A New Model for Heat Flow in Extensional Basins: Radiogenic Heat, Asthenospheric Heat, and the McKenzie Model

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The McKenzie model proposed in 1978, which is widely used in calculating the thermal history of rift basins and other extensional basins, incorrectly assumes that all heat passing through the lithosphere originates below the lithosphere. In reality, heat from radiogenic sources within the lithosphere, especially in the upper crust, may represent more than half the heat flow at the top of basement. Thinning of the lithosphere during extension does indeed result in an increase of heat flowing from the asthenosphere, but this thinning also reduces the radiogenic heat from within the lithosphere. Because these two effects cancel to a large degree, the direct effects of lithospheric extension on heat flow at the top of basement are smaller than those predicted by the McKenzie model. Because of permanent loss of radiogenic material by lithospheric thinning, the heat flow at the top of basement long after rifting will be lower than the pre-rift heat flow.

The McKenzie model predicts an instantaneous increase in heat flow during rifting. The Morgan model proposed in 1983, however, predicts a substantial time delay in the arrival of the higher heat flow from the asthenosphere at the top of basement or within sediments. Using the Morgan model, heat flow during the early stages of rifting will actually be lower than prior to rifting, because the time delay in the loss of radiogenic heat is less than the time delay in arrival of new heat from the asthenosphere.

KEY WORDS: McKenzie model; rifting; radiogenic heat; heat flow.

INTRODUCTION

Because most basins have developed as the result of extensional processes, and because thermal history is important in basin analysis, the thermal regimes associated with lithospheric extension have received much attention and are used in many practical applications. The subsidence and thermal histories of extensional basins are usually modeled using McKenzie's (1978) simple model for rifting. Since the publication of that model, however, our understanding of the tectonic and thermal causes and consequences of lithospheric extension has improved greatly, and some weaknesses in the McKenzie model have been exposed. This paper describes an incorrect assumption in the McKenzie model about sources of heat that has been hinted at by a few workers (Sclater and Christie, 1980; Jaupart, 1986; Kusznir and Park, 1987) but has never been examined in detail. It also proposes a solution to that problem.

THE MCKENZIE MODEL

The McKenzie (1978) model for rifting assumes that lithospheric extension occurs instantaneously by pure shear, and that the magnitude of extension at each location at each moment is uniform through the entire lithosphere. The magnitude of extension is expressed as the tectonic stretching factor Beta ($\beta_{\mathrm{tectonic}}$), which is defined as the ratio of lithospheric

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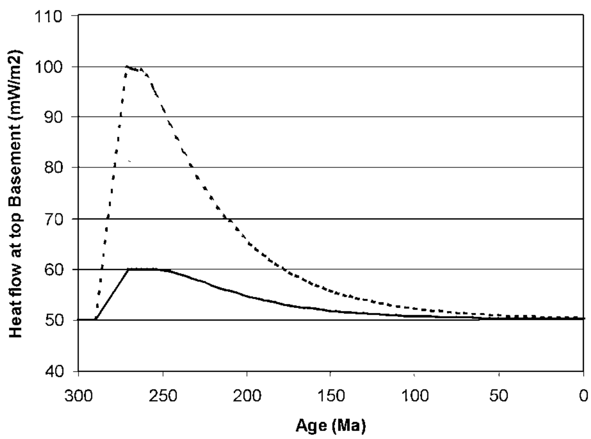

Figure 1. Change in basal heat flow through time for two rifts with different stretching factors. Calculations were performed using Equation (4), derived from McKenzie (1978). Top curve (dashed): $\beta = 2.0$. Bottom curve (solid): $\beta = 1.2$. Duration of rifting is 20 million years (290 Ma to 270 Ma) in both examples. Note that decay time does not depend on stretching factor. It does, however, depend on original thickness of lithosphere.

thickness after stretching to thickness before stretching. Rifting in the McKenzie model is passive, and always results in subsidence, even in the earliest phase.

Instantaneous extension in the McKenzie model results in an initial instantaneous increase in heat flow at both the top and bottom of the lithosphere. β_{thermal}, the factor by which heat flow increases, is taken to be precisely equal to β_{tectonic}, the degree of lithospheric thinning.

The increase in heat flow associated with rifting gradually disappears with time, decaying exponentially after the end of rifting (e.g. Sleep, 1971; Parsons and Sclater, 1977; Pollack and Chapman, 1977; Jarvis and McKenzie, 1980; Royden, Sclater, and von Herzen, 1980; Allen and Allen, 1990). Heat flow returns to near its pre-rift level in about 150 to 250 million years, depending upon the original thickness of the lithosphere and the degree of stretching (Fig. 1).

