PLATE TECTONICS: Lecture 4

CONTINENTAL MARGIN SUBSIDENCE

Passive continental margins are those associated with continental rifting and the subsequent formation of ocean basins. They differ from active continental margins which are associated with subduction. The continental shelves around the Atlantic are typical passive margins: however there are some quite large differences in the morphology of continental margins around the Atlantic: the reasons for which are not fully understood (but see White et al. 1987; White & McKenzie 1989). There is of course considerable interest in continental margins because of their potential as major oil reservoirs. Hence much has been learned in the last few years.

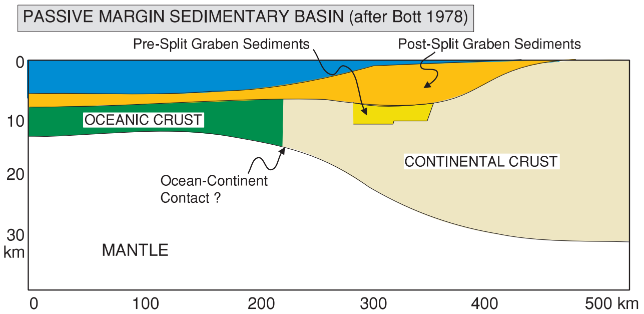

Fig. 1. Simplified relationships at a continental margin. There can be more than 10 km of shallow-water sediments at the margin – implying slow subsidence. How?

One aspect of continental margins that has always been puzzling is the existence of very thick – but relatively shallow-water – sedimentary sequences. There can be as much as 15 km of Mesozoic and later sediments at some continental margins bordering the N. Atlantic. How can these very thick sequences be reconciled with gradual but progressive subsidence? Over the years various ideas (summarised in Bott 1979, 1982) have been put forward:

Gravity Loading Hypothesis: This attributes subsidence to sediment load (effectively replacing seawater with denser sediment), and is based on isostacy.
The amount of subsidence depends on relative densities of seawater (1.03), sediment (2.15 – 2.55) and the underlying mantle (3.3). If the sea is filled with sediment then in theory a sediment thickness of over twice the initial depth can develop. In fact a total thickness of 14 km can form near the base of the initial slope. If the lithosphere is treated as elastic the downwarping can extend about 150 km beyond the local sediment load. See Fig. 2 below.

Problem: This mechanism is not easily reconciled with substantial sequences of shallow water sediment. It can only work if the sediments were deposited in deep water initially. If initial water depth is less than 200 m, then sediment loading effect is negligible.

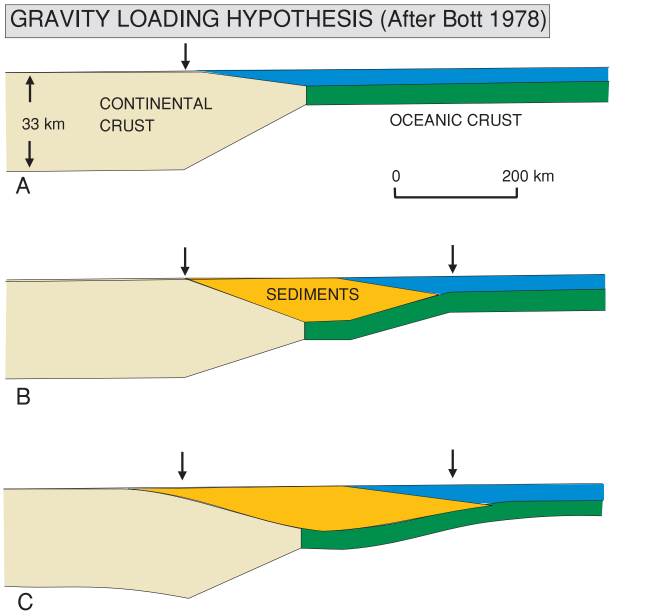

Fig. 2. Gravity loading hypothesis. This depends on replacing low density water by higher density sediment . . .

