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Gravity anomalies, flexure and crustal structure at the Mozambique rifted margin

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Abstract

The free-air gravity "edge effect" anomaly associated with passive continental margins is one of the most distinctive features of the marine gravity field. Early studies attributed the edge effect to the juxtaposition of thick continental with thin oceanic crust. While thinning of the crust due to rifting at the time of continental break-up is a major contributor, it is now recognised that geological processes such as sedimentation and magmatic underplating also contribute. The different amounts of sediment and underplate at rifted margins help, in fact, to explain the diversity of the edge effect, although they obscure the mechanics, styles and geometry of rifting. In this paper, combined 2-dimensional flexural backstripping and gravity modelling techniques are used to quantify the contribution of rifting, sediment loading and magmatic underplating to the edge effect anomaly at the Mozambique margin. This margin formed as the result of a two-stage break-up, the first of which resulted in the separation of Africa and Madagascar in the Early Jurassic. By comparing the observed edge effect to calculations based on simple elastic plate models, we have been able to constrain the elastic thickness, T_e, and, hence, flexural rigidity of the lithosphere that underlies the sediments which accumulated at the Mozambique margin following break-up. The model that best explains the shape (i.e. amplitude and wavelength) of the edge effect high is one in which the earliest Jurassic–Early Cretaceous sediments were deposited on relatively weak lithosphere ($T_e \sim 17.5$ km) while the later Miocene–Recent sediments accumulated on relatively rigid lithosphere ($T_e \sim 40$ km). These results suggest that sedimentation at the Mozambique margin has involved lithosphere which responds to loads in a similar manner as would oceanic lithosphere. Therefore, the thinned "transitional" crust that underlies much of the coastal plain of the Mozambique margin is probably of oceanic rather than continental origin.

Keywords: Backstripping; Stratigraphic; Anomaly

1. Introduction

Rifted continental margins form as a result of the break-up of continents and the formation of new ocean basins. Some margins (e.g. East Coast, USA; Labrador) correlate with up to 15 km in thickness of seaward dipping sediments (Chian, Louden, & Reid, 1995; LASE study group, 1986). Others (e.g. Goban Spur) have only a thin sedimentary cover (Horsefield, Whitmarsh, White, & Sibuet, 1993). Many margins (e.g. Vøring), are associated with magmatism which is expressed in the form of high P wave velocity lower crustal bodies and seaward dipping reflector sequences (Eldholm, Skogseid, Planke, & Gladczenko, 1995). While differences in the thickness of sediment and the amount of magmatic material explain the diversity of rifted margins, they obscure our physical understanding of the rifting process.

Much of our understanding of the rifting process has come from studies of the subsidence and uplift history of the sediments that accumulate at margins during and following rifting. Sediments are a 'tape-recorder' of the various factors that are responsible for margin evolution which include water and sediment loading, thermal contraction and uplift due to heating at the time of rifting and, magmatic underplating. By correcting the stratigraphic record for the effects of sediment loading (Watts & Ryan, 1976) and magmatic underplating (Watts & Fairhead, 1997), it has been possible to constrain the thermal processes involved in rifting. Backstripping, for example, allows estimates of the amount of heating and thinning of the crust that has occurred as a result of rifting.

But, the backstripping technique is based on specific assumptions about the mechanical properties of the rifted crust and upper mantle, through its incorporation of Airy and flexure models of isostasy.

One parameter that is sensitive to the magnitude of the sediment and magmatic loads and their compensation is the

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free-air gravity anomaly. By comparing the calculated anomalies based on simple models of flexure to observations (Cochran, 1973; Karner & Watts, 1982; Walcott, 1972; Watts, 1988), it is possible to constrain the flexural rigidity and, hence, the mechanical properties of the crust and mantle in a rifted margin setting.

An approach that combines backstripping and gravity modelling, therefore, has the potential to constrain *both* the thermal and mechanical properties of the crust and mantle at a rifted margin. In this paper, we review the combined backstripping and gravity modelling technique, and show an example of its application to the Mozambique rifted continental margin.

2. The free-air gravity 'edge effect' anomaly

One of the most distinctive features of rifted continental margins is the free-air gravity 'edge effect' anomaly. In its simplest form, the edge effect comprises of a 'high' which correlates with the shelf break and a 'low' over the continental slope and rise. At some margins, there is also a low landward of the high (e.g. East Coast, USA) and/or a high seaward of the low (e.g. Rockall Trough).

Traditionally (e.g. Worzel, 1968), the gravity edge effect anomaly has been interpreted as the result of the juxtaposition of thick continental crust and thin oceanic crust. Early models, based on Airy isostasy, implied that the main