PREVIOUS MODIFICATIONS OF THE McKENZIE MODEL

Numerous workers have suggested modifications to McKenzie's (1978) model. The original model requires that stretching be instantaneous, a physical impossibility. However, Jarvis and McKenzie (1980) showed that if rifting lasts less than about 20 million years, stretching can be considered effectively to be instantaneous for calculation purposes. In reality, it now seems likely that each rifting event is in fact fairly short, with a maximum duration of 15 to 25 million years (see Baxter and others, 1997). When rifting occurs during a finite time, the heat flow also is assumed to increase through time, in proportion to the degree of lithospheric thinning.

Some workers have suggested that rifting can last for up to 100 million years (e.g. Cochran, 1983; Ziegler, 1990; Allen and Allen, 1990). However, the increasing strength of the lithosphere resulting from cooling associated with slow rifting (that is, strain hardening) would probably terminate slow rifting events (Kusznir and Park, 1987). An alternative approach is to consider long "rifting" events as a series of distinct rifting episodes, with cooling between those episodes [e.g. the South China Sea as discussed by Ru and Pigott (1986); the rift basins of Sudan as described by Browne and Fairhead (1983) and Schull (1988)]. Alternatively, "rifting" of long duration may consist of an initial rifting event followed by one or more wrenching events. A combined rift-wrench model might better explain characteristics of some "rift" basins, including the previously mentioned Muglad Basin in Sudan and many of the basins of SE Asia.

A number of investigators have criticized McKenzie's assumption of uniform extension, because the physical properties of the lithosphere differ greatly with depth. Continental lithosphere is composed of a thin, brittle upper crust (10–15 km thick: e.g. Vierbuchen, George, and Vail, 1982) and a ductile zone comprising the lower crust (about 20 km thick) and the lithospheric upper mantle [usually taken to be about 90 km thick: e.g. Parsons and Sclater (1977)]. Many people have proposed two-layer stretching models, in which the degree of thinning can be different in the brittle upper crust than in the rest of the lithosphere (e.g. Royden and Keen, 1980; Sclater and others 1980; Vierbuchen, George, and Vail, 1982; Hellinger and Sclater, 1983; Steckler, 1985; Moretti and Pinet, 1987; White and McKenzie, 1988; Keen and others, 1990; Vejbæk, 1992; Mudford, Lundegard, and Lerche, 1995; Baxter and others, 1997). The degree of thinning of the brittle upper crust is usually termed δ, whereas that of the ductile lower crust and lithospheric upper mantle retains the name β (Royden and Keen, 1980; Hellinger and Sclater, 1983). One must be cautious, however, because the two symbols may be reversed (e.g. Keen and others, 1990; Poort, van der Beek, and ter Voorde, 1998). In this paper I shall use β to refer to the degree of thinning of the ductile layers (lower crust and mantle), and δ to describe the degree of thinning of the brittle layers (upper crust and noncrystalline basement). Because β and δ as used in this paper refer to degree of tectonic thinning, the subscript "tectonic" will not be explicitly indicated.

Some workers believe that the degree of thinning within the two ductile layers (lower crust and lithospheric upper mantle) can be different. When the asthenosphere upwells, the lithospheric upper mantle undergoes thinning that is not related to extension, whereas the lower crust does not. Ziegler (1990), for example, has created a three-layer model in which he defines the degree of thinning of the lithospheric upper mantle as β_m and that of the lower crust as β_c.

SOURCES OF HEAT FLOW AT THE TOP OF BASEMENT

In the McKenzie (1978) model all heat comes from the asthenosphere; that is, there are no heat sources within the lithosphere itself. In nature, however, it is clear that only a portion of the heat comes from the asthenosphere. A substantial part of the total heat emerging from basement comes from radiogenic sources within the lithosphere, particularly the upper crust.

Asthenospheric Heat Flow

Average or typical values for heat flow emerging at the top of the asthenosphere beneath continental crust ("asthenospheric heat flow" in this paper) have been proposed to be about 12 to 27 mW/m^2 (Vitorello and Pollack, 1980), 15 mW/m^2 (Jaupart, 1986), 18 to 20 mW/m^2 (Zorin, 1989), 28 mW/m^2 (Zhou, 1996), 16 to 24 mW/m^2 (Rudnick and Nyblade, 1999), 11 to 16 mW/m^2 (Gupta, Sundar, and Sharma, 1991), 23 $\pm$ 7 mW/m^2 (Sclater, Jaupart, and Galson, 1980), 24 mW/m^2 (Allen and Allen, 1990, p. 48), or 12 to 14 mW/m^2 (Pinet and others, 1991; Guillou-Frottier and others, 1995; Mareschal and others, 1999). The last five of these estimates were corrected downward by 1 mW/m^2 from the published values, which included radiogenic heat from sources within the lithospheric upper mantle (see next section). That these various estimates are not in particularly good agreement emphasizes both our overall uncertainties and the possibilities of local or regional variations in asthenospheric heat flow. In this paper I shall assume a typical asthenospheric heat flow of 20 mW/m^2, recognizing that many of the most-recent estimates suggest a lower value. However, the lowest proposed values generally refer to unusually thick crust that probably is not typical of the crust beneath extensional basins.

