Formation of the "steer's head" geometry of sedimentary basins by differential stretching of the crust and mantle

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ABSTRACT

If the lithospheric mantle is stretched over a wider region than the crust, postrift stratigraphic onlap will occur at basin margins, giving rise to a "steer's head" geometry. Space problems are avoided by making the total amount of extension in the lithospheric mantle equal to that in the crust. The predicted pattern of onlap agrees well with that observed if the lithospheric mantle is stretched over a fractionally wider region than is the crust. Thus, extensive stratigraphic onlap can be produced easily without recourse to sea-level rise or flexural rigidity.

INTRODUCTION

It is now generally accepted that the lithospheric stretching model (McKenzie, 1978) can explain, at least in outline, the main features of some but not all (e.g., Hajnal et al., 1984) continental sedimentary basins and passive margins (Sclater and Christie, 1980; Sclater et al., 1980; Le Pichon and Sibuet, 1981; Royden et al., 1983; Barton and Wood, 1984; Ye et al., 1985). Several observations cannot, however, be easily explained by the model in its simplest form. One of the more important of these is postrift stratigraphic onlap at basin margins. Such onlapping or transgressive sequences give rise to the so-called steer's head or Texas longhorn basin geometry (Dewey, 1982; Fig. 1). Suggested explanations for this geometry include global or eustatic sea-level rise (Vail et al., 1977; Haq et al., 1987) and increasing flexural rigidity of the continental lithosphere after rifting (Watts, 1982; Watts et al., 1982; Beaumont et al., 1982). As discussed below, there are problems associated with both of these mechanisms. An alternative explanation based on a two-layer lithospheric stretching model is, however, compatible with all of the observations.

SEA-LEVEL CHANGES

Sea level has undoubtedly fluctuated through geologic time. There is considerable debate concerning the magnitude and frequency of these changes and how they affect the geologic record. Originally, Suess (1906) postulated that transgressive and regressive sedimentary sequences could be attributed directly to sea-level rise and fall. Transgression during the Cretaceous was thought to have been so widespread that it implied a global or eustatic rise in sea level. Vail et al. (1977) used patterns of onlap and offlap on seismic-reflection data to construct a curve of global sea-level change with time. Their methodology has subsequently changed, although the global curves that they obtained remain virtually unchanged (Vail and Todd, 1981; Haq et al., 1987). However, as Pitman (1978), Watts (1982), and others have emphasized, there are difficulties in distinguishing sea-level changes from tectonic uplift and subsidence. The few careful attempts that have been made to separate the effects of sea-level fluctuation from tectonic subsidence suggest that if fluctuations occur they are gradual and have amplitudes of less than 150 m (Watts and Steckler, 1979; Watts and Thorne, 1984). Such small changes cannot account for the scale of stratigraphic onlap frequently observed. In Figure 1b, for example, the vertical component of onlap is approximately 2 km. This corresponds to about 600 m of unloaded subsidence. Therefore, eustatic

