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ORIGINAL PAPER

Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinisation and symmetry

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Abstract The symmetry or asymmetry of the process of continental breakup has been much debated over the last 20 years, with various authors proposing asymmetric simple shear models, others advocating more symmetric, pure shear models and some combinations of the two. The unroofing of vast expanses of sub-continental mantle at non-volcanic margins has led some authors to argue in favour of simple shear models, but supporting evidence is lacking. Subsidence evidence from conjugate margin pairs is equivocal, and the detailed crustal and lithospheric structure of such pairs not generally well enough known to draw firm conclusions. In the Porcupine Basin, where the final stages of break-up are preserved, the development of structural asymmetry is demonstrable, and apparently related to late stage coupling of the crust to the mantle following the complete embrittlement of the crust. This agrees with theoretical modelling results, which predict that asymmetric models can develop only on a lithospheric scale when the crust and mantle are tightly coupled. However, whether such asymmetry is maintained during continued exhumation of the mantle is unclear.

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Introduction

The breakup of continents to form oceans is a first order tectonic process and the start of the plate tectonic cycle of plate creation and destruction. However, the extensional evolution going from early rifting through breakup to seafloor spreading remains the subject of considerable discussion. In particular, the large-scale symmetry of the process and of the resulting lithospheric and crustal structure is much debated. Here we review some of the outstanding questions and present some possible solutions.

The terms symmetry and asymmetry applied to the formation of rift basins and rifted margin pairs generally refer to a large-scale (a)symmetry about a vertical axis of crustal structure, subsidence history and/or the presence of master detachment faults that control the extension. Asymmetry in the distribution of any of these may (but need not) reflect an asymmetry in the process of extension. However, it is important here to stress the difference between asymmetry of final structure and that of the process of extension. Rifted margins develop through long and complex phases of extension. Even if each phase of extension is completely symmetric, their distribution in space and time may lead to the formation of an asymmetric overall structure. For instance initial symmetric rifting may form a basin that becomes abandoned before renewed symmetric rifting occurs on the first basin's flanks, leading eventually to an asymmetric margin. In such a case, the extensional process may have always been symmetric but the resulting structure is strongly asymmetric. The key here is to identify the timing of rifting and to distinguish between the process and the resulting structure.

It is also important to consider the scale of asymmetry. Within an individual basin, it is quite common for faults to dominantly dip in one direction for reasons of strain compatibility. One example is the domino model, but it is not necessary for all faults to be active at the same time for such a dip dominance to result. However, unless these faults are somehow linked by a throughgoing detachment of some kind or unless the locus of deep lithospheric and shallow lithospheric thinning are laterally offset, it is quite possible for motion along such faults to produce a symmetric basin. A case in point is the North Sea, discussed below.

Pure and simple shear

Early work on the large-scale symmetry or asymmetry of the process of lithospheric extension focused on two end-member models (Fig. 1): pure shear and simple shear (McKenzie 1978; Wernicke 1981, 1985; Buck et al. 1988). Concepts of a rheological stratification of the lithosphere and in particular the idea of a weak, plastic lower crust (e.g. Kusznir and Park 1987) presented problems with the idea of a simple, throughgoing lithospheric fault, but the simple shear concept resurfaced with the introduction of ramp-flat and other geometries (Lister et al. 1991), in some of which the shear zone cut through the entire lithosphere whereas in others did not. Lister et al. (1991) also proposed models in which the detachment soled out within the crust or at the Moho. Such models remain popular and are invoked still to explain perceived asymmetries in the structure of basins and conjugate margin pairs (e.g. Ziegler and Cloetingh 2004; Maillard et al. 2006).

Gibbs (1987) proposed that the dominant asymmetry in tilt direction of fault blocks in the North Sea could be explained if they were synthetic to a master fault zone in a simple shear model. However, Klemperer (1988) pointed out that a local asymmetry in fault orientation was an expected feature of even symmetric rifts as fault kinematics favoured domains of dominant dip (e.g. the domino model). (Note that the domino model does not imply that all faults are active simultaneously). On the other hand, it rapidly became clear that the asymmetric simple shear model did not necessarily predict grossly asymmetric pairs of margins and/or basins. Attempts to support the pure shear model by Klemperer (1988) from the overall symmetry of North Sea crustal structure, as well as the earlier arguments of Le Pichon and Sibuet (1981) based on apparent match between *total* subsidence and crustal thinning, failed to demonstrate that a simple shear model could not equally well predict such a match. When the subsidence behaviour of the simple shear model was investigated (Voorhoeve and Houseman 1988; Buck et al. 1988; White 1989) it became clear that a through-going linear shear zone would also in its simplest case produce a symmetrical thinning of the crust (Fig. 2), resulting, under conditions of local isostasy at least, in a symmetrical basin or conjugate margin pair. However, the models did show that a finer-scale asymmetry was to be expected, in terms of the relative distribution of synrift and postrift

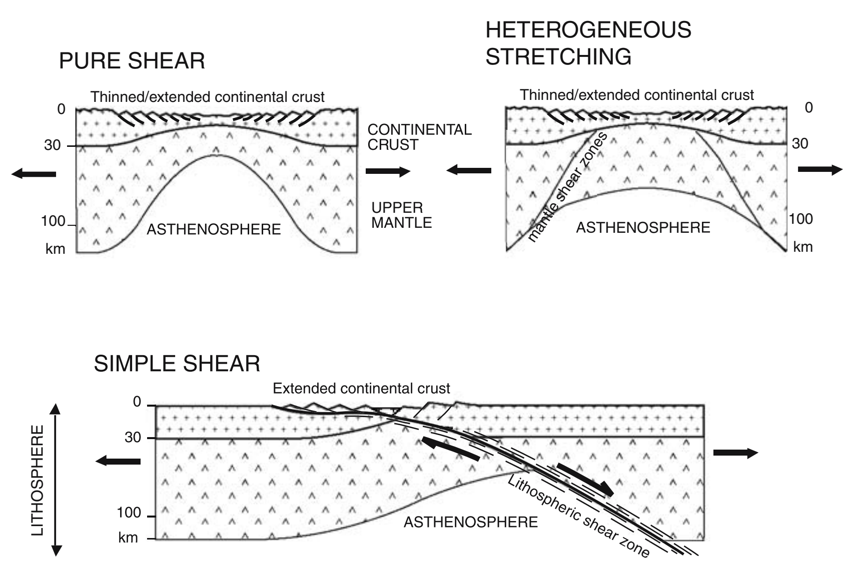

Fig. 1 Models of symmetric and asymmetric lithospheric extension: pure shear (McKenzie 1978), heterogeneous stretching (Reston 1990—both symmetric) and simple shear (Wernicke 1985—asymmetric)