Radiogenic Heat

A widespread assumption is that the radiogenic heat generation A within the igneous crust decreases exponentially with increasing depth (Lachenbruch, 1968):

$$A = A_o \exp(-Z/D) \tag{1}$$

In Equation (1) Z is the depth in km; D is a constant expressed in km (usually between 4 and 16, with a best estimate of about 10: Jaupart, 1986); and A_o is the radiogenic heat generation of the surface crustal rocks. However, considerable vertical and lateral variation in radiogenic heat production is observed in both the upper and lower crust, mainly because of differences in composition of the igneous basement rocks (e.g. Birch, Roy, and Decker, 1968; Vitorello and Pollack, 1980; Furlong and Chapman, 1987). Predicting these variations is beyond the scope of a generalized equation such as (1).

Jaupart (1986) has estimated the average radiogenic heat generation in continental crust to be between about 0.7 and 1 μW/m^3, with a best estimate of about 1 μW/m^3. More recently, Rudnick and Nyblade (1999) estimate the range to be 0.5 to 0.8 μW/m^3, with a best estimate of 0.7 μW/m^3. Using this last value, the total radiogenic contribution would be 24.5 mW/m^2 for a typical continental crust 35 km thick. Using different models for the bulk crust and different calculation methods, McLennan and Taylor (1996) have reached a similar conclusion: values for crustal radiogenic contribution are between 21 mW/m^2 and 34 mW/m^2.

In contrast, little radiogenic heat comes from the lithospheric upper mantle. Recent calculations from Rudnick, McDonough, and O'Connell (1998), Rudnick and Nyblade (1999), and Russell, Dipple, and Kopylova (2001) have shown that radiogenic heat generation in the lithospheric upper mantle beneath Archean crust is low: between 0 and 0.016 μW/m^3. Best estimates of radiogenic heat generation are either 0 (Rudnick and Nyblade, 1999) or 0.012 μW/m^3 (Russell, Dipple, and Kopylova, 2001). For a lithospheric upper mantle 90 km thick, the total radiogenic contribution to mantle heat flow would be between 0 and 1.4 mW/m^2.

Those calculations are for Archean (>2.5 Ga) lithosphere, where extreme depletion of radiogenic elements occurred during melting. Phanerozoic lithosphere, which probably did not suffer as much melting or depletion of radiogenic elements, may be slightly more radiogenic (R.L. Rudnick, personal communication, 2001).

Asthenospheric Heat vs. Radiogenic Heat

Although the relative importances of asthenospheric heat and radiogenic heat from within the lithosphere undoubtedly vary considerably, some generalizations are possible and useful. Using the numbers derived here, it can be calculated that where no extension has occurred, asthenospheric heat flow seems to account for about 40% ± 10% of the heat flow at the top of basement. However, where the crust has been thinned by extension, or where the asthenosphere has upwelled in some fashion, both the absolute amount and proportion of asthenospheric heat are higher than normal (e.g. Čermák and Bodri, 1986, for the Pannonian Basin; Makhous, Galushkin, and Lopatin, 1997, for Algeria). Conversely, radiogenic heat from sources within the lithosphere typically represents about 60% ± 10% of the total heat flow out of basement. This estimate of the great importance of radiogenic heat is consistent with the observation of Birch, Roy, and Decker (1968) that surface heat flow is proportional to the radiogenic heat generation in surface rocks.

A NEW MODEL FOR BASEMENT HEAT FLOW IN EXTENSIONAL BASINS

Introduction

Because a significant proportion—usually a majority—of the heat flowing out of the basement originates within the lithosphere, the thermal effects of lithospheric stretching are more complex than those envisioned by the McKenzie model. As McKenzie proposed, thinning of the lithosphere does indeed increase the amount of asthenospheric heat flow by making the thermal blanket thinner. However, thinning the lithosphere also decreases the amount of radiogenic heat production by reducing the thickness of the radiogenic layers (Sclater and Christie, 1980; Jaupart, 1986; Kusznir and Park, 1987). Whether the heat flow at the top of basement experiences a net increase or decrease at any particular time during or after rifting thus depends on the balance between these two effects. When the pre-rift contributions of asthenospheric heat and radiogenic heat are similar, the positive and negative effects of lithospheric thinning on heat flow will largely cancel, and the net effect of lithospheric thinning on conductive heat flow at the top of basement may be near zero.

Tectonics

The conceptual model proposed here is general, and can be used for any number of layers within the lithosphere. However, for the sake of illustration the given equations assume a two-layer model in which the upper crust extends brittlely, whereas the lower crust and lithospheric upper mantle both extend ductilely. These equations assume further that the amounts of brittle and ductile deformation are not necessarily the same, but that the lower crust and lithospheric upper mantle extend by the same amount. The equations can be modified easily to consider any number of different layers, each with its own stretching factor.