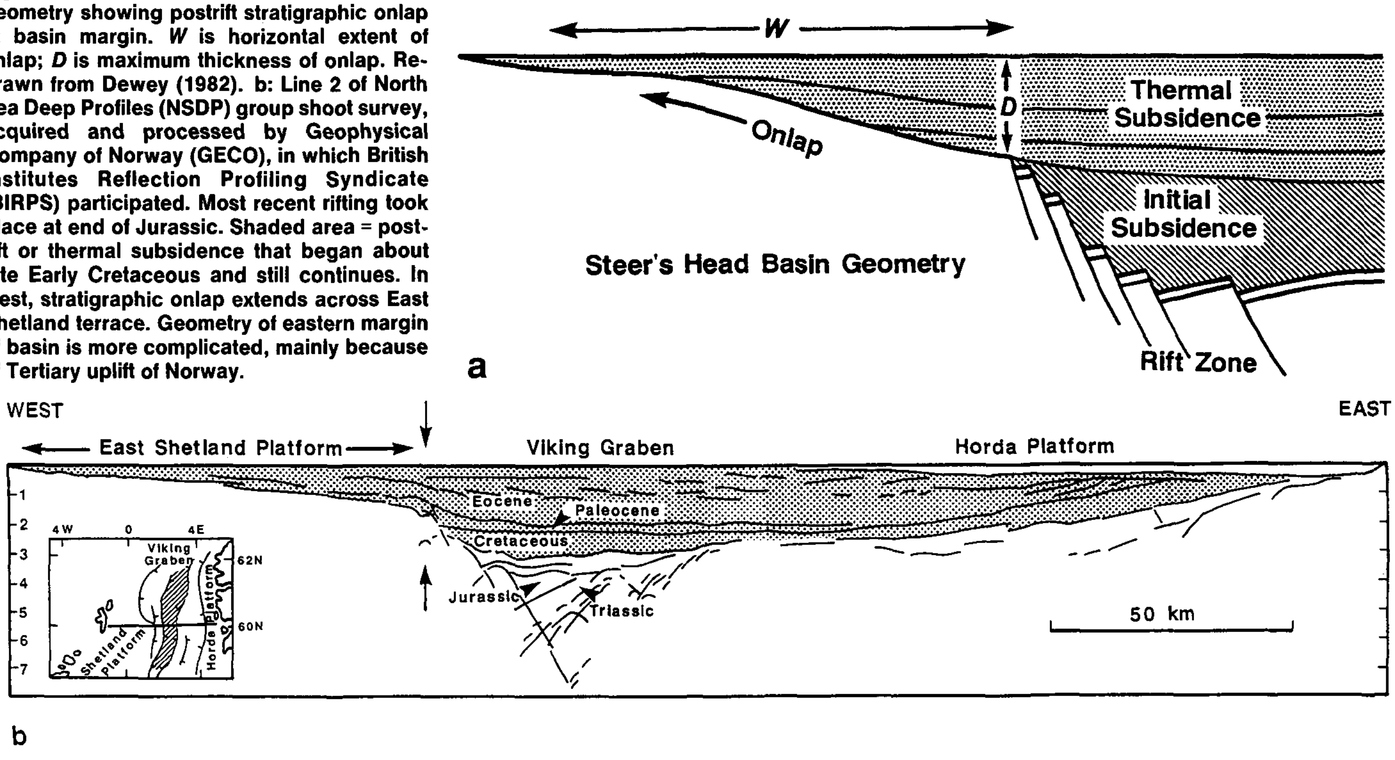

Figure 1. a: Idealized steer's head basin geometry showing postrift stratigraphic onlap at basin margin. *W* is horizontal extent of onlap; *D* is maximum thickness of onlap. Redrawn from Dewey (1982). b: Line 2 of North Sea Deep Profiles (NSDP) group shoot survey, acquired and processed by Geophysical Company of Norway (GECO), in which British Institutes Reflection Profiling Syndicate (BIRPS) participated. Most recent rifting took place at end of Jurassic. Shaded area = postrift or thermal subsidence that began about late Early Cretaceous and still continues. In west, stratigraphic onlap extends across East Shetland terrace. Geometry of eastern margin of basin is more complicated, mainly because of Tertiary uplift of Norway.

sea-level changes alone cannot explain the steer's head geometry of extensional basins, although the internal geometry of the postrift sediments is probably affected by small fluctuations in sea level.

FLEXURE

A more recent explanation for postrift stratigraphic onlap relies on the response of the continental lithosphere to sedimentary loads (Watts, 1982; Watts et al., 1982). Studies of seamounts and oceanic islands show that the elastic thickness of the oceanic lithosphere, T_e, depends on its age at the time of loading (Watts, 1978). Thus, loads formed on young oceanic lithosphere yield small values of T_e and those formed on older oceanic lithosphere give larger values. The elastic thickness of 100 Ma oceanic lithosphere is 30–40 km. Watts (1982) and Watts et al. (1982) argued that stretched continental lithosphere should respond in a similar fashion. As it cools down after stretching, the continental lithosphere should become increasingly rigid in its response to sediment loading. Calculations carried out by Watts et al. (1982) show that the resultant pattern of onlap agrees well with observation. Similar data were used by Vail et al. (1977) to infer sea-level rise. Independent estimates of the elastic thickness of the lithosphere can be obtained by using perturbation theory to relate free-air gravity anomalies and load topography (Lewis and Dorman, 1970; McKenzie and Bowin, 1976). Although values for T_e in the continental lithosphere are fewer in number and are less well determined than those obtained in the deep oceans, several recent studies of passive continental margins and sedimentary basins indicate that T_e remains less than 5 km during the postrift phase (Nunn and Sleep, 1984; Barton and Wood, 1984; Fowler and McKenzie, in prep.). Such values are significantly smaller than those of coeval oceanic lithosphere, where T_e is approximately the depth to the 450 °C isotherm (Watts, 1978). Other studies suggest that in some regions the continental lithosphere may have a much larger elastic thickness (Ahern and Mrkvicka, 1984; Bechtel et al., 1987).