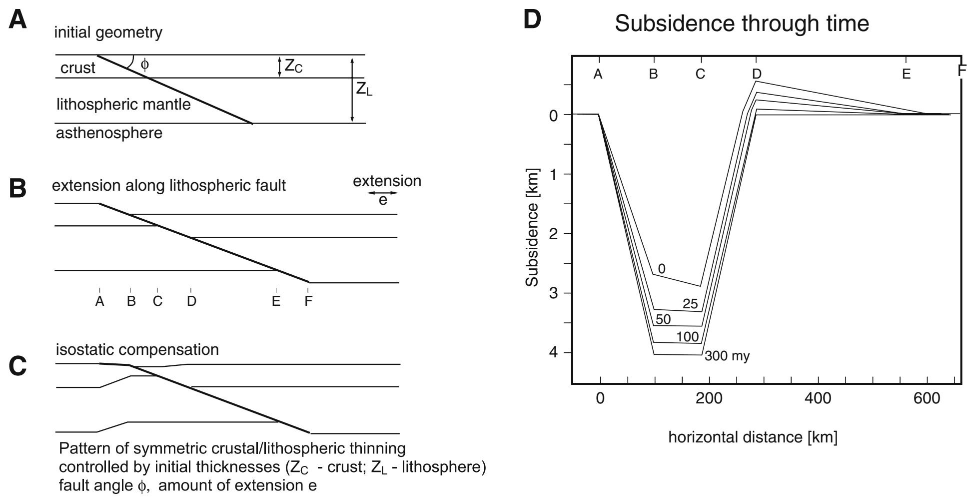

Fig. 2 The effect of simple shear on crustal structure and hence on subsidence (redrawn from Voorhoeve and Houseman 1988). A linear lithospheric shear zone will lead to symmetric crustal thinning, thus to symmetric total subsidence, but different ratios of synrift and postrift subsidence and of upper crustal and lower crustal thinning

subsidence, and in the thinning of different crustal levels: the thinning of the lower crust was displaced down dip from the thinning of the upper crust. Furthermore, Latin and White (1990) pointed out that the simple shear model would predict both a marked offset in the locus of and a marked reduction in the amount of asthenospheric upwelling, leading to vastly reduced magmatism beneath the rift.

Where the stratigraphic controls were best (e.g. in the northern North Sea), the relative symmetries of postrift and synrift subsidence were used to support a pure shear model (White 1989), albeit modified to allow a wider region of mantle than of crustal stretching (White and McKenzie 1988). Reston (1990, 1993) showed that a simple mechanism to widen the region of mantle extension would be through movement along outward-dipping mantle shear zones, following outward-dipping mantle reflections imaged symmetrically on either side of the basin on seismic profiles (Fig. 1). Similar outward-dipping shear zones are also predicted by numerical modelling (e.g. Harry and Sawyer 1992), and mean that crustal extension in the centre of the rift exceeds that in the underlying mantle, an inference that has implications for the geometry of breakup as discussed more below.

Non-volcanic margins

Although results from rift basins indicate that these are not necessarily asymmetric at a crustal or lithospheric scale, and despite the rheological problems with the concept of a through-going shear zone, the perceived asymmetry of conjugate margin pairs has led to the continued advocation by some authors of the simple shear model (e.g. Ziegler and Cloetingh 2004; Maillard et al. 2006). At such margins, studies of the subsidence behaviour have not been able to distinguish between pure shear and simple shear for two reasons. Where the margin is well-supplied with sediment throughout its evolution, the deepest synrift units are so deeply buried that they cannot be sampled; where such margins are sediment-starved, most of the sediments are deposited in deep water where the paleobathymetric controls are so poor that meaningful estimates of tectonic subsidence after back-stripping are impossible. Although studies of active rifts could in principle help address these problems (substituting heat flow measurement for postrift subsidence as a proxy for the thinning of the lithosphere), there are few such margins, and even fewer appropriate studies. Buck et al. (1988) did point out that the structure and heat distribution of the northern Red Sea, once invoked as an example of simple shear lithospheric extension (Wernicke 1985), could be best explained by a symmetric model.

Nevertheless, the observation of apparent detachment faults at non-volcanic rifted margins (e.g. Reston et al. 1996) and the unroofing of wide expanses of mantle rocks (Fig. 3) at these margins (e.g. Pickup et al. 1996) appears to suggest that simple shear does have some role to play in margin tectonics. Here some confusion seems to exist about the term "detachment" and in particular "detachment fault" which some authors use interchangeably with a lithospheric-scale shear zone as envisaged by Wernicke (1985). In this paper the term "detachment" is used for a major structure onto which other faults detach, and a detachment fault is thus a brittle structure (a fault) onto which other (usually steeper) faults detach (Lister and Davis 1989). Neither term implies a structure passing through the entire lithosphere. Thus the

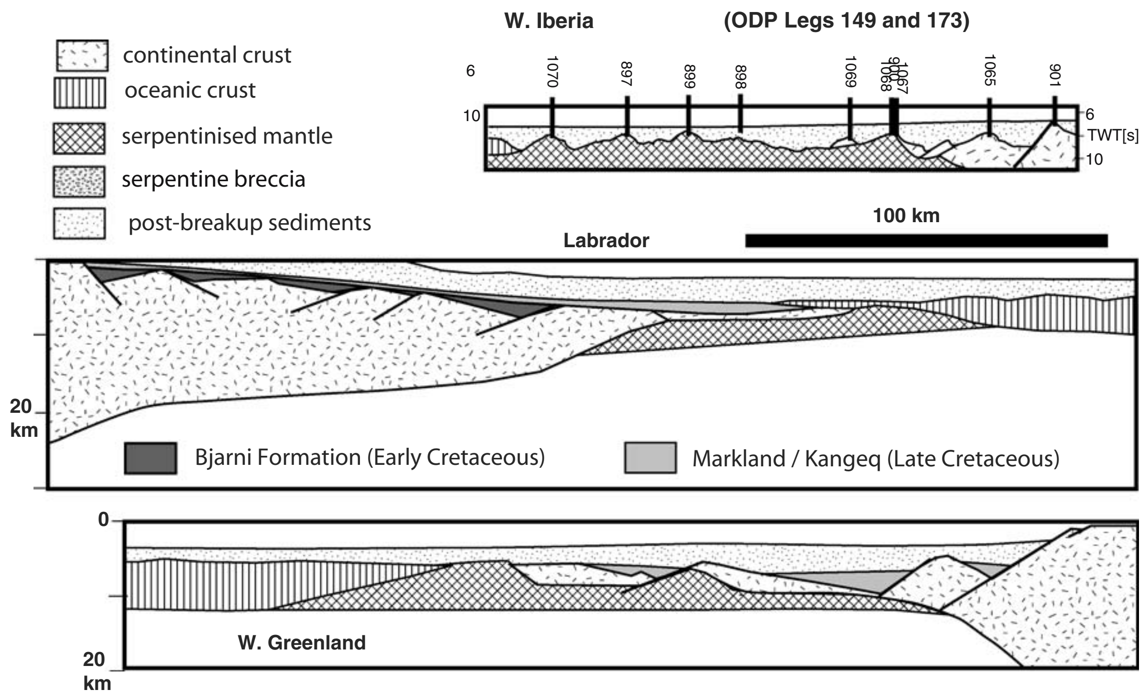

Fig. 3 Non-volcanic margin summaries, at a vertical exaggeration of about 2:1. *Top section* through the west Iberia continent margin (*IAP*) based on seismic profiles and ODP drilling (Whitmarsh et al. 2001); *Middle* the Labrador margin (Chalmers and Pulvertaft 2001) showing extensional faulting of Bjarni but not the Markland Formations, and a zone of mantle serpentinites within the COT. *Bottom* the conjugate west Greenland margin (modified after Chalmers and Pulvertaft 2001): here the transitional crust NE of exhumed mantle peridotites is interpreted as a mix of continental crust and mantle rocks. Note that the Kangeq sequence, age equivalent of the Markland Formation on the Labrador margin, is faulted on the West Greenland margin

observation of probable detachment faults at some margins does not necessarily imply simple shear on a lithospheric scale.