If we are to use a multilayer stretching model, we must specify the amount of stretching in each layer. For a two-layer model Ziegler (1990) has suggested an empirical relationship between stretching in the brittle layer (δ) and that in the ductile layer (β):

$$\delta = 0.33 \cdot (\beta - 1.0) + 1.0 \qquad (2)$$

If one knows either δ or β from a tectonic analysis, one can estimate the other using Equation (2). Alternatively, one can substitute one's own concepts of δ and β.

The average degree of thinning of the total lithosphere, "β", can be calculated as a weighted average of the thinning of the brittle and ductile layers. In this analysis any older sedimentary or metamorphic rocks (e.g. noncrystalline basement) present at the time of rifting are assumed to be part of the brittle layer.

$$\text{“}\beta\text{”} = (\Delta Z_s + \Delta Z_{uc} + \Delta Z_{lc} + \Delta Z_{um}) / ((\Delta Z_s + \Delta Z_{uc})/\delta + (\Delta Z_{lc} + \Delta Z_{um})/\beta) \qquad (3)$$

In Equation (3) ΔZ is the original thickness of one of the four layers of lithosphere, where the subscripts s, uc, lc, and um refer to sedimentary rocks, upper crust, lower crust, and lithospheric upper mantle, respectively. δ and β have their normal meanings.

Local geological information or personal preferences should control final decisions about pre-rift thicknesses of the various components of the lithosphere. Lacking such data or opinions, one can select traditional values for continental lithosphere (upper crust 10–15 km, lower crust 15–20 km, lithospheric upper mantle 85–90 km, total thickness about 110–125 km).

Lacking more-specific information, the model presented here assumes that all layers of the lithosphere suffer extension simultaneously. Rifting is thus not viewed as a top-to-bottom or bottom-to-top unzipping of the lithosphere.

Asthenospheric Heat Flow

Asthenospheric heat flow Q_a at any time depends on the pre-rift asthenospheric heat flow, the average degree of lithospheric thinning "β", the time elapsed since the start of rifting, and the thickness of the lithosphere. As noted earlier, the asthenospheric heat flow at the start of heating, Q_{ao}, normally will be about 20 mW/m^2 for continental crust of normal thickness.

Because the McKenzie model assumes that all heat comes from the asthenosphere and that there is no gain or loss of heat within the lithosphere, the asthenospheric heat flow (at the top of the asthenosphere or the base of the lithosphere) is at all times the same as the heat flow at the top of the lithosphere (top of basement). In the present model, however, where these two heat flows are in general not the same, McKenzie's equations should be used to describe the asthenospheric heat flow.

Asthenospheric heat flow Q_{at} at any time t (million years) after the end of extension-related heating (that is, at any time during thermal relaxation) can be calculated by modifying equation 3.17 of Allen and Allen (1990, p. 58). One required modification in order to get accurate results at short times after the end of rifting heating is to use higher harmonics in the Fourier expansion. (Allen and Allen recommended this procedure, but their example uses only the first harmonic.) The number of required harmonics increases with the degree of stretching. Four harmonics will give excellent results when "β" is less than about 3, and good results up to at least "β" $= 7$. For greater degrees of stretching, however, higher harmonics may be required.

With four harmonics the equation of Allen and Allen becomes

$$\begin{aligned} Q_{at} = {} & (\lambda_r T_a/L)\cdot(2``\beta"/\pi)\cdot\{\pi/2``\beta" + \sin(\pi/``\beta") \\ & \cdot\exp(-t/\tau) + \sin(2\pi/``\beta")\cdot\exp(-4t/\tau)/2 \\ & + \sin(3\pi/``\beta")\cdot\exp(-9t/\tau)/3 + \sin(4\pi/``\beta") \\ & \cdot\exp(-16t/\tau)/4\} \end{aligned} \quad (4)$$

where λ_r is the average thermal conductivity of the lithospheric rocks, T_a is the temperature at the top of the asthenosphere, L is the pre-rift thickness of the lithosphere, "β" is the weighted average degree of lithospheric thinning, and τ is the thermal time constant for the lithosphere (approximately 50 million years). Expansion of Equation (4) to higher harmonics is straightforward, although there is a typographical error in the first equation on p. 58 of Allen and Allen (1990) that has been corrected in deriving Equation (4).