A difference between the elastic behavior of continental and oceanic lithosphere after a stretching event is not unexpected. The rheological behavior of a material is principally controlled by τ, the ratio of the temperature of a material to that of its melting point, both measured in Kelvin (Ashby and Verrall, 1977; Weertman, 1978). Materials can only maintain stresses over geologic time if τ is less than about 0.4. For oceanic lithosphere this approximately corresponds to the 450 °C isotherm, in agreement with Watts (1978). If the rheology of the upper continental crust corresponds to that of wet granite, then $\tau = 0.4$ corresponds to a temperature of about 100 °C. Although this estimate is not accurate, it implies that only the top few kilometres of the continental lithosphere can maintain elastic stresses over significant periods of time. Therefore, the flexure model is not in good agreement with observations from some passive margins and sedimentary basins or with the expected behavior of the continental lithosphere in such areas.

TWO-LAYER STRETCHING

Given the difficulties associated with the mechanisms discussed above, an attempt is made here to explain the steer's head geometry of basins such as the North Sea solely in terms of a modified stretching model. One simple modification is to use a two-layer stretching model in which stretching in the crust and in the lithospheric mantle are distributed differently (Sclater et al., 1980; Royden and Keen, 1980; Hellinger and Sclater, 1983; Rowley and Sahagian, 1986). A feature of many of these calculations is that the lithosphere mantle is stretched more than the crust. In order to generate the steer's head basin geometry, the lithospheric mantle beneath the basin flanks must be stretched and the resultant synrift uplift rapidly eroded away. There are several difficulties with such proposals. The most serious objection is that severe space problems arise if the lithospheric mantle is stretched by a greater amount than the crust. Considerable amounts of uplift followed by rapid erosion are also required (Hellinger and Sclater, 1983). In a variation of the two-layer stretching model that avoids these problems, the total amount of extension is the same in the crust and lithospheric mantle, but it is distributed differently in each.

As before, the lithospheric mantle is stretched over a wider region than is the crust. To avoid the space problems inherent in the standard two-layer model, however, the total amount of stretching in the crust and in the lithospheric mantle are required to be equal. The model we propose is thus similar in some respects to that of Rowley and Sahagian (1986). If a Gaussian function is used to describe the variation of β_c, the stretching factor in the crust, and β_m, the stretching factor in the lithospheric mantle, with distance x from the basin center, then

$$\beta_c = 1 + (\beta_{co} - 1) \exp\left(\frac{-x^2}{2\sigma_c^2}\right), \qquad (1)$$

and

$$\beta_m = 1 + \left(\frac{\sigma_c}{\sigma_m}\right) (\beta_{co} - 1) \exp\left(\frac{-x^2}{2\sigma_m^2}\right). \qquad (2)$$

The variable σ_c and σ_m govern how quickly β_c and β_m decrease with distance from the center of the basin. At the center of the basin, $\beta_c = \beta_{co}$ and $\beta_m = 1 + (\sigma_c/\sigma_m)(\beta_{co} - 1)$. If the mantle is stretched over a wider area than the crust, then σ_m must be greater than σ_c. This result requires β_m to be less than β_c in the central part of the basin (see Fig. 3a). In fact, as discussed below, the difference between the two needed to account for the observations is small.

The values of β_c and β_m at any point can now be used to calculate both the initial subsidence and the time-dependent thermal subsidence. The necessary equations are similar to those derived by Sclater et al. (1980). The resultant basins have all been instantaneously loaded with sediment. Airy compensation is assumed to apply everywhere. If $\sigma_m = \sigma_c$, then the uniform stretching model applies and, as shown in Figure 2b and 2c, there is no synrift uplift and no postrift onlap at the basin margins. If,

