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Preliminary results from a thermo-mechanical model for the evolution of Atlantic-type continental margins

Passive continental margins
Thermo-mechanical model
Lithosphere
Extension
Nova Scotia

Marges continentales passives
Modèle thermo-mécanique
Lithosphère
Extension
Nouvelle-Écosse

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ABSTRACT

The geodynamic evolution of rifted continental margins is discussed, based on preliminary results from a thermo-mechanical model. This model uses the temperature distribution predicted by extension of the lithosphere during rifting to derive the mechanical properties of the lithosphere which in turn determine its response to loading by sediments and water. The model predicts the evolution of the marginal sedimentary basin, the configuration of the crust-mantle boundary, and the gravity anomalies, all of which result from extension during rifting and from the isostatic response to loading. The properties are described in general terms and are also shown to compare favourably with observational data on the Nova Scotian continental margin.

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RÉSUMÉ

Résultats préliminaires d'un modèle thermo-mécanique pour l'évolution des marges continentales de type atlantique.

L'évolution géodynamique des marges continentales en distension est étudiée à partir des résultats préliminaires d'un modèle thermo-mécanique. Ce modèle utilise la distribution de température que l'on peut prévoir à partir de l'extension de la lithosphère pendant la distension, pour en déduire les propriétés mécaniques de la lithosphère, qui déterminent alors la réponse à la charge d'eau et de sédiments. Le modèle prédit l'évolution du bassin sédimentaire marginal, la configuration de la limite croûte-manteau, et les anomalies de gravité, à partir de l'extension pendant la distension et de la réponse isostatique au chargement. Les propriétés sont décrites en termes généraux et s'appliquent favorablement aux données de l'observation de la marge continentale de Nouvelle-Écosse.

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INTRODUCTION

Horizontal extension of the lithosphere during rifting between two continental plates is one process which correctly predicts most of the first order observed properties of rifted, Atlantic-type (or passive) continental margins. These observations include the thinning of the continental crust over lateral distances of several hundred kilometers landward of the ocean-continent boundary (Sheridan *et al.*, 1979 ; Montadert *et al.*, 1979 ; Keen, Hyndman, 1979) ; the subsidence of the margins after the onset of sea floor spreading (Sleep, 1971 ; Watts, Steckler, 1979 ; Watts, Ryan, 1976 ; Keen, 1979 ; Royden, Keen, 1980) ; and listric faulting in the brittle, upper crust across the margins (Montadert *et al.*, 1979). While other processes such as subaerial erosion (Sleep, 1971) ; horizontal outflow of hot continental lithosphere toward oceanic lithosphere (Bott, 1971) ; metamorphic phase changes at depth (Falvey, 1974) ; and magmatic intrusion (Royden *et al.*, 1980) may play important roles in the evolution of the rifted margins, we assume in this paper that extension is primarily responsible for the development of the margins and investigate the thermal and mechanical consequences of this model for isostatic adjustment beneath sediment and water loads. These consequences are important because the isostatic response to the loads greatly amplifies the subsidence caused by cooling and density changes in the lithosphere during and after rifting. Unless this response is evaluated using models that accurately reflect the rheology of the lithosphere, such first order properties as the depth to basement and sediment thickness, the depth to the crust-mantle boundary, and the character of the gravity anomalies across the margins cannot be accurately predicted by model calculations.