Thermal hypothesis: This assumes that continental lithosphere near the embryo margin is heated at time of continental rifting - this reduces density of lithosphere permitting isostatic uplift. Subsequently, as the ocean widens, lithosphere cools with time-scale of ca. 50 my and will subside to original position. However if erosion occurred during uplift stage, real subsidence can occur, enhanced by sediment loading.

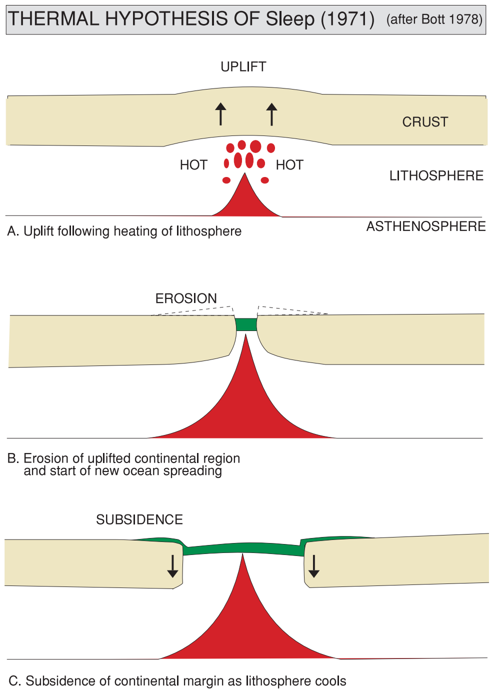

Fig. 3. Thermal hypothesis of Sleep. This was the first to recognise that heating up the mantle (by a plume or whatever) could produce substantial crustal uplift (and erosion), followed by thermal subsidence. Compare the models by McKenzie and Wernicke later . .

Problem: Even with an extreme initial elevation of about 2 km, the amount of subsidence, even with sediment loading, is not much more than 2 km. So not able to explain thick sequences of over 5 km.

A modification of this thermal model assumes that the thermal event transforms the base of the crust to denser granulite facies mineral assemblages, which may also be invaded by basic magma. If this causes an increase in density of 0.2, it can be calculated that the maximum depth of sediment permitted would only be about 3 or 4 km. Thus insufficient to account for large sediment thicknesses.

THERMAL HYPOTHESIS OF FALVEY (1974) (cf. Bott 1978)

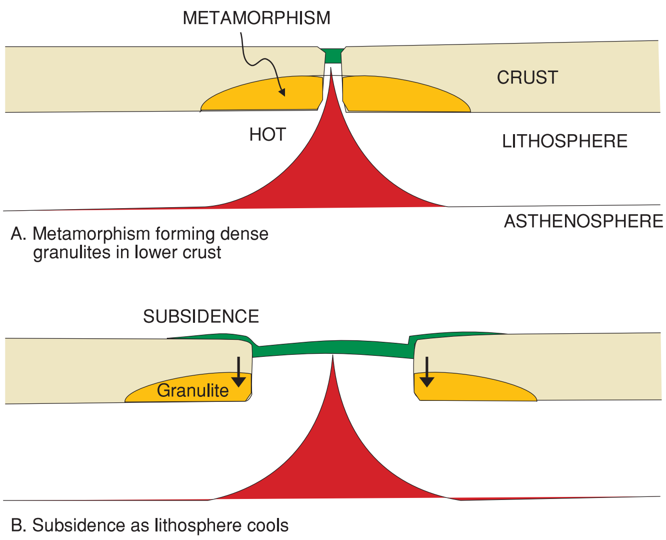

Fig. 4. Modification of thermal hypothesis according to Falvey (who argues that heating will cause dense granulite to form).

Problem: such models predict a gap of many m.y. between onset of spreading and the first marine sedimentation - which is not observed.

Crustal Thinning hypothesis: The continental crust and the lithosphere have an upper brittle zone, 20 km thick, overlying a much weaker layer which deforms by ductile flow. Thus crust may thin by progressive creep of middle and lower crustal material towards the sub-oceanic upper mantle. It is argued that this may give rise to jerky subsidence.