It is important to note that Equation (4), derived from McKenzie, assumes that all heat originates in the asthenosphere. In the present model, which assumes a substantial radiogenic contribution to total heat flow at the top of basement, the heat-flow term $\lambda_r T_a/L$ in Equation (4) must be replaced by the pre-rift asthenospheric heat flow Q_{ao}, since the new model assumes that thermal effects related to radiogenic heat generation do not relax. Equation (4) thus becomes

$$\begin{aligned} Q_{at} = {} & Q_{ao}\cdot(2``\beta"/\pi)\cdot\{\pi/2``\beta" + \sin(\pi/``\beta") \\ & \cdot\exp(-t/\tau) + \sin(2\pi/``\beta")\cdot\exp(-4t/\tau)/2 \\ & + \sin(3\pi/``\beta")\cdot\exp(-9t/\tau)/3 + \sin(4\pi/``\beta") \\ & \cdot\exp(-16t/\tau)/4\} \end{aligned} \quad (5)$$

The asthenospheric heat flow at any time between the beginning and end of rifting heating can be interpolated between Q_{ao} and Q_{a0}, where Q_{a0} is the asthenospheric heat flow 0 million years after the end of rifting heating, as calculated using $t = 0$ in Equation (5). If one believes that the rate of rifting is constant, the interpolation would be linear. Q_{a0} also can be calculated using Equation (6):

$$Q_{a0} = Q_{ao}\cdot``\beta" \quad (6)$$

which is a modification of McKenzie's (1978) original definition of β.

Equations (4)–(6) implicitly assume that there is no change in the temperature at the top of the asthenosphere during extension, and no change in the average conductivity of the lithosphere during extension. The latter assumption probably is incorrect to some degree, but it would be difficult to estimate the direction or magnitude of the change, because changes in mineralogy, temperature, and amount of radiative conductivity (e.g. Clauser, 1988) could all play important roles.

The McKenzie model assumes that heating and rifting are synchronous because rifting involves physical thinning of the lithosphere. Consequently, the geothermal gradient within the lithosphere increases as rifting proceeds, because the temperature at the base of the lithosphere (top of the asthenosphere) remains constant as that boundary approaches the surface. Using this conceptual model there is no time lag between the onset of rifting and the arrival of the higher asthenosphere-derived heat flow at the top of the lithosphere.

However, Morgan (1983) and Wheildon and others (1994) have suggested that if rifting occurs by delamination of the lithospheric upper mantle or some similar mechanism, thermal anomalies resulting from thinning of the lithosphere will not arrive at the top of the lithosphere until well after the rift has been initiated. If we model only from the top of basement upward, then any increase in heat flow at the top of basement resulting from an increase in asthenospheric heat flow will postdate uplift (including thermal doming) and erosion (in active rifts) or the onset of sediment accumulation (in passive rifts). Bodell and Chapman (1982) have shown that the time constant t_L controlling both uplift and heating of the crust from sources in the asthenosphere is given by

$$t_L = Z^2/4\kappa \tag{7}$$

where Z is the thickness of the lithosphere after rifting and κ is the average thermal diffusivity of the lithosphere (assumed to be about 32 km^2/Ma, equivalent to 1 mm^2/sec). Morgan (1983) has shown that arrival of the thermal effects at the surface is delayed by an amount t_d compared to the onset of rifting:

$$t_d = 0.35 t_L \tag{8}$$

Table 1 shows the calculated time delay in the heat pulse arriving at the surface for various post-rift lithospheric thicknesses.

Combining Equations (7) and (8), the amount of delay t_d (in millions of years) in the onset of heating using Morgan's model can be estimated as

$$t_d = 0.00273 \cdot Z^2 \tag{9a}$$

if the thickness of the post-rift lithosphere is known or can be estimated. Alternatively, if it is easier to estimate the thickness L of the pre-rift lithosphere, the time delay can be calculated by substituting L/"β" for Z:

$$t_d = 0.00273 \cdot L^2/\text{“}\beta\text{”}^2 \tag{9b}$$

The end of the heating event also is delayed by the same amount after the end of rifting.

Table 1. Delay in Arrival of Thermal Pulse at Surface for Different Degrees of Extension, Following Model of Morgan (1983)

Post-rift lithospheric thickness (km)	"β"	Time delay (millions of years)
20	6.0	1.1
40	3.0	4.4
60	2.0	9.8
80	1.5	17.5
100	1.2	27.3

"β" is the weighted average between $\beta_{tectonic}$ and $\beta_{tectonic}$. See Equation (3) and text for further explanation.
Calculation of "β" assumes a pre-rift lithospheric thickness of 120 km.

Radiogenic Heat from the Crust

The contribution of radiogenic heat Q_r from the crust decreases in proportion to the degree of crustal thinning. If Q_{ruco} and Q_{rlco} are the pre-rift contributions to basal heat flow from the upper and lower crust, respectively, then the radiogenic contributions to basal heat flow from the end of rifting heating to present day are given by

$$Q_{rucer} = Q_{ruco}/\delta \tag{10}$$

$$Q_{rlcer} = Q_{rlco}/\beta \tag{11}$$

At any time t between the beginning and end of rifting, Q_{ruct} and Q_{rlct} can be interpolated between Q_{ruco} and Q_{rucer}, or between Q_{rlco} and Q_{rlcer}.

