A Multi-Phase Rifting Model for the Victoria Land Basin, Western Ross Sea

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Abstract. The Victoria Land Basin is a deep rift margin basin that lies along the Ross Sea margin of the Transantarctic Mountains, Antarctica. Seismic data indicates that the 140 km wide basin contains some 14 km of sediments. Drilling results from the flank of the basin suggests that most of these sediments are late Eocene or younger in age. Four major sequences are defined on the seismic data by angular unconformities indicating several rift episodes. Constraints on the basin formation are derived using flexural cantilever models. The model reproduces the main features (shape, size, timing and broad stratigraphy) of the basin formation moderately well using four rift episodes on five main faults, but does not match the detailed geometry of the seismic stratigraphy.

Introduction

The Transantarctic Mountains (TAM) are a major morphological feature of Antarctica, stretching for about 3 500 km across Antarctica, and with elevations of over 4 500 m (Fig. 6.3-1). They form the major geological boundary in Antarctica, considered to be a rift margin that separates the older, Precambrian craton of East Antarctica from the younger, more geologically active West Antarctica (e.g., Tessensohn and Wörner 1991). This major discontinuity is also reflected by a sharp change in the upper mantle velocity structure, which shows a high seismic velocity upper mantle under East Antarctica and a low velocity, inferred warmer, mantle under West Antarctica (Danesi and Morelli 2000). The Victoria Land Basin (VLB), a deep rift basin, lies along a 300 km long segment of the TAM in southwest Ross Sea (Fig. 6.3-1). The VLB contains up to 14 km of sediments, which were initially considered to comprise two main units approximately equal in thickness, one unit inferred to be of late Cretaceous age and the other of late Cenozoic age (Cooper et al. 1987). Recent drilling on the west flank of the TAM, however, suggests that the age of most of the sediments is late Eocene or younger (Wilson et al. 1998; Florindo et al. 2001). Reflection seismic data across the southern part of the VLB (Fig. 6.3-2a) have been interpreted to show that the section consists of four major sedimentary packages separated by distinct angular unconformities (Fig. 6.3-2b) (De Santis et al. 2001), indicating several episodes of extension. Several authors have attempted to model the broad features of the rift margin using simple flexural cantilever models (e.g., Stern and ten Brink 1989) and pure shear (e.g., van der Beck et al. 1994; Busetti et al. 1999). However, poor age control has limited the models. In addition, the relatively well defined geometry of the seismic stratigraphy has not been used to constrain rift models. The recent Cape Roberts project (CRST 2000; Florindo et al. 2001) and re-evaluation of the CIROS core in western McMurdo Sound (Wilson et al. 1998) provides significantly more accurate age control for the formation of the basin. In this paper we present initial results of using the flexural cantilever model (Kuznir and Ziegler

