Depth-dependent stretching: A different approach

David B. Rowley
Dork Sahagian
Department of Geophysical Sciences, University of Chicago, Chicago, Illinois 60637

ABSTRACT

Uplift of the crust during rifting is a major problem that has been left unresolved by uniform stretching models. Various depth-dependent stretching models have been proposed to account for this, but these require decoupling of the crust and mantle and result in space problems within the mantle. A significant modification of these discontinuous nonuniform or depth-dependent stretching models is proposed here that accounts for synrift uplift and doming but does not result in these problems. The model involves continuous nonuniform stretching within a polygonal region bounded by symmetrical, outward-sloping boundaries within the mantle. This geometry results in thinning of the lithosphere below crustal regions that are less stretched or unstretched, crustal uplift resulting from asthenospheric upwelling below these regions. This in turn results in stretching factors for the mantle that are less than those for the crust, a relationship opposite to relationships derived by discontinuous nonuniform stretching models. Corollary predictions for mantle-derived heat flow within and outside regions of stretching of these two different depth-dependent models may allow them to be distinguished from each other and from regions where uniform stretching predominates.

INTRODUCTION

The causes of uplift and subsidence associated with continental rifting have been the focus of much study and controversy. An important early step toward the understanding of rifts was the recognition by Sleep (1971) that the subsidence history of the Atlantic-type margin along the east coast of North America followed an exponentially decreasing rate with time, comparable with that of cooling oceanic lithosphere. Considerable attention has recently been focused on quantitative models that allow calculation of subsidence and thermal histories as functions of the amount of extension of the crust due either to thinning and stretching of the crust and lithosphere (McKenzie, 1978) or to dike injection into the

