

### Apatite Fission Track (AFT) Data and Background

Fission-track dating is based on the decay of trace  $^{238}\text{U}$  by spontaneous nuclear fission (e.g., Dumitru, 2000). AFT thermochronology depends on the fact that tracks are partially or entirely annealed (erased) by thermally induced recrystallization at elevated subsurface temperatures, causing reductions in both the lengths of individual tracks and the fission-track ages. In a relatively stable geological environment where temperatures increase uniformly as a function of depth, apatite fission-track age and length decrease systematically with increasing depth (e.g., Naeser, 1979; Fitzgerald et al., 1995). At temperatures less than 60–70°C, tracks that are produced by fission are retained and annealing is relatively minor. In the temperature range known as the partial annealing zone (PAZ), between 60–70°C and 110–140°C, the AFT ages and mean lengths are reduced compared to the original AFT ages and lengths (e.g., Stockli et al., 2001). At temperatures above 110–140°C, tracks are quickly annealed and the fission-track age is zeroed. If, after a period of relative stability, the crust is rapidly cooled during exhumation, the fossil PAZ may be preserved either at the surface or in the subsurface. Thus, the time of cooling, based on the ages recorded below the fossil PAZ, and the paleodepth of the base of the PAZ, which roughly corresponds to the paleo-110°C isotherm, can be estimated (Fitzgerald et al., 1995; Stockli et al., 2000). The AFT dates used in this analysis are from Bryant and Naeser (1981), Kelley and Chapin (1995, 1997, 2004), Kelley et al. (1992), and Naeser et al. (2003). The sample sites in Fig. 2A represent 15–20 samples each, and the AFT dates increase with elevation in each locality; the symbol reflects the timing of the onset of cooling.

### Model Details

Gravity model. We use 3D and 2.5D forward models of Bouguer gravity to study the first-order density structure of the San Juan volcanic field (a middle Tertiary magmatic center that is unaffected by Neogene extensional deformation). To study the feature over the 200 km-wide volcanic field, we first remove a linear, 1000-km regional scale trend from the data. We find that, if the entire 600 km-scale San Juan volcanic field gravity anomaly (Fig. 3) is attributed to a crustal-scale batholith (surface to Moho) alone, then the anomaly is not matched with a cylindrical body of radius 100 km and reasonable density contrast. This radius is constrained by the outcrop of intrusive rocks in the region, and a reasonable density contrast is constrained by average densities in the Southern Rocky Mountains of 2710–2760 kg/m<sup>3</sup> for Precambrian rocks and 2620–2630 kg/m<sup>3</sup> for Tertiary granitic rocks (Isaacson and Smithson, 1976; Tweto and Case, 1972). Instead, for a reasonable density contrast, a geologically unreasonable batholith radius is required (~180 km). Although the inferred structure beneath the San Juan volcanic field is subject to non-uniqueness because of the nature of gravity data, the outcrop of intrusive rocks strongly constrains the subsurface batholith. We find that the best-fitting crustal batholith occupies the upper 15 km, with radius of 70–100 km. We exploit this constraint to determine how much of the 600 km-scale gravity feature can be explained by a crustal body, and how much must be attributed to anomalously low-density mantle. We find that matching the anomaly requires both a ~100-km radius crustal batholith and ~150 km half-width region of low-density mantle beneath. Our models constrain the subsurface mass-deficit in the mantle lithosphere; to obtain an estimate of mantle dedensification, we take a value of 200 km as a representative thickness of North America (Dueker et al.,

2001). Our models then constrain the mantle dedensification to around 1%, assuming an average density of  $3300 \text{ kg/m}^3$ . The models in Fig. 3 are for best-fitting density contrast and geometry for bodies of square cross-section (square prisms). We also investigated the effects of bodies of circular cross section and found no significant difference. Our solutions for vertical cylinders were based on Legendre polynomial expansions (Telford et al., 1976), and for square-prisms we used a 2.5-dimensional Talwani calculation (Talwani et al., 1959). Potential sources of error in the gravity model include the simple assumed geometry of the batholithic body and the region of dedensified mantle; clearly our intent here is to gain a first-order estimate of mass deficit. Additionally, there is always a tradeoff between density contrast and depth of the anomalous mass; we recognize this and calculate a range of mantle dedensification assuming lithosphere thickness of 100-200 km; the predicted range of mantle dedensification is between 1-1.5% in these cases.

