PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Origin of the Lithospheric Tension Causing Basin Formation

M. H. P. Bott

Phil. Trans. R. Soc. Lond. A 1982 **305**, 319-324
doi: 10.1098/rsta.1982.0039

Phil. Trans. R. Soc. Lond. A **305**, 319–324 (1982) [319]
Printed in Great Britain

Origin of the lithospheric tension causing basin formation

By M. H. P. Bott, F.R.S.

Department of Geological Sciences, University of Durham, South Road, Durham DH1 3LE, U.K.

Most fault-controlled basin formation within plate interiors occurs by normal faulting in response to horizontal deviatoric tension in the continental crust. It is suggested that the tension originates either from the plate boundary forces acting at trenches or as a result of isostatically compensated uplifted regions such as East Africa. The tension produced by both mechanisms is greatest in high heat-flow regions where the upper elastic part of the lithosphere is thinned and weakened. Particularly widespread tension in the continental lithosphere occurs when subduction takes place on opposite sides of a large continental mass, such as Pangaea in the early Mesozoic, where it led to widespread graben formation and, in association with hot spot activity, to continental splitting.

1. Introduction

Sedimentary basins form in many tectonic settings and complicated schemes of classification are needed to do justice to the variety of structural environments (see, for example, Bally & Snelson 1980). However, two main classes can be recognized. These are (1) the narrow basins of graben type that subside as a result of faulting in the basement, and (2) the broad basins that form by flexural downwarping without conspicuous faulting. Fault-controlled basins clearly form as a result of stressing of the continental lithosphere. Excluding some thrust-faulted basins in active mountain ranges, fault-controlled basins are generally associated with normal faulting (which may be listric), which indicates horizontal deviatoric tension. This is supported by earthquake mechanism studies in regions where graben are forming at present. In contrast, the flexural subsidence of broad basins such as the Tertiary North Sea basin is probably primarily caused by the cooling of an initially hot lithosphere with sediment loading. The subsidence is apparently not stress controlled. However, the subsidence of the North Sea is dependent on thinning of the crust by about 40 % which occurred possibly before subsidence. Similar thinning of the crust occurs beneath passive margins before their drifting stage of development. McKenzie (1978) suggested that such thinning of the crust occurs as a result of stretching of the continental lithosphere, implying an episode of strong tension before flexural subsidence. This paper examines possible sources of the horizontal deviatoric tension in the continental lithosphere that causes graben formation and more controversially may cause extreme stretching and thinning of the crust.

The deviatoric tension associated with basin formation needs to be substantial. According to Bott (1976), persistent horizontal tension of about 200 MPa (2 kbar) at least is required to form rift valleys a few kilometres deep. The tension also needs to be of a persistent and renewable type as otherwise the amount of strain that can be released would be insufficient to cause subsidence on the observed scale.

Four possible relevant sources of tension in the continental lithosphere are as follows: (1) drag on the base of the lithosphere exerted by upwelling and diverging convection currents moving faster than the lithospheric plates (see, for example, Morgan 1972); (2) plate driving forces acting on the edges of lithospheric plates, notably the 'slab pull' and 'trench suction' forces acting on subducting and overriding plates respectively at trenches (Forsyth & Uyeda 1975); (3) tensile stress associated with isostatically compensated uplifted structures underlain by crustal thickness variations or other lateral density variations in the lithosphere (Bott & Dean 1972; Artyushkov 1973; Bott & Kusznir 1979); (4) membrane stresses, which produce horizontal tension in the interior of a plate moving towards the equator or in the exterior of a plate moving towards the poles (Turcotte 1974). It is assumed here, on geological and thermodynamic grounds, that plates are driven by edge forces rather than by the drag of faster-moving underlying convection currents, so that drag on the base of the lithosphere is not regarded as a primary source of tension. It is doubtful whether the relief of membrane stress can produce enough stretching to form basins on the observed scale. Thus plate edge forces and isostatically compensated elevated features appear to be the most likely sources of the tension giving rise to basin subsidence.

2. Plate boundary forces

The most obvious source of stress in the continental lithosphere and crust is the system of plate-driving forces that are believed to act on the edges of plates at ocean ridges and trenches (Forsyth & Uyeda 1975). The edge forces acting on lithospheric plates at ridges and trenches are counteracted partly by local resistance to plate motion in the vicinity of the plate boundaries and partly by mantle drag on the base of the moving lithosphere.

At ocean ridges, the hot and consequently relatively low-density material that upwells to form new oceanic lithosphere exerts a compressive 'ridge push' force on the adjacent lithospheric plates, acting to force them apart. This produces a horizontal compression of about 30 MPa (300 bar) acting across the thickness of the lithosphere (Forsyth & Uyeda 1975).

