Constraining rates of thrusting and erosion: Insights from kinematic thermal modeling

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ABSTRACT
We present a thermal model of a simple thrust system that can be used to determine thrust rates and erosion rates from low-temperature thermochronology. Unlike previous models, this model incorporates the effects of erosion both during and after thrusting. In particular, we examine the modeled evolving thermal structure and pressure-temperature-time evolution of hanging-wall rocks that undergo fault-bend folding due to transport over a blind footwall ramp. In all cases, rocks cool as they move over the footwall ramp, potentially providing a common pinpoint for determining thrust rates. In the simplest case, low-temperature thermochronology of minerals that pass through their closure temperature over the ramp will yield details on thrust kinematics (thrust rate, timing of initiation, and duration of thrusting). Additional cooling ages of a more comprehensive sample suite can capture cooling due to erosion. In these latter cases, model results can place limitations on erosion rates.

Keywords: thermochronology, erosion, fold-and-thrust belt, thermal model.

INTRODUCTION
Collisional orogens are characterized by the transfer of crustal mass and thermal energy. This transfer of heat and mass can then be recorded in the metamorphic and structural record. A key goal of geological research is to use this preserved record to extract the rates of fundamental orogenic processes. This paper concerns the evolution of a single thrust sheet and the potential for quantifying the velocity of thrust movement and erosion rates from the rock record.

Shi and Wang (1987) presented the first two-dimensional time-dependent thermal model of a simple thrust system. This represented a significant improvement over previous one-dimensional models (e.g., Oxburgh and Turcotte, 1974; Brewer, 1981; Mailhe et al., 1986; Davy and Gillet, 1986) by showing that noninstantaneous thrust velocities can yield complex thermal structures and by providing a useful framework for interpreting pressure-temperature-time (P-T-t) paths (e.g., Florence et al., 1993). However, application of their results is limited by a steep fault ramp (34°), rapid thrust movement (10–10,000 km/m.y.), linear initial geothermal gradient, and planar exhumation only after thrusting ceased. Each of these simplifications limits the applicability of their results to real thrust systems.

In this paper we present a more realistic thermal model of a thrust system. The model resembles that developed by Shi and Wang (1987), but includes modifications in thrust geometry, thrust velocity, initial thermal structure, and exhumation processes that more accurately reflect real orogenic conditions. Because we have included erosion processes during thrusting, our model can also directly track the modeled P-T-t history of rocks. Our results indicate that the thermochronologic record in such a thrust system can be used to obtain information on the erosion rates and kinematics of the thrust system, including timing of initiation, duration, and velocity of thrusting.

MODEL DESCRIPTION
Our new two-dimensional finite difference model incorporates geologically reasonable velocities, radiogenic heat production within the upper crust, and erosion during and following thrust movement of a blind thrust fault. The initial thermal structure of the model is that of a steady-state 120-km-thick continental lithosphere with a 20-km-thick upper-crustal layer with heat-production rate of 1.75 μW/m² (Fig. 1).

The fault geometry is based upon a simple thrust geometry with a blind flat-ramp-flat system such as that interpreted for the Paris-Willard thrust of the Sevier orogenic belt (Dixon, 1982; Rodgers and Janecke, 1992; Coogan, 1992). Flats are located at depths of 15 and 10 km and are separated by a ramp with a dip of 15° (Fig. 1).

At time t = 0 the thrust sheet begins to move with velocity v. We prescribe thrust sheet movement and geometry following standard fault-bend-fold structural calculations (i.e., Suppe, 1983). Concurrent with thrust movement, we also include the effects of erosion of the surface. In active mountain belts, rivers control the development of relief (Howard et al., 1994; Whipple and Tucker, 1999). To capture the physics of fluvial erosion we use the incision law as cast by Howard and Kerby (1983):

\[ \dot{e} = k_A \left( \frac{dh}{dx} \right)^n, \]  

where the erosion rate, \( \dot{e} \), is the rate of elevation change at a given position as material is removed from the surface, A is the drainage basin area taken as a proxy for river discharge, \( \frac{dh}{dx} \) is the magnitude of the local river slope, and \( k, n, \) and \( m \) are empirical parameters. Following Willett (1999), we use the linear stream-power version of this erosion law with \( n = m = 1 \), based on the assumption that river discharge, Q, is proportional to area, A. Additional simplifications of constant uplift rate, constant precipitation rate, and rectangular drainage basin result in a modeled erosion rate of:

\[ \dot{e} = k_X \left( \frac{dh}{dx} \right). \]  

where \( k_X \) is the stream power, \( \frac{dh}{dx} \) is the local slope, and k (erosion parameter) represents precipitation rate and erodibility and has a dimension of t⁻¹. Note that this equation would not allow erosion at the drainage divide, so we set the erosion rate at the divide (\( x = 0 \)) equal to the average of the erosion rates half a grid step (1.85 km) on either side of the divide.

