Rapid exhumation of the Rand schist: constraints from natural garnet diffusion couples

Alan D. Chapman, Jason B. Saleeby, and Peter I. Luffi

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA

1 INTRODUCTION

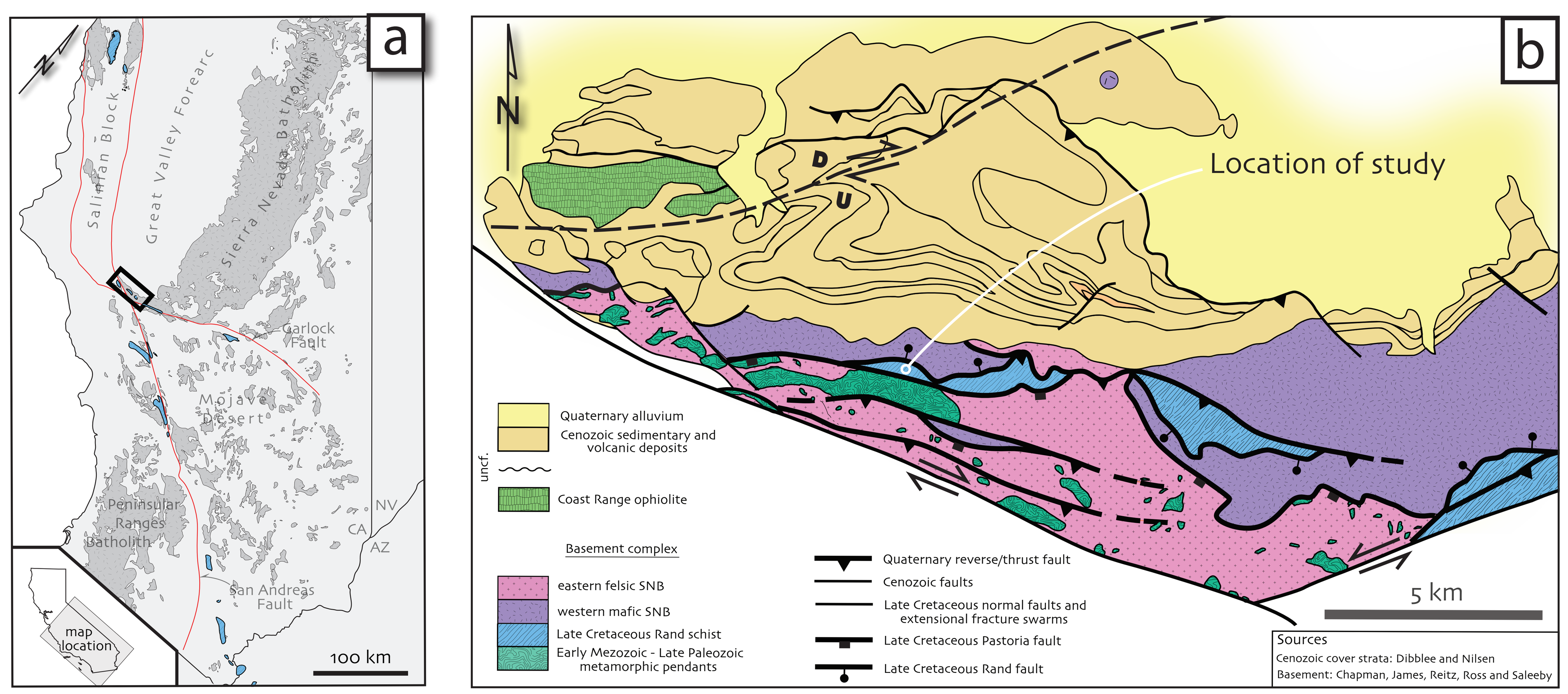
Field photograph showing characteristic texture of the Rand schist of the San Emigdio Mountains

Intensive study of the Rand schist (hereafter referred to as the "schist") of southern California demonstrate convincingly that it formed in the Late Cretaceous by subduction of Cordilleran eugeoclinal detritus along a shallow dipping segment of the Farallon plate. Comparatively little is known about the exhumation history of the schist. Recent thermochronologic and thermobarometric analyses suggest that, in some localities, the schist was deposited, underplated beneath western Sierra Nevada batholithic assemblages (the "upper plate"), and exhumed with them from 30 – 40 km depths in less than 3 million years. Such a rapid cycling interval implies exhumation rates in excess of 5 mm/yr.

To corroborate these existing data on the exhumation rate of the schist, we exploit diffusional annealing of garnet zonation. Some garnets from the schist of the San Emigdio Mountains were broken during late stages of their growth. Overgrowth along broken margins resulted in natural diffusion couples ~ 25 μm inward from the rims, where peak metamorphic temperatures reached 610 °C. A maximum time interval, representing exhumation prior to diffusion cessation, of 1 Ma was estimated from the degree of annealing of the originally sharp compositional step. Similar time intervals were calculated from narrow (10 μm) retrograde zones at the rims of compositionally homogenized garnets belonging to the upper plate. Garnets from the schist conspicuously lack retrograde zonation patterns, likely due to exhumation rates exceeding those of retrograde diffusion.