CRUSTAL FLOW HYPOTHESIS OF BOTT (1971)

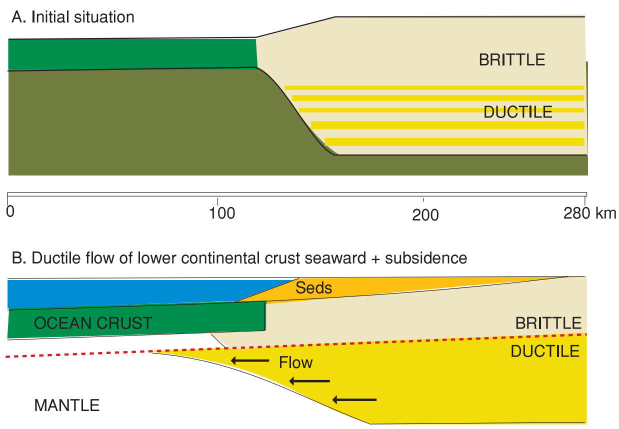

Fig. 5. After the initial rifting the lower crust deforms by plastic flow.
Could the lower continental crust flow UNDER oceanic crust in the manner shown?

An alternative hypothesis suggests that extreme thinning of the continental crust can occur in a rift valley setting by plastic necking.

Then, as the ocean basin forms the passive continental margin will gradually subside.

NECKING OF CONTINENTAL CRUST (after Bott 1978)

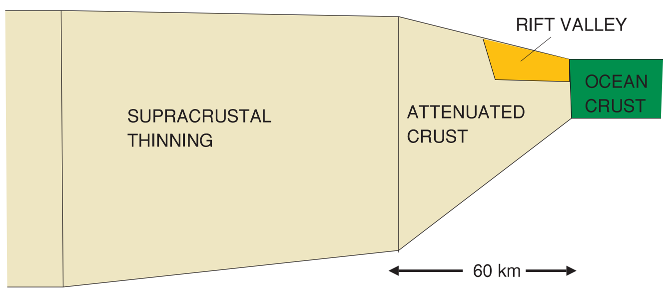

Fig. 6. Necking of continental crust?

Problem: a typical rift zone is about 50 km wide, thus transition zone at a continental margin would be only 25 km wide. Observed continental margin sequences are however much wider than this.

Normal-fault based mechanisms:
Early hypotheses assumed that graben formation required a wedge of crust about 60 km wide to sink isostatically between inward-dipping normal faults. As the upper crust forms graben by wedge subsidence the ductile lower crust compensates by plastic flow.

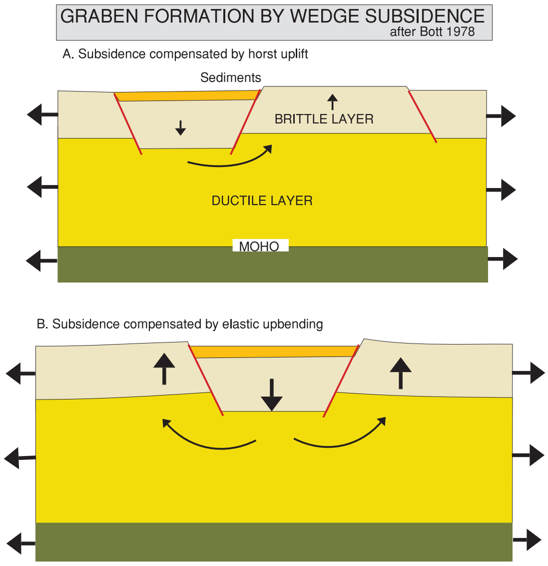

Fig. 7. Can normal faulting lead to displacement of ductile mantle by flow?

Problem: Calculations suggested that a subsidence of ca 5 km could occur for an initial 20 km wide trough. Not really enough. But getting nearer.

Faulting near continent-ocean contact:
This mechanism permits limited subsidence as normal faulting accompanies downdrag of the cooling ocean lithosphere. The oceanic lithosphere subsides on a time scale of about 50 my, so consistent with shallow water sediments. However note that the zone of subsidence is too narrow.