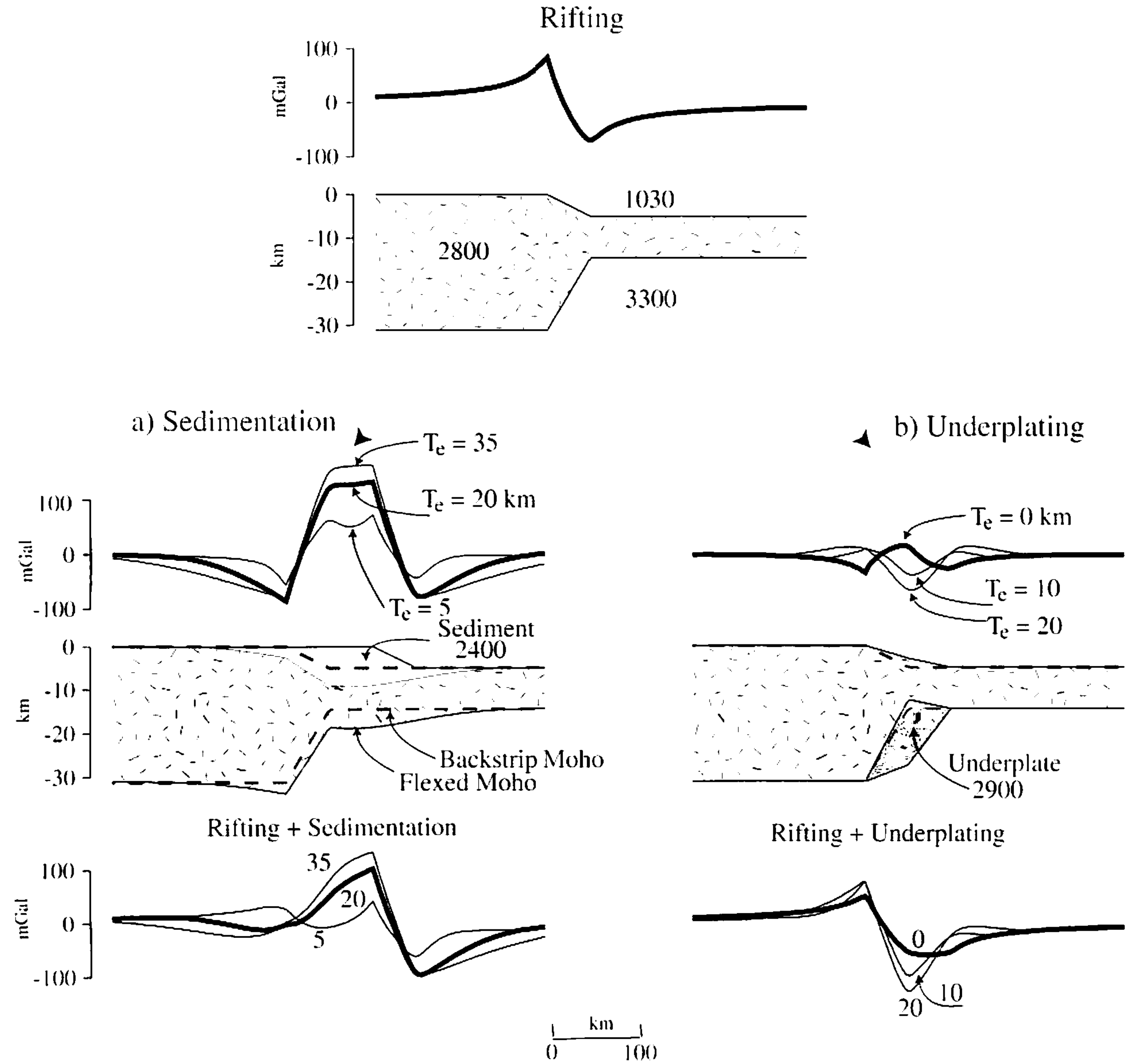

Fig. 1. The gravity anomaly associated with simple models of flexure at rifted continental margins. (a) Sediment loading. (b) Magmatic underplating. The calculated anomalies are based on the uniform densities shown, an elastic thickness, T_e, in the range of 0–35 km and, an initial zero elevation crustal thickness of 31.2 km.

transition between oceanic and continental crust is located at or near the present day shelf break. The existence of prominent Airy isostatic anomalies (e.g. Talwani & Eldholm, 1973) suggest, however, that the continent-ocean transition is not necessarily located at the shelf break.

Recent compilations of surface ship and satellite-derived (Sandwell & Smith, 1997) gravity anomaly data reveal complexities in the edge effect anomaly. While some margins show the 'typical' edge effect of an equal amplitude and wavelength high and flanking low, others show differences. These differences are apparent across, as well as, along-strike of the same age rifted margin. At the East Coast, USA margin, for example, the high alternates in amplitude being sometimes larger than the flanking low and sometimes smaller. Similar patterns of alternating highs and lows have been observed (Watts & Marr, 1995) at other margins. For example, offshore West Africa the high dominates the low along parts of the margin (e.g. Namibia), but is more subdued along others (e.g. Gabon).

3. Sediment loading and magmatic underplating

Once a rifted margin forms, sedimentation and magmatic underplating will modify it. We may expect, therefore, that these processes will also influence the gravity anomaly associated with rifting.

The first question, however, concerns the gravity anomaly that is associated with rifting. McKenzie (1978) argued that the geometry of the crust and mantle in rift-type basins is determined by the amounts of heating and thinning that occurs at the time of initial rifting. This model, which assumes that a local, Pratt-type, isostatic balance is maintained during and after rifting, accounts for the first-order subsidence and uplift history of many rifted margins.

The existence of rift flank uplifts that persist for long periods of time suggests, however, that the lithosphere may have a finite strength during rifting (Weissel & Karner, 1989). The data from experimental rocks suggest that although the strength of the lithosphere is limited by brittle deformation in its upper part and ductile flow in its lower part, there is a central, high strength, 'core' that is capable of supporting stresses for long periods of time. Kooi, Cloetingh, and Burrus (1992) have shown that this vertical stratification in the rheology of the crust and mantle modifies how extension is distributed at depth during rifting. A shallow depth to the strength maxima, for example, results in a shallow basin and a large change in the underlying Moho relief while a deep maxima results in a deep basin and a small change in Moho relief. If flexure is important, then differences in the depth of the strength maxima, may give rise to significant gravity anomalies (Kooi et al., 1992).

We will assume here, a simple model in which the water-filled basin that forms as a result of rifting is compensated for by an Airy model. The use of such a model implies that the lithosphere has no flexural strength during rifting. Some continental rifts (e.g. North Sea) are associated with low values of the elastic thickness, T_e, which is a measure of the long-term (i.e. >1 Ma) flexural strength of the lithosphere. Others (e.g. Western Rift, East Africa) are not. However, as Kooi et al. (1992) has shown, the Airy model may also play a role in rifting models that include strength during rifting. For example, if the strength maxima is at or close to a depth of 7.2 km, the gravity anomaly due to rifting will resemble the Airy case, *irrespective of the actual strength during rifting*.

Fig. 1a illustrates how sediment loading may modify the rifting anomaly. The effect of sediment loading is to flex the underlying crust and mantle downwards beneath the load and upwards in flanking regions. The sediments cause a gravity anomaly, referred to as the sedimentation anomaly, that comprises of a central high which is flanked by two lows. The high arises because sediments are denser than the water that they displace while the low is the result of the downward displacement of the relatively low density sediments into the crust and the relatively low density crust into the mantle by the sediment load.

