## Geophysics

# Contraction and stretching in basin formation

*from Norman H. Sleep*

BASINS on the continental shelves of passive (or Atlantic) margins and platform basins within the continental interior are generally a few hundred kilometres wide and contain several kilometres of nearly flat-lying sediments. The processes underlying the deposition of these sediments have been the subject of extensive investigations in recent years, particularly in the context of oil exploration. Because rocks deposited near sea level are encountered at great depths in bore holes, deposition is thought not to be a simple process of filling in pre-existing depressions but to be controlled by subsidence of the underlying bedrock. Recently, Cochran[1] has presented a detailed model which attributes the subsidence both to thermal contraction and to stretching of the lithosphere.

Cochran's model is grounded on the basic concepts of the formation of passive margins by continental break-up[2–5]. Geologically, a continental rift valley widens into the young margin of a small ocean and finally into the mature passive margin of a major ocean. As a rift develops along the nascent margin during continental break-up, hot mantle is emplaced beneath it in the same fashion as mantle is emplaced at a mid-oceanic ridge. After the rifting event, thermal contraction of the lithosphere beneath the margin causes subsidence, which is followed by deposition of sediments. Crustal thinning during break-up, the second feature of Cochran's model, is necessary if the process is to produce a basin. Without crustal thinning, thermal expansion of the lithosphere would produce an uplift which would return to sea level when it subsided. Erosion during the thermal uplift as the mechanism of crustal thinning was overemphasized by the earlier workers, myself in particular[5], because our data were obtained from boreholes landward of the region of significant stretching and because we were impressed with the major unconformity which followed break-up in these landward areas. We now know that in the more seaward areas, there is no major break-up unconformity; the amount of crustal thinning in the seaward areas is so great that it must be produced by stretching.

Although the original papers on thermal contraction of the lithosphere were published early in the plate tectonic revolution, the idea found little immediate acceptance and it was not until 1976 that the mechanism was discussed in a summary of a conference on Atlantic margins[6]. A partial explanation for the initial resistance is that American geophysicists believed that a proto-ocean existed in the Atlantic and thus excluded the possibility of continental break-up[7] or they believed that the break-up was Permian and thus too early for thermal contraction to cause Cretaceous subsidence (for example, ref. 8; the presently accepted age of the rifting of the East Coast of the United States is near the Triassic–Jurassic boundary[9]). Acceptance of plate tectonics by scientists studying basins was also slower than in other fields of earth science. For example, J. Lamar Worzel, a leading researcher on continental margins, remained strongly sceptical of plate tectonics until at least 1976 (ref.10), by when proponents of thermal subsidence[5,11-13] had convinced a significant portion of the geological community.

The oil shortage and a wealth of new data encouraged the more detailed physical studies which form the immediate basis of Cochran's model. In particular, Watts and Ryan[14] introduced the concept of 'driving load' — the amount of subsidence which would have occurred in the absence of sediment loads and regional redistribution of loads by flexure of the lithosphere. They extracted the history of the driving load from the record of sedimentation on the Atlantic coast of the United States by correcting for sedimentary processes such as compaction, weight of the sediments and changes in water depth. McKenzie[15] subsequently proposed a simple one-dimensional thermal model of continental break-up in which the lithosphere is uniformly and instantaneously thinned by stretching during rifting. In general, this process involves rapid subsidence as the crust is thinned during stretching, followed by gradual subsidence as the lithosphere cools. Subsequent work on basin mechanics, such as Cochran's, has involved combinations, modifications and applications of the methods of Watts and Ryan and of McKenzie, including determination of palaeotemperatures and petroleum maturity within the sedimentary column.

Clearly, McKenzie's model is a simple but elegant approximation. Atlantic margins and interior basins have finite width and even at plate tectonic rates it takes several million years to stretch the lithosphere. For example, the periods of Permian stretching in the Basin of Paris and Tertiary stretching in the northern Red Sea may last more than 20 Myr. Cochran has studied gradual stretching of a finite two-dimensional basin[1]. For rifting events of greater than 20 Myr his results are significantly different from those of the one-dimensional model because of the amount of cooling that occurs during the rifting stage. The post-rift subsidence is reduced by 25 per cent at the centre of the basin and the lateral flow of heat causes minor uplift on the flanks of the basin. After the rifting ends, the lithosphere becomes more rigid and the cooling of the material beneath the rift causes subsidence to extend over the flanks of the rift valley. The basin becomes progressively wider as the lithosphere thickens and stiffens with time. Considerable overestimates of the palaeo-heat flow of the basin result if the gradual syn-rift sedimentation is attributed to post-rift thermal contraction.

Cochran has developed a good starting model for application to an actual basin. How useful it will be will depend on how precisely uniform is the stretching in the crust and mantle lithosphere; stretching may involve nearly intact blocks and highly attenuated zones. Furthermore, the assumption that lithospheric heating is directly related to crustal thinning by the geometry of stretching, which gives McKenzie's and Cochran's formulations much of their elegance, is open to question. Substantial heating of the lower lithosphere, probably by bulk delamination and replacement with hot asthenosphere without significant stretching, is common around hot-spot volcanoes, such as Hawaii[16]. Lithospheric heating is thus possibly more widespread then crustal thinning during continental break-up. If the lithosphere on the flanks of a rift is already hot, then additional uplift from the lateral flow of heat from the rift would be obscured.

Cochran's model is fully analytical and can be evaluated quickly. For practical application to petroleum maturity, it is probably accurate enough because sedimentological effects, such as compaction and the subsequent change in thermal conductivity, give rise to greater uncertainties in palaeotemperature than do the simplifications of the model. Because the importance of slow rifting must be recognized, the industrial geologist should give careful attention to his seismic sections before applying Cochran's model. □

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