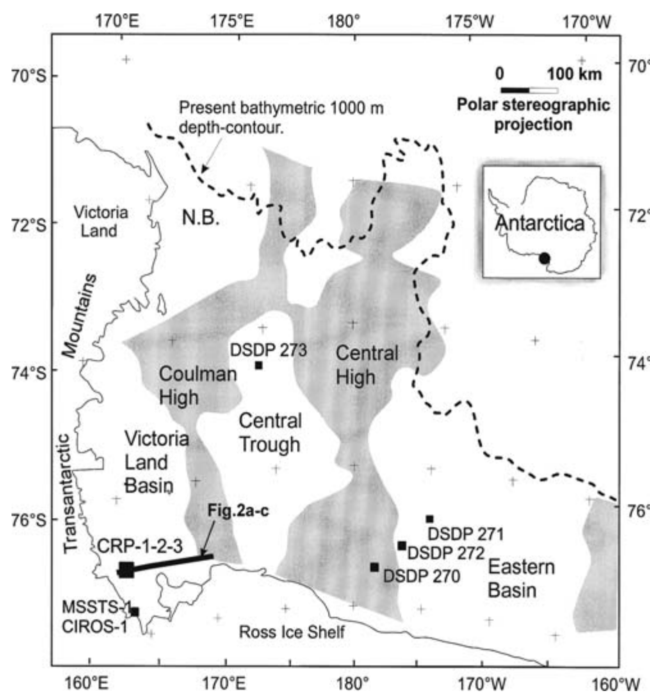

Fig. 6.3-1. Ross Sea, Antarctica, showing the major basins underlying the Ross Sea (*N.B.* is the Northern Basin) and the location of the seismic and modelled profile (*thick line*) across the southern Victoria Land Basin. Deep Sea Drilling Project (*DSDP*) (Hayes and Frakes 1975), Cape Roberts Project (*CRP*) (CRST 2000), *CIROS* (Barrett 1989) and *MSSTS* (Barrett 1986) drill sites marked by *solid squares*. *Inset* shows the location of the figure within Antarctica

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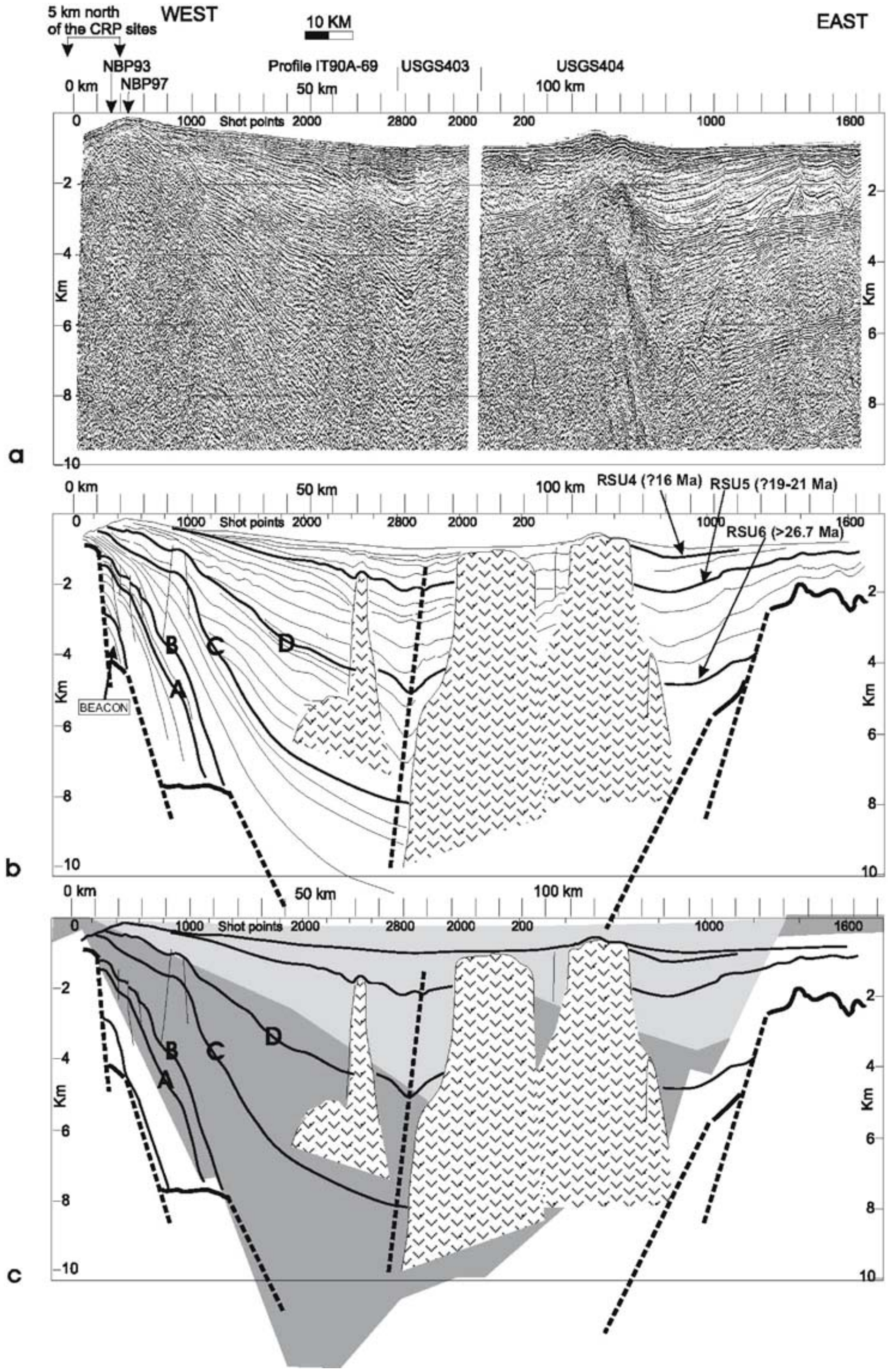