The magnitude and wavelength of the sedimentation anomaly depends strongly on the elastic thickness, T_e. Sediment loading of a relatively 'strong' margin (i.e. $T_e = 35$ km), for example, produces a single large-amplitude gravity anomaly high which is flanked by long-wavelength, lows. In contrast, the same size load when deposited on a relatively 'weak' margin (i.e. $T_e = 5$ km) results in two highs: one located over the original shelf break and the other over the new one. The net result is that sediment loading modifies the rifting anomaly such that the edge effect high and flanking low *migrates* seaward: the migration being more obvious for the case of a strong margin than a weak one.

Fig. 1b illustrates how magmatic underplating may modify the rifting anomaly. The effect of underplating is to thicken the crust and cause uplift. The gravity anomaly associated with underplating, referred to as the underplating anomaly, comprises of two effects: a low due to the underplate and a high due to the displacement of water by the uplifted crust. Like sediment loading, the gravity anomaly associated with underplating depends strongly on the strength of the lithosphere. Depending on where beneath a margin it is applied, underplating may significantly modify the edge effect. Underplating a relatively 'weak' margin (i.e. $T_e = 0$ km) beneath the slope, for example, will reduce the amplitude of the edge effect 'high' and the flanking 'low' and increase its wavelength. In contrast, at a relatively 'strong' margin (i.e. $T_e = 20$ km) the opposite effect occurs with underplating increasing the amplitude of the high and low and decreasing its wavelength.

4. Combined backstripping and gravity modelling

The models in Fig. 1 are 'forward models' in the sense that the amount of crustal thinning, thickness of sediment and underplate and, T_e are all specified *prior to* calculating the gravity anomalies. At many rifted margins, it is possible to image the sediments and underplate in seismic reflection and refraction profile data. The rifting and T_e structure, however, are unknown. What is of interest therefore is whether we can develop a method that uses observations of the thickness of sediment and underplate to determine the rifting structure and, hence, T_e in a margin setting.

One way is to adopt a 'process-oriented' rather than an 'object-oriented' approach to the interpretation of gravity anomalies. This 3 step procedure[1] combines the backstripping and gravity modelling techniques.

- Step 1: use knowledge of the sediment and underplate from seismic data to calculate the depth that basement would have been in the absence of sediment loading and underplating. In the case of sediments, this is achieved by progressively backstripping each stratigraphic layer, summing the contributions, and then adding them to the present day water depth (which can be regarded as the unfilled part of the basin). The sum corresponds to all the tectonic movements that have affected the margin through time, which will be dominated by subsidence. In the case of underplating, the uplift is calculated from the geometry of the underplated body. Since underplating is associated with tectonic uplift, it will generally oppose the tectonic subsidence derived from sediment backstripping and so is *subtracted* from it. Both the sediment and underplate calculations require an assumption about T_e.
- Step 2: calculate the depth to the Moho from the tectonic subsidence and uplift assuming some form of isostatic model (this is the 'backstrip' Moho of Watts & Torné, 1992). This calculation yields the crustal and mantle structure associated with rifting.
- Step 3: calculate the gravity anomaly associated with rifting and add it to the anomaly due to sedimentation and underplating. By comparing observed and calculated anomalies, constrain the T_e structure at the margin.

We know from flexure studies that significant differences exist between the T_e structure of oceanic and continental lithosphere. In the oceans, T_e is given approximately by the depth to the 450°C isotherm based on cooling plate models (Calmant, Francheteau, & Cazenave, 1990; Watts, 1978). T_e increases, for example, from 4–12 km at the mid-oceanic ridge where the lithosphere is relatively young and hot to >30 km at >100 Ma seafloor where the lithosphere is old and cold. Studies in the continents, in contrast, do not show such a simple relationship between T_e and thermal age (Watts, 1992). Rather, there is a spread in the data (Burov & Diament, 1995) such that T_e may change by several tens of km over length scales that are as short as a few tens of km. In general though, weak zones (i.e. low T_e) appear to characterise continental rifts and active regions of convergence while strong zones (i.e. high T_e) are more typical of cratonic shield regions.

If there are significant differences in the long-term flexural behaviour of oceanic and continental lithosphere, then we might be able to use the process oriented approach to determine whether the loads that modify margin structure involve oceanic or continental-type crust. For example, if it can be determined that the edge effect gravity anomaly at a margin is best explained by a model in which the sediments loaded lithosphere that was initially weak and then became stronger with time, this would argue they were deposited on oceanic rather than continental crust. On the other hand, if the anomaly is best explained by weak lithosphere, which remained weak for long periods of time following rifting, then this would suggest that the sediments loaded rifted continental crust.

5. Modelling of the Mozambique margin

The process-oriented approach has now been applied to the East Coast, USA (Watts, 1988), Rockall (Watts & Fairhead, 1997) and West Africa (Watts & Stewart, 1998) rifted margins. At the East Coast, USA margin, for example, the modelling suggests that sediments landward of the shelf break had loaded a relatively weak lithosphere (i.e. T_e is given by the depth of the 150°C oceanic isotherm) while sediments seaward of the break loaded a relatively strong lithosphere (i.e. T_e is given by the depth to the 450°C oceanic isotherm). The strong region has similar flexural properties to oceanic lithosphere and so Watts (1988) suggested that the boundary between the weak and strong zones correspond to the ocean-continent boundary. This is in accord with the magnetic anomaly modelling studies which suggest that the positive magnetic anomaly at the break in slope of the East Coast, USA margin is the result of the juxtaposition of weakly magnetised continental crust against either strongly magnetised oceanic crust (Klitgord, Hutchinson, & Schouten, 1988) or a strongly magnetised sequence of volcanic lavas that were emplaced on oceanic crust during the earliest stages of seafloor spreading (Talwani, Ewing, Sheridan, Holbrook, & Glover, 1995).

One rifted margin where the distribution of oceanic and continental crust is poorly known is East Africa. Cox (1992) has suggested, for example, that the break-up at this margin occurred in two distinct stages, the first of which in the Early Jurassic, was accompanied by the plume related volcanism of the Karoo province. In this stage, the reactivation of old shear zones is thought to have resulted in the north-east motion of Eastern Antarctica with respect to Africa. The second stage took place some 10–30 Ma later as Eastern Antarctica and Madagascar moved as a single

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[1] Further details of the approach can be found by displaying the file margin.eps.gz which can be downloaded by ftp to ftp.earth.ox.ac.uk, logging in as anonymous (using your email address as a password) and then changing directory to pub/tony/margins.

