma (light gray), 65 Ma (black), and 25 Ma (grey). d) Temperature at the top of the mantle at 105 Ma (light gray), 65 Ma (black), and 25 Ma (grey).

region does not change during the first 40 m.y. of extension. By $t=65$ Ma, syn-extensional cooling of the central WARS leaves the unextended region near East Antarctica as the warmest and weakest part of the lithosphere, resulting in migration of extension from the central WARS into the Terror Rift region.

5.2. Modes of extension

To explore the tendency of the model to undergo diffuse vs. focused extension we examine in detail the evolving strength of the model lithosphere and the force required to deform it. The total horizontal force, $\boldsymbol{F}$, needed to extend the lithosphere at a given location must be greater than the sum of the vertically integrated yield stress, $\boldsymbol{F}_{ys}$, and the gravitational deviatoric stress, $\boldsymbol{F}_{bf}$, such that

$$\mathbf{F} \geq \mathbf{F}_{ys} + \mathbf{F}_{bf}.$$

Comparing $\boldsymbol{F}$ in different portions of the model provides an indication of where and how deformation is most easily accommodated. Buck [66] argued that the difference between the total force needed to stretch extended versus unextended portions of the lithosphere, $\mathrm{d}\boldsymbol{F}$, indicates whether a wide or narrow mode of rifting is favored. When $\mathrm{d}\boldsymbol{F}<0$ the lithosphere becomes easier to deform as extension progresses, so rifting remains focused in the same location and a narrow rift zone develops. On the other hand, when $\mathrm{d}\boldsymbol{F}>0$ the net force required to extend the lithosphere increases with extension, making the extending location progressively more difficult to deform. This promotes a shift in deformation into an adjacent unextended region, and a wide rift zone develops.

In the finite element model examined here the strength of the lithosphere varies dynamically in both time and space. Accordingly, a straightforward comparison of the strengths of extended and unextended lithosphere (e.g., [56]) cannot be used to determine whether extension remains focused (narrow rift mode) or is diffuse (wide rift mode). Instead, we track the values of $\boldsymbol{F}$ across the model domain through time to determine the weakest location, and then determine whether the net force to extend this location increases or decreases with time (resulting in diffuse or focused rifting, respectively). Fig. 7a shows the net force required to deform the lithosphere in the WARS and in the Victoria Land Basin region as a function of time, while Fig. 7b shows the rate of change of the total force required to extend the lithosphere, $\mathrm{d}\boldsymbol{F}/\mathrm{d}\boldsymbol{t}$, in these two regions. When $\mathrm{d}\boldsymbol{F}/\mathrm{d}\boldsymbol{t}>0$, the net force increases with time, promoting a shift in extension to another location, and thus favoring a wide rift mode of extension. When $\mathrm{d}\boldsymbol{F}/\mathrm{d}\boldsymbol{t}<0$, the net force required to extend the lithosphere decreases with time, promoting a narrow mode of rifting.

During the first 40 m.y. ($t=105$ to 65 Ma) West Antarctica requires the least amount of force to deform (Fig. 7a). Extension occurs in the eastern and central WARS and relatively little deformation occurs near the East Antarctic/West Antarctic boundary, in agreement with the pattern of crustal thinning shown in Fig. 3. The WARS is in a wide rift mode ($\mathrm{d}\boldsymbol{F}/\mathrm{d}\boldsymbol{t}>0$, Fig. 7b) during this period, and the most easily extended region shifts around within the WARS in response to syn-extensional cooling [62].

Syn-extensional cooling increases the strength of the WARS lithosphere during the first 40 m.y. By ~65 Ma a smaller net force is required to deform the Victoria Land Basin than the WARS (Fig. 7a), favoring abandonment of the WARS as an extensional province and concentration of extension in the Victoria Land Basin. At this time, the Victoria Land Basin is a narrow mode of rifting ($\mathrm{d}\boldsymbol{F}/\mathrm{d}\boldsymbol{t}<0$) and becomes increasingly so with time (Fig. 7b). Consequently, extension and crustal thinning become progressively more focused in the Victoria Land Basin after this time (Fig. 3), resulting in formation of the Terror Rift.