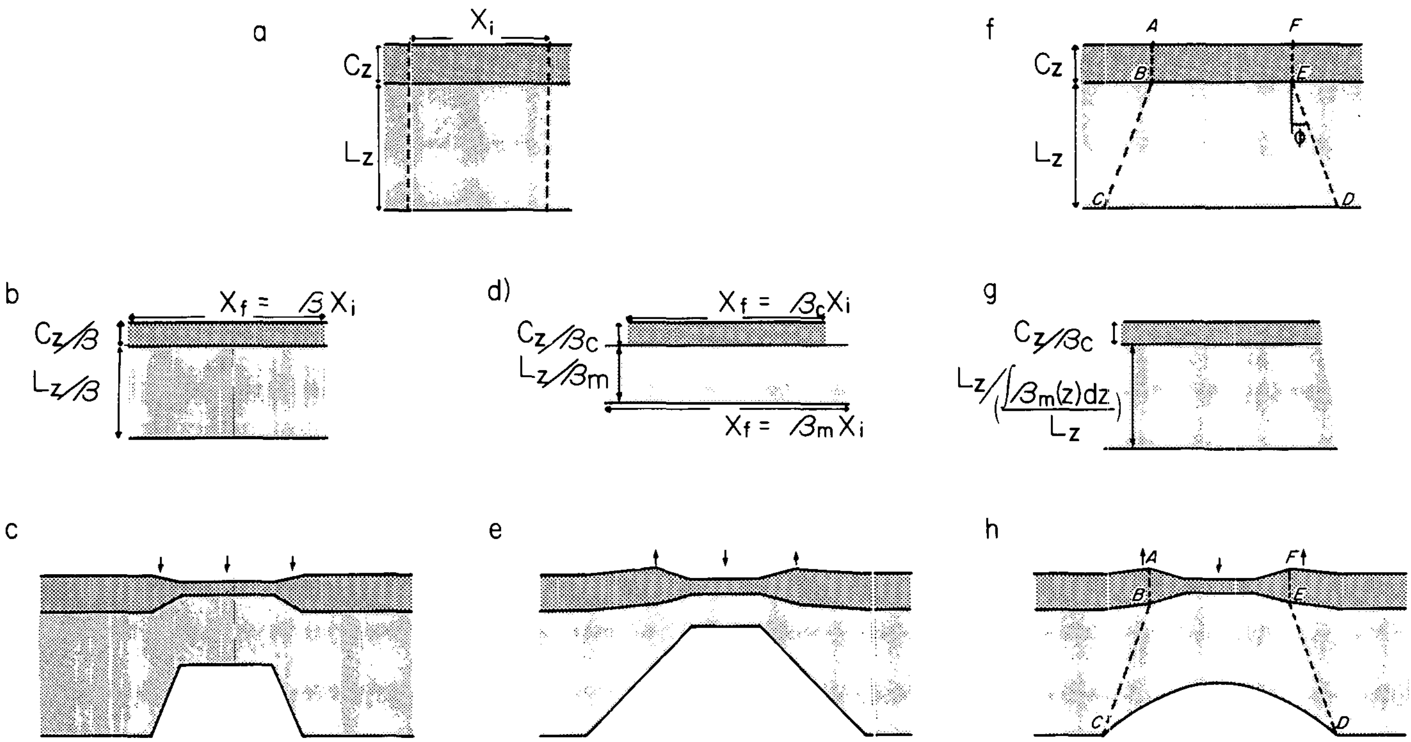

Figure 1. Cross-sectional geometry showing initial and final configuration for three different models of lithospheric stretching. a: Initial state for diagrams b, c, d, and e. Dark shading = crust, light shading = mantle lithosphere; C_z = 30-km thickness, L_z = 95-km thickness; X_i = initial horizontal width. b: Uniform stretching of initial state a by $\beta = X_f/X_i$, where X_f is final horizontal width and does not vary with depth (McKenzie, 1978). c: Geometry immediately after instantaneous uniform stretching. Arrows indicate direction of syn-stretching vertical movement. d: Discontinuous nonuniform stretching (Royden and Keen, 1980; Beaumont et al., 1982) where β_c and β_m are independent, but are uniform for the crust and mantle lithosphere, respectively. e: Geometry immediately after discontinuous nonuniform stretching. f: Initial geometry of continuous nonuniform stretching. g: Crust and mantle lithosphere geometry resulting from continuous nonuniform stretching. h: Geometry immediately after instantaneous, continuous nonuniform stretching.

lithosphere (Royden et al., 1980). The model developed by McKenzie has been widely adopted; subsequent work has concentrated on refinements and implications of the original model as well as its application to various rift-related sedimentary basins of the world. The purpose of this paper is to examine the cross-sectional geometries of various models and to propose a configuration, not previously considered, that might be responsible for uplift of rift shoulders during stretching.

STRETCHING MODELS

The first-order geophysical and geologic properties of rift-related sedimentary basins have been shown to be the consequences of concomitant thinning and stretching of continental crust and subcrustal lithosphere (McKenzie, 1978; Fig. 1). In the uniform stretching model of McKenzie (1978), the following assumptions are made: (1) the amount of stretching (β) is defined as the horizontal extention of a line, such that

$$\beta = \text{length (final)/length (initial)} \tag{1}$$

is uniform with depth (e.g., β_c [crust] = β_m [mantle]); (2) stretching occurs virtually instantaneously (e.g., <20 m.y.); (3) initial rift-related subsidence is accomplished by local, Airy-type compensation; and (4) poststretching subsidence follows a time$^{1/2}$ cooling path.

The focus of more recent work has been on the implications of (1) stretching over finite time periods (Jarvis and McKenzie, 1980; Beaumont et al., 1982; Cochran, 1983a); (2) spatial and temporal changes in the mechanical behavior of the crust and lithosphere in the vicinities of rifting (Steckler and Watts, 1982; Beaumont et al., 1982); (3) shallow- versus deep-level mechanical behavior of the crust and upper mantle during large-scale regional stretching (Montadert et al., 1979; Le Pichon and Sibuet, 1981; Wernicke and Burchfiel, 1982; Beaumont et al., 1982); and (4) so-called nonuniform (Royden and Keen, 1980) or depth-dependent (Beaumont et al., 1982) stretching models in which the amount of stretching in the crust (β_c) and subcrustal lithosphere (β_m) is not the same (Royden and Keen, 1980; Beaumont et al., 1982) (Fig. 1d and 1e). This last group of models is hereafter referred to as discontinuous nonuniform stretching because of the required intralithospheric discontinuity separating regions with different values of β.