Thus, the elevation of a given column in the hanging wall changes through time as it is thrust across the system and subjected to erosion such that

\[ \frac{dh}{dt} = v \sin \Theta - k_X \left( \frac{dh}{dx} \right). \]  

where \( \Theta \) is the dip of the fault directly below.

To explore the first-order effects of thrusting and erosion on the thermal evolution of a thrust system, we input the evolving kinematics and

Figure 1. Schematic illustration of initial model setup and thermal boundary conditions. See text for discussion.
study the effects of differing thrust rates and (with concurrent erosion), then thrusting stops erosion parameters (\(v_x\) and \(v_y\)) during the thrusting stage. The foreland land slopes develop distinctly different profiles. More than 2 km of material has been removed. The foreland and hinterland slope, where more than 2 km of material erosion has significantly modified the hinterland structure as the thrust system evolves for a total of 50 m.y. In our simulations, we begin thrusting at \(t = 50\) Ma, and follow the topographic and thermal evolution until present time, \(t = 0\) Ma. During the 50 m.y. evolution, the thrust sheet is displaced a total of 65 km (with concurrent erosion), then thrusting stops and the system is subject to erosion alone. To study the effects of differing thrust rates and erosion rates, we run simulations with thrust velocities \((v)\) of 2, 5, and 10 km/m.y. and with erosion parameters \((k)\) of 0.25, 0.5, and 0.75 m.y.\(^{-1}\).

**MODELED TOPOGRAPHIC EVOLUTION**

Figure 2 displays the simulated evolution of a nominal thrust system based on a moderate thrust velocity of \(v = 5\) km/m.y. and erosion parameter of \(k = 0.5\) m.y.\(^{-1}\) (see Fig. DR\(^1\) for simulated evolution with no vertical exaggeration). Topography develops as thrusting commences at \(t = 50\) Ma. After 20 km of slip \((t = 46\) Ma\), the maximum height of 4.85 km has been achieved directly above the upper ramp-flat transition, while erosion has removed as much as \(\sim 150\) km of material from the slopes. After 60 km of slip \((t = 38\) Ma\), the topographic high spans more than 70 km, with a peak elevation of \(\sim 4\) km. By this time, erosion has significantly modified the hinterland slope, where more than 2 km of material has been removed. The foreland and hinterland slopes develop distinctly different profiles during the thrusting stage. The foreland slope quickly achieves a concave-up profile, which it roughly maintains as the slope retreats toward the hinterland. The hinterland slope, however, has a very long, shallow profile after 60 km of slip \((t = 38\) Ma\) and does not develop the concave-up profile until well after thrusting stops. This asymmetry in profiles results in the pinning of the drainage divide near the front of the thrust sheet, which is then passively transported across the orogen with the advancing thrust sheet.

Following the cessation of thrusting \((t = 37\) Ma\), erosion continues to act on the topographic high. The maximum elevation reduces to \(\sim 3\) km after 10 m.y. of postthrusting erosion \((t = 27\) Ma\), and the width of the topographic high reduces to \(\sim 30\) km. In addition, erosion steepens the hinterland slope, which has begun to develop a concave-up profile. Erosion rates through the thrusting stage are commonly \(\sim 0.3\) km/m.y., with maximum rates of \(\sim 0.8\) km/m.y. Following cessation of thrusting the erosion rates reduce, and after 10 m.y. \((t = 27\) Ma\), erosion rates are commonly \(\sim 0.1\) km/m.y. with a maximum rate of \(<0.3\) km/m.y.