At subduction zones, the negative buoyancy of the sinking slab exerts a pull on the plate to which it is attached, causing tension. This force is referred to as 'slab pull'. Less obviously, the subduction process may also give rise to tension in the overriding plate (Elsasser 1971; Forsyth & Uyeda 1975). This is the 'trench suction' force, which can be attributed to the lack of support for the overriding plate at the trench. The effectiveness of the slab pull and trench suction forces in giving rise to horizontal tension within the adjacent plates depends critically on the local resistances to plate motion, which may vary in the short or long term, but stress differences of at least 30 MPa can probably be produced under favourable conditions. At present, the trench suction force appears to be more in evidence along the western margin of the Pacific, where marginal basins occur, than along the eastern margin. This may be because the older dense lithosphere is being subducted in the west or it may be related to differences in absolute plate motions at the two sides of the ocean.

The edge forces acting on plates at ridges and trenches can give rise to a variety of stress régimes within the plates. A plate with ocean ridges on opposite sides would be expected to be in horizontal compression throughout from the ridge push forces acting on both edges. If an ocean ridge occurs on one side and a trench on the opposite side, then gradation from compression at the ridge end possibly to tension at the trench end would be expected, depending on the resistance near the trench (figure 1*a*, *b*). The trench suction force acting on opposite sides of a plate formed entirely of continental lithosphere would cause the whole plate to be subjected to horizontal deviatoric tension (figure 1*c*). Such a continental plate would not override the adjacent oceans as Asia and the Americas are now overriding the Pacific Ocean. Consequently, the trench suction force would not be opposed by local resistive forces to the extent that probably now applies around the Pacific. Consequently, the trench suction force would be more effective at stressing the continental plate than at the present time.

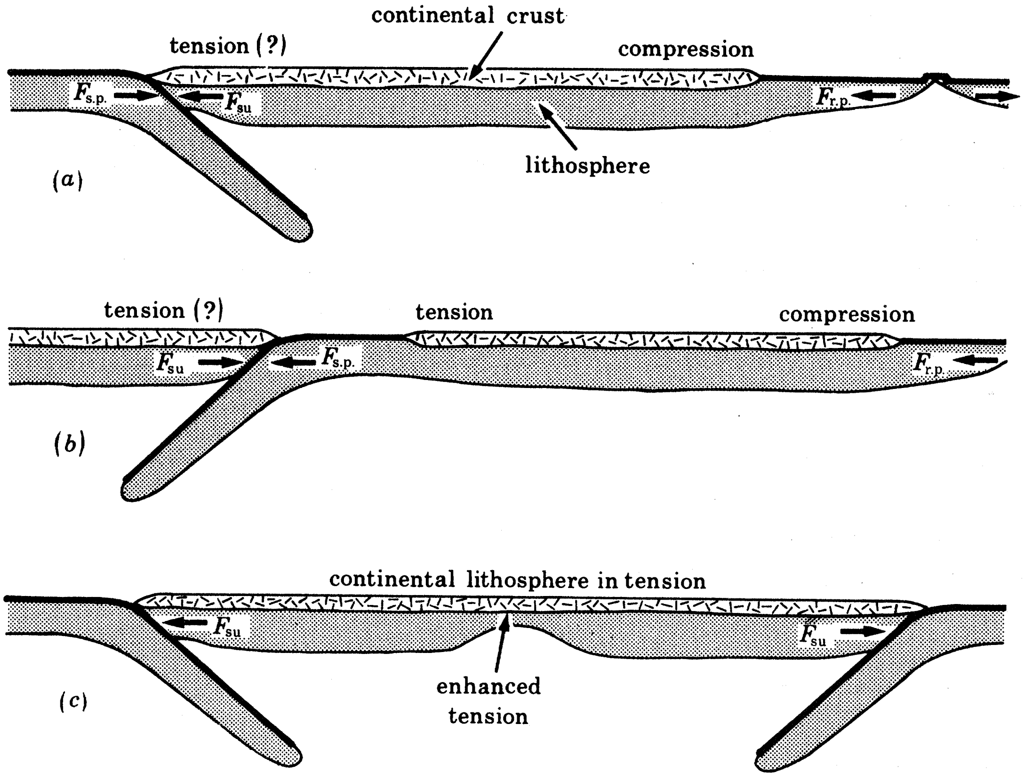

FIGURE 1. Tension in the continental lithosphere produced by plate edge forces. (*a*) Trench suction (F_{su}) at one edge and ridge push ($F_{r.p.}$) at the other edge causing a linear gradation of stress from compression near ridge possibly to tension near trench, depending on the extent of resistance near the trench. An example is the present-day South American plate. (*b*) Tension developed in a continent marginal to a narrow closing ocean as a result of the slab pull force ($F_{s.p.}$). An example is the formation of Carboniferous basins on the northern flank of the closing Hercynian Ocean. (*c*) Tension throughout a continental plate produced by trench suction at subduction zones on opposite sides. An example is Pangaea in the early Mesozoic.