The primary impetus for the development of the nonuniform stretching models is the observation that many rifts and rifted continental margins, including Nova Scotia and Labrador (Royden and Keen, 1980; Beaumont et al., 1982), the East African Rift (Brown and Girdler, 1980; Mohr, 1982), and the Red Sea (Cochran, 1983b), are characterized by initial uplift, at least outside the regions of crustal extension, during the stretching phase (Royden and Keen, 1980). In McKenzie's uniform stretching model, crustal uplift occurs only within the region of stretching, and then only when the ratio of crustal thickness (C_z) to lithospheric thickness (L_z) is less than about 0.2. Uplift is explained in the discontinuous nonuniform models by the proposal that initial uplift occurs when $\beta_m > \beta_c$, and is a consequence of the replacement of relatively more dense lithosphere by warmer, less dense asthenosphere below relatively less stretched crust (Fig. 1e). Subsequent poststretching subsidence is dependent upon the amount of stretching of the initially uplifted crust (β_c) and the amount of material eroded off the rift shoulders (Sleep, 1971), but not on the amount of stretching of the subcrustal lithosphere (β_m). Although the discontinuous nonuniform stretching models can account for this aspect of the evolution of many rifts, these models are not without their difficulties. Primary among these are (1) the requirement of a marked structural discontinuity within the lithosphere, usually taken to be at the base of the crust; (2) the lack of a reasonable mechanism by which the mantle is detached and stretched by an amount different from the overlying crust; and, importantly, (3) the space problems resulting from greater stretching of the lower, subcrustal lithosphere than of the overlying crust (Fig. 1d and 1e). In this paper we propose an alternative model that we believe accounts for initial uplift but does not create these difficulties.

MODEL

An implicit assumption of the uniform stretching model is that extensional strain and strain rate do not vary with depth within the crust and mantle lithosphere. This results in the value of β being independent of depth. However, β should be dependent upon depth if depth-related changes in deformation mechanisms affect the mode of accommodation of the extensional strain. An example of this type of change is the transition from brittle to ductile behavior (Beaumont et al., 1982; Dokka and Pilger, 1984). We therefore allow the mantle response to extension to vary as a function of depth, such that the strain rate decreases with increasing diffusion of strain over a wider region. We model this geometry in two dimensions (Fig. 1f–1h) by defining the region of stretching to be bounded by the polygon ABCDEF outside of which no stretching occurs. Stretching results from horizontal elongation of the polygon by an amount k. In our example, the crust within the polygon is constrained to stretch uniformly because the bounding planes (AB and EF) are parallel. Depth dependence in the mantle lithosphere results from the fact that the initial lengths of horizontal lines within the polygon BCDE vary with depth, and hence β must also vary.

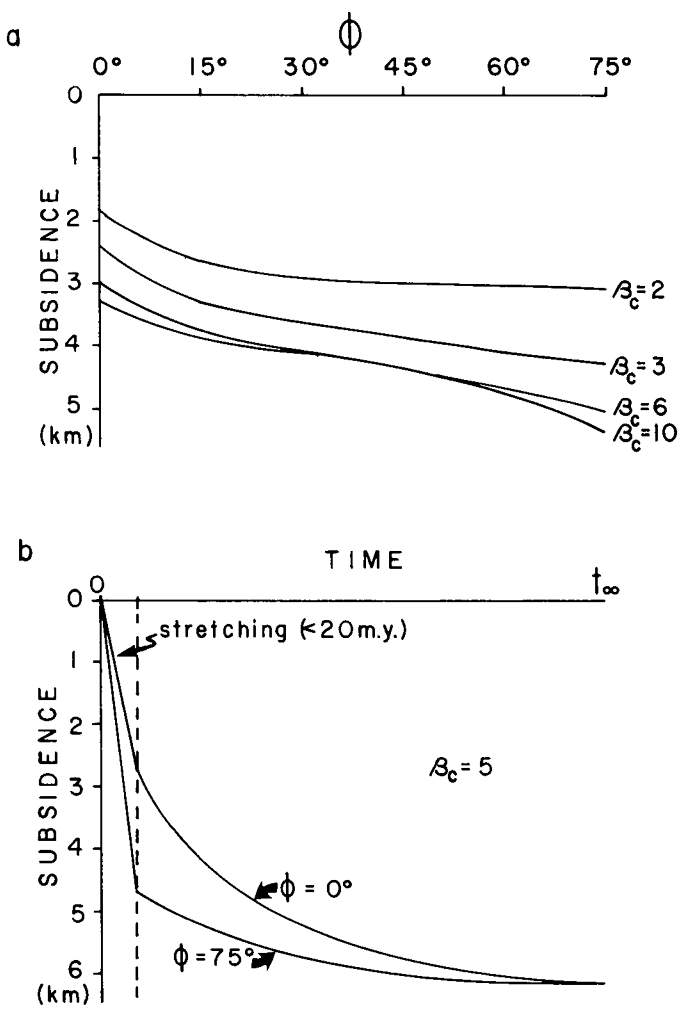

Figure 2. a: Dependence of immediate crustal subsidence on ϕ for various values of β_c. Initial width (C) = 10 km. b: Dependence of immediate and poststretching thermal subsidence histories for ϕ = 0° and ϕ = 75° at the same β_c = 5.