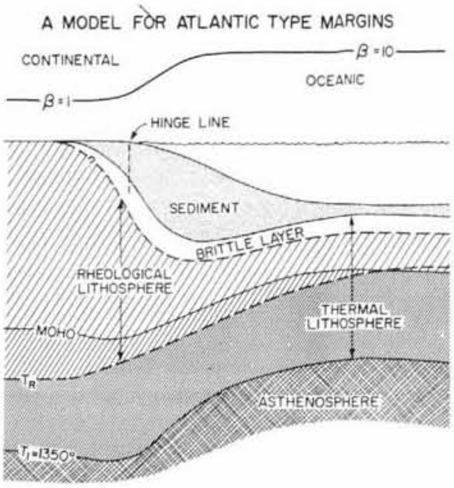

Figure 1

Schematic representation of a thermo-mechanical model of a rifted continental margin. The thermal properties of the lithosphere are described by extension and thinning of the lithosphere by amounts, β, during rifting (McKenzie, 1978). Values of β control the amount of thinning and are largest on the oceanic side of the margin. The thermal lithosphere, whose base is defined by temperature T_l, *is subdivided into three zones of differing rheological properties. The upper zone consists of incompetent rocks ; the sediments deposited during and after rifting and extension and the uppermost crustal layer which was faulted during rifting and has since acted as part of the incompetent layer. The middle zone, here called the rheological lithosphere, is the layer which supports surface loads of sediment and water and behaves as a perfectly elastic layer, buoyed up by the underlying layer whose mechanical properties are those of an incompressible fluid. The boundary between the rheological lithosphere and the underlying fluid occurs at the relaxation isotherm,* T_R. *The depth to this isotherm will change with time and with position across the margin. The elastic behaviour of the rheological lithosphere will cause bending or flexure when loaded. Some subsidence will occur due to this flexure landward of the hinge line, where* $\beta \rightarrow 1$ *and there is little or no tectonic subsidence due to extension. The thermal and mechanical properties of the lithosphere in the models are described by the following physical properties : thickness of the lithosphere before extension = 125 km ; thickness of the crust before extension = 35 km ; thermal time constant = 62,8 Ma ; coefficient of thermal expansion =* $3{,}2 \times 10^{-5}\,°C^{-1}$ *; thermal conductivities of lithosphere and sediment = 3.06, 1.65* $Wm^{-1}\,C^{-1}$ *; densities of mantle, crust and sediment at 0°C = 3,300, 2,860, 2,300* kg/m^3 *; Poisson's ratio = 0,25 ; Young's modulus =* 2×10^{11} *Pa.*

CONCEPTUAL MODEL

Thermal properties

The thermal aspects of the extension of the lithosphere during rifting are based on McKenzie's (1978) model of instantaneous stretching of the lithosphere. If the crust and lithosphere are stretched by an amount β, hot asthenosphere will rise beneath the stretched region. This produces an *initial subsidence*, which is caused by the isostatic response of the thinned and heated lithosphere to density changes (McKenzie, 1978). The initial subsidence is followed by the *thermal subsidence*, which occurs as the plate cools, contracts and thickens after rifting has ceased and sea floor spreading has begun between the two rifted continental margins. These two components of subsidence will together be called the *tectonic subsidence* to distinguish it from the subsidence caused by isostatic response to loading by sediments and water.

Stretching across a rifted margin will result in a transition from unmodified continental lithosphere ($\beta = 1$) to oceanic lithosphere, where β is large. The larger the value of β, the more thinning, heating and overall tectonic subsidence. A value f $\beta = 10$ was chosen for oceanic lithosphere. More properly, the thermal and subsidence history of oceanic lithosphere should be modelled using $\beta = \infty$, so that all of the original continental lithosphere is destroyed in the extension process. Because the details of generating oceanic lithosphere were not of particular concern, we chose for simplicity to model the generation of oceanic lithosphere by approximating its behavior by large but finite extension. The justification for this approximation is that a value of $\beta = 10$, when combined with reasonable physical properties of the lithosphere (see caption Fig. 1), gives an initial subsidence, 2.66 km, equal to the depth of ocean crust newly formed at mid-ocean ridges. Furthermore, the subsidence and thermal history computed for finite extension by 10 is very similar to that obtained for oceanic lithosphere (see McKenzie, 1978), and allows for a finite thickness of oceanic crustal material, which is not predicted when $\beta = \infty$. Horizontal variations in β are included in the model by interpolating between one-dimensional solutions for temperature as a function of time and depth, an approach which assumes that horizontal heat conduction is unimportant.

The calculations were made using a one-dimensional finite difference model, parameters for which are given in Figure 1, rather than the analytical solutions given by McKenzie (1978). This allowed the effect of thermal blanketing by the low thermal conductivity sediments to be included, an effect which will slow the cooling of the lithosphere. This effect is particularly important in studies of older rifted margins where large thicknesses (~ 15 km) of sediments have been deposited.

Rheological properties

Isostatic compensation under water and sediment loads across rifted margins is less likely to be achieved by the Airy model of local isostatic adjustment in the later stages of their evolution because, following rifting, the cooling and thickening lithosphere will become increasingly strong with time and will exhibit bending or flexural characteristics. Figure 1 illustrates the way in which this has been included in the models. The depth to an isotherm, here called the relaxation isotherm, T_R, is determined from the thermal model ; and this depth is used to define the thickness of an elastic plate whose mechanical response to loading is then determined. This model is similar to the flexure of a uniform elastic plate that has previously been used (e.g. Watts, Ryan, 1976), but differs from this simpler flexural model in that its thickness will vary both with time as the lithosphere cools, and with position across the margin. Consequently, the isostatic response must be computed numerically ; we use a two-dimensional finite element model.