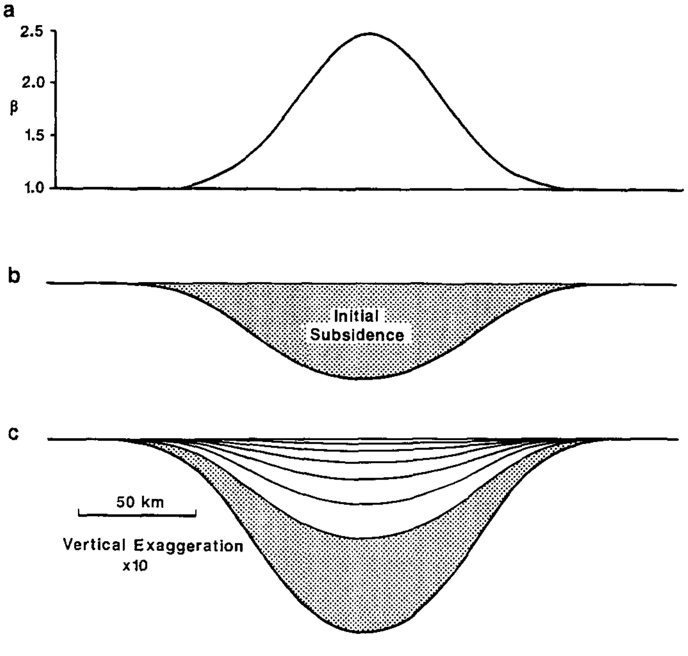

Figure 2. a: β, stretching factor in crust and upper mantle, is plotted as function of distance using equations 1 and 2 (see text); $\sigma_m = \sigma_c = 30$, so stretching in crust and upper mantle is identical. In center of basin, $\beta_c = \beta_m = 2.5$. b: Initial subsidence immediately after stretching. Basin has been loaded with sediment having density of 2.0. Other parameters have same values as in McKenzie (1978). c: Total subsidence 150 m.y. after rifting. Thermal subsidence is represented by time lines drawn every 25 m.y. Thermal subsidence dies out at same position as initial subsidence.

however, $\sigma_m > \sigma_c$, a different basin geometry is obtained (Fig. 3). After instantaneous stretching, minor uplift occurs adjacent to the flanks of the basin (Fig. 3b). This behavior is in agreement with observations from the margins of very young rift zones such as the East African Rift and the Gulf of Suez (Morgan, 1983; Steckler, 1985). In older basins (e.g., the North Sea) synrift uplift is inferred from the geologic record (Ziegler, 1982; Leeder, 1983). As the thermal anomaly produced by stretching the mantle decays, stratigraphic onlap is generated at the flanks. The *total* subsidence in Figures 2c and 3c is identical, because this is only governed by crustal thickness. The only difference is the distribution of initial and thermal subsidence. In Figure 3b, the basin flanks are initially uplifted, even though the crust beneath has been stretched by a small amount, because the effect of stretching the lithospheric mantle by a greater amount is to cause uplift first and subsidence later. The resultant basin geometry is similar to that calculated by assuming a postrift increase in elastic thickness (Watts et al., 1982). In the model presented here, however, it is assumed that the elastic thickness of the continental lithosphere is negligible. No erosion of the basin flanks is required to generate considerable onlap.

DISCUSSION

Figure 4a shows how the horizontal extent, W, and the maximum depth, D, of the postrift onlap varies with σ_c and σ_m, the two parameters that determine how rapidly β_c and β_m decrease away from the center of the basin. Clearly, significant values of W and D can be obtained if the ratio F (= σ_c/σ_m) is only fractionally less than 1.0. It is unlikely that the small difference between β_c and β_m in the center of the basin could be detected using the standard techniques (Sclater and Christie, 1980; Le Pichon and Sibuet, 1981; Barton and Wood, 1984). In the northern North Sea, minor amounts of extension are observed in the basin flanks. This is consistent with the model presented above.

Basin geometry is generally more complicated than shown in Figures 2 and 3. Other factors such as sediment supply, sedimentation rate, and compaction all affect the stratigraphic pattern. Therefore, the results shown in Figure 4a cannot be compared directly with observation. Figure 4b shows some observed values of W plotted against corresponding values of D. Shallow and deep seismic reflection data from the northern North Sea