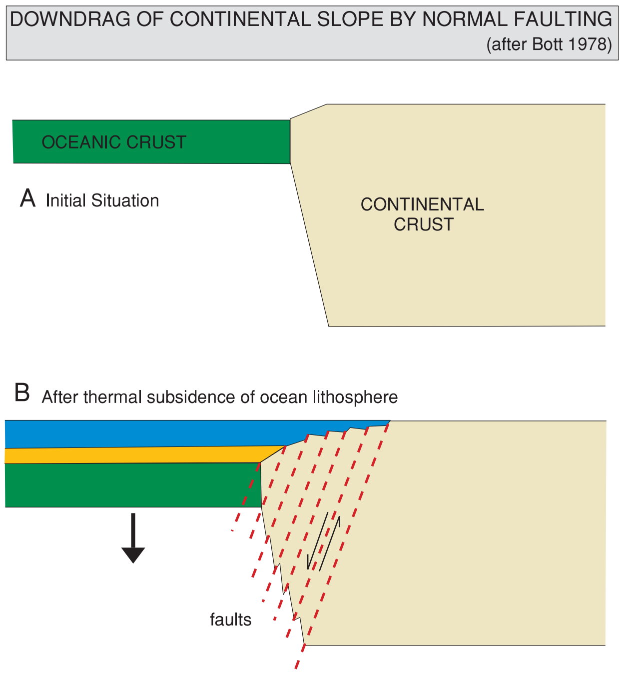

Fig. 8. Does normal faulting occur at continental margins in the manner shown in B ?

Conclusions

None of the above mechanisms, either alone or together, seem capable of explaining the observed thick sedimentary sequences at continental margins that are formed at the start of the Wilson Cycle. New ideas were clearly required. These began to develop in the late 1970's as we began to understand more about the thermal behaviour of the lithosphere and about the nature of listric faults.

Continental Lithosphere: The mantle forming the plates is more rigid than the underlying asthenosphere. But this rigid *mechanical boundary layer* (MBL) varies in thickness. It is thin at the ridges, but thickens to 60 or even 100+ km in old oceanic lithosphere. It may be much thicker under the continents, but it is also older - in fact the lithosphere under the continents is usually as old as the continent above. So it may be cool, and may have experienced enrichment by small degree mantle melts, the components of which may be stored in hydrous minerals.

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CONTINENTAL EXTENSION AND FORMATION OF SEDIMENTARY BASINS

There is no doubt that when ocean basins open there is considerable subsidence of the continental shelves over a wide area, and not just over the immediate rifted margin. This is well exempified by the South Atlantic at ca. 127 Ma, just as the first oceanic crust formed:

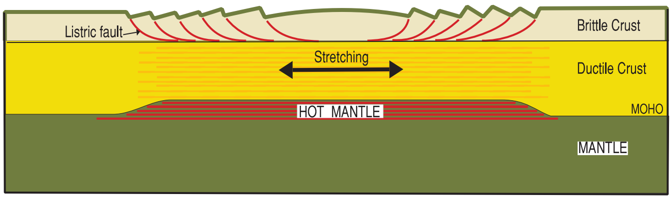
Fig. 9. A very large area in the south Atlantic was submerged following break-up at 127m.y. Why?
Both Chile and Argentina have modest on-land oil reserves in Patagonia to the west of the Falkland Plateau. DSDP site 330 drilled oily sediments in 1974. Why did Argentina go to war over the Falklands?

Drilling at the eastern spur of the submerged Falkland Plateau revealed that it was continental (granite gneisses) and that there was a dry caliche surface (Mediterranean climate) just before opening of the Atlantic, but that there had been at least 2 km subsidence since then. Initial sediments very oily, deposited under anoxic conditions in a basin with restricted circulation. So the initial rift stage was the one that favoured oil accumulation. Why? It is important to understand the mechanism of development of these basins.