The relaxation isotherm cannot be specified in an *a priori* way although results from studies of olivine micro-rheology (Beaumont, 1979) and of the isostatic response of oceanic lithosphere to various loads (e.g. Watts, 1978), suggests that $450°C \leq T_R \leq 750°C$. Therefore, T_R is considered to be a variable to be determined from comparison of model results with observations. A further complication, not specifically addressed here, is that an incompetent, brittle upper crustal layer may be created by faulting during rifting (Fig. 1). Therefore, the rheological lithosphere, which is the part of the thermal lithosphere which undergoes flexure, should be strictly defined as the region below the brittle layer and above the relaxation isotherm : in this paper it is defined as the region below the sediments and above T_R. This is partly compensated by choosing lower values of T_R than indicated above and is discussed in more detail later.

The justification for modelling the mechanical behavior of the lithosphere as outlined here is based on the assumption that relaxation of stress, σ, is through viscous flow and that the effective viscosity, υ, follows a thermal activation law of the type (Weertman, 1970),

$$\upsilon = \upsilon_0 F(\sigma) \exp(-AT/T_m),$$

where T/T_m is the homologous temperature and A is an activation energy. Even for a power law rheology, where $F(\sigma) = \sigma^n$, $n \sim 3$, relaxation will be mainly determined by temperature, and for a linear temperature gradient, ν will be an exponential function of depth. This suggests that to a first approximation the mechanical properties may be modelled as those of an elastic plate with a thickness determined by temperature, T_R. This approach assumes that over geological time scales ($\sim$ 10 Ma) deviatoric stress in regions where $T \geq T_R$ is totally relaxed and that such regions act as an incompressible fluid. For $T \leq T_R$ no stress relaxation occurs and surface loads are compensated by elastic deformation of this upper region, supported by the buoyancy of the underlying region. This is obviously an approximation to the true variation of viscosity with depth but probably provides a sufficiently sensitive rheological model because viscosity changes by many orders of magnitude over a small temperature range.

Computational methods

The results shown in this paper have been obtained for two classes of models ; "archetypal" models which depict characteristics common to most rifted margins without reference to a specific region, and models for the Nova Scotian rifted margin off eastern Canada where a wide variety of geological and geophysical observations are available for comparison with the model calculations (e.g. Jansa, Wade, 1975 ; Keen, Hyndman, 1979). For each model the variables to be chosen are : 1) the variation of β as a function of position across the margin ($\beta(x)$) ; 2) the value of T_R ; and 3) the sediment input as a function of time and position.

Calculations are then performed by stepping the models through time, in time steps Δt, usually chosen to be 10-20 Ma. The procedure is as follows : 1) at $t = 0$, stretching occurs resulting in the initial subsidence as predicted by local isostatic adjustment. This depression is then filled with a combination of sediment and water to simulate loading of the continental margin just after formation. Isostatic adjustment to this load is calculated using the mechanical model described above ; 2) a time interval Δt elapses during which the lithosphere cools and subsides as predicted by the thermal model ; the position of the isotherm T_R also changes and a further load of water and sediment accumulates. Isostatic adjustment is again calculated by the mechanical model, adjusted for the new depth of T_R ; 3) this process is continued over the number of time steps necessary to simulate the evolution of the margin. After each time step, the depths to the sea floor and to the basement, the position of the M discontinuity, and the gravity anomaly across the margin are computed.

In the archetypal models, the $\beta(x)$ function was arbitrarily chosen to reflect a generalized model for crustal thinning across rifted margins (see for example Fig. 1). The sediment budgets correspond to two extreme cases ; in one case a starved margin on which no sediment is deposited, and in the other a deltaic margin on which large quantities of sediment have been allowed to accumulate, accompanied by progradation of the shelf. A value of $T_R = 450°C$ was chosen for these models. Time steps of 10 Ma were used to describe the evolution up to 80 Ma after rifting ceased. Results for these models are shown in Figures 2 and 3.