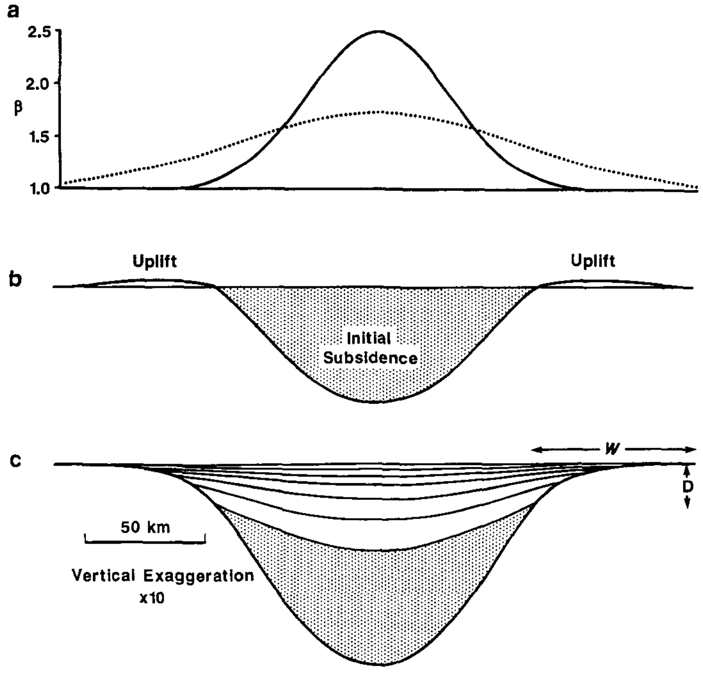

Figure 3. a: β_c, stretching factor in crust (solid line), and β_m, stretching factor in upper mantle (dotted line) are plotted as function of distance using equations 1 and 2 (see text); $\sigma_m = 60$ and $\sigma_c = 30$, as in Figure 2. In center of basin, $\beta_c = 2.5$ as before, but now $\beta_m = 1.75$. All other parameters are identical to those used in Figure 2. b: Initial subsidence immediately after stretching. Note localized uplift along flanks of basin. c: Total subsidence 150 m.y. after rifting. Thermal subsidence is represented by lines drawn every 25 m.y. Onlap produced by thermal subsidence at basin margin results in steer's head geometry. W is horizontal extent of onlap and D is its maximum thickness. Note that *total* subsidence in Figures 2c and 3c is identical; only difference is relative proportion of initial subsidence to thermal subsidence.