**MODELED THERMAL EVOLUTION**

Figure 2 also displays the thermal evolution of the nominal thrust system. The 100 °C, 200 °C, and 300 °C isotherms are initially horizontal at depths of \(\sim 4.8\) km, \(\sim 10\) km, and \(\sim 17\) km, respectively. As the hanging wall moves over the footwall, the isotherms move upward and generally follow the shape of the topographic surface, forming a “thermal bulge.” This thermal bulge can be attributed to two factors; additional heating due to thickening of heat-producing crust, and the upward advection of heat due to thrusting and erosion of the surface (Huerta et al., 1996, 1998). Following cessation of thrusting, the isotherms flatten as erosion reduces the topographic high (and the thickness of the heat-producing crust) and erosion slows.

To explore the thermal history of hanging-wall rocks as they are transported through the evolving thrust system, we track six points (Fig. 2). The upper points \((A1, A2, \text{and } A3)\) are initially located just below the 100 °C isotherm \((T_i = 105°\text{C})\). As each point is transported over the ramp it cools through the 100 °C isotherm. These points continue to cool as they are thrust across the upper flat and after thrusting ceases and erosion continues to lower the surface. The lower points \((Z1, Z2, \text{and } Z3)\) are initially located \(\sim 2\) km below the 200 °C isotherm \((T_i = 220°\text{C})\). As each of the Z points moves over the ramp, the point approaches or passes through the 200 °C iso-

\[
\frac{1}{\kappa} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{v_x}{\kappa} \frac{\partial T}{\partial x} + \frac{v_y}{\kappa} \frac{\partial T}{\partial y} + \frac{R(x, y)}{K},
\]

where \(\kappa\) is the thermal diffusivity (10^\(-6\) m^2/s), \(v_x\) and \(v_y\) are the horizontal and vertical components of the thrust velocity, respectively, \(R\) is heat production rate, and \(K\) is thermal conductivity (2.5 W/mK). Our model tracks the evolving thermal structure as these processes \((1)\) modify the topography, and thus the shape of the \(T = 0°\) boundary, and \((2)\) advect material and heat through the system, as erosion brings material closer to the surface and thrusting places warmer rocks over colder rocks.

\(^1\)GSA Data Repository item 2006105, modeled structural, topographic and thermal evolution of a nominal thrust system, no vertical exaggeration, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, PO. Box 9140 Boulder, CO 80301-9140, USA.
records regional cooling of the crust as erosion planes much of the region back to base level (and original thickness of heat-producing crust) and erosion slows.

During the initial stage of thrusting, the hinterland points (A3 and Z3) undergo near-isobaric heating as they approach the ramp (50 Ma < t < 41 Ma; Fig. 3). This heating reflects the regional warming of the crust due to the 9 m.y. of thickening of the heat-producing crust. (Note that Z3 experiences a slight increase in depth as the stratigraphy above it is tilted along the hinge line of the syncline.) As the points move over the ramp, they cool due to erosional exhumation (t = 41–37 Ma). Postthrusting erosion (37 Ma < t < 0 Ma) continues to cool the points until they achieve their final state. This later cooling records both the cooling of the points as they pass through the thermal structure, and the regional cooling as erosion thins the heat-producing layer.

Figure 3 also shows the fission track partial annealing zones (PAZ) for apatite and zircon. Each of the four points tracked passes through the appropriate PAZ while moving over the footwall ramp. However, this would not be true for all points in the hanging wall. Although the P-T-t path of any material point will be similar to those displayed in Figure 3, the initial and final temperatures may be different, depending on the starting depths. Thus, a point with an initial temperature between 100 and 200 °C would not pass through the apatite PAZ until long after it had moved over the footwall ramp.

**FISSION TRACK ANALYSIS AND THRUST KINEMATICS**

Low-temperature thermochronology (e.g., fission tracks in apatite) could potentially capture the cooling of rocks in real thrust systems. What would such ages actually record? To answer this question, we use the thermal model described here and determine the time when rocks from a variety of locations would finally cool below the apatite fission track blocking temperature (we assume \( T_b = 105 \) °C). We track rocks whose initial temperatures are between 110 and 170 °C and plot the results as x-t graphs (Fig. 4), the x axis showing the final horizontal position of the rock relative to the top edge of the footwall ramp and the y axis displaying the apatite age, i.e., the age when the points cool through the 105 °C isotherm in our simulated thrust system that began movement at 50 Ma.