Once extension begins to focus in the Victoria Land Basin region there is a positive feedback in the strength evolution as the lithosphere is thinned and warmed from

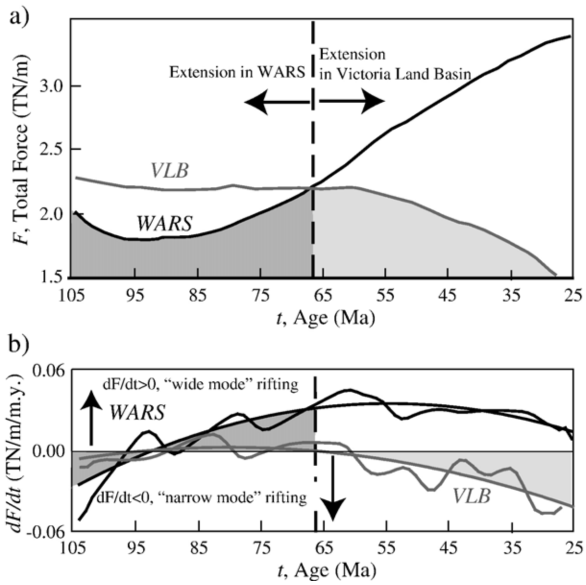

Fig. 7. Change in force required to drive extension in the model. a) Total force required to deform the lithosphere. b) Rate of change in total force required to deform the lithosphere. Positive indicates strengthening, a mode of deformation favoring diffuse extension. Negative indicates weakening, a mode of deformation favoring focused extension. Irregular lines are model results that include numerical noise. Smooth lines are best fit second order polynomial curves that better represent long-term evolution of lithosphere strength.

the upwelling mantle, and strain becomes restricted to an ever-decreasing cross-sectional area as the lithosphere thins. Thus, once lithospheric necking in the Victoria Land Basin region begins, no further shifts in the loci of extension are expected.

6. Parameter sensitivity and other modeled extensional evolutions

The model described above represents one of three distinct classes of deformational evolution observed in the suite of finite element models that we examined. The three classes are:

i) models that undergo a significant amount of diffuse extension in West Antarctica followed by focused extension at the boundary between East and West Antarctica,
ii) models that undergo diffuse extension in the WARS region throughout the entire simulation and do not develop a later stage of focused rifting, and
iii) models that undergo a short-lived phase of diffuse extension followed by focusing on the right-hand boundary of the model domain (farthest away from the boundary between East and West Antarctica).

In this section, we briefly examine how robust our preferred model is, and how sensitive the basic model behavior is to changes in key model parameters. Model behaviors similar to ii) and iii) have been studied in detail by Bassi et al. [44].

6.1. Other extensional evolutions

Fig. 8 displays examples of the three modes of extensional evolution; protracted diffuse extension followed by focused extension at the boundary with East Antarctica (Class i), protracted diffuse extension that continues indefinitely (Class ii), and a short period of diffuse extension followed by focused extension at the right-hand boundary (Class iii). All examples have identical initial geometries and boundary conditions, but with different initial thermal conditions.

The primary factors that control the style of extension are the initial temperature at the top of the WARS mantle and the relative importance of crustal heat production and asthenospheric heat flow in controlling the upper mantle temperature. All models examined with intermediate initial mantle temperatures in West Antarctica (between ca. 680 °C and 780 °C) behave similarly to the preferred model (Fig. 8, Class i) as long as crustal heat production accounts for 40–50% of the temperature of the upper mantle. In these cases, thinning of the WARS crust results in a decrease in upper mantle temperature and an increase in lithospheric strength that promotes an initial prolonged history of diffuse extension in West Antarctica. Eventually, the region near East Antarctica becomes the weakest, and the locus of extension shifts to this area. Because this relict weak area is relatively narrow, extension is highly focused once it begins in this region, leading to rapid mantle necking and the onset of focused rifting near the boundary between East and West Antarctica.