One possibility is that symmetric extension evolves into more asymmetric extension with time (Sibuet 1992; Whitmarsh et al. 2000). In this paper we argue that the observations are consistent with such a transition from symmetric to asymmetric rifting during late-stage extension and that this transition follows the embrittlement of the crust and the serpentinisation of the uppermost mantle.

This paper is largely concerned with the so-called non-volcanic rifted margins (NVRMs) where the structural controls on extension are best known, but some volcanic margins also show a marked asymmetry (Hopper et al. 2003). The causes of asymmetry at volcanic margins may, however, be rather different from those of NVRMs, reflecting for instance the relative location of an underlying plume and the resultant thermal and magmatic weakening as well as the component of deviatoric tension caused by plume uplift. However, little is known about the asymmetry of such margins and they are beyond the scope of this paper.

Numerical modelling of rifting

Numerical modelling has shown that asymmetric rifting is to be expected if the starting model is asymmetric (e.g. Braun and Beaumont 1987, 1989; Dunbar and Sawyer 1989). In some models, asymmetry also develops during extension, for instance when rift localisation is initially controlled by a local crustal weakness: a mantle weakness develops through strain softening at the edge of the crustal rift, leading to breakup at the edge of an abandoned earlier basin (Dunbar and Sawyer 1989). However, these models are not strictly simple shear as no throughgoing shear zone develops due to the presence of a lower crustal decoupling zone.

Braun and Beaumont (1987, 1989) explored the effect offset crustal and mantle weaknesses could have on lithospheric deformation. They showed that the viscosity of the weak lower crustal layers was critical here as it limited the distances over which extension could be transferred between upper and lower crust. The resultant shearing of the lower crust provides a possible explanation for its highly reflective nature (Reston 1988, 1990).

Huismans and Beaumont (2002) investigated asymmetry developed during early rifting before breakup by modelling the development of major faults by allowing strain softening within the shear zone. They showed that the presence or absence of a decoupling zone at the base of the crust strongly influences whether rifting becomes asymmetric or not: a through-going structure could develop if the various lithospheric layers are strongly coupled (Fig. 4). Just as rheologically weak layers make lithospheric simple shear unlikely, the absence of such layers may allow it to develop. In this regard, the rheological evolution of the crust/lithosphere during extension is particularly apposite.

Bassi (1995) took a different approach, investigating the effects of lithospheric weakening and strengthening during rifting leading to breakup. The weakening is due to thermal thinning at high extension rates; the strengthening at slow extension rates is due to the thickening of the mantle portion of the lithosphere by cooling (Kusznir and Park 1987). This work showed that asymmetry in the position of continental breakup could develop following slow extension of warm lithosphere due to strengthening in the centre of the rift (replacement of weak crust by stronger mantle), with breakup finally occurring at the edge of the basin. A similar explanation was invoked by Davison (1997) to explain local asymmetry in the margins of the South Atlantic. However, at faster extension rates, such an effect does not happen as insufficient strengthening takes place (Bassi 1995); furthermore, for cooler models where the crust is not so weak, the relative strengthening also does not take place, and so breakup remains symmetric.

An additional effect was explored by Buck (1991) and Hopper and Buck (1996), namely the resistance to localised extension caused by the work against gravity required to bring high density mantle up to the surface. This meant that strain hardening could also occur at faster extension rates, leading to a broadening of the rift. Eventual breakup in this model occurred at one edge of the broad zone.

Thus a feature of many of the modelling studies is the change from roughly symmetric initial extension to asymmetric late stage extension and breakup. However, none of these previous studies investigated the effect of mantle serpentinisation on the localisation of strain and the development of asymmetric structures. As discussed below, this may be a major control on the development of late-stage detachments and hence on the asymmetry of both late stage continental extension and final breakup.

Rheological evolution of the lithosphere

Numerical modelling of the rheological evolution of the lithosphere (Pérez-Gussinyé and Reston 2001; Pérez-Gussinyé et al. 2006) shows that as extension proceeds, the crust thins and deep crustal rocks are brought closer to the surface. The resulting pressure drop serves to make brittle deformation (controlled by overburden pressure but independent of temperature) easier, whereas any concomitant cooling makes plastic deformation or creep (controlled by temperature but not by pressure) more difficult. The overall effect is for creeping rocks to become brittle (Fig. 5). Eventually creeping zones in the mid and lower crust disappear, moving the entire upper lithosphere into the brittle regime.

Brittle deformation is by its very nature dilatant. As a result, fluids, in particular water, are drawn into the

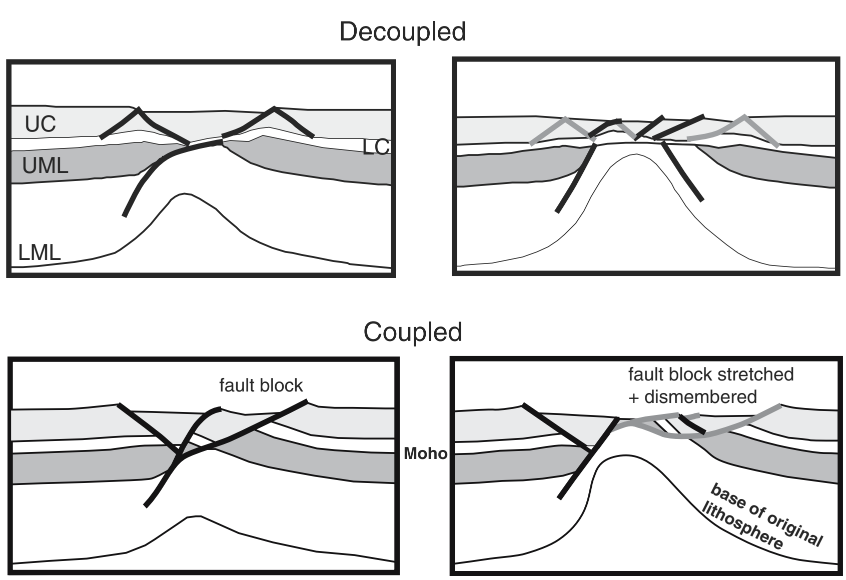

Fig. 4 Summary of the effects of lower crustal decoupling/coupling on the symmetry of extension. Asymmetry is favoured when the upper crust is strongly coupled to the mantle (Huismans and Beaumont 2003). *UC* upper crust, *LC* lower crust, *UML* upper mantle lithosphere, *LML* lower mantle lithosphere