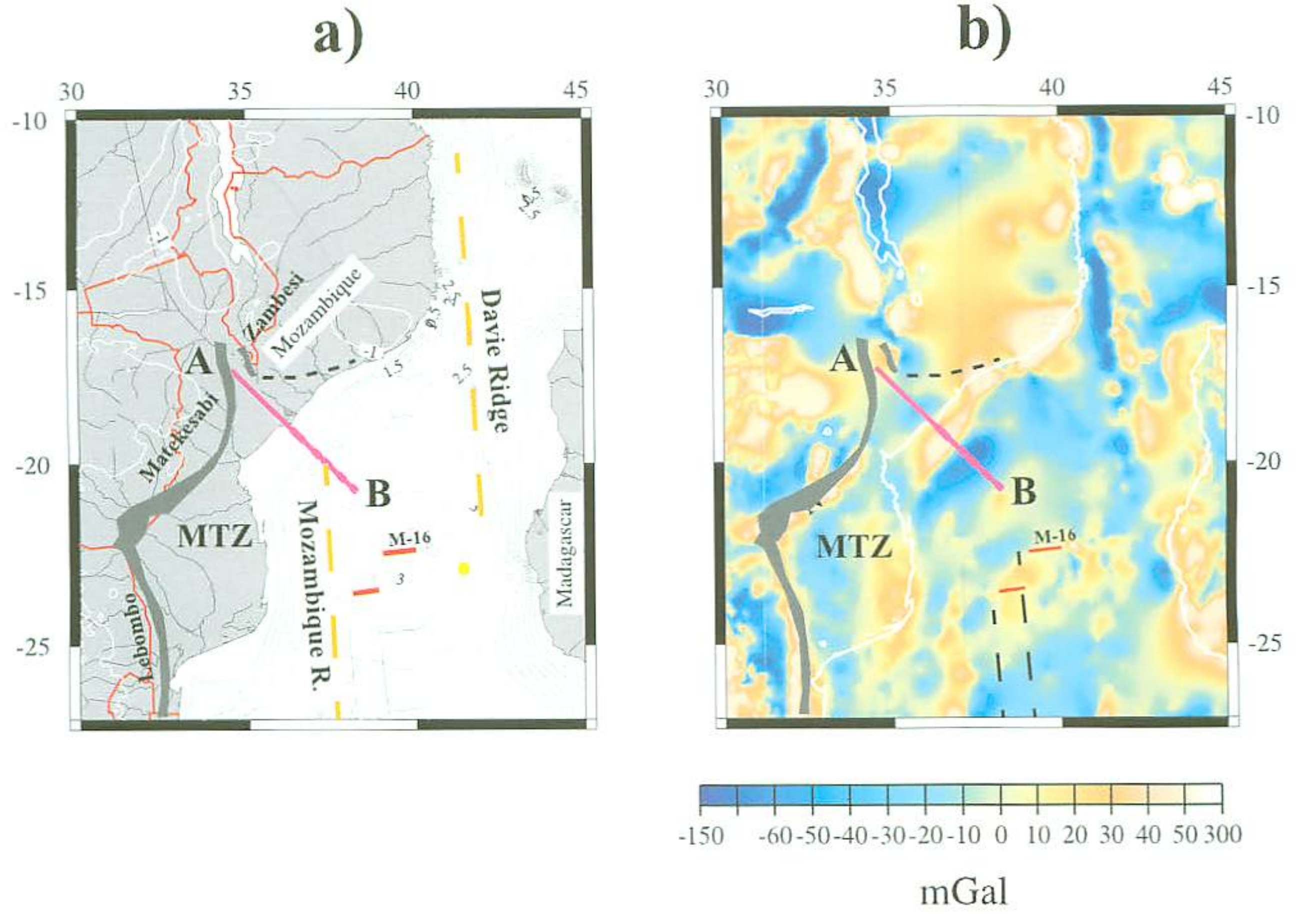

Fig. 2. Topography and gravity anomaly map of the Mozambique margin in the vicinity of the Zambesi river delta. (a) Topography. (b) Gravity anomaly. Offshore = free-air anomaly; BA = Bouguer anomaly. Dark grey shades show the Karoo volcanic monoclines of Lebombo, Matekesabi and Zambesi (Cox, 1992). MTZ, Mozambique Thinned Zone. AB shows the location of the profile modelled in Figs. 4–6.

plate southwards relative to Africa. The movement was accomplished along active transform faults and resulted in the formation of the oldest-known oceanic crust of the Indian ocean in the Mozambique and Somali basins (Simpson et al., 1979).

One consequence of the two-stage break-up was the creation of a broad zone of 'transitional' crust that now underlies much of the coastal plain of southern Mozambique. Dubbed the Mozambique Thinned Zone (MTZ) by Cox (1992), it is not clear from existing geophysical data whether it represents thinned continental, oceanic crust or, some combination of these crustal types.

Recently, BPX made available a seismic reflection profile which intersects the rifted margin offshore southern Mozambique, in the region of the Zambesi river delta (Fig. 2). The NW–SE trending profile extends from the upper reaches of the Zambesi river, across the northeastern extremity of the MTZ, and into the Mozambique basin. Gravity anomaly compilations by GETECH (Fairhead et al., 1988) show that the seismic profile crosses a large-amplitude (up to +50 mgal) gravity anomaly 'high' at the shelf break. The high is bounded by prominent lows (up to −75 mgal) on both its seaward and landward side. A similar pattern of gravity anomalies characterises the margin further to the south.

The first step in modelling was to progressively backstrip the main stratigraphic units identified on the seismic profile. A total of four stratigraphic units were identified by workers at BPX using seismic and well ties (e.g. Fig. 3). The tectonic subsidence and uplift obtained by backstripping each unit was then used to compute the backstrip Moho assuming an Airy isostatic model. The next step was to calculate the rifting anomaly (from the tectonic subsidence and uplift and the backstrip Moho) and the sedimentation anomaly (from the sediment load and its compensation at the top and base of the crust). Finally, the two anomalies were summed and compared to the observed free-air gravity anomaly.