All models that exhibit continuous diffuse extension (Fig. 8, Class ii) have high initial temperatures at the top

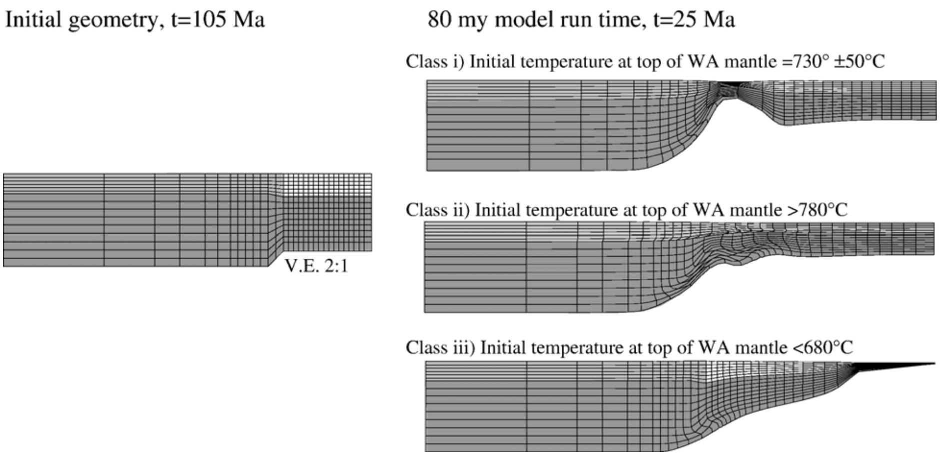

Fig. 8. Different styles of deformation observed in various models. Class i models undergo a diffuse stage of extension in WARS followed by a later stage of focused rifting in the Victoria Land Basin. Class ii models undergo prolonged diffuse extension without focusing. Class iii models rapidly develop and end-neck at the edge of the model domain.

of the mantle (>780 °C). Within the range of lithosphere thicknesses examined this requires a relatively large crustal heat production that accounts for >ca. 50% of the upper mantle temperature. In these cases, the warm upper mantle initially results in an extremely weak lithosphere in the WARS. The lithosphere strengthens slightly during extension, but the high heat production keeps the WARS weaker than other parts of the model, so extension is diffusely accommodated across this region. In the example shown (Fig. 8, Class ii), we assigned a thick initial heat producing layer in the crust that extends to 45 km depth, resulting in an initial temperature at the top of the mantle of 790 °C and a very weak WARS lithosphere (1.7 TN/m). Throughout the modeled 80 m.y. extensional history, lithospheric thinning is distributed across the WARS region and extension does not focus.

Simulations that result in focusing of extension on the right-hand boundary (Fig. 8, Class iii) have initial temperatures at the top of the mantle of <~680 °C. Within the range of lithosphere thicknesses examined, crustal heat production contributed less than 40% of the upper mantle temperature in these models. During extension, the temperature of the upper mantle is dominated by heat conducted from the ascending asthenosphere (represented by the 1300 °C temperature boundary condition). Hence, thinning results in warming and weakening, conditions that promote focusing of extension. Since the region near the East Antarctic boundary has thicker and stronger lithosphere, extension focuses at the far edge of the model domain. In the example shown (Fig. 8, Class iii), the crustal heat production decays exponentially with depth with a decay constant of 34 km, resulting in a cool upper mantle with an initial temperature of 660 °C, and a strong WARS lithosphere. (4.6 TN/m). Early in the evolution, extension is accommodated across the WARS region, but strain quickly localizes on the right-hand boundary.

6.2. Effect of the basal thermal boundary condition.

Because the thermal state of the lithosphere plays such an important role in controlling the style of deformation, we further consider the basal thermal boundary condition used in the model. The models described above all use a constant temperature boundary condition at the base of the lithosphere. This minimizes cooling of the lithosphere during extension, promoting progressive localization of extension once necking begins to focus [e.g., 44]. We examined two alternative boundary conditions: a constant heat flux boundary condition, (which maximizes cooling of the mantle lithosphere during extension) and a basal temperature prescribed by adiabatic cooling of the upwelling lithosphere/asthenosphere boundary (which moderately cools the lithospheric mantle during extension). In our constant heat flux simulations, we fix heat flow at the base of the lithosphere to be equal to the initial heat flux of our preferred simulation (18 mW m^{-2} in West Antarctica to 16 mW m^{-2} in East Antarctica). The adiabatic model begins with a temperature of 1300 °C at the base of the lithosphere, and reduces the temperature on this boundary by 0.3 °C km^{-1} as it ascends [57].