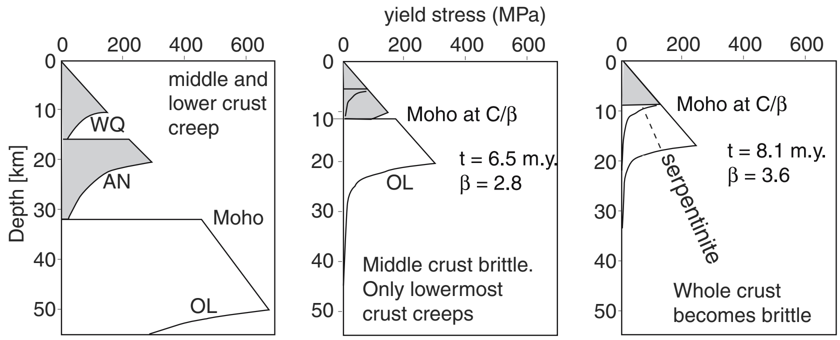

Fig. 5 Rheological evolution of the lithosphere during extension, expressed as yield strength envelopes. Initial plastic zones in the mid- and lower crust disappear as the crust thins (pressure release makes brittle deformation easier) and cools (making plastic creep more difficult). Eventually the whole crust becomes brittle and faults can penetrate from the seafloor into the mantle, leading to serpentinisation. Note that the integrated strength of the lithosphere (the area to the left of the curve) is decreasing even as the ''weak'' lower crust becomes brittle

fault, a process sometimes described as seismic pumping. When throughgoing faults develop, voluminous water is drawn into the entire length of the fault zone; when these faults cut across the entire crust, surface water can reach the mantle for the first time. At temperatures below 500°C, olivine reacts with water to produce serpentine, which has an unusually low friction coefficient. The root zones of such faults in the mantle are therefore likely to become the focus of further rifting.

The volumes of water that can reach the mantle by these means are huge. Assuming a fault spacing of 5 km, a fault dilatancy of only 1 cm, and activity every 100 years over 10 Myr implies that a volume of water equivalent to 20% of the brittle uppermost mantle can be pumped into it, sufficient to cause about 50% serpentinisation. Increasing the rift duration beyond the lower limit of 10 Myr or the amount of fault dilatancy, or decreasing either the fault spacing or earthquake interval would all correspondingly increase the volume of water reaching the mantle. Hydrothermal or convective circulation would also increase the volumes involved. Thus, the volumes of water that can be pumped into the mantle can explain over 50% serpentinisation of the brittle upper mantle, consistent with observations from margins described below. More critical but also more difficult to estimate may be the rate and distance the fluids can penetrate away from the fault into the fractured serpentinising zones in the hangingwall and footwall of the faults.

Pérez-Gussinyé and Reston (2001) numerically modelled the embrittlement of the crust and the resulting serpentinisation of the mantle. Using a 1-D finite difference code to track temperature and lithology and hence to predict rheology, they investigated when the entire crust should become brittle. They further tracked the portions of the mantle where the temperature was less than 500°C to estimate the maximum depth beneath the Moho at which serpentinisation can take place. For the sort of crustal and lithospheric structure expected for west Iberia, Newfoundland, Labrador and West Greenland (Pérez-Gussinyé et al. 2001), the models show that the crust becomes brittle at a stretching factor of about 4, and that a thickness of about 6–8 km of the upper mantle should become partially serpentinised.

West Galicia margin and conjugate Flemish Cap margin

The overall extension mechanism of the continental lithosphere can be partly deduced from seismic images and crustal structure. For instance, wide-angle data (Pérez-Gussinyé et al. 2003) show that the crust of the Galicia Interior Basin thinned to ~10 km during rifting, consistent with a stretching factor of 3 (Fig. 6). Theoretically this is just less than needed for the entire crust to become brittle (Pérez-Gussinyé and Reston 2001). The seismic velocity structure is indeed consistent with an overall symmetric thinning, despite the dominant eastward-dip of the faults (discussed above). The most recent faults (solid) can be traced on the seismic depth image to within a few km of the Moho beneath the centre of the basin but do not cut the Moho. Seismic velocities in the uppermost mantle preclude large-scale serpentinisation, also suggesting that complete crustal embrittlement did not occur here.

However, the margin further west shows the effects of further extension, the embrittlement of the crust and the onset of serpentinisation. At the deep Galicia

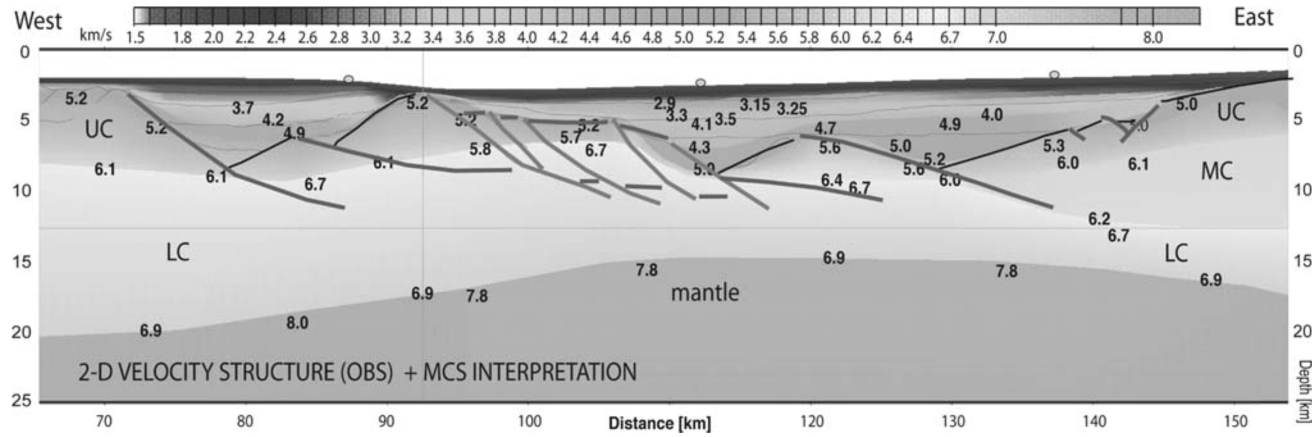

Fig. 6 Velocity structure of the Galicia Interior Basin, showing how the crust thinned to ~10 km during rifting, just insufficient for faults (two phases have been identified, early faults shown here as *bold broken lines*, late faults as *bold solid lines*—Reston 2005) to reach the mantle. Crustal structure is largely symmetric, apart from inherited differences (Central Iberian and Ossa Morena Terranes) to the east and west of the basin (Pérez-Gussinyé et al. 2003)

margin (DGM) east of 12°15′W, the margin consists of large rotated fault blocks bound by west-dipping faults. West of here, the fault blocks are far smaller, are bound by younger faults that detach onto a bright west-cutting structure, the S reflector (Fig. 7). Seismic velocities show that most of S corresponds to the boundary between crust and partially serpentinised mantle (Zelt et al. 2003); only at its eastern end does it cut up through the crust to a basement offset. From the seismic velocities (Zelt et al. 2003) beneath S