The Nova Scotian margin underwent rifting about 200 to 180 Ma ago. It is presently occupied by large thicknesses of sediments whose stratigraphy is relatively well known, thus allowing the sediment input to be modelled (Jansa, Wade, 1975 ; Barss *et al.*, 1979). Variations in crustal thickness have also been determined from seismic refraction measurements, allowing estimates of β on the assumption that the crust was uniform before stretching. Gravity data across the margin are also available. Some of these data are discussed in more detail by Royden and Keen (1980), who estimated $\beta(x)$ from subsidence curves and compared the results with refraction data. In this study, an initial model was designed using the $\beta(x)$ values reported by Royden and Keen but these were too small to allow sufficient subsidence, given that the lithosphere exhibits a finite strength in the mechanical model used here. Consequently larger values of β were used (see Fig. 4). The sediment input was constrained by biostratigraphic data from deep exploratory wells (Barss *et al.*, 1979) supplemented by seismic stratigraphies derived from multi-channel seismic reflection data, and seismic refraction data defining the depth to the pre-rift basement rocks. Eleven time steps with an average value of 18 Ma

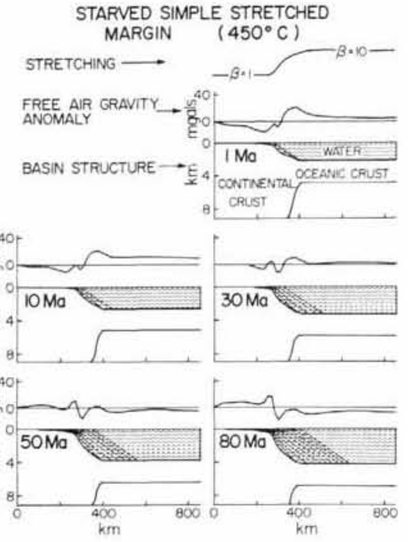

Figure 2

Evolution of a basin caused by subsidence at a starved rifted continental margin where no sediment has been deposited and the basin is filled entirely with water. The β values used are shown in the upper right hand panel and the value of T_R was 450°C. Five stages of evolution are shown ; times for which are given in Ma since rifting ceased. The free air gravity anomalies corresponding to each stage are shown above the basin configuration in each panel. The shading represents water. The dashed lines, which indicate the development of the basin in time steps of 10 Ma, would under most circumstances represent the sediments deposited in the basin. Here, however, there is no sediment and the lines cannot be related to basin stratigraphy.

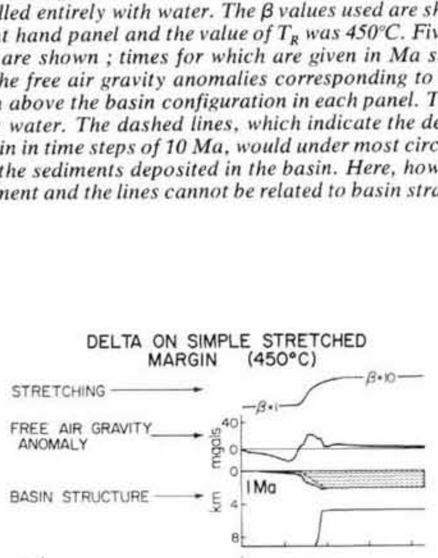

Figure 3

Evolution of a basin at a rifted margin to which large quantities of sediment have been added to form a delta. The β values used are shown in the upper right hand panel and the value of T_R was 450°C. Five stages of development are shown ; times for which are given in Ma since rifting ceased. The stippled region represents sediments. The solid lines within this region represent the sediment added at 1 Ma after rifting and at 10 Ma steps thereafter.

were used to compute the evolution of this margin over 185 Ma. The results are shown in Figure 4 for two models which differ only in having T_R = 450°C and 100°C. Figure 5 depicts the predicted and observed gravity anomalies, the predicted crustal structure and temperature distribution for the present configuration of the margin..

DISCUSSION OF RESULTS

Before describing the results of model calculations, it is important to emphasize that all results were determined entirely from the input variables described in the last section ; $\beta(x)$, T_R, and the sediment budget. No arbitrary adjustment of the configuration of the basin or of crustal structure were made to force the results to resemble any observational data. In this manner, the validity of the conceptual model can be properly assessed. This is particularly important in interpreting the gravity anomalies across rifted margins : often somewhat arbitrary models are presented which are justified solely on the fit of the model's gravity anomaly to the observations. Given the non-uniqueness of gravity modelling techniques ; such results may not be meaningful. In the present case, however, agreement between predicted and observed gravity anomalies provides a powerful constraint on acceptable models.