Thermal and isostatic model. We examine the combined influence of temperature and buoyancy associated with regional scale middle Tertiary magmatism on the position of middle Tertiary isotherms near Santa Rosa, New Mexico. This location is roughly 250-290 km away from the middle of a hypothetical caldera complex centered on a line connecting the San Juan and Mogollon-Datil volcanic fields. Exhumation and faulting in the vicinity of the Rio Grande rift would locally enhance tilting of isotherms (Ehlers et al., 2001; House et al., 2003), but are ignored here. We ignore the effects of faulting for two main reasons: the lack of significant Tertiary faulting on the High Plains; and because flexural wavelengths in regions surrounding the Rio Grande rift are too short to account for tilting over a  $>200 \text{ km}$ -wide region; Roy et al., 1999; Brown and Phillips, 1999.)

A 2D, explicit, finite difference model with insulated side boundaries (Jaluria and Torrance, 1986) was used to calculate the temperatures around an intrusion with a half-width of 150 km ranging from granitic ( $800^\circ\text{C}$ ) to basaltic ( $1200^\circ\text{C}$ ) in composition emplaced at the base of a 40 km thick crust. The intrusion was centered on a line along the eastern margin of the Colorado Plateau that connects the San Juan and Mogollon-Datil fields. The temperature field around the intrusion was superimposed on temperatures related to a background heat flow of  $60 \text{ mW/m}^2$ , a heat flow characteristic of the High Plains near Santa Rosa (Reiter et al., 1975). The geometry of the region over which the intrusion is emplaced is constrained by the gravity model above to be  $\sim 150 \text{ km}$  half-width. Following Lachenbruch and Morgan (1990), we represent lithospheric thermal perturbations as equivalent changes in Moho temperature,  $\Delta T_{\text{Moho}}$ . The temperature field is thus calculated by heatflow and temperature boundary conditions at the Moho and is symmetric about the line  $x=0$  (Fig. 4A). The intrusions were turned on for 20, 30, and 40 Ma and then allowed to cool.

We calculate isostatic rock uplift due to a range of thermal perturbations,  $\Delta T_{\text{Moho}} = 200\text{--}600^\circ\text{C}$  (in  $200^\circ\text{C}$  increments) for intervals of 20–40 m.y. (in 10 m.y. increments). Shallow isotherms are tilted due to heating from the magmatic center, and to this thermal tilt we add tilting due to isostatic rock uplift due to buoyancy modification (mass deficit constrained by gravity; Fig. 3C) and thermal expansion. We use simple Airy isostasy to estimate rock uplift (with background densities  $\rho_{\text{crust}} = 2760 \text{ kg/m}^3$  and  $\rho_{\text{mantle}} = 3300 \text{ kg/m}^3$  and approximate middle Tertiary crustal thickness of 45 km in the Southern Rocky

Mountain–Rio Grande rift region, based on estimates of present crustal thickness in unextended areas; Sheehan et al., 1995). For the contribution from thermal expansion, we assume that the coefficient of thermal expansion is  $\alpha = 3.5 \times 10^{-5} / ^\circ\text{C}$ . The total predicted tilting of middle Tertiary isotherms is therefore a sum of effects due to heat conduction (from the thermal model) and rock uplift due to dedensification (from gravity model) and thermal expansion (based on the temperature field from the thermal model). We find that to cause the requisite regional tilting of shallow isotherms roughly 250–290 km from the magmatic center, we require thermal perturbations of  $\Delta T_{\text{Moho}} = 600^\circ\text{C}$  (actual temperature  $T_{\text{Moho}} \approx 1200^\circ\text{C}$ , consistent with partial melting in the upper mantle) for an interval of 40 m.y. (Fig. 4A).

Potential sources of error in our first-order models include: the assumption of a constant thermal conductivity of 3.35 W/m-K, which does not account for possible variations in crustal composition across this broad region, nor the approximately 10% decrease in thermal conductivity with increasing temperature (Clark, 1966); the simple, 2D symmetric geometry of the model, which predicts symmetric responses surrounding the magmatic center; the decoupled thermal and isostatic calculations; and finally the lack of erosion and isostatic response to erosion in the models. In future work, we plan to address the spatiotemporal history of rock uplift and exhumation of the Southern Rocky Mountains–Rio Grande rift region by combining heat conduction, isostasy, and erosion into a coupled evolution model.

### Additional Notes on Figures

Maps in Figs. 1A and 3 used Generic Mapping Tools (Wessel and Smith, 1991). Geology data in Fig. 1B is modified from de Cserna (1989), Ortega-Gutierrez et al. (1992), and Reed and Bush (2001).

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