Modern Ideas

It became apparent from COCORP-type deep reflection seismic profiling that many (if not the majority) of steeply dipping normal faults are actually curved (concave-upward) and become shallow-dipping and sub-horizontal at depth. These are now known as listric faults. As the lithosphere is stretched during continental extension, the ductile deeper crust thins by pure shear, while the upper crust is broken up and pulled apart by listric faults which 'bottom out' in the ductile layer. At the surface of course these have the appearance of graben. This is the essence of McKenzie-type and other recent models of basin formation. As the sub-continental (i.e. mantle) lithosphere is thinned by stretching it is of course partly replaced by hotter asthenosphere. This will gradually cool on a time scale of the order of 50 - 100 m.y., and as it cools it becomes denser and the shallow basin above gradually subsides and is progressively filled with shallow-water sediment. The amount of subsidence will depend on the initial amount of stretching. This can usually be estimated and is known as the stretching factor, or "beta factor". The parameter β is defined quite simpy as ***b***/***a*** where ***a*** was the initial width and ***b*** is the stretched width. A β factor of 1.2 will give ca. 3 km subsidence. With complete rifting (to form ocean crust and an ocean basin) then β approaches infinity.

McKenzie Uniform Pure Shear Model



Note that during the development of sedimentary basins, subsidence occurs in two stages:

(1) as a result of **tectonic stretching** – on a short time scale, ca. 10 my, and

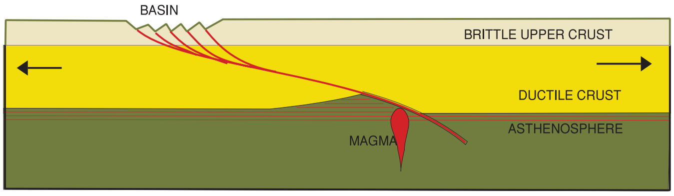
(2) as a result of **thermal subsidence** – long time scale, ca. 50 – 100+ my.

Considerable information is now available on North Sea basins as a result of drilling operations and syntheses of the large amount of seismic data (see, e.g. Badley et al. 1988; Gibbs 1984; Sclater & Christie 1980) so their subsidence history is well known. The northern Viking Graben suffered two episodes of rifting – in the Permo-Triassic and in the Middle Jurassic – during which the basin was progressively widened. Stretching factors in the Permo-Triassic were quite small (β = 1.1 – 1.3), whereas in the Late Jurassic were much larger in the northern N. Sea (β = >1.6). Each rifting episode was followed by more substantial thermal subsidence. In the central part of the Viking Graben almost 10 km of sediment has accumulated since the onset of the first rifting episode. As the second rifting phase ended 140 my ago at least 90% of the subsidence resulting from thermal relaxation must have occurred by now. Note that whereas normal faults during the rifting phase tend to be listric, those accompanying thermal subsidence are planar.

An important secondary factor in such models is that the sediments initially deposited in such basins will be 'cooked' slightly as a consequence of the increased heat from the underlying asthenosphere – vital in maturation and migration of petroleum. But sedimentary basins are not only important as oil reservoirs: the expulsion of heated fluids from such basins can leach metals too, thus if suitable host rocks exist valuable mineral deposits can be formed. A number of important mineral deposits are attributed to this mechanism.

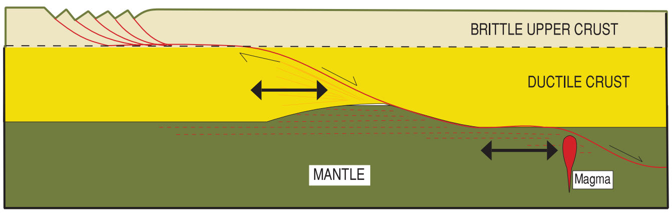
Further development of lithosphere stretching models have been proposed by Wernicke, by Lister et al., Coward and others (see references below).

WERNICKE SIMPLE SHEAR MODEL



The important difference is in the recognition of low-angle detachments (superficially like thrusts, but with movement sense as in normal fault), first proposed for the Basin & Range province in the western USA. These may bottom out in the lower crust or the upper mantle. The main effect is to introduce asymmetry compared with the pure shear uniform-stretching McKenzie-type model, so that basins associated with the thermal subsidence phase may be offset from the thin-skinned basins associated with the initial rifting. Magmatic effects (melting resulting from the uprising asthenosphere) may be offset from the main sedimentary basins. Because of the asymmetry, the continental margins on the two sides of an opening ocean may have very different profiles. Many other complications may ensue. Consult the references below if you want the full story!