The values of β at any depth can be calculated by specifying the depth below the crust (z), the initial length (c) over which stretching occurs, and the difference between the initial and final line lengths (k) of stretched lines in the relation

$$\beta_m(z) = 1 + (k/(c + 2\,|z \tan\phi\,|)), \tag{2}$$

where ϕ is the angle between the vertical and the lines BC and/or DE (Fig. 1f). In cases where lines BC and DE slope outward, $\beta_m(z)$ decreases with depth, and is everywhere less than β_c, the magnitude of the difference being dependent upon ϕ and z. The amounts of initial and final subsidence are then calculated using modifications of McKenzie's (1978) equations by integrating $\beta_m(z)$ from the base of the crust to the base of the lithosphere. The effect of ϕ on initial subsidence is illustrated in Figure 2a, where $\phi = 0°$ represents the uniform stretching case. The impact of ϕ on stretching and poststretching thermal-driven subsidence histories is shown in Figure 2b.

The value of ϕ can be estimated from surface data using (1) the limits of the region affected by crustal extension and (2) the horizontal extent of uplifted rift shoulders as measured perpendicular to the rift. From the geometry illustrated in Figure 1f and 1h, it is clear that uplift outside of the region of crustal stretching is related to ϕ and L_z by the relationship

$$\tan\phi = X/L_z, \tag{3}$$

where X is the horizontal width over which this uplift occurs. For example, in the southern Red Sea where crustal stretching has been active since late Tertiary time (Cochran, 1983b), X is about 250 km, implying a value of ϕ of about 70°.

The consequences of this model are illustrated in Figure 3, which shows the uplift/subsidence histories for several points across a very simplified rifted sedimentary basin. All points between the rift shoulders experience only subsidence (curve C, Fig. 3b), whereas points between A and B experience uplift and then subsidence back to their original elevation or slightly below if material is eroded from the uplifted region (Sleep, 1971). Initial uplift of the points between A and B results from the replacement of relatively cooler, more dense lithosphere with warmer, less dense asthenosphere below a region of unstretched crust.

A somewhat more realistic example is illustrated in Figure 4a in which β_c varies laterally from unstretched on the margins to a maximum in the middle of the rift. The uplift/subsidence histories for this geometry are illustrated using topographic profiles, one before stretching (t_i), one immediately following stretching (t_s), and a third at t_∞. Once again, points within the central region of the rift experience only subsidence, whereas those points immediately to the right of A record initial rift-related uplift followed by thermal subsidence.

DISCUSSION

Discontinuous nonuniform stretching models were initially proposed to explain why many rifts record initial uplift during stretching.