Both garnet-based geospeedometry and thermochronometric studies indicate that the schist was exhumed at rates comparable to lateral tectonic plate motions (> 5 mm/yr). This conclusion, in the context of field-based analyses suggestive of west-directed ductile transport of the schist relative to the upper plate during exhumation, reveals a profound Late Cretaceous extensional event. These results yield important insight into the timing of Late Cretaceous schist ascent, in addition to the mechanisms necessary for such a rapid process.

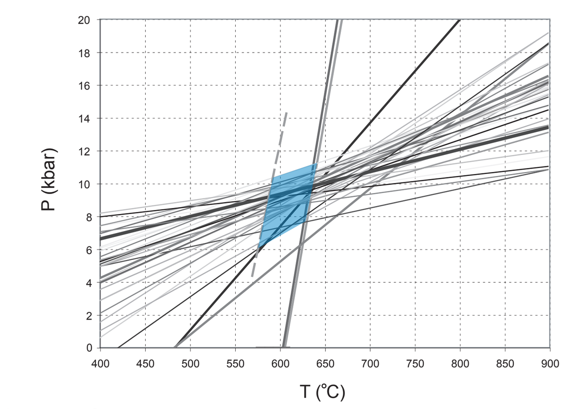
2 GEOLOGY OF THE SAN EMIGDIO MOUNTAINS



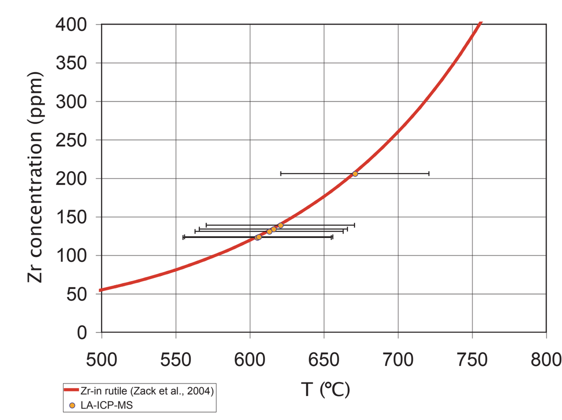
The Pelona, Orocopia, and Rand (POR) schists (shown in blue) are best described as high pressure-intermediate to high temperature rocks that underlie North American continental basement along brittle to ductile detachment faults. (a) Map of Late Cretaceous to Early Tertiary POR schist distribution throughout southern California and adjacent areas. Cretaceous and older batholithic and metamorphic rocks are shown in gray with pattern, redrawn after Kidder and Ducea (2006) (b) Geologic map of the crystalline basement of the San Emigdio Mountains.

3 THERMOBAROMETRY

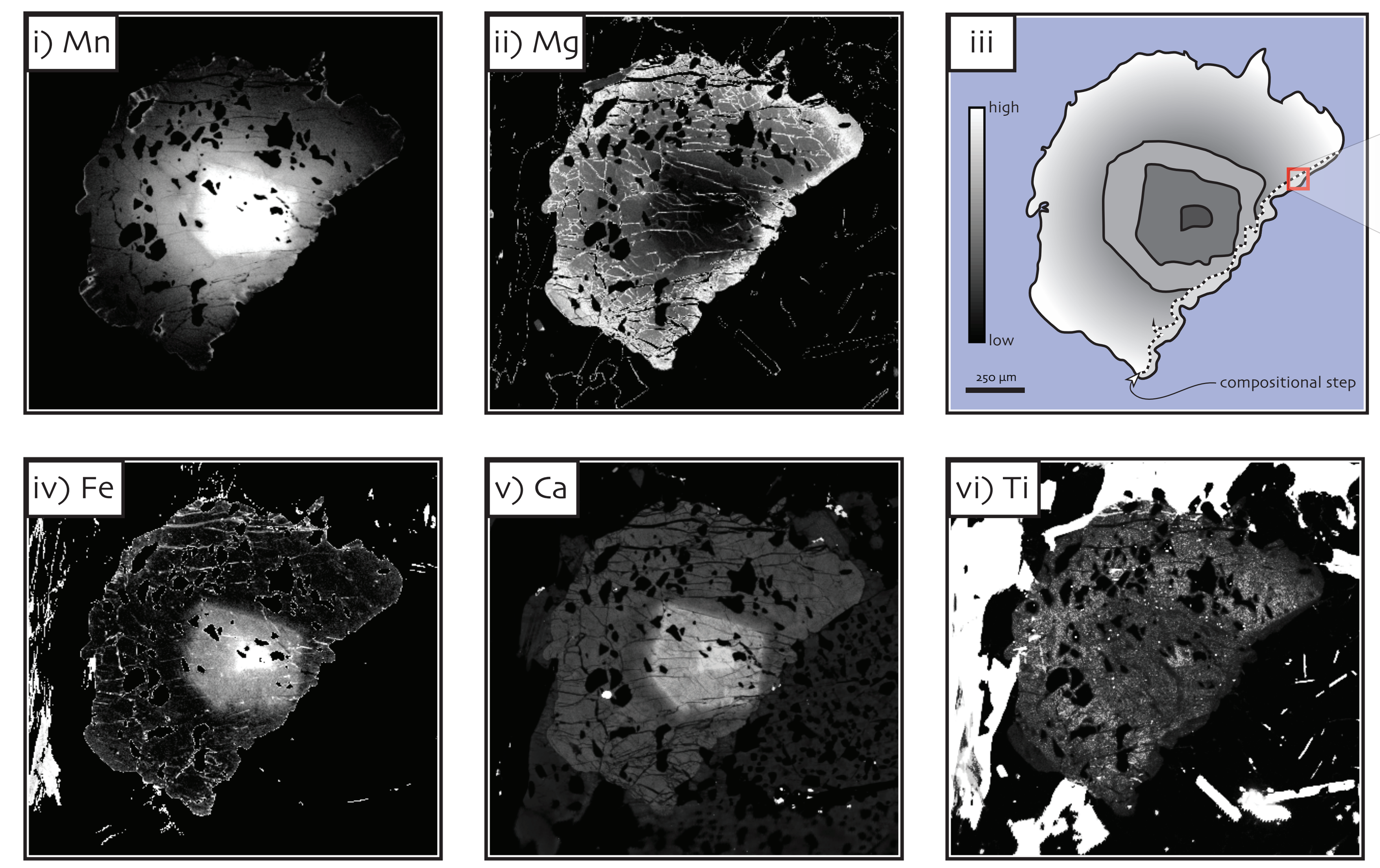
Calculations based on muscovite - biotite - plagioclase - garnet geobarometry and garnet - biotite geothermometry yield peak P-T conditions of 9 kbar and 600 ˚C.



