Supporting Information for "Late-Cretaceous construction of the mantle lithosphere beneath the central California coast revealed by Crystal Knob xenoliths"

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Thermal modeling setup

In this section, we discuss parameters and techniques used in modeling. Standard values for thermal conductivity from *Fowler* [2005] yield good results. Increasing the thermal conductivity of the model domain substantially depresses the modeled geotherms (lowering predicted temperatures at a given depth), but does not affect the relative temperatures predicted by the geotherms. Radiogenic heat flow for the continental marginal crust is estimated conservatively, and changes result in only minor changes to modeled geotherms across the board.

Slab window crustal replacement

In model group **A**, we model shallow slab-window upwelling. The emplacement of slab-window asthenosphere directly under the coastal central California crust entails the truncation of a low-temperature forearc geotherm at the base of the crust and the substitution of an asthenospheric adiabat below this level. The model begins at 24 Ma, corresponding to the time of opening of the Mendocino slab window under southern California [*Wilson et al.*, 2005]. The geotherm begins as a steady-state profile to 600 °C at 30 km, truncated by a mantle adiabat. The mantle is held at asthenospheric conditions for a set period which is varied between model runs (from 0 to 6 Myr) to simulate a period of active convection, after which it relaxes conductively to the conclusion of the model.

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Subduction and underplating

Thermal conditions during subduction are tracked using the *Royden* [1993] steady-state forearc model. The samples then relax to the present. After subduction and underplating, the cooled oceanic lithosphere re-equilibrates with an overlying 30 km of forearc crust until the present, or for our xenolith samples until the time of ca. 1.7 Ma entrainment and eruption.

Progressive subduction of the downgoing slab beneath the forearc wedge is modeled as stepwise advection beneath a linearly thickening forearc wedge conforming to the *Royden* [1993] thermal model using the parameters outlined above. For all cases, the final depth of the underplated subduction interface is taken to be 30 km, and the distance landward of the subduction zone is taken to be 100 km. No effort is made to differentiate 'flat-slab' and baseline subduction geometries. Though increasing the slab dip angle will result in a cooler subduction interface at a given depth, the overall effect on the evolution of the thermal scenarios appears to be minimal.

Oceanic geotherm

For the Neogene stalled Monterey plate and Late Cretaceous Farallon mantle nappe scenarios, the Global Depth and Heat (GDH) model [*Stein and Stein*, 1992] is used to trace the thermal evolution of the oceanic lithosphere from its emplacement at the spreading ridge until subduction. This model is a Taylor-polynomial fit of cooling parameters to global heat-flow and depth datasets. This fit yields higher geotherms than half-space cooling models that are directly based on Equation 1 (e.g., *Fowler* [2005]), and tends to produce higher geotherms for old oceanic lithosphere.

With the GDH model in conjunction with the *Royden* [1993] subduction model, we predict low temperatures (~235-245 °C) at the subduction interface for the oldest stalled slabs modeled. For the Monterey Plate scenario (with young oceanic crust) the temperature at the subduction interface is predicted to be 980 °C.

All oceanic-cooling models, including GDH and half-space cooling models, significantly overestimate heat flux from young oceanic plates, a fact that is likely attributable to vigorous hydrothermal circulation in young submarine lithosphere [*Stein and Stein*, 1992; *Stein*, 1995]. This may result in overestimates of geothermal gradients for the scenarios with the youngest subducted oceanic crust, such as the Monterey Plate scenario at the left of Figure 20.

Supra-subduction geotherm

The geotherm of the forearc wedge during subduction is calculated using the *Royden* [1993] analytical solution for the steady-state thermal structure of continuously-subducting systems. Shear heating on the subduction thrust is ignored, as recent studies suggest that it is not an important factor [*Kidder et al.*, 2013]. Forearc rock uplift and erosion, as well as accretion and erosion on the subduction megathrust are ignored. In reality, megathrust accretion rates of 0.2-3.6 km/Myr are favored by *Kidder et al.* [2013] based on the Pelona schist, and some rock uplift is evident for the Coast Ranges.

The coastal California accretionary crust is represented homogenously as a material with a thermal conductivity of 2.71 W/m/K, specific heat capacity of 1000 J/kg/K, density of 2800 kg/m^3 and a radiogenic heat flux of 2 uW/m^3, values that are close to average for the continental crust [*Fowler*, 2005] and those used by *Kidder et al.* [2013] to model the thermal conditions along the Late Cretaceous shallow subduction megathrust segment. A radiogenic heat production in the crust of 2 uW/m^3 is actually a relatively conservative estimate given the fluxes shown for Sierra Nevada batholithic material by *Brady et al.* [2006], and the fact that much of the Franciscan material within the subduction channel is pelitic sediment rich in radiogenic elements [*Vilà et al.*, 2010]. Still, lower radiogenic heat production in the crust yields only a slight decrease in modeled geotherms across the board, not impacting conclusions.

Thermal model sensitivity and bias

Generally, changes in model parameters such as radiogenic heat flux, thermal conductivity, and heat capacity do not impact the relative results for modeled scenarios, due to the consistent lithologic structure of the model domains.

Due to widely varying timescale of equilibration for modeled scenarios in groups **B** and **C**, the model is sensitive to assumptions about steady-state cooling of the oceanic mantle lithosphere. The choice of the "GDH" model to track the evolution of the suboceanic thermal structure is an important control on the scale of temperature variation in Figure 20b. Though GDH is well-calibrated, oceanic cooling models tend to overestimate the heat flow from young oceanic plates [*Stein*, 1995]. Thus, the modeled geothermal gradients for the younger stalled slab model runs may be too high.