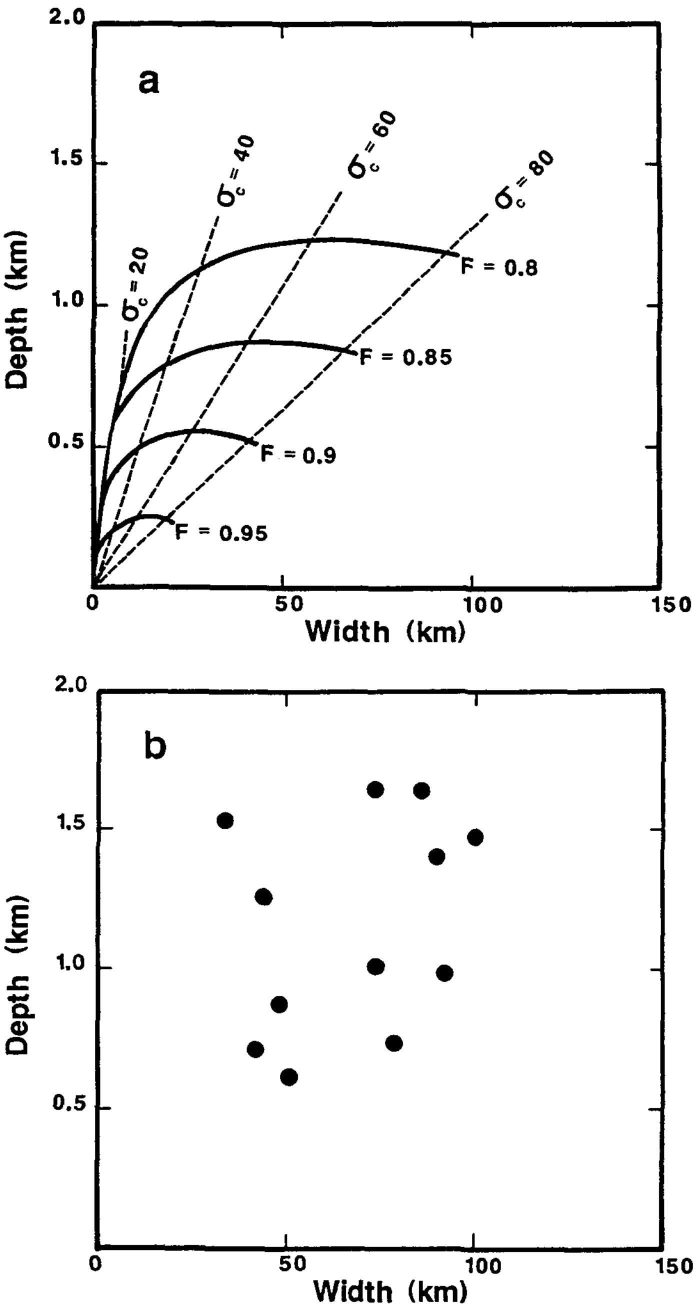

Figure 4. a: Horizontal extent of postrift stratigraphic onlap, W, is plotted against D, maximum thickness of onlap for different values of σ_c and σ_m. Each solid curve corresponds to particular value of F, where $F = \sigma_c/\sigma_m$. Broken lines indicate different values of σ_c ranging from 20 to 80. Cutoff of 10 m onlap was used in calculating W. b: Observed values of W plotted against corresponding values of D. Values have been obtained from interpreted seismic-reflection profiles from northern North Sea (provided by Norwegian Exploration Consultants [NOPEC a.s.] and by British Institutes Reflection Profiling Syndicate [BIRPS]).

were used for this purpose. All measurements were made on the western side of the basin because the geometry of the eastern margin has been complicated by the uplift of Norway during the Tertiary (Fig. 1b; Ziegler, 1982). The calculations yield values of W and D that are comparable to those observed (cf. Fig. 4a and 4b). D is larger than expected. This is not surprising because the effect of flank erosion was ignored in the calculations. D will also tend to be larger than expected if the initial subsidence basin is not completely filled with sediment immediately after extension.

CONCLUSIONS

The steer's head geometry of extensional sedimentary basins is usually explained either by a large eustatic sea-level rise or by a significant postrift increase in the flexural rigidity of the continental lithosphere. Both of these mechanisms are inconsistent with several observations. Here a simple thermal model, based on two-layer lithospheric stretching and consistent with observations, is proposed. Postrift stratigraphic onlap is generated when the lithospheric mantle is stretched over a wider region than is the crust. Only a small amount of basin-flank uplift occurs, and no erosion is required. The space problems typical of most two-layer stretching models are also avoided. The lithospheric mantle need only be stretched over a region fractionally wider than is the crust to result in significant vertical and horizontal components of onlap. Although these calculations cannot be compared directly with observation, the calculated values of horizontal extent and maximum depth of onlap agree with data from the northern North Sea.

REFERENCES CITED

Ahern, J.L., and Mrkvicka, S.R., 1984, A mechanical and thermal model for the evolution of the Williston Basin: Tectonics, v. 3, p. 79–102.

Ashby, M.F., and Verrall, R.A., 1977, Micromechanisms of flow and fracture, and their relevance to the rheology of the upper mantle: Royal Society of London Philosophical Transactions, ser. A, v. 288, p. 59–95.

Barton, P., and Wood, R., 1984, Tectonic evolution of the North Sea basin: Crustal stretching and subsidence: Royal Astronomical Society Geophysical Journal, v. 79, p. 987–1022.

Beaumont, C., Keen, C.E., and Boutilier, R., 1982, On the evolution of rifted continental margins: Comparison of models and observations for the Nova Scotian margin: Royal Astronomical Society Geophysical Journal, v. 70, p. 667–715.

Bechtel, T.T., Forsyth, D.W., and Swain, C.J., 1987, Mechanisms of isostatic compensation in the vicinity of the East African Rift, Kenya: Royal Astronomical Society Geophysical Journal, v. 90, p. 445–465.

Dewey, J.F., 1982, Plate tectonics and the evolution of the British Isles: Geological Society of London Journal, v. 139, p. 371–412.

Hajnal, Z., Fowler, C.M.R., Mereu, R.F., Kanasewich, E.R., Cumming, G.L., Green, A.G., and Mair, A., 1984, An initial analysis of the earth's crust under the Williston Basin: Journal of Geophysical Research, v. 89, p. 9381–9400.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Hellinger, S.J., and Sclater, J.G., 1983, Some comments on two-layer extensional models for the evolution of sedimentary basins: Journal of Geophysical Research, v. 88, p. 8251–8269.

Leeder, M.R., 1983, Lithospheric stretching and North Sea Jurassic clastic sourcelands: Nature, v. 305, p. 510–513.