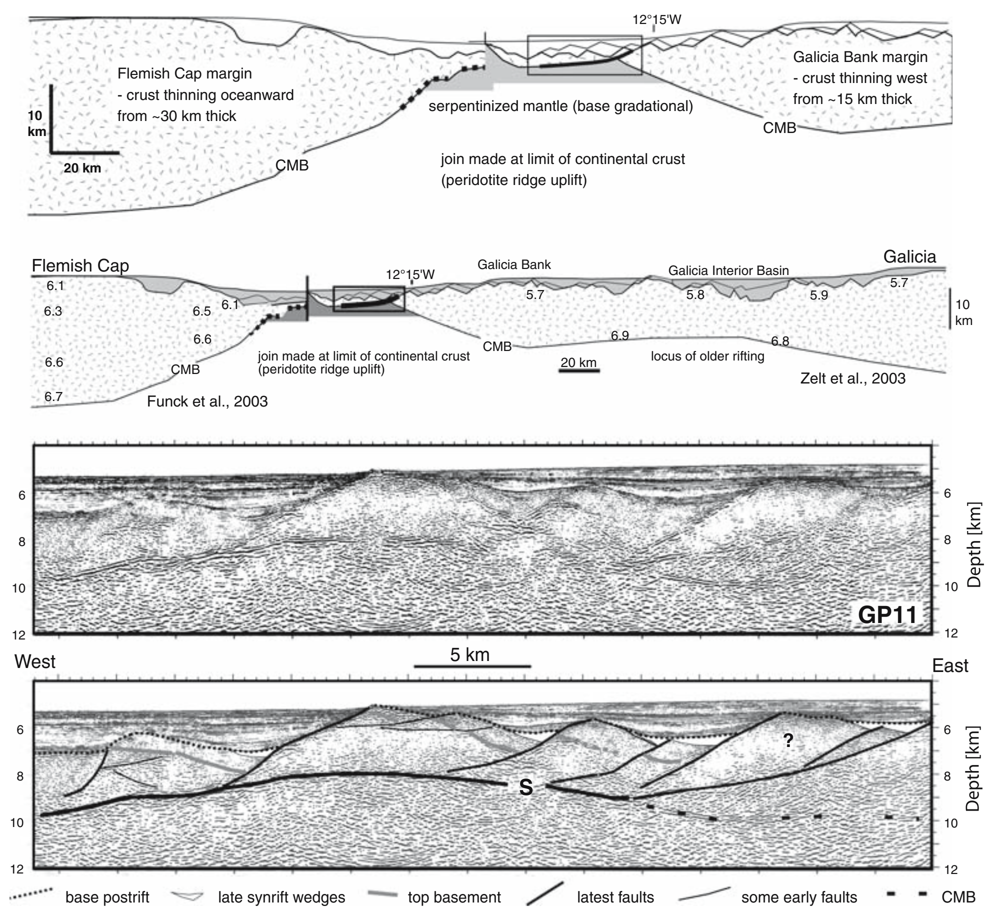

Fig. 7 Top. Conjugate Flemish Cap—Galicia Bank margin pair showing general crustal structure (modified from Funck et al. 2003; Zelt et al. 2003; Hopper et al. 2004) and detail of the Deep Galicia Margin (*box*), showing fault blocks bound by west-dipping faults detaching onto the S reflector, considered to be a serpentinite detachment. S may continue on the Flemish Cap side as a tectonic CMB cutting to depth along the Moho. Below: Seismic profile GP11 across the deep Galicia margin showing fault blocks bound by west-dipping faults detaching onto the S reflector

(>7 km/s), the degree of serpentinisation is probably less than 25% (consistent with estimates of water supply discussed above) and decreases downwards; true mantle velocities are reached less than 5 km beneath S.

The change in margin structure occurs where the crust was thinned to ~8 km during extension. This corresponds to the point where the entire crust should have become brittle (Pérez-Gussinyé and Reston 2001). The development of a detachment (or detachments) in response to the rheological welding of the crust and mantle would at first glance appear paradoxical, but is a logical consequence of removing a thin plastic (but not weak) zone at the base of the crust and the dramatic weakening of the uppermost mantle: the removal of the thin plastic zone has resulted in an overall weakening of the lithosphere (Fig. 5).

The change in margin structure here corresponds also to a local uplift of the ODP site 639 fault block at 12°15′W. This may reflect the flexural-isostatic response to the unloading of the footwall by the collapse of the block immediately to the west into a series of far smaller fault blocks. Thus the onset of serpentinisation and consequent control on collapse of blocks overlying a serpentinised mantle detachment zone has affected the stratigraphic evolution of adjacent blocks.

The symmetry/asymmetry of the development of detachment faulting cannot be addressed at one margin alone, but requires examination of conjugate margin pairs. The conjugate to the west Galicia margin is considered to be the Flemish Cap margin. Overall crustal structure is asymmetric. Major crustal thinning occurs over ca. 300 km on the Iberian side, from the Iberian shelf, over the Galicia Interior Basin and the Galicia Bank to the deep Galicia margin, whereas on the Flemish Cap margin, the crust thins from close to 30 km to zero over about 100 km. This asymmetry however, reflects the various phases of rifting occurring on the margins (the Galicia Interior Basin developed before final rifting at the Deep Galicia margin, Reston 2005) rather than any single phase of asymmetric extension.

At the deep margins, there are aspects of both symmetry and asymmetry. As on the Deep Galicia margin, seismic velocities (Funck et al. 2003) show that the feather edge of the Flemish Cap margin crust is underlain by a zone of reduced mantle velocity, interpreted as partially serpentinised peridotites. Within this unit the velocity increases downwards from about 7 km/s (<25% serpentinisation) to typical unserpentinised mantle velocities (8 km/s) over a thickness of about 6 km, consistent with the modelling results of Pérez-Gussinyé and Reston (2001). The landward limit of the serpentinites occurs where the crust is about 8 km thick, consistent with the complete embrittlement of the crust; Hopper et al. (2004) report the presence of possible faults cutting down through the entire crust, but no east-cutting ‘‘Z reflection’’ on the Flemish Cap margin forming a mirror image to S off Galicia. The most obvious place to interpret a detachment at this margin (Fig. 7) would be along the crust-mantle boundary, dipping landward as a possible continuation of S (Reston et al. 1996). Thus this margin appears to have developed a late stage asymmetry in the extension process, with one detachment cutting down from the Galicia to the Flemish Cap side.