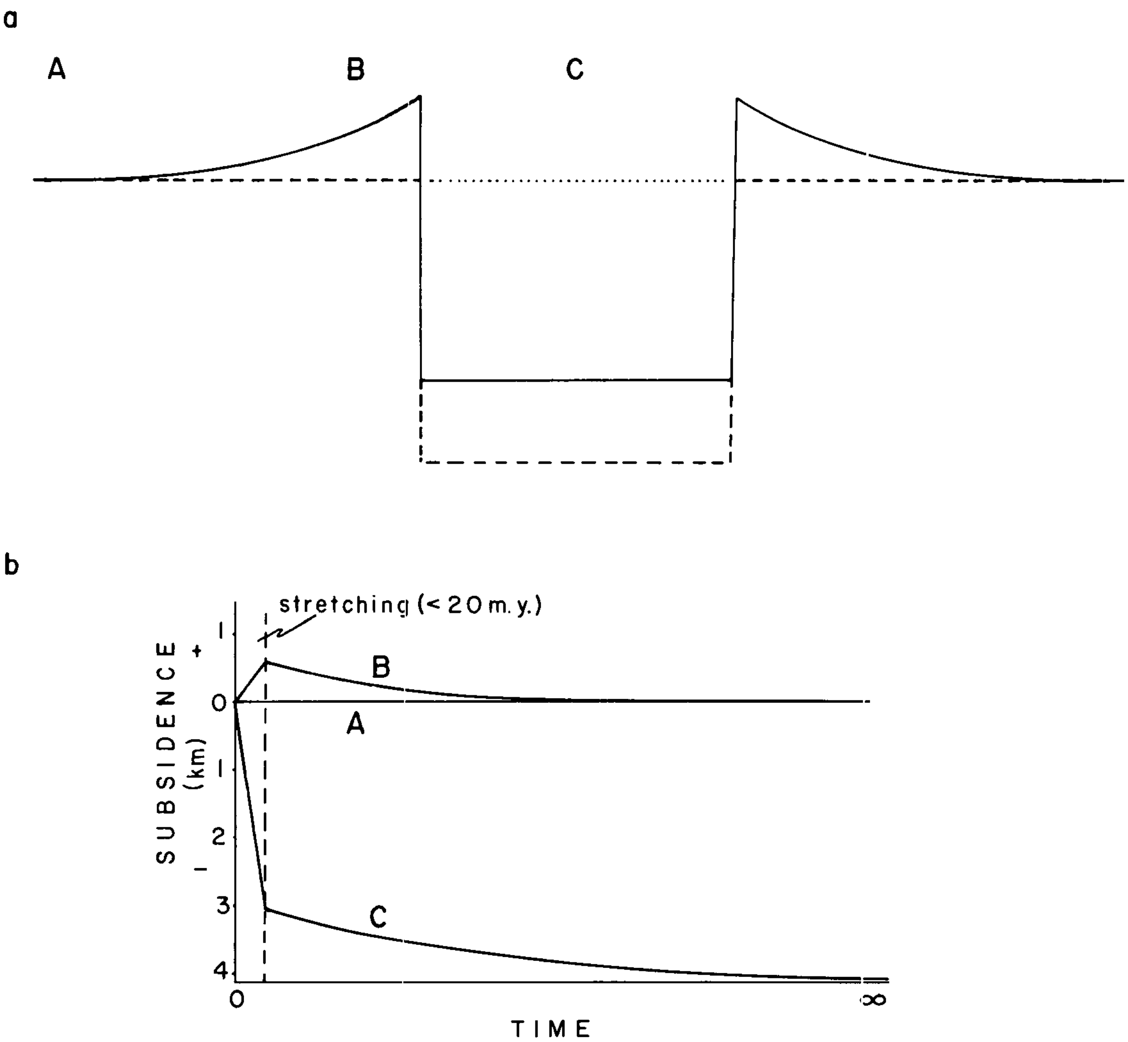

Figure 3. a: Model results of continuous nonuniform stretching without horizontal variation in β_c. Dotted line = initial unstretched profile; solid line = profile immediately after instantaneous stretching; dashed line = profile after infinite time without erosion from rift shoulders. b: Subsidence histories for points A, B, C in 3a for C = 20 km, β_c = 2, ϕ = 45°.

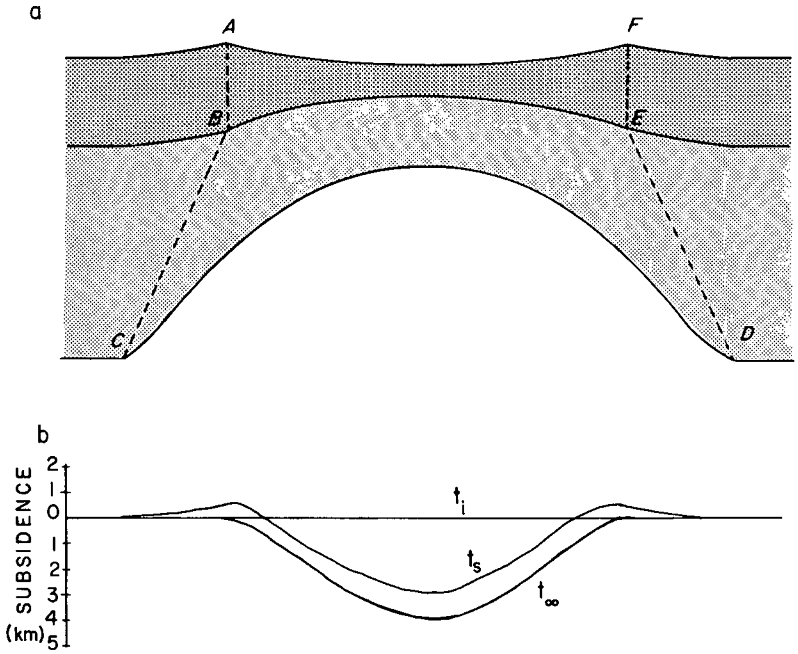

Figure 4. Continuous nonuniform stretching with horizontally varying β_c and β_m; only β_m is dependent on depth. a: Geometry immediately after instantaneous stretching. Darker shading = continental crust; lighter shading = mantle lithosphere. b: Topographic profiles before instantaneous stretching (t_i), immediately after instantaneous stretching (t_s), and at t_∞.