Fig. 4 compares the calculated and observed gravity anomalies. The rifting anomaly is characterised by two edge effects, one corresponding to the former position of the shelf break, inland of the coastline, and the other to the region where the Mozambique Ridge intersects the margin. The sedimentation anomaly is characterised by a

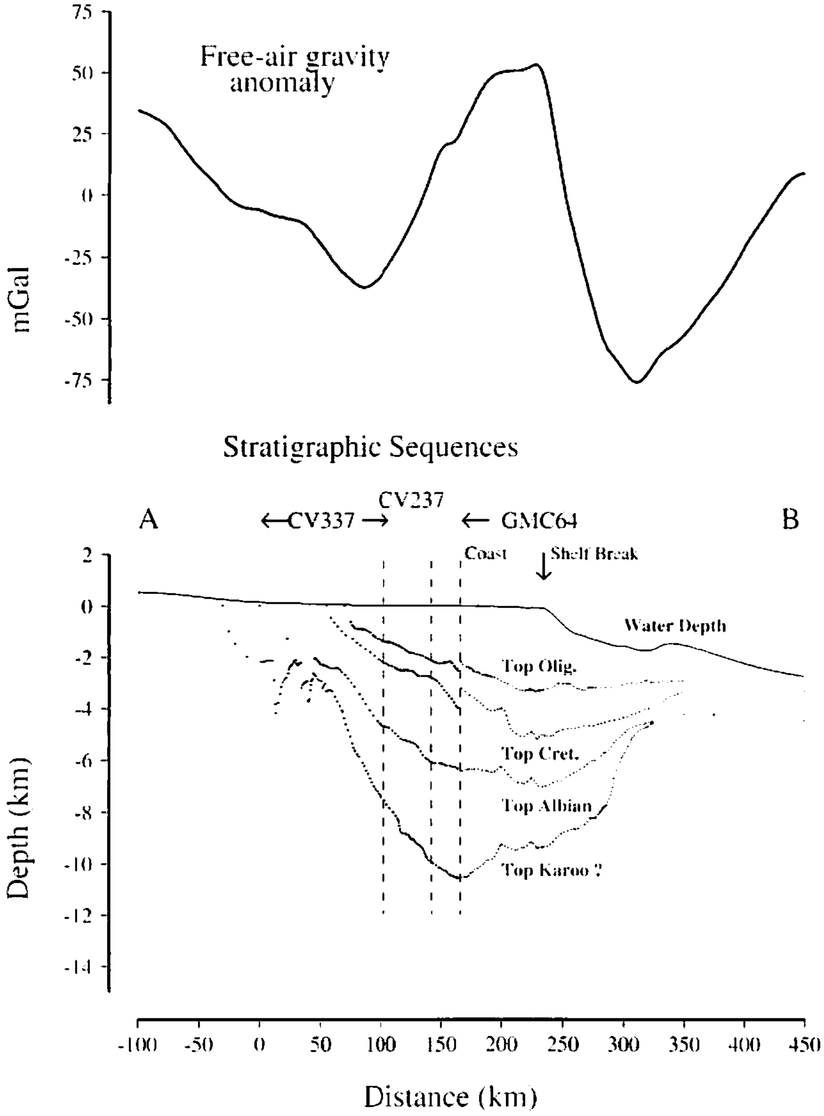

Fig. 3. Summary of the gravity anomaly and seismic reflection profile data along Profile AB of the Mozambique margin (Fig. 2). The gravity anomaly is based on data compiled by GETECH as part of its African Gravity Project. The dots show the digitised points that were used to define the boundaries of the main stratigraphic units on depth-converted seismic reflection profiles. CV237, CV337 and GMC64 refer to onshore and offshore profiles acquired by BPX.

large amplitude gravity high which is flanked by two lows. Since the rifting anomaly is relatively subdued in the region between the two edge effects, the sum anomaly resembles the sedimentation anomaly with its large amplitude central high and two flanking lows. The sum anomaly generally accounts for the pattern of gravity anomalies that are observed (i.e. the distribution of highs and lows), but fails to explain the detailed shape of the anomalies.

The calculations in Fig. 4 assume $T_e = 35$ km. In order to improve the fit between calculated and observed gravity anomalies we therefore backstripped the sediments using a wider range of T_e values, including values that varied with the age of the stratigraphic unit since rifting (which we assumed to occur at 170 Ma). Fig. 5 for example, shows the sum anomalies for four cases where T_e follows the depth of the 150, 300, 450 or 600°C oceanic isotherms. In each case, T_e is low initially because of the proximity of the margin to the mid-ocean ridge and then increases as the lithosphere cools and increases its strength with age as the ridge increases its distance from the margin.

The figure shows that a T_e varying with age model is unable to explain all the details of the observed profile. However, portions of the profile *can* be quite well explained. The landward slope of the high, for example, can be explained by the calculated anomaly that is based on a T_e that depends on the depth to the 450°C isotherm. Lower isotherms predict a slope that is too gentle while a higher isotherm predicts one that is too steep. Other parts of the profile appear to require different controlling isotherms.