Another potential confounding factor affecting the older scenarios of **B** and **C** is the thermal effects of continued subduction beneath the underplated mantle nappes. After rollback and underplating of the modeled section of oceanic mantle lithosphere, a downgoing slab at depth could, depending on its age, cool the forearc lithosphere from below. However, this effect is considered minimal and diminishes over time due to the progressive subduction of younger, hotter oceanic lithosphere. Reconstruction of the Pacific–Farallon spreading ridge history show that, between ca. 70 and 30 Ma, oceanic lithosphere entering the southwest Cordilleran subduction zone got younger at a rate of ~1 Myr/Ma [*Atwater and Stock*, 1998; *Liu et al.*, 2010; *Seton et al.*, 2012] corresponding to the approach of the ridge to the subduction zone. This factor coupled with slab window emplacement starting at ca. 24 Ma leads to the interpretation that cooling from below by continued subduction was of second-order significance.

Surface erosion is not modeled, but may bias the results. Any erosion will yield higher apparent heat flows and increased geotherm convexity, as heat is advected from the top of the model domain by material removal [*Mancktelow and Grasemann*, 1997; *England and Molnar*, 1990]. Geologic constraints suggest that 15-20 km of exhumation is likely to have occurred in a major pulse of unroofing coincident with flat-slab underplating and rollback in the Cretaceous [*Saleeby*, 2003; *Chapman et al.*, 2012], and is thus likely to disproportionately affect the older models. The lack of erosion in the model framework biases towards predicting lower geothermal gradient overall. For the slab window and underplated Monterey plate scenarios (model groups **A** and **B**) this effect would push the final geotherm to or beyond the limit of xenolith thermobarometry [Figure 21a and b]. In the underplated mantle nappe scenario (model **C**) this effect would push the final modeled geotherm towards the centroid of the xenolith thermobarometric array [Figure 21c and 22].

The uncertainties inherent in this model bias the results towards predicting lower-temperature, less-convex geotherms over the model domain. These potential biases affect comparisons comparisons with measured values of heat flux and xenolith thermobarometry, which are not subject to these biases [Figure 22]. Thus, geotherms predicted by this model might be underestimates for potential mantle temperature at a given depth, especially for the older tectonic scenarios modeled.

Factors not incorporated in the model

Several simplifications are made to create an internally consistent model framework. Subducted oceanic crust is not considered to have distinct thermal properties from the oceanic mantle. Additionally, though there are no reliable estimates of the mantle heat flux that cover the model domain, the model is run to great depth to avoid any influence of this uncertainty on the surface geotherm.

Subduction zone rollback

The confounding factor of an active subduction zone just outboard of the scenarios for the older models is also not included within the model. When the trench interface jumps with the emplacement of an oceanic mantle nappe beneath the forearc, the new subduction interface will cool the detached nappe from below. This is not modeled because it would substantially increase model complexity (requiring a fully iterative approach to the forearc geotherm), and at this distance (~100 km) inboard of the final trench interface, there is limited scope for further episodic rollback after emplacement of the nappe(s) of presumed xenolith source [e.g. Figure 18c]. Further, although an active subduction interface at depth will cool the mantle lithosphere from below, the subduction of progressively younger crust until cessation at ~27 Ma will yield gradually increasing heat on the subduction interface [*Royden*, 1993]. The models for scenarios **B** and **C** [Figure 22b and c] are already near the coolest permitted by our xenolith constraints. As these geotherms are already quite cold, introducing this added complexity will not significantly change the model results. However, late-Cretaceous underplating and other stalled-slab scenarios can be treated as maximum temperatures because of the influence of the subducting slab.

Change in convergence rate of rotating microplates

Potential Monterey Plate mantle lithosphere beneath Crystal Knob would have been emplaced under the ridge at 27 Ma (corresponding to the chron 7 magnetic anomaly) and subducted shortly thereafter [*Atwater and Stock*, 1998; *Wilson et al.*, 2005]. Due to slower margin-normal convergence during microplate fragmentation and rotation [*Wilson et al.*, 2005], the parcel would take ~3 Myr to reach its final stalled position (~100 km behind the trench) as shown in Figure 18b. This is responsible for the kink in the “Age of initial oceanic lithosphere” curve in Figure 20b. For model simplicity, we do not incorporate this disequilibrium shift into the starting parameters of the *Royden* [1993] subduction model.

Erosion of the forearc

Surface erosion after underplating is taken to be zero. Any erosion will result in higher apparent heat flow values and increased geotherm convexity, as heat is advected from the top of the model domain by material removal. Geologic constraints suggest that the majority of erosion to the mid-crustal levels now at the surface in Salinia is likely to have occurred in a major pulse of unroofing coincident with flat-slab underplating and rollback [*Saleeby*, 2003; *Chapman et al.*, 2012], and is thus likely to disproportionately affect the older models. The 30 km of crust shown in the study area is based on modern estimates of the Moho depth, so recent erosion is unlikely to have biased the whole-lithosphere geotherm significantly. Still, the lack of erosion in the model framework will likely bias the results towards predicting a lower geothermal gradient overall, and lower temperatures in the mantle lithosphere, as upward advection of material by erosion increases the geothermal gradient [*Mancktelow and Grasemann*, 1997; *England and Molnar*, 1990]. Thus, these values need to be biased to higher temperatures to accurately capture the relationship between xenolith constraints on the actual temperature and temperatures derived from this modeling.