Porcupine Basin

The postulated asymmetry of the S detachment (Galicia Bank–Flemish Cap margin pair) is supported by seismic images from the Porcupine Basin. Here a reflection P cuts down to the west from top basement on the east flank of the basin (Fig. 8). P passes beneath the centre of the basin (where the overlying fault blocks are ~3 km thick) and roots at depth beneath the west flank of the basin (Reston et al. 2001). Gravity modelling suggests that P marks the top of serpentinised mantle (Reston et al. 2004); wide-angle data collected during 2004 (Meteor cruise M61/2) should test this hypothesis further. More immediate is the remarkable resemblance between P and S: both are bright, west-dipping reflections onto which the overlying block-bounding faults appear to detach; both cut across and appear to truncate deeper east-dipping reflections interpreted as the crust-mantle boundary (Reston et al. 2004); both develop in regions where extreme crustal thinning is observed and predicted to be accompanied by serpentinisation. Because of these similarities, it seems likely that P and S represent similar structures, namely serpentine detachments at the base of highly thinned continental crust.

The striking difference between P and S is that the former is a single asymmetric feature occurring beneath a largely symmetric basin, whereas the latter is observed on a single margin, with only poor constraints on the absence of a symmetric structure on the conjugate margin. Thus unlike S, P provides clear evidence that the development of a serpentine detachment after the embrittlement of the entire crust and the coupling of the crust to the mantle can be asymmetric. Applying this result to the Newfoundland–Iberia conjugate pair would imply that no ‘‘Z reflection’’ need be expected off Newfoundland, and that instead, any continuation of S may follow the crust-mantle boundary (CMB) there.

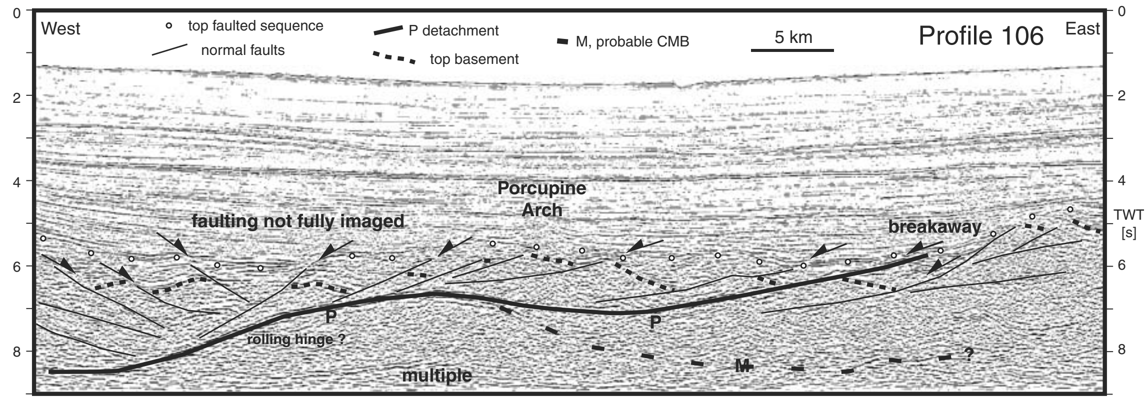

Fig. 8 Seismic profile 106 across the middle of the Porcupine Basin and the Porcupine Arch. Fault blocks are bound by west-dipping faults detaching onto the P reflector, considered to be a serpentinite detachment. Note that P is an asymmetric structure, implying that initial mantle unroofing is likely to be asymmetric

Southern Iberia Abyssal Plain (IAP) margin

Extension in the Porcupine Basin provides a snapshot of the crustal structure immediately prior to crustal separation. However, the subsequent exhumation of a wide zone of continental mantle is perhaps best studied at the IAP margin, south of the Galicia Bank. Here the zone of unroofed mantle is in places over 100 km wide (Fig. 3). The landward limit of this zone is marked by a series of tilted fault blocks, comprising both continental crustal basement and mantle—the faults cut and offset the Moho (Krawczyk et al. 1996; Whitmarsh et al. 2001). From seismic velocities (Chian et al. 1999; Dean et al. 2000), the mantle beneath the crustal blocks is thought to be serpentinised, with the degree of serpentinisation decreasing from ca. 25% to zero less than 8 km beneath the crust, consistent with the expected supply of water along faults (see above). Beneath the oceanward edge of continuous (continental) crustal fault blocks, a bright reflection (H-Krawczyk et al. 1996) marks a detachment fault, in places a tectonic CMB as it follows the top of serpentinised mantle rocks (Fig. 9). Reconstructions (Manatschal et al. 2001; Manatschal 2004) show that H developed when the crust had already been thinned to about 6 km (Fig. 9), implying a stretching factor of about 5 and consistent with the model results of Pérez-Gussinyé and Reston (2001). H itself can be traced to the top of a fault block where ODP drilling (Whitmarsh et al. 1998) sampled serpentinites (site 1068), sheared mafic granulites (site 900) and anorthosites and tonalites (site 1067), i.e. moving from west to east across H drilling sampled first mantle at site 1068 then lower crustal lithologies at the next two locations. (Note there is no evidence that lower crustal rocks are missing more than the upper crust across the non-volcanic margins of west Iberia). Thus H appears a good candidate for a late stage detachment fault that asymmetrically unroofed mantle rocks in the continent-ocean transition zone (COT). However, there are two problems with this simple interpretation. First, H itself is cut by a later west-dipping structure (F-Krawczyk et al. 1996), so that it appears that no single master detachment can have controlled the unroofing of mantle rocks as in the simple shear model. Second, it is not clear if a mirror-image reflection is present on the conjugate Newfoundland Basin margin, as the quality of seismic images from that margin are presently inferior to those from the west Iberia margin. It is worth noting that ODP drilling on the Newfoundland margin recently found outcrops of serpentinised mantle at site 1277 within the COT as well (Tucholke et al. 2004).

Labrador–West Greenland conjugate margin pair

The symmetry of final break-up can also be discussed with reference to the Labrador–West Greenland conjugate pair (Fig. 3). A major topic of debate here is whether the ‘‘transitional crust’’ between the last continental fault block and anomaly 27 is very thinned continental crust (Chalmers and Laursen 1995), slow-spread oceanic crust (Srivastava and Roest 1999) or unroofed continental upper mantle (Chalmers and Pulvertaft 2001). The imperfect fit of the magnetic anomalies to a slow-spreading model (Chalmers and Pulvertaft 2001), even with a postulated ridge jump (Srivastava and Roest 1999), coupled with an only quasi-linearity of the anomalies (similar to that observed off west Iberia at about 12°W—Whitmarsh and Miles 1995) and the velocity structure (Chian et al.