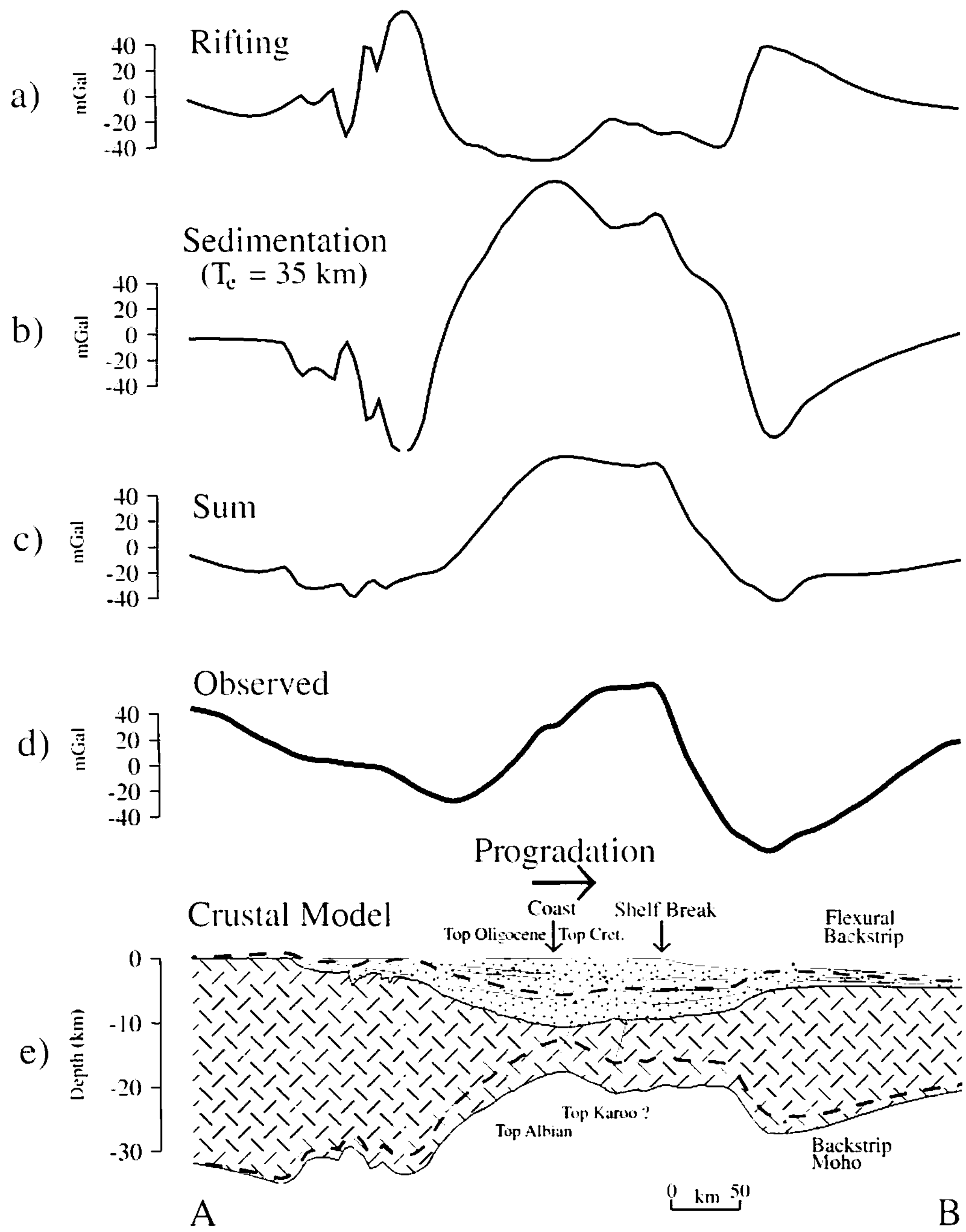

Fig. 4. Combined backstripping and gravity modelling of the stratigraphic data along Profile AB. (a) Rifting anomaly; (b) sedimentation anomaly; (c) sum anomaly; (d) observed gravity anomaly (offshore = free-air, onshore = Bouguer) and (e) crustal model. The flexural backstrip (heavy dashed line) was obtained by progressively backstripping the sediments using a uniform T_e of 35 km and densities of 2600, 2400, 2300 and 2100 kg m^{-3} for stratigraphic units 1 (Jurassic–Early Cretaceous), 2 (Late Cretaceous), 3 (Palaeocene–Oligocene) and 4 (Miocene–Recent), respectively. The backstrip Moho was computed from the flexural backstrip assuming a local model (Airy) of isostasy with a zero elevation crustal thickness of 31.2 km.

The crest of the high, for example, seems to be best fit by a higher controlling isotherm whilst the low on the landward side of the high favours a lower one.

Since we know from oceanic island and seamount loading studies (Watts, 1978) that oceanic T_e depends on the depth to the 450°C oceanic isotherm, then the results in Fig. 5 suggests that at least part of the high offshore the Zambesi delta is underlain by oceanic crust. The margins of the oceanic crust are not well determined. However, the low on the landward side of the high suggests that a relatively low rigidity characterises this region.

Fig. 6 shows that a model in which T_e varies spatially across the margin offshore southern Mozambique from low values in the interior to high values beneath coastal regions explain the observations. In particular, a model in