CONTINENTAL EXTENSION: DELAMINATION MODEL OF Lister et al. (1986)



At least 3 types of continental margin have now been recognised:

(1) **volcanic**,
(2) non-volcanic and
(3) rift-transform.

(1) **Volcanic margins** tend to be narrow and have a thick igneous crust between continental and normal ocean crust. A thick zone (3 – 5 km) of seaward-dipping volcanic reflectors is typical. Suggestions of convective circulation in uprising asthenosphere to explain volcanism, or that the underlying asthenosphere was hotter than usual. Examples: Voring Plateau, western Rockall Bank, East Greenland. See White et al. (1987 & 1988).

White & McKenzie (1989) have developed these models further to quantitatively relate the volume of volcanics produced at continental margins to the temperature of the underlying mantle. If the temperature is 100°C above normal the volume of magma will be doubled. Also they have developed a relationship between the degree of stretching and the temperature of the mantle to predict whether the rifted margin will rise above sealevel or subside below it. When rifting occurs above hotspot plumes there is usually an accompanying large volume of magma.

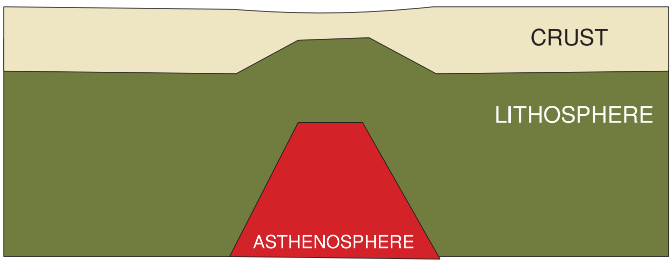
(2) Lithospheric deformation on non-volcanic margins is dominated by block faulting and many listric faults. Stretching over a broad zone (100–300 km). May be sediment starved (Red Sea, Galicia Bank, Goban Spur– Irish Sea) or heavily sedimented (e.g. eastern USA margin).

(3) Rift-transform margins evolve in environments where there was a significant component of strike-slip shear as well as extensional strain deformation during opening (e.g. region between W. Africa and Brazil; Falklands Plateau; also Gulf of California).

These different types of margin may have very different petroleum potential. Need to know more about them to aid in locating future supplies. Note that the important petroleum reservoirs in the North Sea are in 'failed-rifts' – where the North Atlantic tried (unsuccessfully) to open quite a long time before it eventually succeeded!

There is a rapidly growing literature on models for continental rifting and basin formation: try to read some of those below, and especially note the diagrams. In any case they may prove useful to you next year.
Another problem of concern is why do we get basaltic magmatism associated with some basins and not with others. Latin and White (1990) have tried to argue that magmatism is more likely with uniform pure shear stretching (McKenzie model) than the asymmetric simple stretching model of Wernicke. This is because asthenosphere uprise is more focussed in pure shear model:

PURE SHEAR MODEL



SIMPLE SHEAR MODEL

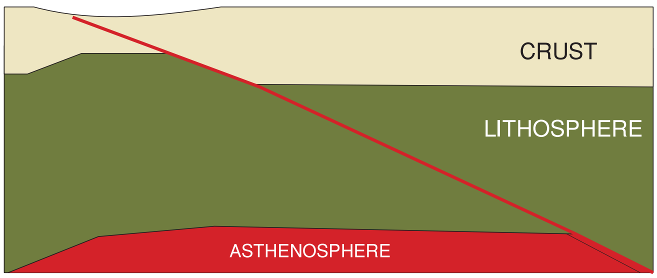


Fig. 13. Comparison of thermal conseqences of McKenzie's pure shear model and Wernicke's pure shear model of extensional sedimentary basins.
It is argued with the simple shear model it is very difficult to produce sufficient decompression to allow magma formation.