If rifting occurs by physical thinning of the lithosphere, as in the McKenzie model, the decrease in heat generation from the radiogenic layer occurs simultaneously with the increase in heat from the asthenosphere, because there is no time delay in either process. However, timing of radiogenic effects and timing of asthenospheric effects are not the same in the Morgan model, because the radiogenic layer is closer to the surface. If Equation (9) is modified to use δ and the original thickness of the crust for the Morgan model, it is evident that the loss of radiogenic heat will be felt almost immediately after the stretching event (Table 1).

Radiogenic Heat from the Mantle

There are two ways in which this original mantle radiogenic heat flow could be modified by the effects of rifting. First, as a result of thinning of the mantle, the post-rift radiogenic mantle heat flow Q_{rmer} will decrease from the pre-rift value (Q_{rmero}) as an inverse function of β in the same way that it does for the lower crust:

$$Q_{\text{rmer}} = Q_{\text{rmero}}/\beta \tag{12}$$

Second, the occurrence of extensive rift-induced metasomatism may increase the radiogenic heat generation of the lithospheric upper mantle (Dawson and Smith, 1988; Chesley, Rudnick, and Lee, 1999; Lee and Rudnick, 1999). The magnitude of this effect is not well known. Although it may be of local importance, its regional effect will probably be small.

Given the small amount of radiogenic heat production in the lithospheric upper mantle and our uncertainties about metasomatic effects, it is probably acceptable to assume a constant contribution of about 1 mW/m^2 to total heat flow from radiogenic sources within the lithospheric upper mantle. Any postulated change in radiogenic heat from the lithospheric upper mantle during rifting would be assumed to occur with little or no time delay. Although this assumption is probably not completely correct, the change in radiogenic heat from the lithospheric upper mantle always will be small, and thus the question of its timing also is largely academic.

Radiogenic Heat from Noncrystalline Basement

In some basins the upper part of "basement" comprises sedimentary or metamorphic rocks rather than crystalline. In such situations radiogenic heat from those rocks must be included in the model, because it is not included in the models of radiogenic heat from crystalline basement as discussed.

The amount of radiogenic heat from noncrystalline basement will decrease during crustal thinning in the same way as radiogenic heat from the upper crust, because both deform brittlely. Therefore, the contribution of radiogenic heat Q_{rnx} from noncrystalline basement immediately after rifting will be given by

$$Q_{\text{rnx}} = Q_{\text{rnxo}}/\delta \tag{13}$$

where Q_{rnxo} is the total radiogenic heat from noncrystalline basement prior to rifting.

AN EXAMPLE

Table 2 shows relevant geologic information and assumptions for this example. Let us suppose that passive rifting and sediment accumulation begin 180 Ma. Original thicknesses of upper crust, lower crust, and lithospheric upper mantle are assumed to be 15 km, 20 km, and 90 km, respectively. The brittle and ductile layers begin to thin at 180 Ma, and continue to do so until 162 Ma, when rifting ceases. The stretching factor (δ) in the brittle upper crust is estimated from seismic data to be 1.3. The known present-day thickness of noncrystalline basement is 1540 m.

We begin by calculating $\beta = 1.90$ using Equation (2) and the data in Table 2. We then calculate "β" $= 1.79$ and the thickness of the lithosphere after rifting $= 71$ km using Equation (3). Then we calculate the pre-rift thickness of the noncrystalline basement (2.0 km: Table 3) as the present-day thickness multiplied by δ, because noncrystalline basement is assumed to deform brittlely.

Let us first assume that we are using the model of Morgan (1983), which indicates a time delay in transferring heat from the asthenosphere to the top of basement. We calculate this delay as about 13.3 million years using Equation (7). Other calculated lithosphere parameters are shown in Table 3.

Next we calculate the asthenospheric heat flow as a function of time. Taking the time delay into account, flow of heat from the asthenosphere out of the top of basement began to increase about 166.7 Ma (180 − 13.3). This flow increased by a factor of 1.79 during the next 18 million years, and then, starting at 148.7 Ma, began its gradual decay to its present level (Table 3).

Let us assume, after Rudnick and Nyblade (1999) that before the onset of rifting the total radiogenic heat from the crust contributed 25 mW/m^2 to the heat

Table 2. Input Data for Example

Pre-rift data	
Upper crustal thickness	15 km
Lower crustal thickness	20 km
Lithospheric upper mantle thickness	90 km
Asthenospheric heat flow	20 mW/m^2
Lithospheric upper mantle radiogenic contribution	1 mW/m^2
Post-rift data	
Noncrystalline basement thickness	1.54 km
Rifting data	
Brittle layer stretching factor (δ_{tectonic})	1.3
Onset of passive rifting	180 Ma
End of rifting	162 Ma

Table 3. Calculated Values for Example Assuming Time Delay in Asthenospheric Heat Flow (Morgan Model)

Pre-rift value (180 Ma)	
Noncrystalline basement thickness	2.00 km
Post-rift values (at end of rifting 162 Ma)	
Upper crustal thickness	11.54 km
Lower crustal thickness	10.53 km
Lithospheric upper mantle thickness	47.37 km
Lithospheric thickness	70.98 km

Contributions to heat flow (mW/m^2) at top of basement

Time (Ma)	Asth.	Lith. U. mantle	Lower crust	Upper crust	Noncryst. basement	Total
180	20	1	5	20	2.0	48.0
166.7	20	1	3.2	16.4	1.7	42.3
162	24.1	1	2.6	15.4	1.5	44.6
148.7	35.8	1	2.6	15.4	1.5	56.3
140	35.7	1	2.6	15.4	1.5	56.2
120	32.2	1	2.6	15.4	1.5	52.7
100	28.4	1	2.6	15.4	1.5	48.9
80	25.7	1	2.6	15.4	1.5	46.2
60	23.8	1	2.6	15.4	1.5	44.3
40	22.6	1	2.6	15.4	1.5	43.1
20	21.7	1	2.6	15.4	1.5	42.2
0	21.1	1	2.6	15.4	1.5	41.6

flow, with 20 mW/m^2 coming from the upper crust and 5 mW/m^2 from the lower crust. These values are consistent with those predicted by Equation (1). After rifting, the radiogenic contribution from the upper crust has been reduced by a factor δ to 15.4 mW/m^2, whereas that from the lower crust has been reduced by a factor β to 2.6 mW/m^2 (Table 3).

Radiogenic heat from the noncrystalline basement was calculated assuming a radiogenic heat generation of 1.0 μW/m^3, about the global average for sedimentary rocks (e.g. Deming and Chapman, 1989; Funnell and others, 1996). Using an original thickness of 2 km, the pre-rift contribution from noncrystalline basement was calculated to be 2.0 mW/m^2 (Table 3). The radiogenic heat from the lithospheric upper mantle is assumed to remain constant at 1 mW/m^2 during rifting.

The contributions to total heat flow through time from these various sources, shown in Table 3 and plotted in Figure 2, are different from those that would be expected from the McKenzie model. The heat flow at the top of basement immediately after the beginning of rifting actually is lower than before rifting, as a consequence of the nearly immediate loss of radiogenic contribution and the time lag in the increase in asthenospheric contribution. Moreover, the maximum ratio of post-rift heat flow to pre-rift heat flow is lower than the McKenzie model would predict. This ratio is only 1.12, whereas the McKenzie model would calculate it to be 1.79, equivalent to the average degree of lithospheric thinning "β". Finally, the heat flow is decaying toward a final

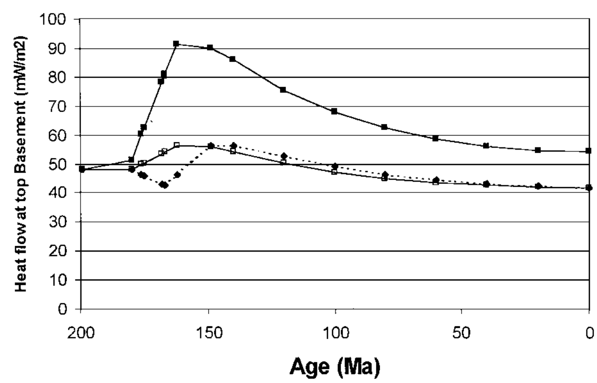

Figure 2. Heat flow at top of basement as function of time in rift in which $\delta = 1.3$ and $\beta = 1.9$ calculated in three ways. Rifting began 180 Ma and ended 162 Ma. Rifting heating in McKenzie models was assumed to be synchronous with rifting, whereas in model proposed in this paper rifting heating ws delayed by 13.3 Ma. (See text for further discussion.) Top curve (filled squares): Calculated using McKenzie model employing average stretching factor "β" = 1.79 for lithosphere. Middle curve (filled diamonds, dashed): Calculated using model proposed in this paper with time delay in arrival of new asthenospheric heat, as suggested by Morgan (1983). Bottom curve (open squares, solid): Calculated using model proposed in this paper with no time delay in arrival of new asthenospheric heat, as suggested by McKenzie (1978).

Table 4. Calculated Values for Example Assuming No Time Delay in Asthenospheric Heat Flow (McKenzie Model)

Pre-rift value (180 Ma)	
Noncrystalline basement thickness	2.00 km
Post-rift values (at end of rifting 162 Ma)	
Upper crustal thickness	11.54 km
Lower crustal thickness	10.53 km
Lithospheric upper mantle thickness	47.37 km
Lithospheric thickness	70.98 km

Contributions to heat flow (mW/m^2) at top of basement

Time (Ma)	Asth.	Lith. U. mantle	Lower crust	Upper crust	Noncryst. basement	Total
180	20	1	5	20	2.0	48.0
162	35.8	1	2.6	15.4	1.5	56.3
140	33.7	1	2.6	15.4	1.5	54.2
120	29.6	1	2.6	15.4	1.5	50.1
100	26.5	1	2.6	15.4	1.5	47.0
80	24.4	1	2.6	15.4	1.5	44.9
60	23.0	1	2.6	15.4	1.5	43.5
40	22.0	1	2.6	15.4	1.5	42.5
20	21.4	1	2.6	15.4	1.5	41.9
0	20.9	1	2.6	15.4	1.5	41.4

value lower (40.5 mW/m^2) than the pre-rift heat flow (48.1 mW/m^2).

Let us also consider a second possibility: that heat flow begins to increase when thinning begins (the McKenzie thinning model). In this model asthenospheric heat flow increases by a factor of 1.79, but the increase takes place during rifting (from 180 Ma to 162 Ma), as shown in Table 4. All other input parameters are the same as in the Morgan model.

Results (Table 4, Fig. 2) show that the maximum heat flow is the same as that achieved in the Morgan model (56.3 mW/m^2), but that it is reached 13.3 million years earlier. As a result, decay of the heat flow begins 13.3 million years earlier in the McKenzie model, yielding heat flows through time that are slightly lower than in the Morgan model. Moreover, the initial decrease in heat flow in the Morgan model between 180 Ma and 166.7 Ma (before the arrival of additional heat from the asthenosphere) does not occur in the McKenzie model (Table 4 and Fig. 2).

From these analyses we might be tempted to conclude that the new model presented in this paper is in error, because rifts are "known" to have elevated heat flows. However, high heat flows are not ubiquitous in rifts—even in young rifts—and where they do occur they are not the direct result of lithospheric thinning. Rather, they are a consequence of two other decisive factors: radiogenic heat from the thick clastic sediment package present in most rifts, and convective heat transfer via ascending magmas and hydrothermal fluids (see Waples, 2002, in preparation). In fact, Morgan (1983) and Wheildon and others (1994) noted that background heat flows in young rifts were normal to subnormal, rather than elevated. The high-heat flows in rifts are localized in time and space, and are the result of convective processes (hydrothermal fluids, volcanism) rather than conduction (Lysak, 1992; Wheildon and others, 1994).

CONCLUSIONS

The model of McKenzie (1978), which is used widely in calculating the thermal history of rift basins and other extensional basins, assumes incorrectly that all heat passing through the lithosphere originates below the lithosphere. In reality, heat from radiogenic sources in the lithosphere, especially in the upper crust, may represent more than half the heat flow at the top of basement. Thinning of the lithosphere during extension does indeed result in an increase of heat flowing from the asthenosphere, but this thinning also reduces the contribution of radiogenic heat from within the lithosphere. Because these two effects cancel to a large degree, the direct effects of lithospheric extension on heat flow at the top of basement are smaller than those predicted by the McKenzie model. The heat flow at the top of basement long after rifting will be lower than the pre-rift heat flow because of the permanent loss of radiogenic material by lithospheric thinning.

A new model has been created to calculate the total heat flowing out of the top of basement as a function of time. This model is illustrated here assuming that the brittle upper crust and noncrystalline basement extend by a different degree than the ductile lower crust and lithospheric upper mantle. However, the model can be adapted easily for any number of different layers within the lithosphere. A typical example is calculated here: the average stretching factor for the entire lithosphere is 1.79, but the conductive heat flow at the end of rifting heating increases only by a factor of 1.12.

The McKenzie model predicts an instantaneous increase in heat flow during rifting. The model of Morgan (1983), however, predicts a substantial time delay in the arrival of the higher heat flow from the asthenosphere at the top of basement or within the sediment column, from which temperature data are normally obtained. Using the Morgan model, heat flow during the early stages of rifting will actually be lower than prior to rifting, because the time delay in loss of radiogenic heat is much less than the time delay in arrival of new heat from the asthenosphere.

This new model correctly predicts that young rifts will have normal to subnormal heat flows in areas where conductive heat transfer dominates. Regions of high heat flow do exist within young rifts, but they are spatially and temporally limited to those areas with active hydrothermal or volcanic activity (see Wheildon and others, 1994). Those phenomena must be modeled separately from conductive heat flow.

This model can be incorporated easily into a spreadsheet to permit calculation of heat flow through time for any rift using any set of desired input parameters. Alternatively, it could be incorporated easily into existing maturity-modeling software to provide heat flow at the top of basement through time.

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