Le Pichon, X., and Sibuet, J.C., 1981, Passive margins; a model of formation: Journal of Geophysical Research, v. 86, p. 3708–3720.

Lewis, B.T.R., and Dorman, L.M., 1970, Experimental isostasy, 2, an isostatic model for the U.S.A. derived from gravity and topographic data: Journal of Geophysical Research, v. 75, p. 3367–3386.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.

McKenzie, D.P., and Bowin, C.O., 1976, The relationship between bathymetry and gravity in the Atlantic Ocean: Journal of Geophysical Research, v. 81, p. 1903–1915.

Morgan, P., 1983, Constraints on rift thermal processes from heat flow and uplift: Tectonophysics, v. 94, p. 277–298.

Nunn, J.A., and Sleep, N.H., 1984, Thermal contraction and flexure of intracratonic basins: A three-dimensional study of the Michigan Basin: Royal Astronomical Society Geophysical Journal, v. 76, p. 587–635.

Pitman, W.C., III, 1978, Relationship between eustasy and stratigraphic sequences of passive margins: Geological Society of America Bulletin, v. 89, p. 1389–1403.

Rowley, D.B., and Sahagian, D., 1986, Depth-dependent stretching: A different approach: Geology, v. 14, p. 32–35.

Royden, L., and Keen, C.E., 1980, Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence data: Earth and Planetary Science Letters, v. 51, p. 343–361.

Royden, L., Horvath, F., Nagymarosy, A., and Stegena, L., 1983, Evolution of the Pannonian Basin System; 2. Subsidence and thermal history: Tectonics, v. 2, p. 91–137.

Sclater, J.G., and Christie, P.A.F., 1980, Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the Central North Sea Basin: Journal of Geophysical Research, v. 85, p. 3711–3739.

Sclater, J.G., Royden, L., Horvath, F., Burchfiel, B.C., Semken, S., and Stegena, L., 1980, The formation of the intra-Carpathian basins as determined from subsidence data: Earth and Planetary Science Letters, v. 51, p. 139–162.

Steckler, M.S., 1985, Uplift and extension at the Gulf of Suez: Indications of induced mantle convection: Nature, v. 317, p. 135–139.

Suess, E., 1906, The face of the earth (volume 2): Oxford, England, Clarendon Press, 556 p.

Vail, P.R., and Todd, R.G., 1981, Northern North Sea Jurassic unconformities, chronostratigraphy and sea level changes from seismic stratigraphy, *in* Illing, L.V., and Hobson, G.D., eds., Petroleum geology of the continental shelf of north-west Europe: London, Institute of Petroleum, p. 216–235.

Vail, P.R., Mitchum, R.M., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 49–212.

Watts, A.B., 1978, An analysis of isostasy in the world's oceans, 1. Hawaiian-Emperor seamount chain: Journal of Geophysical Research, v. 83, p. 5989–6004.

——1982, Tectonic subsidence, flexure and global changes of sea level: Nature, v. 297, p. 469–474.

Watts, A.B., and Steckler, M.S., 1979, Subsidence and eustasy at the continental margin of eastern North America: American Geophysical Union, Maurice Ewing Series v. 3, p. 218–234.

Watts, A.B., and Thorne, J., 1984, Tectonics, global changes in sea level and their relationship to stratigraphic sequences at the U.S. Atlantic continental margin: Marine and Petroleum Geology, v. 1, p. 319–339.

Watts, A.B., Karner, G.D., and Steckler, M.S., 1982, Lithospheric flexure and the evolution of sedimentary basins: Royal Society of London Philosophical Transactions, ser. A, v. 305, p. 249–281.

Weertman, J., 1978, Creep laws for the mantle of the earth: Royal Society of London Philosophical Transactions, ser. A, v. 288, p. 9–26.

Ye, H., Shedlock, K.M., Hellinger, S.J., and Sclater, J.G., 1985, The north China basin: An example of a Cenozoic rifted intraplate basin: Tectonics, v. 4, p. 153–169.

Ziegler, P.A., 1982, Geological atlas of western and central Europe: The Hague, Shell Internationale Petroleum Maatschappij, B.V., 130 p.

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Reviewer's comment

This paper raises some important questions about the magnitude of rigidity in continental lithosphere and, especially, about evidence from basins bearing on rigidity.

Gerard Bond