Fig. 6.3-2.
a Depth-converted composite seismic profile (IT69-USGS403/404) across the southern Victoria Land Basin along the line shown in Fig. 6.3-1. Note the profile has been limited to a depth of 9.5 km. **b** Interpretation of the seismic profile. *Solid lines* marked *A–D* are the unconformities related to the proposed rifting. *A:* 34 Ma, *B:* 32.5 Ma, *C:* 29 Ma, *D:* 24 Ma (after De Santis et al. 2001; and based on the Cape Roberts drill-holes). In eastern VLB the *RSU* series of unconformities (Brancolini et al. 1995) are marked. *Dashed lines* mark the major basin forming faults inferred from the seismic data. *V shading* delineates inferred igneous bodies. **c** The final stage (*shaded*) of the rift model for the Victoria Land Basin (Fig. 6.3-3) superimposed on the interpreted seismic profile shown in **b** above. *Light shading* delineates sediments associated with the last rifting event, dark shading delineates sediments from the earlier rifting phases

1992) to reproduce this seismic stratigraphy (Fig. 6.3-2) and provide constraints on the rifting history of the VLB. Simple models of multiple extension rifting are in broad agreement with the basin dimensions, broad stratigraphy and crustal thickness but it has not been possible to reproduce the detailed stratigraphy.

Method

We used the rift modeling program STRETCH (Badley Earth Sciences (Computing) Ltd.) that develops models of a rifted lithosphere for a range of physical variables, e.g., brittle depth, rheology, planar or listric fault, and erosion level. It uses the flexural cantilever model and was developed for rifted continental shelves (Kuznir et al. 1991). However, it does not allow a variable rheology or a variable degree of erosion along a model (as may be expected to occur from East to West Antarctica). Variations in these two parameters would be important for a comprehensive model of the rifting along this boundary since the initial break-up of Gondwana in Mesozoic times, and particularly since uplift of the TAM commenced in the Cretaceous (Fitzgerald 1994). We note however, that the VLB, the major rift margin basin, lies only along a limited part of the TAM rift margin, and that it has a much younger age (late Eocene). These latter two factors can be interpreted as indicating *(i)* an early rift phase, probably associated with the break-up of New Zealand and Australia from Antarctica (100 Ma approx., Davey and Brancolini 1995), forming the Antarctic wide Transantarctic Mountains rift margin and the associated thinning of the West Antarctic-Ross Embayment, and *(ii)* a later, localized, rift that formed the VLB, probably commenced at about 34–37 Ma (Wilson et al. 1998; CRST 2000; Florindo et al. 2001), and formed mainly in the thinned Ross Embayment crust. The pre-existing rift margin along the TAM-Ross Sea boundary may have acted as a zone of weakness for this later rifting, i.e. the initial major east dipping fault on the western margin of VLB. However, the limited along strike extent of the VLB with no major changes in the morphology of the adjacent TAM at its north and south extremities, indicates that for preliminary modeling studies the rifting that formed the VLB can be modeled separately from that forming the TAM uplift. Furthermore, a local (southwest Ross Sea) strike-slip environment has been proposed for causing the VLB (Wilson 1995; Salvini et al. 1997; ten Brink et al. 1997). We have therefore modeled the VLB as a rift occurring in lithosphere of constant rheology since 34 Ma (based on the Cape Roberts drill core results as our profile passes through that location). We use 2D modeling software and do not address the issue of strike-slip tectonics. As noted above, the proposed rifting will have affected the adjacent TAM, but a more comprehensive model is needed to quantify this. However, the simple modeling shown here provides constraints on the amount and timing of rift faulting that formed the VLB and its associated crustal thinning.