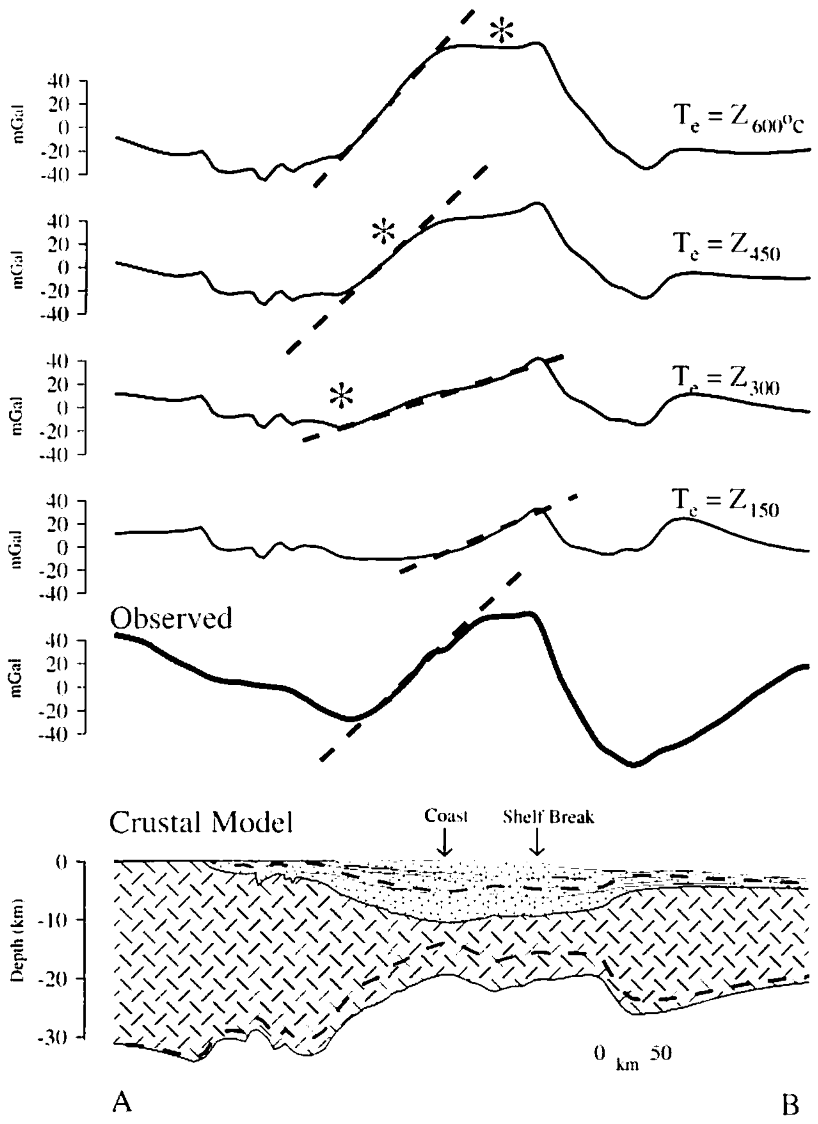

Fig. 5. Calculated gravity anomalies based on a T_e that varies with age since initial rifting. The asterisks indicate those portions of the calculated profiles that agree well with the observations.

which T_e is low between the upper reaches of the Zambesi and a point 100 km inland of the coast and then increases across a 30–50 km wide transition zone to values expected by the depth to the 450°C oceanic isotherm explains the amplitude and wavelength of the anomalies along much of the western end of the profile.

The main problem is not being able to account for the low at the eastern end of the profile. We found that no combination in T_e structure could explain this low. The low correlates with a bathymetric high and the intersection of the N–S trending Mozambique Ridge (Fig. 2) with the Mozambique margin. One possibility therefore is that the ridge is overcompensated such that the crust is thicker than has been predicted from the sediment backstrip. We found, for example, that a model in which the crust is thicker by about 4 km than predicted by an Airy model explains the data. The origin of the thickened crust is unclear but, it might represent magmatic material that has underplated the newly formed oceanic crust.

Irrespective of the origin of the gravity low, it is clear that a major portion of the sediments that make up the present day coastal plain of southern Mozambique loaded oceanic crust. The region underlain by oceanic crust is bounded to the east by the N–S trending Mozambique ridge and to the west by the Karoo volcanic sequences that make up the Lebombo, Matekesabi and Zambesi monoclines. Between these two features is the MTZ of Cox (1992). Hence, a significant part of the MTZ appears to be underlain by oceanic rather than extended continental crust and we speculate that it represents the 'missing' crust that was generated by sea-floor spreading during the first stage of break-up of Africa and Antarctica.

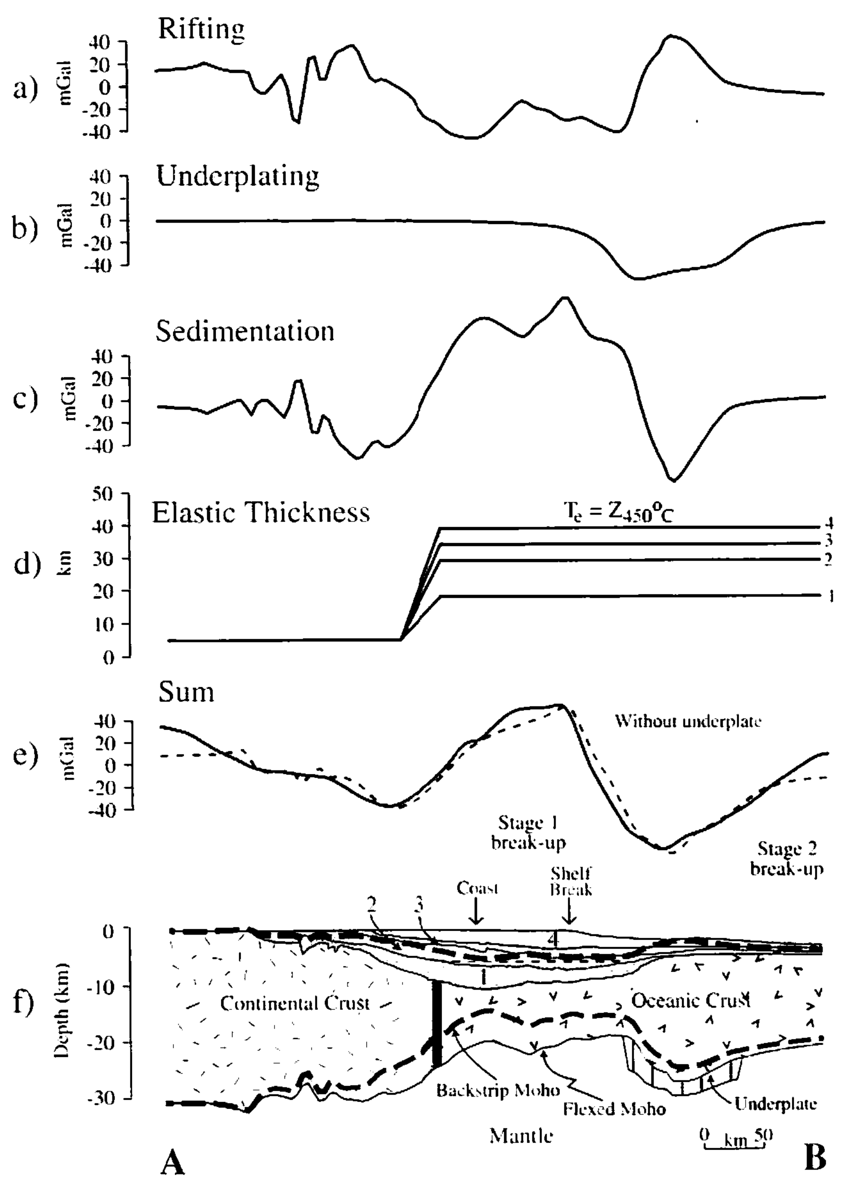

Fig. 6. Comparison of the best fit calculated and observed gravity anomalies along profile AB. (a) Rifting anomaly; (b) underplating anomaly; (c) sedimentation anomaly; (d) T_e structure assumed for stratigraphic units 1–4 and (e) sum anomaly. Black line = observed; dashed line = calculated; grey line = calculated *without* the underplated body. (f) Crustal model.