During Tertiary to Recent time, all the major plates have an ocean ridge on at least one side, and thus any tension resulting from plate boundary forces is likely to be restricted to the part of the plate in the vicinity of a trench. At certain periods in the past, however, plate arrangements have been more favourable to widespread tension, such as when subduction was probably occurring on opposite sides of the Permo-Triassic supercontinent Pangaea before and during its early Mesozoic break-up. This tension may have caused the widespread formation of fault-controlled basins characteristic of the early Mesozoic and may also have given rise, with hot spot activity, to the continental break-up.

It has been suggested that tension may occur throughout a continental plate at certain rather special periods in Earth history when subduction is occurring on opposite sides, and that more generally, tension may occur in those parts of plates sufficiently close to adjacent trenches. The stresses in the vicinity of the trenches would also be expected to fluctuate on a short and long timescale as the subduction process evolves, and this may cause time variation in the subsidence, including the periodic type of subsidence that produces 'cyclic' sedimentation. Relatively simple stress systems have been considered here. More complicated situations must occur as a result of local conditions near plate boundaries, such as transform faulting and irregularities in the plate boundaries. These may produce local regions of tension of types not discussed above.

If the lithosphere is treated as an elastic solid, then plate boundary forces would be expected to give rise to lithospheric stress differences not exceeding about 40 MPa. This seems to be too low to allow graben containing 5 km of sediment to form. If, however, the lithosphere is more realistically regarded as an upper elastic layer overlying a lower ductile layer that can be treated as viscoelastic, then stress relaxation must occur in the lower viscoelastic region, causing a corresponding increase in stress in the elastic layer roughly in proportion to the ratio of lithospheric thickness to elastic layer thickness (Kusznir & Bott 1977). The stress differences produced in this way are greatest in regions where the elastic layer is thinnest, that is in regions of high heat flow. Thus the stress differences resulting from plate boundary forces would be expected to be smallest in cool shield regions and greatest in regions overlying mantle hot spots where the lithosphere has been thinned and the elastic layer may only be about 10 km thick. Stress differences of the order of 200 MPa or more can thus develop locally in the upper crust as a result of plate boundary forces, giving a possible explanation of the formation of certain types of fault-controlled basins.

Exceptionally large horizontal tensile stress might be expected to occur locally during the continental splitting process. If a crack develops in the interior of a continental plate that is subjected to general tension, then greatly increased tension would be expected to occur at the ends of the magma-filled propagating crack. It would behave like a large-scale Griffith crack filled with fluid under pressure and subjected to tension. Extreme tension developing in this way may cause substantial stretching and thinning of the continental lithosphere along the line of the newly developing passive margin.

3. Stresses associated with elevated regions

Localized tension within the continental crust occurs in regions of major surface elevation that are isostatically supported by low density rocks beneath, such as mountain ranges and plateau uplift regions (Artyushkov 1973; Bott & Kusznir 1979). The horizontal deviatoric tension is the result of the increased vertical pressure caused by the load of the surface topography and the upthrust of the compensating low density rocks beneath. This type of stress system causes the continental side of a passive margin to be in tension relative to the oceanic side (Bott & Dean 1972). Similarly, local crustal tension occurs in elevated plateau regions that are supported by low density rocks in the underlying upper mantle, such as the western United States and East Africa.

If the lithosphere is treated as wholly elastic, then the stress differences associated with an elevated plateau 2 km high that is isostatically compensated in the upper mantle are about 40 MPa. However, if the lithosphere is more realistically modelled in terms of an upper elastic layer underlain by a viscoelastic region (figure 2), then stress differences of about 200 MPa are produced in an elastic layer 10 km thick. Thus in elevated regions of high heat flow such as East Africa and the Basin and Range province of the western United States, tensile stress adequate to form substantial rift valleys is probably present. These elevated regions are the