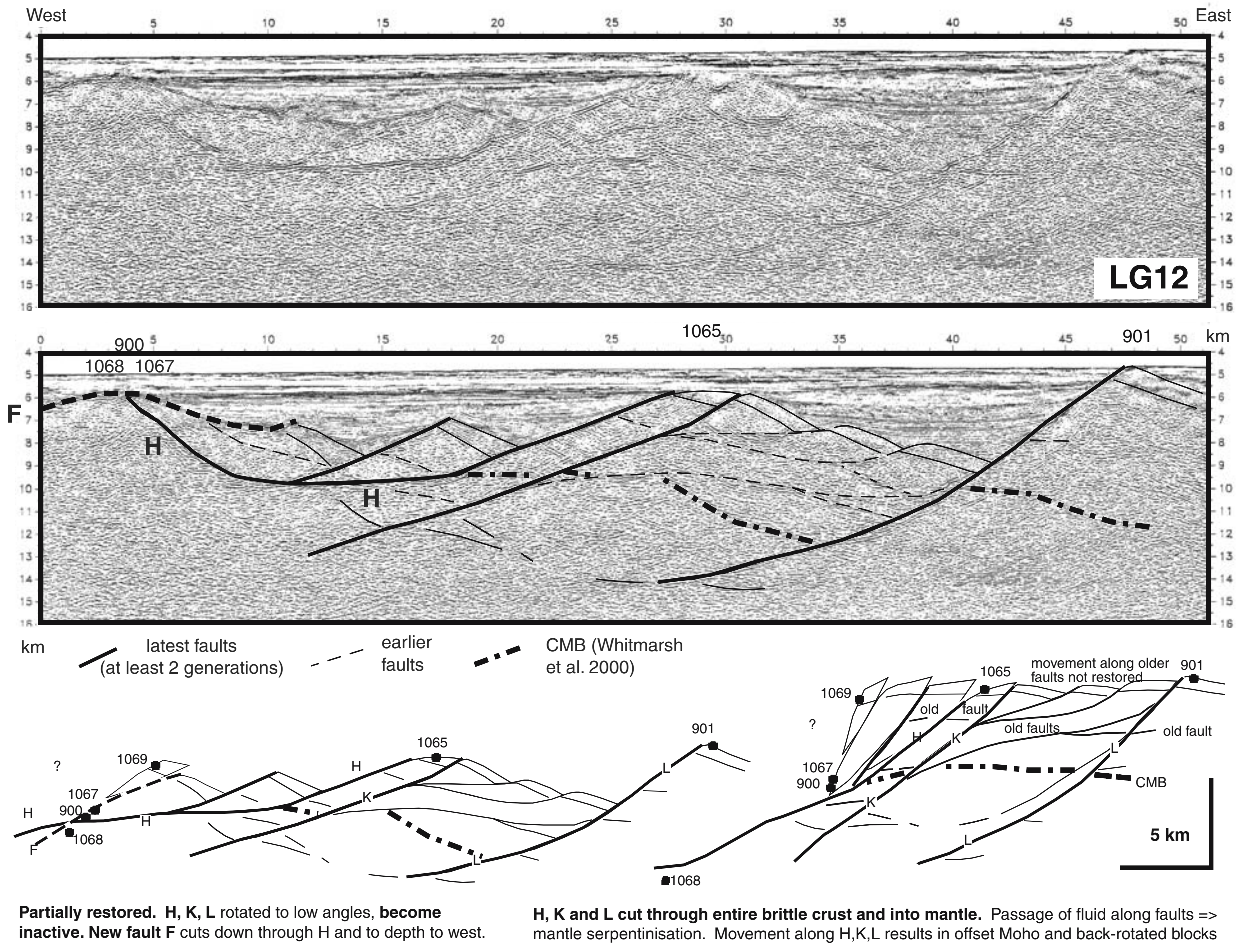

Fig. 9 Seismic depth section of profile LG12. Top image from prestack depth migration in region of ODP sites 900–901 (Krawczyk et al. 1996). Middle, revised interpretation, showing main faults (*bold*), earlier faults (*thin dashed lines*), top fault blocks and top basement (*thin continuous lines*), and the crust-mantle boundary (*CMB*). H is both a fault and the CMB. Shape of H is thought to be due to back-rotation accompanying movement along F (*solid dashed line*). *Bottom left* partial restoration (after Reston 2006), removing movements along F: 1,069 block (see Fig. 3) restored from further to the west, and H unfolded. *Bottom right* further restoration, removing displacements along bold faults. Site 1068 sampled mantle peridotites, sites 900 and 1067 drilled continental lower crust, sites 1069, 1065 and 901 pretilting sediment (*upper crust*?)

1995), leads us to prefer an interpretation in terms of unroofed mantle, but geological samples are lacking. Geophysical evidence for expanses of mantle rocks are however, well documented on the West Greenland margin (Chian et al. 1995; Chalmers and Pulvertaft 2001): beneath crust thinner than 8 km, the mantle displays a strong velocity gradient with velocities increasing from below 6.4 to 7.4 km/s over a vertical distance of less than 8 km. This is consistent with the degree of serpentinisation decreasing downward from 40 to <15% within the brittle upper mantle.

The interpretation of the ‘‘transitional crust’’ as unroofed mantle is consistent with the non-volcanic nature of much of this margin (Chian et al. 1995; Chalmers and Pulvertaft 2001). Chian et al. (1995) proposed that rifting was fundamentally asymmetric, with Greenland as the upper plate margin. They based this interpretation on the asymmetric crustal structure, with a broader zone of crustal thinning and the unroofing of high velocity lower crust on the proposed lower plate margin (Labrador) and the presence of a possible master detachment (‘‘S’’) on the Greenland margin. However, at the Galicia Interior Basin, the unroofing of lower crust can be explained by two-phase extension without recourse to master detachments (Reston 2005). Furthermore, Reston et al. 1996 showed that off Galicia, the S reflector is within the lower plate margin, if such a scheme can be used at all. Furthermore, Chalmers and Pulvertaft (2001) pointed out that this feature does not closely resemble the S detachment observed off Galicia (nor the P detachment beneath the Porcupine Basin—see above) and argued that rifting was at least initially symmetric, thinning the crust to perhaps slightly less than half its original thickness, a stretching factor of ~2.5. In contrast to Chian et al (1995), Chalmers and Pulvertaft (2001) further suggested that rifting only became asymmetric during final breakup, occurring along a detachment dipping to the SW (i.e. with Greenland as the *lower* plate margin) at least where the Labrador Sea is crossed by profile BGR/77-17. These conflicting interpretations illustrate the difficulty in using an upper–lower plate classification.

To clarify the situation further it is worth briefly reviewing what is known of the rift history of the Labrador–Greenland system. Rifting can be described in several phases: following minor extension and dike intrusion (Alexis Formation in Labrador), there was a main phase of crustal extension, lasting perhaps 25 Myr, during which the synrift Bjarni Formation and equivalent Kitsissut (inferred)/Appat Formations were deposited on the Labrador and Greenland margins, respectively. Seismic profile BGR/77-17 published by Chalmers and Laursen (1995) clearly shows that the Labrador margin in places is a rollover margin, with the main faults dipping landward, and the synrift Bjarni units rotated seaward. Such a pattern could be interpreted as evidence that the Labrador margin is the upper plate margin to a SW-dipping detachment, but is also a logical continuation of extension along en-échelon arrays of faults such as the domino faults described for the North Sea by Klemperer (1988): if the faults dip dominantly in one direction, then on one margin they dip oceanward and on the other landward. Thus it need not indicate any larger scale asymmetry (e.g. detachments) than observed in the North Sea. Based on the two-way time to basement and on the velocity structure of the margin (Chian et al. 1995) Chalmers and Pulvertaft (2001) proposed that the crust was thinned symmetrically to about 13 km during this phase of extension, corresponding to a stretching factor of about 2.7 for crust initially 35 km thick (Chalmers and Pulvertaft rounded the factor down to a slightly lower value –2.5). Only subsequently did the extension become asymmetric (Chalmers and Pulvertaft 2001).