6. Discussion

The process oriented modelling approach is based on potential field data and so carries with it an inherent ambiguity. We believe, however, that by adopting a combined backstripping and gravity modelling approach, which takes into account plausible thermal and mechanical models for the manner that sedimentary and magmatic material might load the lithosphere, we have significantly reduced the ambiguity.

While we have demonstrated its application to the southern Mozambique margin, the approach may not always provide a definitive answer on crustal type. This is partly because of problems to do with data. The approach relies, for example, on high-quality seismic images of the sediments and the underlying 'basement'. Because of salt tectonics or basaltic flows, however, such images may be difficult to obtain.

Other problems relate to uncertainties in the rheology of extended continental lithosphere. We have assumed in modelling the Mozambique margin, for example, an Airy model to compute the rifting gravity anomaly. Such a model implies a lithosphere that is intrinsically weak. As several workers have pointed out, there is evidence from the rift flank uplifts that persist for long-periods of time at many rifted margins, that the lithosphere has a certain strength during rifting (Kooi et al., 1992; Weissel & Karner, 1989). The role that the strength of the lithosphere plays, in contributing to the rifting gravity anomaly depends, however, on the depth of the strength maxima in the lithosphere. There is a certain depth (about 7.2 km) that the rifting anomaly will resemble the predictions of the Airy model — *irrespective of the strength during rifting* (Kooi et al., 1992). Rifted margins where variations in the strength maxima have been taken into account give mixed results. Some (e.g. Nova Scotia, West Greenland, Tyrrhenian Sea, Gulf of Lion) require either large or shallow depths in the strength maxima in order to account for the amplitude and wavelength of the observed gravity anomalies (Cloetingh, van Wees, van der Beek, & Spadini, 1995; Keen & Dehler, 1997). Hence, strength during rifting is probably important at these margins. Others (e.g. Gabon, Goban Spur, Southern Grand Banks, Orphan Basin, Labrador), however, are compatible with depths in the strength maxima that are within a few km of what would be expected for an Airy model (Keen & Dehler, 1997; Watts & Stewart, 1998). In these basins, the rifting anomaly will resemble the Airy case, irrespective of the actual strength during rifting.

Our approach in modelling the Mozambique margin has been to use the simple Airy model to compute the rifting anomaly. While such a model explains the observed gravity anomaly data, we do not mean to imply that it might not be possible to explain the data with a model that incorporates some degree of strength during rifting. The point here, which was also made offshore Gabon, is that the gravity anomaly data over the Mozambique margin do not require a model that incorporates strength during rifting in order to explain them.

Finally, there is the problem that there may not have been sufficient time for the youngest sedimentary sequences on rifted margins to have been isostatically compensated. This is suggested by the close association of unusually large-amplitude free-air gravity anomaly highs with rapidly deposited Pliocene and younger sediments at some rifted margins in the western Mediterranean (Watts & Torné, 1992) and Arctic oceans (Vogt, Jung, & Brozena, 1998). Thus, margins may appear to be strong and have a high T_e, even if most of their sediment was actually deposited on weak lithosphere.

We believe, however, that with the application of the combined backstripping and gravity modelling approach to more margin systems we should be able to address the rheology problems in the future. We have recently developed, for example, a method (Watts & Stewart, 1998) that is able to use the tectonic subsidence and uplift deduced from backstripping to compute the backstrip Moho that takes into account the possibility of strength during rifting.

Our modelling results have a number of implications to the hydrocarbons industry. First, the determination of crustal type beneath a sedimentary basin (i.e. whether stretched continent or oceanic) is important with regard to source rocks. Second, the crustal structure is an important constraint on heat flow at a rifted margin. Since the rate of maturation of organic matter in sediments depends strongly on the duration of heating, the crustal thickness can be used, together with the depositional architecture (e.g. porosity, permeability), to better understand the sub-surface fluid circulation in rifted margins.

Finally, the modelling should help better understand the gravity anomaly 'segmentation' that is observed along-strike of some rifted margins. The origin of the segmentation is not clear. It might be related to kinematics of the newly formed ocean basin. Cochran and Martinez (1988) for example, suggest that in the Red Sea, accomodation zones that take-up displacement between sets of fault blocks, extend perpendicularly across the margin *and* the mid-ocean ridge. Furthermore, Behn and Lin (2000) have shown that gravity anomalies along-strike of the East Coast, USA margin display a segmentation at length scales of 100–150 km, which is similar to the segmentation of the mantle Bouguer anomaly observed along the present day mid-oceanic ridge. Alternatively, the segmentation may reflect fundamental differences in the thermal and mechanical properties of the continental lithosphere. Watts and Stewart (1998) for example, suggest that the gravity anomaly segmentation offshore West Africa reflects along-strike variations in the flexural strength of extended continental lithosphere. We do not know, however, whether these strength variations are the consequence of re-setting by rifting or represent intrinsic differences in the flexural strength of the African lithosphere which have been 'inherited' by the developing margin. Irrespective of the origin, along-strike variations in the strength of rifted continental lithosphere would be expected to influence not only the tectonic history, but also the pattern of faulting (e.g. fault lengths) in the basement and, hence, the geometry of the syn-rift sedimentary fill. It might also influence the hydrocarbon play. We know, for example, that some margins (e.g. East Coast, Canada) are highly segmented as regards their productivity in oil and gas, with some segments being rich (e.g. Newfoundland) and others being poor (e.g. Nova Scotia), even though the age of rifting is approximately the same along-strike of the margin. The development of new national and international programmes in deep-water continental margins offer an exciting new possibility to address this, and other related problems, in the future.

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