Input Parameters and Assumptions

A lithosphere of constant thickness and rheology is assumed as a starting condition for the model. The initial thickness and rheology are parameters that were tested during the modeling. Pre-rift topography was assumed to be at sea level with a preexisting sedimentary section 1 km thick. Syn-rift and post-rift sediments were assumed to be a 40:30:30% sand-silt-clay mix (e.g., Barrett and Anderson 2000). Four separate phases of extension, on one or more of five main faults, were inferred to occur instantaneously, at 34 Ma, 32.5 Ma, 29 Ma, and 24 Ma based on CRP drilling results and the seismic stratigraphy. The seismic stratigraphy indicates that a younger (less than 17 Ma) extensional event may have occurred but we have no age control for it and it has not been considered. Erosion and thermal subsidence were modeled after each rift episode. The Central Trough was modeled as a single rift episode at 34 Ma to allow for some influence of this extension on the adjacent VLB model – it is not very critical since its effect is largely on the Moho morphology. Prograding sedimentation was assumed for the early sedimentation associated with the western brittle faulting when extension and subsidence was greatest, and horizontal basin in-fill for subsequent basin development related to the listric eastern faults.

Output Model

The final model, showing the stages of development of the VLB, is shown in Fig. 6.3-3a–e. A comparison of the final stage with the depth converted seismic section is shown in Fig. 6.3-2c.

The following variables were tested to provide the best fit (by inspection) of the output model (Table 6.3-1) to the interpreted seismic section:

1. location, dip and extension of faults (as derived from interpretation of the seismic section in Fig. 6.3-2b).
2. lithosphere effective elastic thickness (*Te*). A range from *Te* = 3 km to *Te* = 50 km was tested, and the best value to get the observed flexure of the broad (140 km) VLB was *Te* = 10 km. Assuming (1) above, *Te* = 15 km gave too broad a basin and Moho morphology, *Te* = 5 km increased the convex up geometry of the unconformities and would not fit the Moho morphology under the VLB.
3. brittle lithosphere layer. A range from 10 km to 35 km was tested. The preferred value was 15 km to get the closest Moho morphology to that derived from gravity modeling (Davey and Cooper 1987). For planar faults this value defines the depth to which brittle faulting is carried in the model. The software default value of 15 km is a common hypocentral depth for continental earthquakes. For listric faults this defines the depth at which the fault system detaches. Below this depth all deformation is plastic pure-shear for both fault styles. A value of <15 km made it difficult to fit the basin depth, a value = 20 km gave a more asymmetric morphology then that computed from gravity data for the Moho under the VLB.

4. pre-rift crustal thickness. A range from 40 km to 20 km was tested. The best fit value was 33 km. This was thicker than expected. Values <30 km were difficult to model to give the depth of the basin without making the depth to Moho much smaller than the gravity model, whereas depth values >35 km gave depths to Moho that were too deep.
5. amount and timing of erosion after each rift phase. Any topography above sealevel was assumed to erode to 500 m above sealevel after the first three extensional events, and to 200 m above sealevel after the last extension.

The four major rifting phases are as follows:

Phase A (Fig. 6.3-3a) 34 Ma

Initial major rifting phase, corresponding to the rapid subsidence observed at Cape Roberts drill site (CRST 2000; De Santis et al. 2001). A graben structure is needed to get the final basin depth. Planar faulting is required to produce a steep western dip of Moho. The rifting that formed the Central Trough is assumed to occur at this time. Erosion of all the crustal rocks higher than 0.5 km above the sea level is assumed to occur after this extensional phase. Thermal subsidence occurred until 32.5 Ma.

Phase B (Fig. 6.3-3b) 32.5 Ma

East dipping extension occurred on a single planar fault to give nearly the maximum depth of the basin. The total extension (phase A and B) is limited by minimum Moho depth modelled using gravity data. Erosion of all the crustal rocks higher than 0.5 km above the sea level is assumed to occur after this extensional phase. Thermal subsidence occurred until 29 Ma.