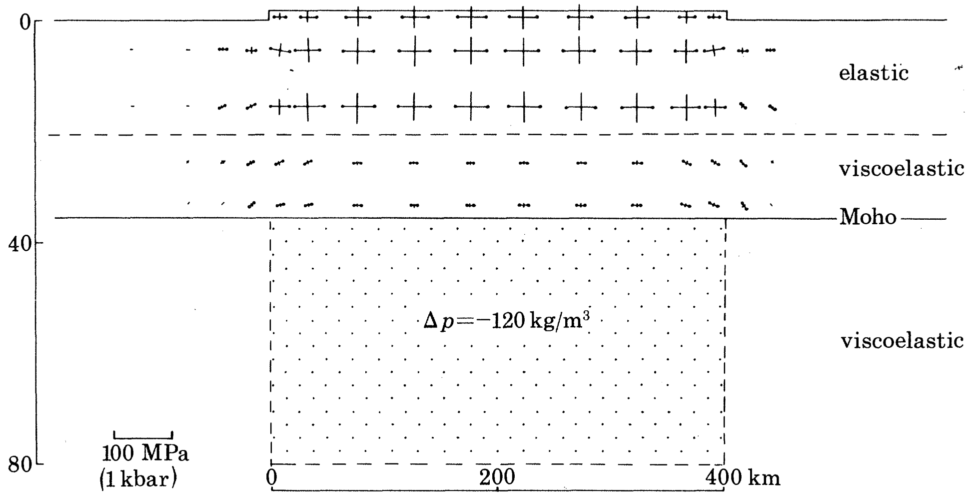

FIGURE 2. Deviatoric stresses in the continental crust produced by a compensated plateau uplift structure as a result of surface loading and upthrust of the compensating low-density mantle, assuming an upper elastic crust underlain by a viscoelastic lower crust and upper mantle. Even larger stresses are produced if the elastic layer is thinner. Dots indicate deviatoric tension. Modified from Bott & Kusznir (1979) and reproduced from Bott (1981).

location of some of the most conspicuous graben formation occurring during the Tertiary. The graben probably form as a result of the local stress system (Bott & Kusznir 1979).

4. DISCUSSION

In summary, horizontal deviatoric tension large enough to account for fault-controlled basin subsidence may occur both as a result of plate boundary forces at trenches and also in local regions of isostatically compensated elevated topography. The most widespread graben formation probably occurs at periods when a continental region is bordered on opposite sides by subduction zones. The largest tensions may occur at the time of continental splitting at the tips of the propagating crack.

Three examples of the application of these mechanisms to existing basins are as follows.

(1) *Slab pull*: the Lower Carboniferous basins of Britain formed on the northern shelf of the closing Hercynian marginal sea. It is suggested that the tension causing the formation of dominantly east–west fault-controlled basins originated as slab pull at the opposite edge of the closing ocean (Johnson 1981). Periodic variation in the stress as the subduction evolved in the closing ocean may give rise to the cyclic sedimentation so characteristic of the Carboniferous.

(2) *Trench suction*: the dominantly north–south orientated Permo-Triassic and Jurassic grabens of the North Sea and adjacent regions may have formed as a result of tension throughout Pangaea before and during break-up, originating as a result of subduction on opposite sides of the supercontinent.

(3) *Hot spot activity*: the Tertiary grabens of East Africa and the Basin and Range province are attributed to the local stress systems associated with these isostatically compensated elevated regions where the lithosphere is heated and thinned, rather than to plate boundary effects.

References (Bott)

Artyushkov, E. V. 1973 *J. geophys. Res.* **78**, 7675–7708.
Bally, A. W. & Snelson, S. 1980 *Mem. Can. Soc. Petrol. Geol.* **6**, 9–94.
Bott, M. H. P. 1976 *Tectonophysics* **36**, 77–86.
Bott, M. H. P. 1981 *Tectonophysics* **73**, 1–8.
Bott, M. H. P. & Dean, D. S. 1972 *Nature, phys. Sci.* **235**, 23–25.
Bott, M. H. P. & Kusznir, N. J. 1979 *Geophys. Jl R. astr. Soc.* **56**, 451–459.
Elsasser, W. M. 1971 *J. geophys. Res.* **76**, 1101–1112.
Forsyth, D. & Uyeda, S. 1975 *Geophys. Jl R. astr. Soc.* **43**, 163–200.
Johnson, G. A. L. 1981 *Proc. Yorks. geol. Soc.* **43**, 221–252.
Kusznir, N. J. & Bott, M. H. P. 1977 *Tectonophysics* **43**, 247–256.
McKenzie, D. 1978 *Earth Planet. Sci. Lett.* **40**, 25–32.
Morgan, W. J. 1972 *Bull. Am. Ass. Petrol. Geol.* **56**, 203–213.
Turcotte, D. L. 1974 *Geophys. Jl R. astr. Soc.* **36**, 33–42.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES