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THERMAL MODELING OF EXTENSIONAL TECTONICS: APPLICATION TO PRESSURE-TEMPERATURE-TIME HISTORIES OF METAMORPHIC ROCKS

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Abstract. One- and two-dimensional finite difference models are used to generate theoretical pressure-temperature-time (PTt) paths for rocks uplifted from deep and intermediate crustal levels during extension via ductile stretching of the entire lithosphere ("pure shear") and via movement of crustal blocks along rooted large-scale low-angle normal faults ("simple shear"). The temperature-time paths of rocks uplifted by these pure shear and simple shear mechanisms have similar morphologies, although rocks from pure shear settings reach their final depth at higher temperatures than do rocks uplifted by simple shear, and experience a greater amount of posttectonic cooling. The depth-temperature paths of rocks uplifted from deep crustal levels (30 km depth) via pure shear extension are often characterized by a period of nearly isothermal (high dP/dT) uplift during the early stages of extension. A modified pure shear extension model that includes enhanced heating in the lower lithosphere during extension generally produces PTt paths characterized by a more protracted period of nearly isothermal uplift. In contrast, simple shear uplift along low-angle normal faults produces almost linear depth-temperature paths with moderate dP/dT, and isothermal uplift is not observed. For a given initial geotherm, the single factor controlling the PTt paths of rocks unroofed below gently dipping normal faults that dip less than 30° is the rate at which unroofing takes place (unroofing rate is defined as the rate of uplift relative to the surface), and the syntectonic PTt paths are insensitive to fault dip or horizontal displacement rate. Current geothermometric and geobarometric techniques yield typical uncertainties in real pressure-temperature and temperature-time data of ±1 kbar and ±50°C. Thus it will be difficult to distinguish between these various extensional mechanisms on the basis of PTt data derived from a single sample or from a single structural level, although use of data from samples collected from a broad range of structural levels may improve resolution. Ultimately, the best prospect for distinguishing between simple shear and pure shear mechanisms through petrologic work lies in improving the precision of metamorphic pressure and temperature measurements to ±0.5 kbar and ±25°C.

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INTRODUCTION

In recent years, much attention has been focused on the processes and structures associated with extension of the continental lithosphere. Controversy over the nature of crustal thinning in highly extended terranes has led to the emergence of two major theories. The first theory, referred to as the simple shear model, proposes that extreme thinning of the crust occurs by normal displacement along master detachment surfaces or a series of imbricate surfaces [Wernicke, 1981, 1985]. During displacement of the hanging wall, footwall rocks from progressively deeper crustal levels are exposed. An alternate theory, the pure shear model, explains extreme continental extension as the result of penetrative ductile stretching of the lithosphere [Hamilton and Myers, 1966; Stewart, 1971]. Pure shear of the lithosphere does not result directly in the unroofing of deeply buried rocks but instead causes rocks at intermediate and deep crustal levels to be brought nearer the surface by stretching of the entire lithospheric column. (The terms pure shear and simple shear are used in this paper in the sense of Wernicke [1985] and do not have any rock mechanical connotations.) These two extensional models, illustrated in Figure 1, represent end-members of the full range of

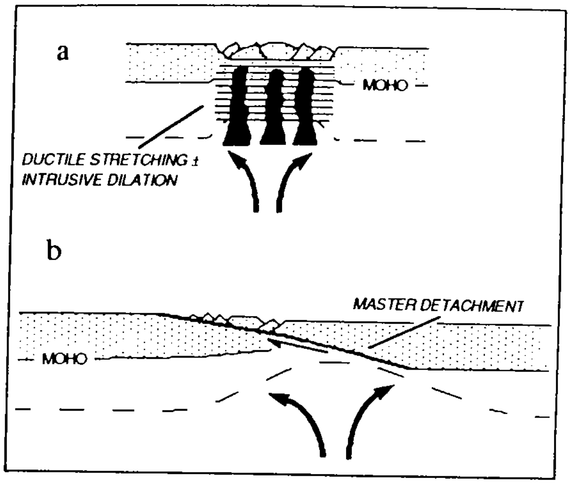

Fig. 1. Schematic diagrams of (a) pure shear and (b) simple shear extensional models after Wernicke [1985].

mechanisms proposed to explain large-scale extension; several workers [e.g., Miller et al., 1983; Gans, 1987] have proposed intermediate extensional mechanisms that combine brittle deformation or large-scale faulting in the upper crust with ductile deformation in the lower crust and lithosphere.

Distinguishing between the proposed extensional mechanisms requires not only the analysis of available structural and geophysical data but also an understanding of the theoretical thermal and mechanical effects of thinning the lithosphere. Zuber et al. [1986] used a strength-stratified lithospheric model in attempting to establish theoretical constraints for the type of extensional deformation observed in the Basin and Range. Furlong and Londe [1986] use theoretical one-dimensional models for the thermal and mechanical effects of pure shear and simple shear extension in the Basin and Range to argue that both extensional mechanisms predict the general features of the observed gravity, heat flow, and topography data. Recent work by Buck et al. [1988] has shown, however, that simple shear and pure shear extension produce distinct heat flow and topography signatures and that observations in the Red Sea area are most consistent with thinning of the lithosphere by pure shear over a zone that has narrowed since the initial rifting event.

Although geophysical observations have not proved particularly diagnostic of the regional extensional mechanism, the study of the local thermal evolution of individual rocks during extension may be important in understanding the effects of pure shear and simple shear. Recent advances in metamorphic petrology and thermochronology have provided a new means of reconstructing the pressure-temperature-time (PTt) evolution of rocks from metamorphic terranes [e.g., Spear et al., 1984; Thompson and England, 1984]. If simple shear and pure shear of the lithosphere produce distinctive thermal and uplift histories, it may be possible to use PTt data generated for metamorphic rocks that occur in such extensional settings as the metamorphic core complexes of the North American Cordillera [Coney, 1979; Armstrong, 1982] to constrain the relative importance of the two extensional mechanisms. One of the primary goals of this study is to understand how variations in extensional parameters and styles affect the PTt paths of metamorphic rocks unroofed or uplifted from intermediate and deep crustal levels.

METHODS AND MODELS

Modeling the thermal evolution of the extending lithosphere requires solving the heat flow equation for temperature structure as a function of position and time. Lithospheric extension via simple shear is most properly modeled as a two-dimensional problem with mass movement and heat flow in both the horizontal and vertical directions. Figure 2 illustrates the model geometry of lithosphere extending via the simple shear mechanism. The physical system involved in simple shear of the lithosphere is modeled here by extracting the footwall block from beneath the hanging wall block at a constant rate throughout the extensional period and requiring the unroofed detachment to remain at $z=0$. Although material is transported both vertically and horizontally along the fault surface, the horizontal thermal gradients are generally much smaller than the vertical thermal gradients, and we found that, in most cases, temperatures in the models that ignore horizontal conduction of heat are within a few percent of those generated by the full two-dimensional models following several million years of relaxation. Nevertheless, the simple shear models presented below are full two-dimensional solutions to the heat flow equation. For the case of laterally homogeneous stretching of the lithosphere described by the pure shear mechanism, one-and two-dimensional solutions produce the same results because no lateral thermal gradients are created by the extensional process.

We use standard one- and two-dimensional explicit discretization of the conductive heat flow equation [Carslaw and Jaeger, 1959] with added heat production terms. The magnitudes of time and distance steps in the finite difference grid were chosen as 1250 years and 500 m for most simple

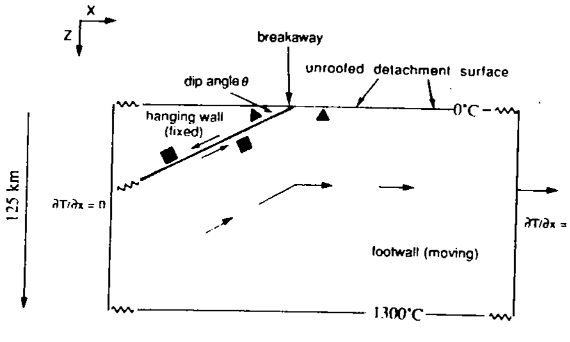

Fig. 2. Simple shear thermal model. In our models the footwall is pulled out from beneath the hanging wall, unroofing a portion of the detachment surface. The breakaway is defined as the point at which the fault intersects the surface. Boundary conditions are zero horizontal heat flux along the sides of the two-dimensional grid and 0° and 1300°C at the surface and 125 km depth, respectively.

shear cases and 10^4 years and 1000 m for the pure shear models in accordance with mathematical constraints on the stability of the system. This fine spacing of grid points eliminates the possibility that significant inaccuracies can develop where $\partial^2T/\partial z^2$ is large due to temperature discontinuities at the detachment surface. The angles of dip of the faults used in the simple shear cases were chosen such that the fault passed exactly through a grid point at every 500-m depth increment. Most of the runs were done using a fault whose dip angle has an integral cotangent of 6, corresponding to a dip of 9.5°.

We model the lithosphere as a homogeneous slab with uniform initial thickness (125 km), uniform diffusivity (10^{-6} m^2/sec) and conductivity (3.12 W/m°C), and a laterally invariant initial geotherm. Radiogenic heat production was assumed to be 1.5 μW/m^3 in the upper 10 km of the crust and zero elsewhere. Boundary conditions are constant temperatures of 0°C at the surface and 1300°C at the base of the lithosphere (125 km). For the two-dimensional models we impose additional constraints of zero horizontal heat flux at the sides of the grid. The position of the sides of the grid were chosen to be sufficiently far from the breakaway zone that the temperature structure in the extending region was not affected by the zero heat flux boundary conditions at the sides.

Two initial temperature structures were used. The first is given by:

$$T=T_m\left[\frac{1-e^{-Cz/L}}{1-e^{-C}}\right]$$

which satisfies the boundary conditions of $T=T_m$ at $z=L$ (base of lithosphere) and $T=0$ at $z=0$ (surface). Temperatures of approximately 500°C and pressures equivalent to 30 km depth are often observed together in metamorphic terranes, and we solved for $C\approx1.5$ to fit this constraint. This geotherm is termed the perturbed initial geotherm and is shown in Figure 3. In order to determine the dependence of PTt paths on the choice of an initial geotherm we also present one model in which the initial geotherm is equal to the background equilibrium geotherm or steady state geotherm defined by maintaining a constant temperature of 0°C and 1300°C at the top and bottom of the lithosphere and a radiogenic heat production rate of 1.5 μW/m^3 in the upper 10 km of the lithosphere. We ignore frictional heating along the fault as a possible source of thermal perturbations in the extending lithosphere.

Extension via pure shear and simple shear affect the distribution and magnitude of heat sources in different ways. Simple shear of the lithosphere does not change the magnitude of the heat sources but causes the distribution to be disturbed by the downdip movement of the hanging wall (or updip movement of the footwall). On the other hand, pure shear extension by a factor β thins a lithospheric slab of thickness z with heat production A to thickness z/β and reduces heat production to A/β in a vertical column. Because the time scale of extension and subsequent thermal relaxation is much shorter than the half-lives of important radiogenic isotopes, we ignore the decrease in heat production through time.

Our models assume that unroofing results exclusively from extension of the lithosphere and not from any associated erosion. Incorporating erosion into the extensional models renders them less applicable to the generalized problem of lithospheric thinning but also more realistic. Since conduction of heat takes place primarily in the vertical direction even in the two-dimensional models, the qualitative effects of erosion are essentially the same as a faster rate of uplift. Moreover, in most geologic settings, observations indicate that the rate of erosion is probably small compared with the rate of unroofing by faulting.

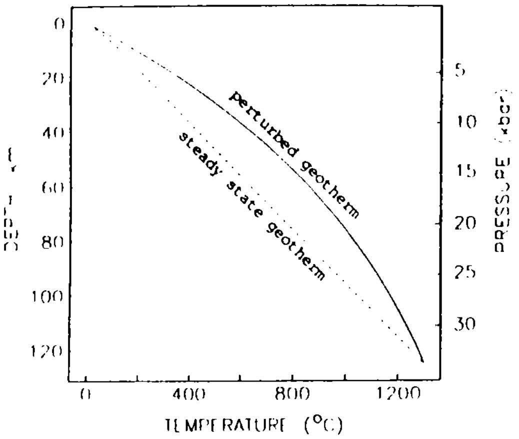

Fig. 3. The initial geotherms used in this study. The perturbed geotherm is described by the function given in the text and is chosen to fit an initial condition of 500°C at 30 km. The perturbed geotherm will decay to the steady state resulting from the superposition of the background thermal gradient of 10.4°C/km and the effects of constant heat production at 1.5 μW/m^3 due to radiogenic sources in the upper 10 km.

The rate of movement along faults is generally measured either along the fault surface or along the horizontal, but comparison between simple shear and pure shear models is easiest if displacement along the detachment surface is measured in terms of the vertical distance between the surface and a rock particle in the footwall of the detachment fault. The rate at which the footwall rocks move upwards relative to the surface will be referred to as the unroofing rate (or uplift rate) and is equal to the product of the horizontal displacement rate and the tangent of the angle of dip of the fault surface. In simple shear models, both the extension rate and the unroofing rate are held constant. For pure shear models, except where specified otherwise, the extension rate is held constant, meaning that the uplift rate decreases with time.

GEOLOGIC RELEVANCE

In the models presented below we examine the uplift and thermal paths of intermediate and deep rocks brought nearer to the surface via pure shear of the lithosphere by amounts ranging from 200 to 900%. Most of the geologic data from highly extended terranes fall in the lower and middle parts of this range of values. In the Snake Range of east central

Nevada, Miller et al. [1983] estimate that progressive ductile to brittle deformation beneath a large-scale detachment accounts for 300-550% extension. In other extensional settings, such as the rifted margin of the Nova Scotia and Labrador shelves, a modified pure shear model with 30-300% lithospheric extension accompanied by the introduction of additional heat into the subcrustal lithosphere has successfully been applied in the analysis of thermal and subsidence data [Royden and Keen, 1980]. Generally, pure shear thinning up to 400% seems to be consistent with structural and geophysical data in several types of extensional settings. Larger estimates of lithospheric pure shear can be obtained if part of the thinning is incorrectly attributed to extension as opposed to erosion.

Comparison of our simple shear models to observations in extensional terranes can be made on the basis of total displacement along the low-angle normal fault and on the rate of slip along the fault. For all but one of the simple shear models, the total amount of displacement lies in the 80- to 120-km range. Displacements on this order are observed in many extensional settings (e.g., 60 km throw on the Snake Range décollement reported by Bartley and Wernicke [1984]). The chosen range of displacements therefore seems reasonable in light of the geologic data. Slip rates along normal faults are estimated at up to or more than about 10 mm/yr [Davis and Lister, 1988]. Generally, we confine the displacement rates in our models to the range of 6-12 mm/yr, although we also present PTt paths generated by slip at an upper limit of 25 mm/yr to show the effects of very fast uplift rates.

The simple shear models presented here require simplification of the geometry of the large-scale normal faults. Although single large-scale low-angle normal faults are thought to play an important role in many extensional terranes (e.g., the Snake Range décollement as described by Bartley and Wernicke [1984]), much of the movement associated with simple shear extension is accomodated along sympathetic normal faults in the hanging wall of the larger normal faults. Because of the thermal and geometric complications introduced by the presence of multiple sets of faults, we have chosen to present here only the results of simple shear extension via displacement along a single low-angle detachment surface. Although we recognize that displacement along smaller faults is an important mechanism in some extensional settings, a study of these geometries is beyond the scope of this paper.

In all of the simple shear models we track only the PTt paths of rocks that are within 10 km of the detachment surface because these rocks experience the largest thermal effects related to unroofing and movement of cool hanging wall material over the detachment surface. Rocks located deeper than about 10 km below a detachment fault are also less commonly exposed at the surface by movement on the detachment, even when extension is coupled with erosion.

PURE SHEAR VERSUS SIMPLE SHEAR

In order to compare the effects of uplifting a rock particle via the pure shear and simple shear mechanisms we charted the PTt paths of rock particles whose initial depths, final depths, and duration of uplift are the same in both modes of extension. The first group of models compares the PTt paths of rocks uplifted from intermediate and deep crustal levels. We charted the PTt paths of a rock particle initially at 30 km depth and uplifted to a depth of 3 km at an uplift rate of 1 mm/yr (Figure 4). Uplift via simple shear was accomplished by assuming that the rock particle was initially located 3 km below a detachment fault dipping 9.5°. The total extension period thus lasted 27 m.y., and the horizontal displacement rate was about 6 mm/yr. Uplift via pure shear was assumed to occur over the same time interval at a constant rate of extension with a total extension of $\beta=10=900\%$. Although this β value is very large and would result in the thinning of a 125-km-thick lithosphere to less than 15 km, it is useful for our theoretical approach because it permits direct comparison of the thermal effects of rocks that begin and end at the same depth, although uplifted by different extensional mechanisms.

The temperature-time curves for the simple shear and pure shear models are similar, although the syntectonic cooling rate decreases with time in the pure shear model and increases for the case of lithospheric thinning via the simple shear mechanism. In the pure shear case, rocks remain hotter for a longer period of time after they have reached their final depths. For the simple shear model, the rate of cooling per kilometer of uplift is about 10°C/km between 500° and 300°C but greater than 18°C/km between 300° and 100°C. The form of the depth-temperature path for the pure shear case contrasts with that of the simple shear model and is characterized by a period of isothermal uplift in the first 10 km or more of uplift, followed by simultaneous cooling and uplift at a rate of 40°C/km between 300° and 100°C.

Note that by holding the extension rate constant in the pure shear case the uplift rate for any particle was constrained to decrease through time. It is therefore not clear from Figure 4 whether the differences between the pure shear and the simple shear PTt paths are entirely a reflection of the extensional mechanisms, or whether they partly result from time-dependent variations in uplift rate. While it is difficult to think of a physical mechanism that would result in a constant uplift rate via pure shear, it is informative to compute the PTt paths that result from a constant uplift rate via pure shear and compare them with the paths generated by the simple shear mechanism.

Figure 5 shows the PTt paths generated by simple shear and pure shear of the lithosphere with a constant uplift rate of 1 mm/yr in both cases. Comparison of Figures 4 and 5 shows that for the pure shear model the constraint of constant uplift rate slows the cooling of the uplifted particle with time and also eliminates the period of isothermal uplift that immediately follows the onset of extension. Figures 4 and 5 together indicate that purely vertical conduction of heat in the pure shear model is not as efficient in cooling the extending lithosphere as the combined effects of conduction and the movement of cool hanging wall rocks over deeper and hotter rocks in the simple shear case.

In order to compare the thermal and uplift paths of rocks at deep crustal levels to those of rocks at intermediate crustal depths we charted the PTt paths of rocks initially at 15 km depth uplifted to 3 km depth again at an uplift rate of 1mm/yr (Figure 6). For the simple shear case the fault dip was again taken to be 9.5°, the horizontal displacement rate was 6 mm/yr, and the particle lies 3 km below the detachment surface. For

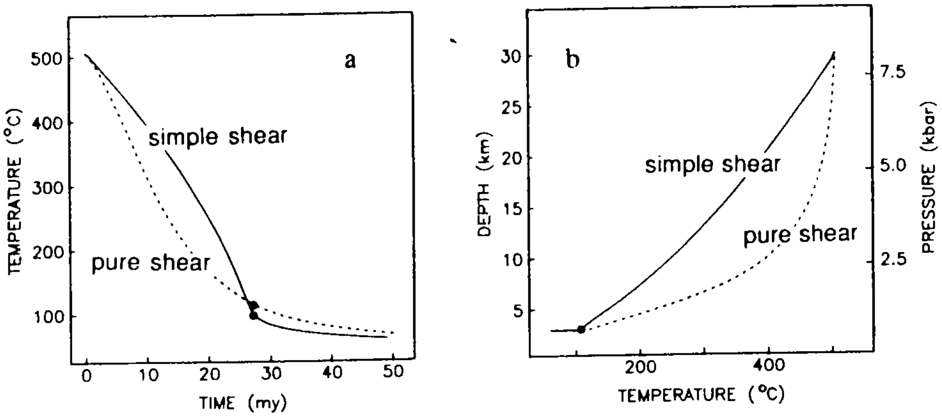

Fig. 4. (a) Temperature-time and (b) depth-temperature paths for rocks uplifted from 30 to 3 km by simple shear (solid lines) and pure shear (dashed lines) of the lithosphere using the perturbed initial geotherm. For the simple shear case the detachment surface dips at 9.5°, lies 3 km above the rock particle, and is unroofed at 1 mm/yr by horizontal displacement of the hanging wall at 6 mm/yr. Extension rate is held constant for the pure shear model, and the duration of extension is 27 m.y. for both cases. Dots mark the end of the extensional period.

the pure shear case, extension was assumed to occur at a constant rate, with a total extension given by β=5.0 or 400% extension.

The time-temperature paths for this midcrustal rock display the same qualitative relationships as those shown in Figure 4a for a deep crustal rock. For the simple shear case, the depth-temperature curve of the rock from mid-crustal depths has the same overall shape as that of the rock from deep crustal levels. In the pure shear models, however, the depth-temperature curves show significant qualitative differences in the uplift and thermal histories of intermediate and deep crustal rocks. The rock from deep crustal levels undergoes initial isothermal uplift, but a rock from intermediate crustal levels experiences little, if any, isothermal uplift. The cooling of rocks is caused by a complex interaction of uplift rate, depth relative to the surface, geothermal relaxation, and distribution and magnitude of heat sources. The simultaneous onset of cooling and uplift for a midcrustal rock in the pure shear model is related to all of these factors.

The features of the PTt paths presented here also depend on the choice of initial thermal structure for the lithosphere. For example, if the steady state geotherm is used instead of the perturbed geotherm (Figure 3), rocks at any initial depth have lower initial temperatures and therefore undergo less net cooling during the unroofing episode. Figure 7 shows the temperature-time and depth-temperature paths for a deep crustal rock (30 km) uplifted to shallow crustal levels (3 km) via the simple shear and pure shear mechanisms using the initial

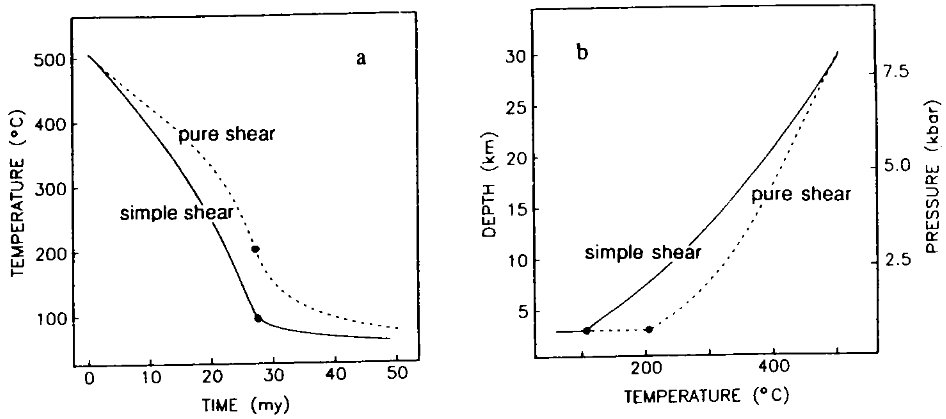

Fig. 5. (a) Temperature-time and depth-temperature paths for rocks uplifted from 30 to 3 km by simple shear (solid lines) and pure shear (dashed lines) of the lithosphere using the perturbed initial geotherm. For the simple shear case, the detachment surface dips at 9.5°, lies 3 km above the rock particle, and is unroofed at 1 mm/yr by horizontal displacement of the hanging wall at 6 mm/yr. Uplift rate is constant for the pure shear case at 1 mm/yr, and the duration of extension is 27 m.y. in each model. Dots mark the end of the extensional period.

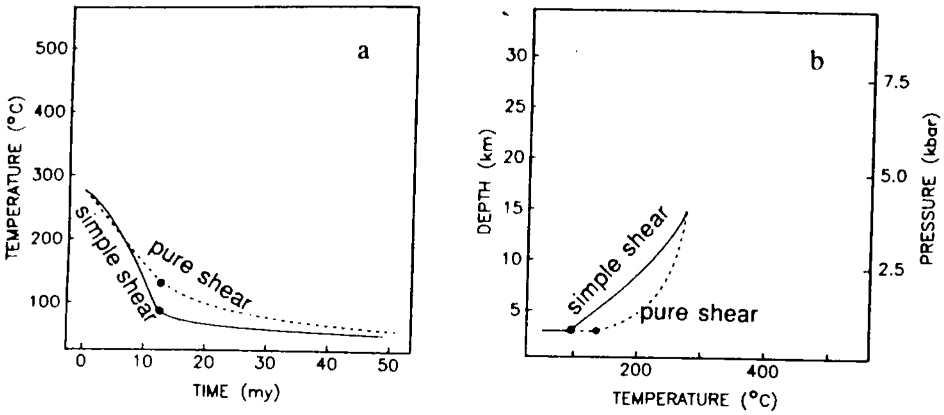

Fig. 6. (a) Temperature-time and (b) depth-temperature paths for rocks uplifted from 15 to 3 km by simple shear (solid curves) and pure shear (dashed curves) of the lithosphere, using the perturbed initial geotherm. For the simple shear case, the detachment surface dips at 9.5°, lies 3 km above the rock particle, and is unroofed at 1 mm/yr by horizontal displacement of the hanging wall at 6 mm/yr. Extension rate is constant for the pure shear case, and extension lasts 12 m.y. for both models. Dots mark the end of the extensional period.

conditions used for Figure 4 but with the steady-state initial geotherm in the place of the perturbed geotherm. Note that the form of the paths is qualitatively similar to those shown for the perturbed initial geotherm (Figure 4), but the increase in cooling rate with time (and therefore curvature of the paths) for the simple shear case is more pronounced when the steady state geotherm is used. For the pure shear mechanism, the PTt path is nearly isothermal during the first 8 m.y. (or 23 km) of extension.

As discussed above, a reasonable upper bound on the rate of displacement along these faults is probably several centimeters per year. In order to examine the effects of very fast uplift rates on the PTt paths generated by the two different extension mechanisms we charted the PTt path of a rock particle uplifted at a rate of 4 mm/yr (Figure 8), corresponding to a horizontal displacement rate of 24 mm/yr. The initial conditions are the same as those used to generate Figure 4 except for the higher rate of unroofing and horizontal displacement and the correspondingly shorter duration of extension (6.75 m.y. as opposed to 27 m.y.). The rate of extension in the pure shear case was held constant.

The nearly vertical slope of the syntectonic portion of the temperature-time path in Figure 8a indicates that even when the uplift rate is very rapid, most of the cooling still takes place during the extensional period. From Figure 8b, however, it is clear that for the pure shear case, almost all of this cooling occurs in the final 7 km of uplift, resulting in an isothermal depth-temperature curve between 30 and 10 km depth. In the

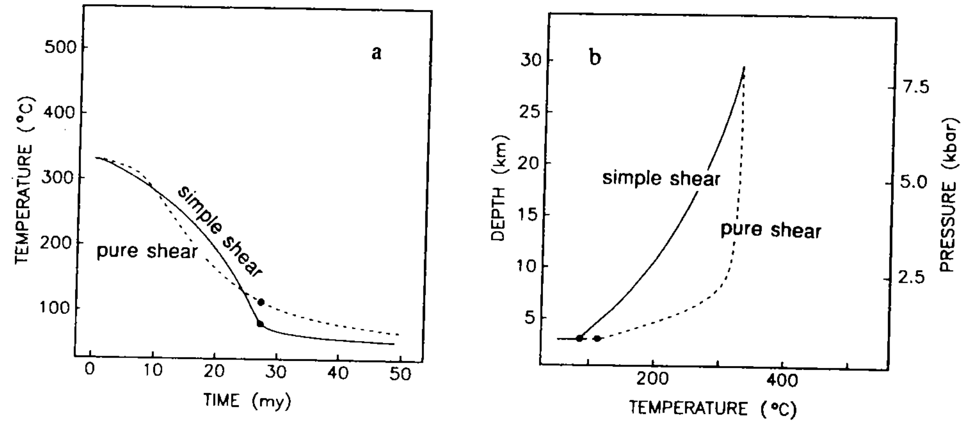

Fig. 7. (a) Temperature-time and (b) depth-temperature paths for rocks uplifted from 30 to 3 km by simple shear (solid curves) and pure shear (dashed curves) of the lithosphere using the steady state initial geotherm. For the simple shear case, the detachment surface dips at 9.5°, lies 3 km above the rock particle, and is unroofed at 1 mm/yr by horizontal displacement of the hanging wall at 6 mm/yr. Extension rate is constant for the pure shear case, and extension endures for 27 m.y. for both models. Dots mark the end of the extensional period.

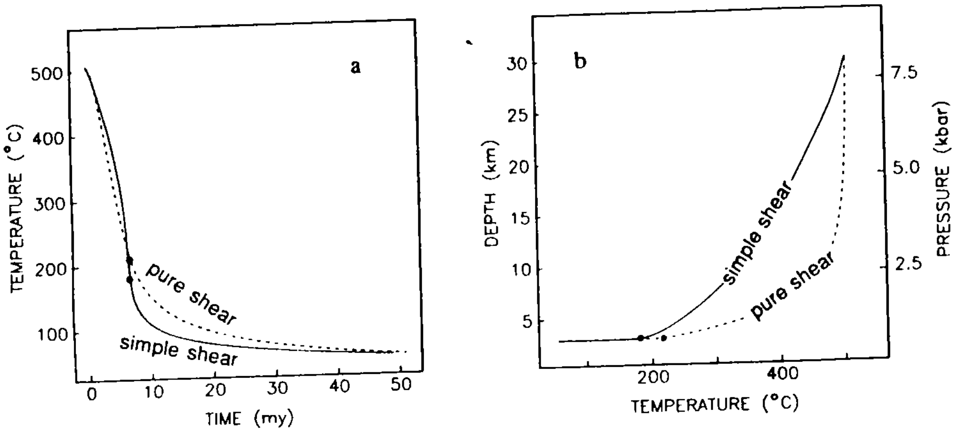

Fig. 8. (a) Temperature-time and (b) depth-temperature paths for rocks uplifted from 30 to 3 km by simple shear (solid curves) and pure shear (dashed curves) of the lithosphere, using the perturbed initial geotherm. For the simple shear case, the detachment surface dips at 9.5°, lies 3 km above the rock particle, and is unroofed at 4 mm/yr by horizontal displacement of the hanging wall at 24 mm/yr. Extension rate is constant for the pure shear case, and extension lasts 6.75 m.y. Dots mark the end of the extensional period.

simple shear case, cooling and uplift occur simultaneously from the onset of extension, and the increase in cooling rate per kilometer of uplift is reflected in the concavity of the depth-temperature curve.

MODIFIED PURE SHEAR

One weakness of the pure shear model as it is described above is that it assumes that the lithosphere is subject to the same amount of extensional deformation at every point. This uniform pure shear model ignores thermal, mechanical, and compositional heterogeneities in the lithosphere, particularly a postulated brittle to ductile transition between the upper and lower lithosphere. Additionally, extra heating in the lower lithosphere may result from thermal perturbations caused by magmatic underplating, small-scale mantle convection, intrusion of magmatic material, or other processes associated with rapid upwelling of the asthenosphere. Because these heating processes greatly complicate thermal models, we choose to mimic them by using a large β value for the lower lithosphere and a smaller stretching parameter for the uppermost lithosphere.

In order to compare the thermal and uplift paths produced by simple shear and uniform and modified pure shear of the lithosphere we chose to monitor the PTt conditions of a rock uplifted from deep (30 km) to intermediate (10 km) crustal levels at an uplift rate of 1 mm/yr. The extensional episode spanned 20 m.y. in each model. For uniform pure shear of the lithosphere, β, determined by the ratio of the initial to final depths of the uplifted rock, was chosen as 3.0 (or 200% extension of the lithosphere). In the modified pure shear model we chose 10 km as the depth to the zone of decoupling and tested two models, one with upper lithosphere parameter $\delta=1.66$ and lower lithosphere parameter $\beta=5.0$ and another with $\delta=2.0$ and $\beta=4.0$. In the simple shear case we monitor a rock particle initially at a depth of 30 km as it is uplifted to 10 km by movement along a detachment dipping at 9.5°. The rock particle is located 10 km below the detachment fault and unroofed at 1 mm/yr, corresponding to horizontal displacement of the hanging wall at 6 mm/yr.

Figure 9 shows the depth-temperature and time-temperature paths of the rock carried from 30 to 10 km depth via the simple shear and uniform and modified pure shear mechanisms, using the perturbed initial geotherm. As expected, the time-temperature paths for the simple shear and uniform pure shear cases have the same qualitative relationship observed in Figures 4a and 6a, although the extensional period is shorter. A minor difference between uplift from deep to intermediate crustal levels (Figure 9) and uplift from deep to shallow crustal levels (Figures 4a and 6a) by the uniform pure shear and simple shear mechanisms shows up in the amount of posttectonic cooling necessary to reach the equilibrium temperature. Rocks uplifted from deep to intermediate crustal levels experience greater cooling during the posttectonic period primarily because, at their final depths, they are still far below the surface, and the cooling effects associated with uplift or unroofing have not fully propagated downward to intermediate crustal levels.

For the case of uplift via modified pure shear Figure 9 shows that the PTt paths of lower lithosphere rocks depend on the amount of heating in the lower lithosphere, represented by β in our models. For the model with the smaller β value of 4 the temperature-time and depth-temperature curves are similar to those generated by uniform pure shear extension of the entire lithosphere, but cooling occurs more slowly and uplift is nearly isothermal over a longer portion of the temperature-depth path. Raising the β value still higher to 5 decreases the cooling rate to the point that the rock arrives at its final depth 40°C hotter than for the uniform pure shear model and 70°C hotter than for the simple shear model. Cooling for the modified pure shear model with $\beta=5$ occurs at a rate of 3°C/km between 30 and 15 km depth compared with 5°C/km for the case of $\beta=4$,

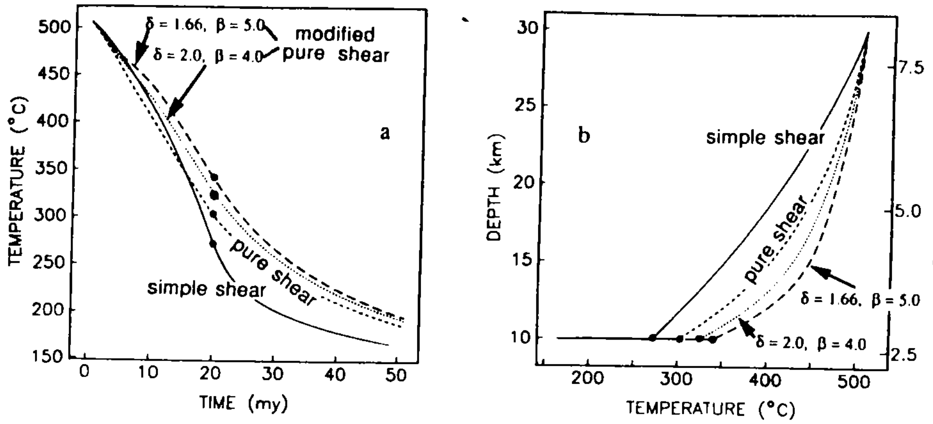

Fig. 9. (a) Temperature-time and (b) depth-temperature paths for rocks uplifted from 30 to 10 km by simple shear (solid curves) and uniform and modified pure shear (dashed curves) of the lithosphere, using the perturbed initial geotherm. The modified pure shear cases correspond to an extension factor δ above 10 km depth and an extension factor β below 10 km depth. For the simple shear case the detachment surface dips at 9.5°, lies 10 km above the rock particle, and is unroofed at 1 mm/yr by horizontal displacement of the hanging wall at 6 mm/yr. Extension rate is constant for the pure shear cases as described in the text, and the duration of extension is 20 my. Dots mark the end of the extensional period.

nearly 7°C/km for uniform pure shear, and 10°C/km for the simple shear model.

SIMPLE SHEAR MODELS

In the discussion above we have focused primarily on explaining how different extensional mechanisms affect the PTt paths of rocks unroofed or uplifted from intermediate and deep crustal levels. Another goal of this study is to understand how variations in the extensional parameters that describe normal faulting affect the PTt paths of footwall rocks. Toward this end, we first designed simple shear models to study how the PTt paths of footwall rocks are affected by the dip angle of the detachment surface when the unroofing rate (or uplift rate) is held constant. We chose dip angles that have integral cotangents of 12, 6, 4, and 2, corresponding to dips of 4.7°, 9.5°, 14°, and 26.6°. In each model the footwall was unroofed at a rate of 1 mm/yr until 20 km of tectonic denudation had occurred. The total duration of extension was 20 m.y., and the rates of horizontal displacement were 12, 6, 4, and 2 mm/yr, respectively.

Furlong and Londe [1986] have previously noted that if horizontal heat conduction is ignored, the depth-temperature and temperature-time paths are dependent only on the unroofing rate and are independent of fault dip because changes in fault dip have no meaning in the absence of lateral conduction of heat. Therefore comparison of temperature-time and depth-temperature paths for rocks unroofed at the same rate below detachments dipping at different angles is an implicit test of the importance of lateral heat conduction in determining the morphology of PTt paths.

Figure 10 illustrates the temperature-time and depth-temperature paths of a rock uplifted from 25 to 5 km depth by displacement along a simplified low-angle normal fault. In each case the rock experiences nearly 300°C of syntectonic cooling followed by less than 50°C of posttectonic isobaric cooling. During the syntectonic period, different fault dips produce the same temperature-time and depth-temperature paths because displacement of the hanging wall relative to the footwall and vertical conduction of heat predominate as the principal modes of heat transport. Divergence of these paths in the first 40 m.y. of posttectonic cooling is caused by conductive cooling across exposed detachment surfaces dipping at different angles. The qualitative relationships reported here for rocks from this depth range are also observed for rocks uplifted from shallower crustal levels. The lower initial temperature of shallower rocks simply reduces the amount of overall cooling these rocks experience during uplift and thermal reequilibration.

Figure 10 indicates that for faults that dip less than about 30° horizontal conduction of heat has no effect on the depth-temperature path and no effect on the temperature-time path during active unroofing. Posttectonic cooling is only marginally affected by fault dip. Given the errors inherent in measuring metamorphic temperatures and pressures (see below), the horizontal conduction of heat can be safely neglected for faults that dip 30° or less. Figure 10 also shows that the horizontal displacement rate during extension does not significantly affect the temperature-time and depth-temperature paths, provided that the unroofing rate is fixed. For gently dipping faults the only parameter that affects the paths of foot wall rocks is the unroofing rate.

In order to test the effects of varying the unroofing rate we compared the depth-temperature and temperature-time paths for rocks that begin at 25 km depth and are uplifted to 5 km depth by displacement along a fault dipping 9.5°. The rocks are initially located 5 km below the fault and are unroofed at 0.5, 1.0, and 2.0 mm/yr, corresponding to horizontal displacement

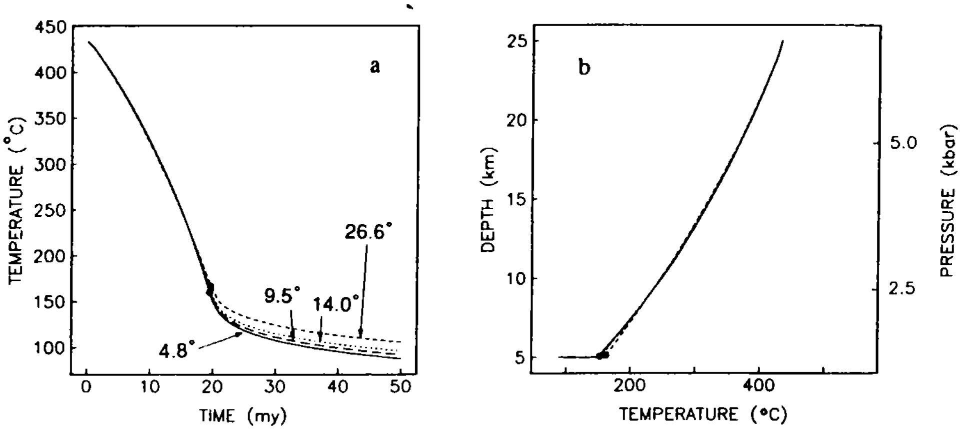

Fig. 10. (a) Temperature-time and (b) depth-temperature paths of rocks uplifted from 25 to 5 km depth via simple shear. The detachment faults dip 4.8°, 9.5°, 14.0°, and 26.6°. The unroofing rate is 1 mm/yr, and the rock is 5 km below the detachment surface in each case.

rates of 3, 6, and 12 mm/yr and extensional episodes lasting 40, 20, and 10 m.y., respectively. These variations in the rate of unroofing produce marked changes in the slopes of the temperature-time and depth-temperature paths (Figure 11). This occurs because most of the cooling of rocks located 5 km below the detachment occurs during movement on the fault. For the faster unroofing rates, more posttectonic cooling is necessary to reach equilibrium because the downward propagation of cooling associated with the movement of cooler hanging wall rocks over deeper and hotter footwall rocks cannot keep pace with rapid unroofing. Cooling therefore continues after the unroofing of the footwall has stopped, and the rock unroofed at 0.5 mm/yr reaches its final depth approximately 70°C cooler than does the rock unroofed at 2.0 mm/yr.

The slope of the depth-temperature curves is approximately the same for the different rates of unroofing, particularly during the last half of the extensional period. Between temperatures of 300° and 200°C the slope of the temperature-depth path is 16°C/km for each case. During the first part of the syntectonic period, however, the rock unroofed at a rate of 0.5 mm/yr undergoes 15°C/km of cooling between 400° and 300°C, while unroofing at 2.0 mm/yr causes only 11°C/km of cooling. Clearly, the temperature-depth paths are not very sensitive to a variation by a factor of 4 in the unroofing rate, particularly during the last part of the extensional period.

DISCUSSION

In detail, pure shear and simple shear extensional mechanisms produce similar temperature-time paths but different pressure-temperature (PT) paths. PT paths for rocks uplifted by pure shear are nearly isothermal (high dP/dT) during the initial stages of uplift, whereas PT paths for rocks uplifted by simple shear are characterized by moderate dP/dT and fairly constant slopes. Isothermal uplift would be observed

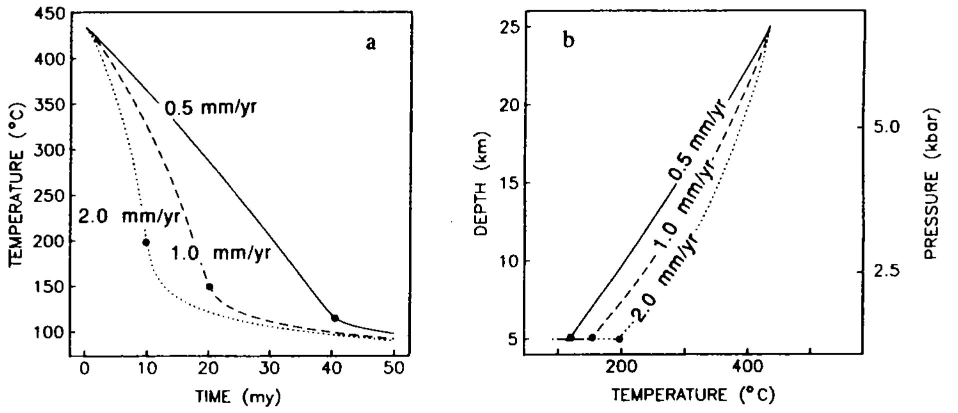

Fig. 11. (a) Temperature-time and (b) depth-temperature paths of rocks uplifted from 25 to 5 km depth via simple shear at unroofing rates of 0.5, 1.0, and 2.0 mm/yr. The dip of the fault is 9.5°, and the rock is 5 km below the detachment surface in each case.

in simple shear settings only if the initial geotherm were roughly isothermal with depth. Temperature-time paths for pure shear and simple shear have similar morphologies, although cooling rate (dT/dt) decreases with time for the pure shear models and increases with time for the simple shear case. The primary difference between temperature-time paths produced by pure shear and simple shear is the amount of posttectonic cooling necessary for rocks to reach equilibrium temperature: rocks from simple shear settings are generally cooler by the end of the extensional episode than rocks uplifted by pure shear and must therefore undergo less posttectonic cooling.

It is appropriate to ask whether PTt data for extensional terranes can constrain the mechanism of extension. The answer depends on the magnitude of uncertainties involved in PTt path calculations. Pressure-temperature paths are determined through a combination of standard thermobarometric techniques [Essene, 1982], mineral inclusion thermobarometry [St-Onge, 1987], and thermodynamic modeling of mineral zoning [Spear and Selverstone, 1983]. Although the propagation of analytical uncertainties through thermobarometric calculations is straightforward [Hodges and Crowley, 1985; Hodges and McKenna, 1987], the uncertainties in thermodynamic modeling are less well constrained. The nominal uncertainties in the position of pressure-temperature points on a path are 50°C and 1 kbar. If we note that the range of pressures over which PT measurements may typically be made is only about 7 kbar (between 30 and 10 km depth) and the range of temperatures is only about 400°C (250°-650°C), then we cannot expect to reconstruct the slope of a pressure-temperature path with even moderate precision. This precision is insufficient to distinguish between pure shear and simple shear uplift except in instances of uplift rates corresponding to very rapid displacement along the fault zone or significant heating (corresponding to large β values) in the lower lithosphere during pure shear extension.

Uncertainties in temperature-time paths include errors in calculated ages for various mineral-isotope systems, as well as uncertainties in the closure temperatures of these systems. On the basis of the propagation of nominal uncertainties in diffusion data for radiogenic species through closure temperature equations [e.g., Dodson, 1973], we calculate closure temperature uncertainties of roughly 25°-75°C for many commonly used mineral-isotope systems (e.g., hornblende K-Ar, biotite K-Ar, and microcline K-Ar). Absolute age uncertainties of the order of a few million years are realistic for Tertiary cooling events like those that occurred in the North American metamorphic core complexes and even greater for older events. Given these uncertainties, it is difficult or impossible to differentiate between various extensional mechanisms using current petrologic techniques and temperature-time data from a single rock particle or from rock particles that have been uplifted from the same structural (crustal) level.

With the limitations imposed by current petrologic techniques the best method for distinguishing between pure shear and simple shear mechanisms may lie in analysis of samples collected from the broadest possible range of structural levels. Clearly, examination of PTt paths for rocks in both the hanging wall and the footwall of a detachment fault should reveal if uplift were accomplished primarily through movement along that particular fault or primarily by pure shear extension and thinning of the crust. Comparison of footwall samples from different structural levels may also enable one to determine if the vertical separation between those samples was greater in the past than at present. Ultimately, however, the best prospect for distinguishing between simple shear and pure shear mechanisms through petrologic work lies in improving the precision of metamorphic temperature and pressure measurements. Even an improvement in precision to ±25°C and ±0.5 kbar could enhance our capability to constrain types of extensional deformation-based petrologic data.

CONCLUSIONS

1. Temperature-time paths for rocks uplifted via pure shear thinning and extension of the lithosphere are, in some instances, different from those produced by rocks uplifted at the same rate by simple shear unroofing along large, gently dipping normal faults. In particular, rocks from pure shear settings reach their final depth at higher temperatures than do rocks uplifted by simple shear, and experience a greater amount of posttectonic cooling. However, it would be difficult or impossible to distinguish the temperature-time paths of rocks uplifted by pure shear from those of rocks uplifted by simple shear but at a more rapid rate.

2. The depth-temperature paths of rocks uplifted from deep crustal levels (30 km depth) via pure shear extension are often characterized by a period of nearly isothermal (high dP/dT) uplift during the early stages of extension, but rocks from intermediate crustal levels (15 km depth) experience a markedly shorter period of isothermal uplift. In contrast, simple shear uplift along low-angle normal faults produces almost linear depth-temperature paths with moderate dP/dT. Isothermal depth-temperature curves would be expected for the simple shear case only if the initial geotherm were isothermal with depth.

3. An important factor in determining the characteristics of the thermal and uplift histories of deep crustal rocks in a pure shear model modified to include additional heating in the lower lithosphere is the amount of heating, described by stretching parameter β, in the lower lithosphere. These modified pure shear models, with large amounts of lower lithospheric heating, generally produce PTt paths characterized by lower syntectonic cooling rates and a more protracted period of nearly isothermal uplift.

4. For a given initial geotherm the single factor controlling the PTt paths of rocks unroofed below gently dipping normal faults is the rate at which unroofing takes place (unroofing rate is defined as the rate of uplift relative to the surface). For faults that dip less than about 30°, changing the fault dip and the rate of horizontal displacement has no appreciable effect on either the PT path or on the syntectonic part of the time-temperature path and only a marginal effect on the post-tectonic part of the temperature-time path. These results indicate that for faults that dip about 30° or less, horizontal conduction of heat is not very important and for most purposes can be ignored. These results further indicate that a consideration of more detailed geometric models (e.g., listric fault geometries) is not warranted because

the fault geometry is only important insofar as it affects the unroofing rate of footwall rocks.

5. Propagation of typical uncertainties in real pressure-temperature and temperature-time data shows that it is difficult or impossible to distinguish between various extensional mechanisms solely on the basis of PTt data derived from a single sample or from a single structural level through the use of current geothermometric and geobarometric techniques. With the limitations imposed by current petrologic techniques the best method for distinguishing between pure shear and simple shear mechanisms may be the analysis of samples collected from the broadest possible range of structural levels. Ultimately, however, the best prospect for distinguishing between simple shear and pure shear mechansims through petrologic work lies in improving the precision of metamorphic temperature and pressure measurements to ±25°C and ±0.5 kbar.

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