Figures 2 and 3 show the basin development and gravity anomalies for the archetypal models. Perhaps the most interesting and fundamental result to emerge from this analysis is the dynamic nature of the gravity anomalies, which change significantly with time in response to the geodynamic changes predicted by the subsidence, cooling, and loading of the lithosphere. This is particularly clear in Figure 2, in the starved margin model. It is important to note that the gravity anomaly at each stage is the sum of three distinct contributions which interact in a complex manner ; each of these may be an order of magnitude larger than their sum. These contributions are from density distributions that reflect : 1) the shape of the basin after tectonic subsidence and loading, including the relative contribution of sediment and water ; 2) the depth of the crust-mantle boundary after extension and deformation due to subsidence and flexure ; and 3) temperature changes in the crust and mantle produced by the varying amounts of extension across the margin. These density changes occur throughout the entire lithosphere and the total plate thickness must be included in evaluating the temperature induced contribution. We know of no other study where the last effect has been included. In the archetypal models, for times less than 30 Ma after rifting, the gravity anomalies show a minimum over the outer shelf, with a maximum centred over the continental slope. At times greater than 30 Ma, a maximum evolves over the outer shelf, with a minimum near the foot of the slope. The details of the evolution of these anomalies are shown in Figures 2 and 3.

Effects of flexure of the elastic plate are observed in the sediment distribution and the gravity anomalies for several hundred kilometres on each side of the zone in which β changes, a result that reflects the choice of T_R. They are most noticeable for large loads, in the deltaic model, where the wavelengths and amplitudes of the main anomalies (> 200 km and 50 mgal) are much larger than those in the starved margin model (~ 100 km and 20 mgals). This illustrates the importance of sediment input. Gravity anomalies

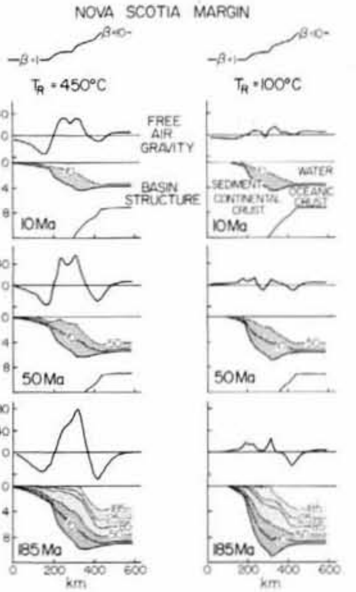

Figure 4

Theoretical evolution of the sedimentary basin on the Nova Scotian continental margin and the corresponding gravity anomalies. The location of the cross-section is shown on the insert, Figure 5. Three stages of evolution are shown for two models ; $T_R = 450°C$ (left) and $T_R = 100°C$ (right). Times are given in Ma since rifting ceased. The solid lines within the sediments show the sediment input at five of the eleven time steps used in the computations and the corresponding times are indicated by the numbers associated with each line — in Ma since rifting ceased. The three types of shading within the sediments indicate strata of Tertiary (light stipple), Cretaceous (medium stipple) and Jurassic (dense stipple) age. The observed basin structure is essentially identical with that shown for the $T_R = 100°C$ model for 185 Ma. The values of β, which are the same for both models, are shown in the top panel of the diagram.

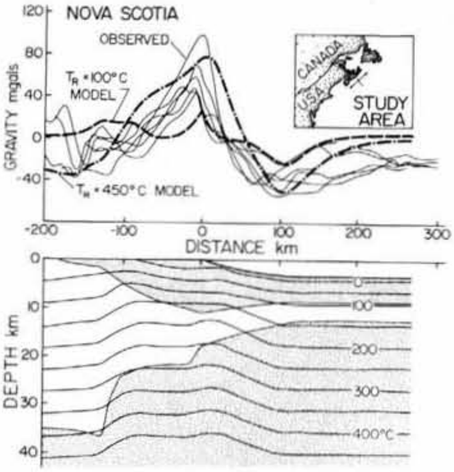

Figure 5

Upper : Observed (thin solid lines) and computed (heavy broken lines) free air gravity anomalies for the Nova Scotian margin. Six observed profiles, from different locations along the length of the margin, are shown to demonstrate the variability of the character of the anomalies. The insert shows the locations of this margin ; and the position of the cross-section in Figure 4. The extent of the margin over which the six observed profiles were obtained are denoted by the arrows.