Neither of the alternative boundary conditions produces models that behave substantially differently than those shown in Figs. 3 and 8. In each case the timing of events vary slightly, but the style of extension remains the same. Specifically, models with initial temperatures of 730±50 °C at the top of the WARS mantle display prolonged WARS extension followed by focused necking in the Victoria Land Basin, regardless of the basal thermal boundary condition. The lack of a significant affect on model behavior by the basal thermal boundary condition is attributed to the relatively large amount of heat production in the crust. This causes crustal thinning and cooling to dominate the thermal evolution of the strong parts of model (the crust and upper mantle) during extension, with the basal thermal boundary condition playing a relatively minor role. Likewise, models with initial conditions similar to Class ii and Class iii simulations produce indefinite extension in the WARS or end-necking, respectively, regardless of the basal thermal boundary condition.

6.3. Other parameters

The simulation in Fig. 3 is from the class of models that displays a significant amount of diffuse extension followed by focused extension near the boundary between East and West Antarctica. The specific parameters used for this simulation are those that best fit the timing, magnitude, and location of strain migration particular to the WARS. While all simulations of this class have similar temperatures at the base of the WARS crust (730±50 °C), the choice of crustal heat generation in WARS and East Antarctica exert primary control on the exact location and timing of focused extension. Higher heat production in the WARS crust delays focusing. Lowering the heat production in East Antarctica crust results in a relatively cool and strong lithosphere at the boundary between East and West Antarctica, causing extension to focus away from the boundary in the central WARS. Different choices of initial lithosphere and crust thickness and changes in the geometry of the boundary between East and West Antarctica have similar affects, changing the details of timing of events and amounts and distribution of extension, but they do not change the fundamental behavior of the model for a given upper mantle temperature.

7. Conclusions

The finite element model shown here demonstrates that the transition from diffuse to focused extension as observed in the Ross Sea region of West Antarctica can result from intraplate processes and the natural dynamic evolution of the rift system under constant regional extension rates and deep mantle thermal conditions. It is not necessary to call on either changes in plate motions or mantle thermal flux (e.g., impingement of a plume) to change the extensional style from diffuse extension during Late Cretaceous to middle Paleogene time to focused rifting beginning in the late Paleogene.

The finite element model indicates that distributed extension throughout West Antarctica between 105 and ~65 Ma can arise from an initially warm and weak lithospheric structure. In the models, thinning of the crust and the associated reduction of heat generation causes cooling of the upper mantle and strengthening of the extending WARS lithosphere. This results in a wide mode of rifting across West Antarctica during this time. By 65 Ma most of the modeled WARS becomes strong enough to restrict extension to the Victoria Land Basin region near the East Antarctic boundary. Confinement of extension within this narrow region causes strain weakening of the lithosphere in this area, favoring a progressively narrowing mode of rifting and development of the Terror Rift. This focusing of extension creates a positive feedback effect that promotes progressive localization of rifting that continues until extension ceases in the late Paleogene period.

There is a distinct suite of models that predict a transition from diffuse to focused extension. These models all begin with an initial upper mantle temperature of ~730±50 °C beneath West Antarctica with sufficient crustal heat production to account for 40–50% of the mantle temperature. Simulations with a cooler upper mantle (less heat from the crust) rapidly develop focused rifting at the edge of the model domain. Simulations with high upper mantle temperatures (greater heat production in the crust) experience a much longer stage of diffuse extension and do not evolve into a focused rift. These results again emphasize the importance of crustal heat production in the deformational evolution of continental lithosphere [e.g., [67–69].

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