If the lower crust was dominated by anorthosites, which are a feature of high grade terranes, extension by a factor of 2.7 over 25 Myr or more would be just sufficient to bring the entire crust into the brittle regime (Pérez-Gussinyé et al. 2001), initiating mantle serpentinisation. Pérez-Gussinyé and Reston (2001) suggested that following complete crustal embrittlement, extension focuses above the weak serpentinising zones, implying that the locus of intitial serpentinisation may control the resultant pattern of crustal thinning and eventual crustal separation. As the final pattern of thinning is somewhat asymmetric, with a shorter slope on the Greenland side, it would seem likely that mantle serpentinisation developed closer to the Greenland than the Labrador shelf at this time, causing a gradual focussing of subsequent extension towards a point (nearer Greenland than Labrador) where crustal separation finally occurred. This may help explain the contrast between the gradually thinning of the Labrador crust oceanward and the more abrupt Greenland margin. A focussing of extension towards the Greenland margin is supported by the stratigraphic record: while faulting continued on the Greenland margin (deposition of the Kangeq sequence in half-grabens), the equivalent Markland Formation on the Labrador slope is unfaulted.

The timing of crustal separation is not well constrained but must have occurred after the end of the initial symmetric rifting phase (deposition of the Bjarni (Labrador) and Kitsissut/Appat sequences (Greenland), i.e. from c. 125 to 100 Ma), and the initiation of seafloor spreading before anomaly 27 time (61 Ma). After 100 Ma, continued rifting accompanying mantle serpentinisation probably took place on the Greenland side of the rift during the deposition of the Kangeq sequence which is known only up to c. 85 Ma (Chalmers and Pulvertaft 2001). We estimate that crustal separation followed by mantle unroofing may have occurred at about this time at the SW limit of the Kangeq rift. It is thus likely that the duration of crustal rifting and thinning is considerably less than commonly supposed. It is also clear that the rift first focussed toward the NE (Kangeq deposition off Greenland) and then refocussed furher to the SW (edge of Kangeq).

Following final crustal separation, a large expanse of mantle rocks was unroofed. The faulting of these implies that the mantle was also not simply exhumed by a single master detachment, but rather exhumed and further extended by a series of faults. However, either mantle unroofing was somewhat asymmetric, or the focus of divergence again moved slightly towards Labrador as the zone of exhumed mantle is wider on the Greenland than the Labrador margin.

Thus extension may have become progressively more asymmetric with time and breakup may have occurred in two or three asymmetric stages, leading first to late synrift deposition only on the Greenland margin (Kangeq sequence), then to crustal separation at the SW edge of this and finally to seafloor spreading closer to Labrador. Given the proposed initial symmetry of the rift (Chalmers and Pulvertaft 2001), the changes in asymmetry during breakup, and the absence of conclusive evidence for an individual master detachment fault, it seems inappropriate to use lower plate and upper plate margin terminology.

Discussion: late-stage asymmetry and detachment faulting

The late stage asymmetry of lithospheric extension once the crust and mantle have become tightly coupled is completely consistent with the modelling of Huismans and Beaumont (2002). However, maintaining such a system once the uppermost mantle has been serpentinised seems counter-intuitive: it might be expected that the weak serpentinised zone would effectively decouple the crust from the majority of the underlying mantle. We propose that faults cutting through the upper lithosphere remain favoured as:

- when the entire crust becomes brittle, the continuation of brittle structures into the mantle occurs through a direct continuation of the crustal faults to depth. This throughgoing fabric is maintained during subsequent deformation,
- deformation, even in the presence of serpentinites, is fundamentally brittle, so that during an earthquake the upper lithosphere is likely to rupture along planes crossing from crust into the mantle

Despite the local importance of detachment faulting during final crustal separation, it seems neither necessary nor likely that a detachment at this level cuts through the *entire* remaining lithosphere. Although a broad zone of unroofed mantle is observed in the southern IAP west of Iberia, it is unclear if these correspond to deeper lithospheric levels as one moves oceanward (Reston 2006), and the only basement sample on the conjugate Newfoundland Basin margin indicates the presence of exhumed mantle on that margin as well (Tucholke et al. 2004). It thus seems unlikely that the unroofing of the mantle is controlled by a single detachment fault. Instead, several generations of detachment faults may be required to explain the unroofing of the mantle at such margins (Manatschal et al. 2001), providing the opportunity for the asymmetry of the system to switch. It should be borne in mind that if early extension is heterogeneous as is believed for rifts such as the North Sea (White and McKenzie 1988; Reston 1990), the uppermost mantle in the middle of the basin is less thinned than the crust. Further extension is thus likely to lead to complete crustal separation even while the lithospheric mantle is relatively thick beneath the rift axis. Furthermore, as extension of the unroofed mantle proceeds further, the upper mantle layers will quickly be pulled apart along brittle faults, while the deepest portions of the mantle are likely to remain plastic and hence remain coherent. Just as the embrittlement of the crust can result in its separation and the unroofing of the underlying mantle rocks, so can the brittle behaviour of the uppermost mantle lead to the oceanward unroofing of deeper mantle levels and a gradual oceanward structural deepening of the brittle-plastic transition as faults cut into the deeper lithospheric levels brought nearer the surface.

I close with a word of caution. Rifting is a 3-D process, whereas most of the modelling that has been carried out has been in 2-D. In rifts, the 3D expression is marked by pronounced segmentation of the rifts into domains with opposing dominant fault directions separated by accommodation zones. It seems likely that a similar segmentation will persist until breakup, although the 3-D data needed to demonstrate this are as yet lacking. However, as the thickness of the brittle layer changes (first decreasing as the crust thins and then increasing again once faults cuts down through the entire crust and into the mantle), the scale of segmentation is likely to change. The result is likely to be a complex 4-D evolution of the rift system leading to breakup. Only through detailed 3-D studies of rift evolution at various stretching factors is the complete process of continental breakup likely to be understood.

Conclusions

In this paper, we have examined evidence of symmetry/asymmetry of well-known basins and margins in the light of results from numerical modelling. The main points can be made:

- Mature but intact rift basins such as the North Sea appear largely symmetric, consistent with models in which the upper and lower lithosphere are decoupled.
- Ongoing extension leads to the gradual embrittlement of the crust and the eventual coupling of the crust to the mantle.
- At this stage, throughgoing faults can develop, leading to late stage-asymmetric rifting along serpentine-detachments. Such asymmetric structures can be seen beneath the Porcupine Basin and are inferred west of Iberia.
- Further extension may lead to mantle unroofing, but it is unclear whether a dominant asymmetry persists, especially as a succession of controlling faults develop and die.
- The complex evolution from symmetric to asymmetric extension, and perhaps back to symmetric,

make terms such as upper plate and lower plate unhelpful in characterising rifted margins.

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