This then has very different thermal consequences:

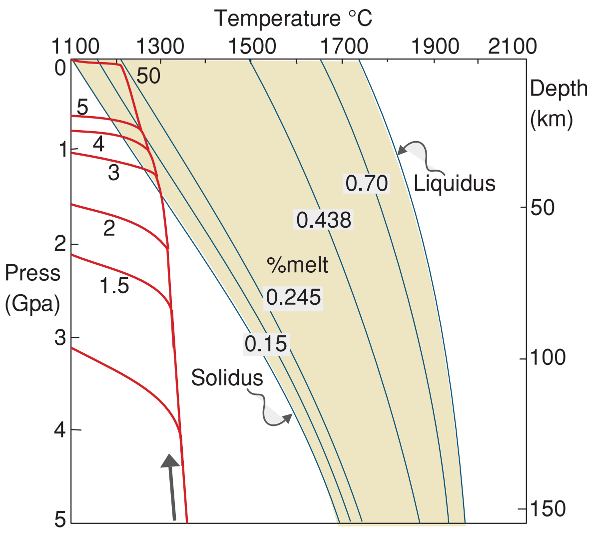


Fig. 14. With pure shear the temperature of the uprising asthenosphere an exceed the solidus of the mantle and allow melting.

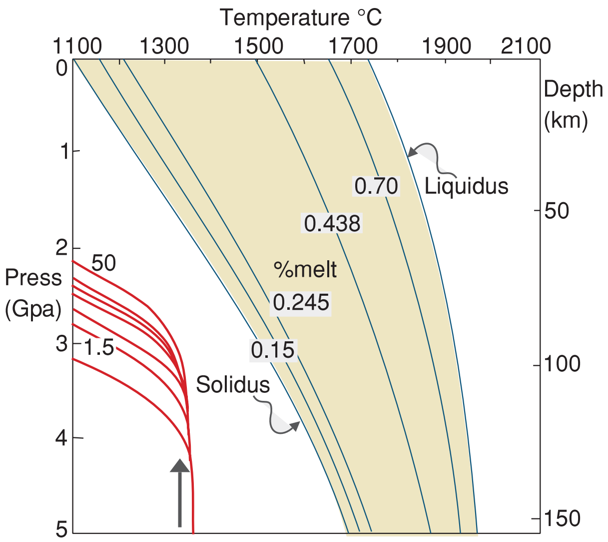


Fig. 15. With simple shear the temperature of the uprising asthenosphere never reaches the solidus - so no melting occurs.

Basin Inversion

Basins that have formed by rifting and thermal subsidence don't always remain basins. and may suffer later uplift and erosion. This is known as basin inversion. This happened to many of the Permo-Triassic basins in Western Europe (see Ziegler 1982) and is particularly evident in the NW part of the British Isles and adjacent continental margin. Could this be due to tectonic compression before all the thermal subsidence took place, with the excess sediment being removed by erosion? It is apparent that most of NW Britain was blanketed by Mesozoic sediment that has been removed (viz. Chalk in calderas on Arran) since the early Tertiary, and deposited in basins to the east. Some offshore basins with b factors near 2.0 have a short fall in the expected sediment thickness of ca. 4 km. So something has caused epeirogenic uplift in the early Tertiary over most of NW Britain.

Unfortunately, there is no evidence of enough tectonic compression (Roberts 1989) to account for this uplift by crustal thickening. So what else? Brodie & White (1994) have suggested instead that it may result from magmatic underplating by basalt. They calculate that 5 km of basalt (density 2.8) underplated into the lower crust above the Moho would initially cause 600m uplift. Additionally, with the "amplification" effect of erosion this may increase to ca. 2.5 km. Of course in this general region we know that the Iceland plume was initiated ca. 60 Ma ago (early Tertiary), and one 'rrr' arm extended down through Western Scotland to Lundy. A lot of basalt lavas were erupted. But was much more magma underplated? We know from their geochemistry that many of these basalt magmas have suffered crustal contamination. Are they just a small representative of much more that was ponded in the lower crust? See later lecture on plumes.

The interesting point is that many sedimentation features – basin development, basin inversion, epeirogenic uplift enhancing erosion – may all have their origin in mantle thermal processes. Hence it is important to understand the mantle!

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