Lower : Crustal structure and isotherms predicted by the $T_R = 100°C$ model for the present time. Dots and line pattern indicate sediments and the mantle respectively. The isotherms are shown at 50°C intervals. Note how these are distorted by the low conductivity sediments and that the 0°C isotherm does not coincide exactly with the sea floor. This is because the sediments deposited at 0°C in the last timestep have not yet reached thermal equilibrium.

due to flexure of a continental margin were described by Walcott (1972) for large sediment loads and these are similar to the model shown here for the later evolutionary stages of the deltaic margin. The excessively long wavelength of the gravity anomalies in this the 450°C model reflect too large a value for T_R.

In Figures 4 and 5 preliminary results for the Nova Scotian margin are shown. These are similar to the behaviour of the archetypal models with respect to the dynamic character of the gravity anomalies and the large flexural effect exhibited by the $T = 450°C$ model. Much less flexure and smaller gravity anomalies are observed in the $T = 100°C$ model. In the latter, the position of the 100°C isotherm is sufficiently shallow seaward of the hinge line (where $\beta > 1$, see Fig. 1) that Airy isostatic adjustment is achieved. This is not true landward of the hinge line (Fig. 5), where a finite elastic plate thickness is defined. The choice of the 100°C and 450°C isotherms to determine the mechanical behaviour of the lithosphere may thus represent the two extremes of plate thickness : the 450°C model produces an excessively thick plate while the 100°C model yields zero plate thickness over most of the margin. These values of T_R are lower than the suggested range of T_R values ; $450°C \leq T_R \leq 750°C$. As mentioned above, the presence of a brittle mechanically incompetent crustal layer which will reduce the thickness of the rheological lithosphere (Fig. 1) has not been considered. However, a comparable reduction may have been effected here by choosing unrealistically low values of T_R. That values of $T_R \geq 450°C$ predict unacceptable results strongly suggests the need to include the brittle layer.

The basin configuration shown for the Nova Scotian margin (Fig. 4) is similar to the observed sedimentary stratigraphy. The large thickness of Jurassic sediments beneath the outer shelf is almost as great as the total thickness of younger sediments (Jansa, Wade, 1975 ; Keen, Cordsen, in prep.).

The total depths to basement also agree reasonably well with the observational data. The 100°C model appears to provide a somewhat better fit to the observed basin configuration in several respects. It predicts a more realistic amount of flexure landward of the hinge line ; the 450°C model exhibits too much flexure in that region, although erosion may have contributed to the presently observed configuration. Also, the 100°C model allows sufficient subsidence for the appropriate sediment thicknesses to be added to the basin, whereas the subsidence predicted by the 450°C model is too small and the sediment input is less than the data require. This is particularly noticeable in the Tertiary. Conversely, the paleowater depths predicted for both models in the first 100 Ma after rifting are significantly greater than those measured in biostratigraphic studies (Gradstein *et al.*, 1975). This is, in large part, because the model sediments are deposited with their present level of compaction. However, the choice of an intermediate value for T_R would improve the model predictions in this respect.

A comparison of the observed and computed gravity anomalies across the margin (Fig. 5) shows that the computed anomalies have similar characteristics to the measurements ; a gravity maximum of 25-80 mgals near the edge of the shelf, and a minimum of 25-50 mgals near the base of the continental slope. Most of the observational data lie between the curves predicted by the models, again suggesting that an intermediate choice of T_R may provide a better fit to the data. The depths to the crust-mantle boundary predicted by these models are slightly less than those obtained from seismic refraction measurements. Beneath the outer shelf, measured depths to this boundary lie between 26 and 35 km (Keen, Hyndman, 1979 ; Keen, Cordsen, in prep.), while the computed depth is 20-22 km. This discrepancy arises because the values of β were chosen to be large enough to produce the necessary basin subsidence. These values predict somewhat more crustal thinning than is observed. More work is required to assess whether a better fit to the pre-rift crustal thicknesses can be achieved, while simultaneously providing the desired subsidence.

In summary, the preliminary results presented above suggest that the combined thermo-mechanical models yield a promising and powerful method of investigating the geodynamic evolution of rifted margins. The properties predicted by the models are sensitive not only to the initial mechanism of rifting but also to the implications of this mechanism for the mechanical behaviour of the lithosphere when loaded and to sediment supply. The requirement that the models satisfy the known basin structure, the observed crustal thicknesses, and the observed gravity anomalies provide rigid constraints on the range of possible models. This may allow both the initial rifting history and the mechanical properties of the lithosphere to be better understood.

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