Phase C (Fig. 6.3-3c) 29 Ma

West dipping listric extension occurred along two faults on eastern margin of basin. The mid-basin fault is required to emulate the stratigraphy in western part of the basin and depress the sediments in the central part of the basin. A large fault is not detected in this location on the seismic section. However, small offset faulting of strata and volcanic intrusion in the seismic section suggest the occurrence of vertical discontinuities (Fig. 6.3-2). The volcanic intrusions imaged on the seismic data would have provided an additional load on the crust and an associated downwarp. However, the size of the intrusive bodies is not well constrained and only minor disturbance of sediments is apparent on the seismic data, and they have not been included in the modelling. The intrusive bodies may be associated with the proposed mid-basin fault. Thermal subsidence until 24 Ma and erosion of all the crustal rocks higher than 0.5 km above the sea level occurred.

Phase D (Fig. 6.3-3d) 24 Ma

Additional west dipping listric extension occurred along the two faults on eastern margin of basin, with erosion to 0.2 km above sea-level, and thermal post rift subsidence with sediment infill to 0.3 km water depth, from 24 Ma to present.

The modelling software does not retain the detailed geometry of the stratigraphy from earlier rift episodes in its output. We have therefore sketched in the major unconformities on Fig. 6.3-3. To model the stratigraphy imaged on the seismic data, we assumed prograding sedimentation for the basin in-fill associated with the west faults and flat-lying sedimentation for sedimentation associated with the eastern faults. This gives the basement parallel bedding of the sediments laid down after the east dipping faulting occurred and the subsequent stratigraphy of sediments that onlap to the west and were deposited after the west dipping faulting occurred.

Discussion

A major problem with the derived model is that the nature of the flexural cantilever model gives rise to the major unconformities between sediment packages being convex upwards, in contrast to that seen on the stratigra-

Table 6.3-1. Fault parameters used for modeling the VLB

Fault no.	Present *X*-coord (km)	Present horizontal extension (km)	Present dip (deg)	Dip direct. right = west	Fault type	Time of faulting Ma
1	0	25	20	Right	Planar	34
2	10	15	20	Right	Planar	32.5
3	90	10	20	Left	Planar	34
4	90	10	40	Left	Listric	29.24
5	130	20	20	Left	Listric	29
6	155	15	20	Left	Listric	24
7	210	20	8	Right	Listric	34
8	280	20	8	Left	Listric	34