The continuous nonuniform stretching model proposed here explains this phenomenon, but without requiring any strain discontinuities or space problems within the lithosphere. An interesting contrast between the discontinuous and continuous types of nonuniform stretching models is that in the discontinuous models initial uplift occurs when β_m is everywhere greater than β_c, whereas in the continuous nonuniform stretching model proposed here, initial uplift occurs when the bounding surfaces of the stretched region slope outward, which results in β_m being less than β_c inside the rift. This difference may provide a means of testing the two models because the predicted heat flow should be different for the two models. In our model the mantle-derived heat flow within the rift should be less than that predicted by the uniform stretching model and discontinuous depth-dependent models. Outside the region of crustal stretching, the heat-flow predictions range from highest for discontinuous nonuniform stretching to lowest for uniform stretching, our model predicting intermediate values. This difference in heat flow may have important implications for the maturation potential of hydrocarbons within rifts, but this is beyond the scope of this paper.

An additional advantage of the continuous depth-dependent stretching model proposed here is that there is a direct correlation between β_c and β_m because there is no decoupling between them. In the Royden and Keen (1980) (discontinuous) model, the magnitude of β_m is only determinable by the best fit of theoretical subsidence curves with empirically derived tectonic subsidence curves because of poststretching thickening of the subcrustal lithosphere due to thermal reequilibration (Beaumont et al., 1982). In our model, β_m is constrained by β_c, which is determinable from regional geophysical methods (e.g., thickness of stretched versus unstretched crust), to a range of values that are only dependent upon ϕ. The value of ϕ may in turn be constrained by the lateral extent of the region of uplift and by the heat-flow values outside the rift.

REFERENCES CITED

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.

Brown, C., and Girdler, R.W., 1980, Interpretation of African gravity and its implications for the breakup of continents: Journal of Geophysical Research, v. 85, p. 6443–6445.

Cochran, J.R., 1983a, Effects of finite rifting times on the development of sedimentary basins: Earth and Planetary Science Letters, v. 66, p. 289–302.

—— 1983b, A model for the development of the Red Sea: American Association of Petroleum Geologists Bulletin, v. 67, p. 41–69.

Dokka, R.K., and Pilger, R.H., Jr., 1984, Continental rifting by non-uniform extension: EOS (American Geophysical Union Transactions), v. 65, p. 281.

Jarvis, G.T., and McKenzie, D.P., 1980, Sedimentary basin formation with finite extension rates: Earth and Planetary Science Letters, v. 48, p. 42–52.

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

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

Mohr, P., 1982, Musings on continental rifts, *in* Continental and oceanic rifts: American Geophysical Union Geodynamics Series, v. 8, p. 293–309.

Montadert, L., de Charpal, O., Roberts, D., Guennoc, P., and Sibuet, J.C., 1979, Northeast Atlantic passive continental margins: Rifting and subsidence processes, *in* Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironments: American Geophysical Union Maurice Ewing Series, v. 3, p. 154–186.

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

Royden, L., Sclater, J.G., and Von Herzen, R.P., 1980, Continental margin subsidence and heat flow—Important parameters in formation of petroleum hydrocarbons: American Association of Petroleum Geologists Bulletin, v. 64, p. 173–187.

Sleep, N., 1971, Thermal effects of the formation of Atlantic continental margins by continental breakup: Royal Astronomical Society Geophysical Journal, v. 24, p. 325–350.

Steckler, M.S., and Watts, A.B., 1982, Subsidence history and tectonic evolution of Atlantic-type continental margins, *in* Dynamics of passive margins: American Geophysical Union Geodynamics Series, v. 6, p. 184–196.

Wernicke, B., and Burchfiel, B.C., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, p. 105–115.

ACKNOWLEDGMENTS

Supported by the Paleogeographic Atlas Project. We thank Fred Ziegler for discussions that led to the development of these ideas, and the rest of the Paleogeographic Atlas Project team for discussions and encouragement. We also thank Dan McKenzie for discussions regarding stretching models, and the reviewers for helpful comments.

Manuscript received April 9, 1985
Revised manuscript received August 28, 1985
Manuscript accepted October 1, 1985