Rocks whose initial temperatures were between 110 and 120 °C exhibit a linear increase in fission track age from hinterland to foreland (Fig. 4). These samples (similar to the A points in Fig. 2) cool below 105 °C as they pass over the thrust ramp. Because all these samples, regardless of their lateral position, cooled below \( T_b \) at the same location in the thrust system, they yield valuable information about thrust kinematics. Samples on the leading edge record the initiation of thrusting, and samples on the trailing edge record the end of thrusting. A suite of samples collected between these two locations would potentially yield a pattern of ages with an \( x/t \) slope of 5 km/m.y., identical to the velocity of thrusting. Thus, apatite fission track analysis of these rocks would yield significant results including the age of initial thrusting, duration of thrusting, and velocity of thrusting.

In contrast, hanging-wall rocks whose initial temperatures exceed 120 °C show a non-linear pattern of fission track ages with anomalously young ages in the central region (Fig. 4). These young ages do not record thrusting over the footwall ramp, but instead cool below \( T_b \) during later erosion of the highland. Samples with initial temperatures \( \geq 120 \) °C retain progressively broader zones of young ages, reflecting the progressively longer duration of the thermal bulge with depth.

**VARYING INPUT PARAMETERS**

To explore the effects of varying thrust velocities and erosion parameters, additional simulations were performed with erosion parameter values (k) between 0.25 and 0.75 m.y. 1 and thrust velocities between 2 and 10 km/m.y. Two end-member patterns are shown as a function of the magnitude of \( k/v \): Modeled thrust systems with a high \( k/v \) ratio do not develop much topography or thermal bulge (Fig. 5), and many of the apatite cooling ages record cooling during movement over the footwall ramp. The relatively subdued topographic relief in this model may be an appropriate analog to that observed in modern thrust belts. In contrast, when the \( k/v \) ratio is relatively low, the thrust sheet develops pronounced topography and a thermal bulge, and apatite cooling ages are most likely to record erosion long after thrusting has ceased (Fig. 5).

Figure 3. Temperature-depth paths of four points, including foreland points (A1, Z1) and hinterland points (A3, Z3), in hanging wall of thrust system shown in Figure 2. See text for discussion. Note that we follow thermobarometric convention such that depth is measured below overlying evolving erosion surface, not below constant reference level (i.e., England and Molnar, 1990). Gray bands indicate partial annealing zones (PAZ) for fission tracks in apatite and zircon.
To simulate erosion in our thermal model, we used the linear, stream-power version of the fluvial incision erosion model (i.e., we used the linear, stream-power version of the erosion parameter). Model runs with \( k / v > 0.4 \) yield flat topography and AFT age pattern. Although not shown, model runs that vary thrust velocity (\( v \)) and hold erosion parameter (\( k \)) constant result in same patterns. Thus, although the details of simulated cooling ages curves may not match real cooling age curves, the general shapes provide key information on the relative efficiency of erosion.

**EXTRACTING INFORMATION FROM REAL SYSTEMS**

Information on thrust kinematics and erosion rates of real thrust systems can be extracted using thermal modeling and targeted sampling strategies. Ages of initiation, duration, and rates of thrusting can be directly determined from a suite of samples collected in the hanging wall above the upper footwall of the thrust system, along a horizon whose initial temperature was slightly higher than the blocking temperature of the thermochronometer being used (Fig. 5).

Once the thrusting rate of a system is determined, the efficiency of erosion (i.e., \( k \) as well as erosion rates) can be extracted from deeper samples in the hanging wall. Cooling ages of a vertical sample transect above the footwall flat will display a range of cooling ages, and this range of ages is controlled by erosional efficiency. For example, in Figure 5 we see that, in the case of \( k = 0.75 \text{ m/Myr}^{-1} \), a vertical transect located 20 km from the top of the footwall ramp, spanning from \( T_1 = 110 \text{ C} \) to \( T_2 = 130 \text{ C} \) (\(-1 \text{ km of structural relief} \)), will display a range of cooling ages from 43 to 41 Ma. In contrast, in the case of \( k = 0.25 \text{ m/Myr}^{-1} \) the range of ages is 43–29 Ma, a significantly greater spread. Thus, in a real thrust system, cooling ages from a few vertical transects can be compared to modeled cooling age plots to extract \( k \) and erosion rates.

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