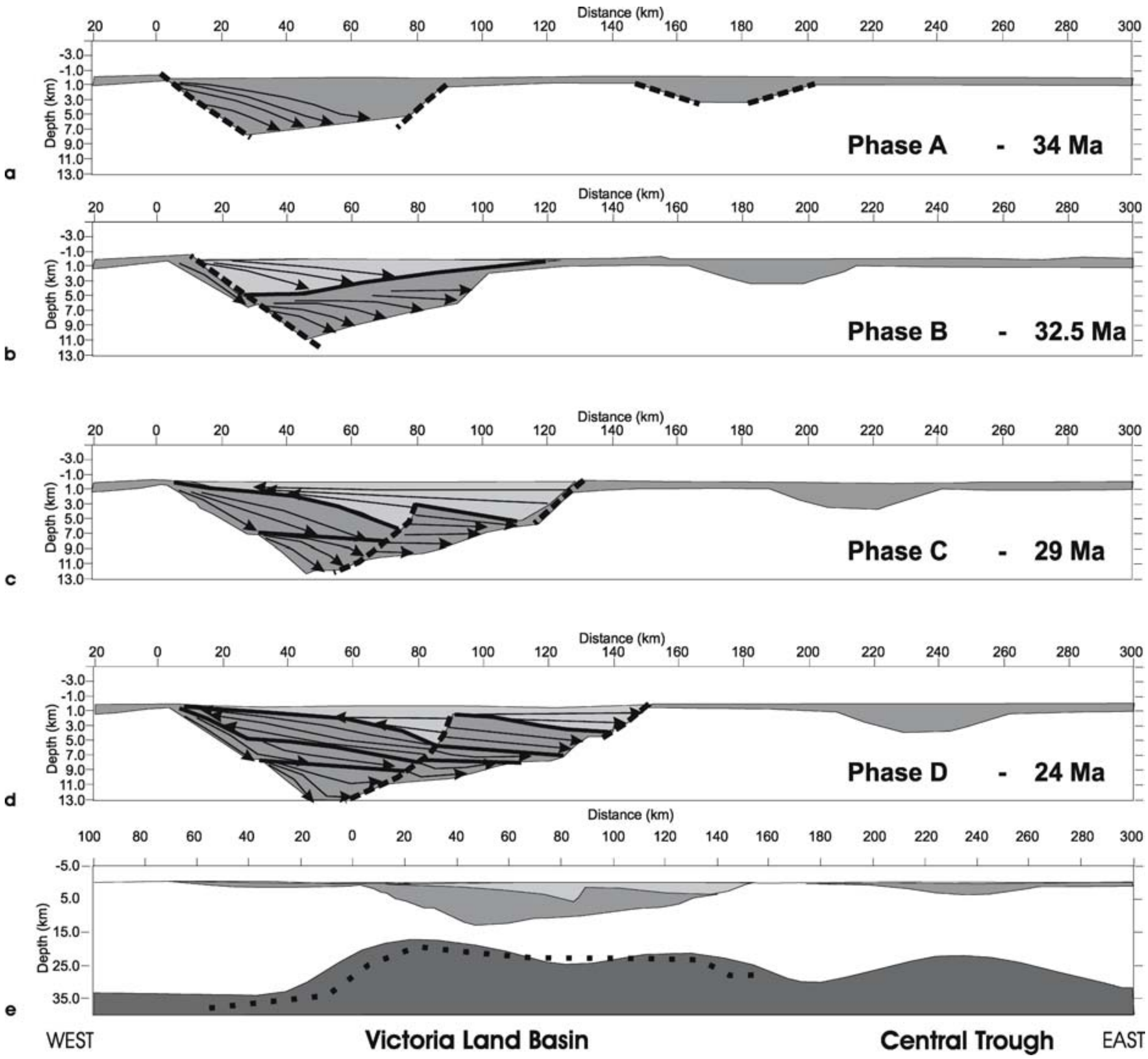

Fig. 6.3-3. The four phases of rifting of the Victoria Land Basin showing the faults and detailed basin structure. The depositional stratigraphy is indicated by the light lines with arrowheads at the onlap margin. Unconformities formed by the four rift phases are shown by *thick lines*. Faults active in each phase are shown by the *heavy dashed line*. For the fourth phase, the upper part is the detailed basin structure, and the lower part the crustal section. The *dotted line* on the crustal structure is the Moho modelled from gravity data (after Davey and Cooper 1987). *Light shading* (new rift phase) and *medium shading* (previous rift phases) are sediments, the crust has *no shading*, *dark shading* is upper mantle

phy. Thermal subsidence is not sufficient to reverse the curvature and give the concave unconformities imaged and we would speculate that a more complex fault model, with blind faults under the sediments in the centre of the basin, where crustal stretching is greatest, is needed. Alternatively, some pure shear model could be proposed, but the large degree of crustal thinning was not obtainable over a relatively small basin width (150 km approx.) with any reasonable pure shear model.

The seismic stratigraphy of the Victoria Land Basin (Fig. 6.3-2) can be matched moderately well by an extensional multiple rifting of a slightly thinned (33 km) continental crust. The model replicates the size and shape of the basin but does not reproduce the detailed stratigraphy well, particularly the concave basins in the western part of the basin, as noted earlier. Our study shows that the development of the Victoria Land Basin since 34 Ma can be modelled by a minimum of five major faults. Rifting commenced on the western margin of VLB and subsequently moved to the eastern margin (a similar conclusion to De Santis et al. 1994). Early, east dipping, brittle planar faulting, with about 50 km of extension, offshore from the TAM rift margin, formed an initial rift graben that reached a depth of about 10 km. Subsequently, major west dipping listric faulting at 29 Ma (30 km extension) and 24 Ma (15 km extension) further extended the rift and resulted in a more symmetric feature. Post rift subsidence of about 2 km has occurred since 24 Ma, giving a final basin depth of about 14 km. The amount of extension is 95 km, and has resulted in a thinning of the continental crust to 6 km and a maximum local stretching factor (beta) of 3. The causes of changes in the locus of faulting from west to east and the style of faulting from planar to listric, and in the location of the eastern faults, has not been addressed. We would speculate that they are probably related to the extreme thinning of the crust by the initial western faulting at 34 Ma and the subsequent internal crustal stresses that this generated.

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