Zr-in-rutile thermometry supports peak temperatures of ~ 610 ˚C experienced by the schist.



4 GARNET ZONING



X-ray compositional maps of a broken garnet from sample 06SE23. Light colors in X-ray images represent relatively high concentration with white for the highest and black for the lowest. Scale is stretched to enhance features. (iii) Schematic diagram showing major garnet zones and the location of the detailed map in section 6. (i, ii; iv-vi) Major and trace element maps. Note that the compositional step delineated in (iii) is present in Mn, Ca, and Ti, whereas it is lacking in Fe and Mg. Also note the cracking-related sharp compositional step preserved in Ti. The same boundary is more diffuse in Mn and Mg.

5 EBDC MODELLING

Concept: Effective Binary Diffusion Coefficient

Reduces multicomponent (Ca, Fe, Mg, Mn) diffusion in garnet to a pseudobinary system.

Diffusion of an individual species (e.g. Mn) can be characterized by a single coefficient:

$$D_{Mn(EB)} = D_{MnMn} + D_{MnMg}\, \partial C_{Mg}/\partial C_{Mn} + D_{MnFe}\, \partial C_{Fe}/\partial C_{Mn}$$

difference between [Mn] on both sides of the diffusion couple

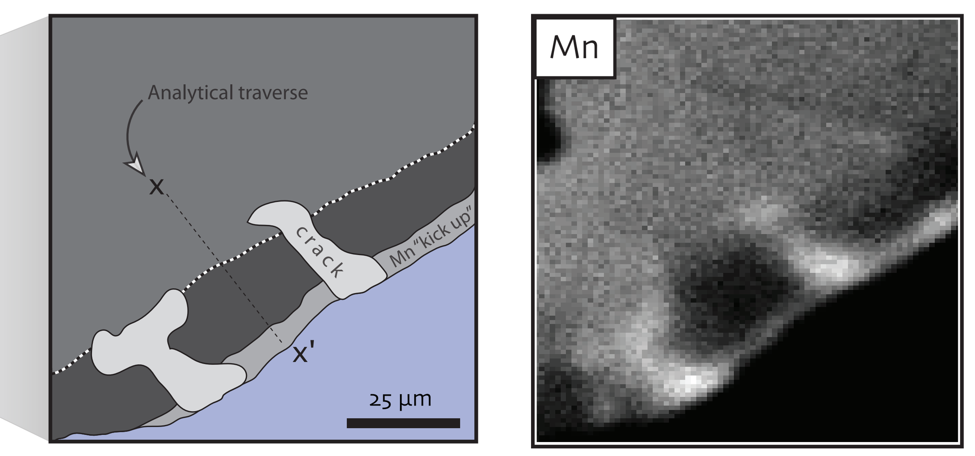
$$C_i(t,x) = C_{Mn}(0) + C^0_{Mn}/2\,[1 - \mathrm{erf}(x(\sqrt{4D_{Mn(EB)}}t))]$$

lower of two initial [Mn]

distance

time

6 RESULTS



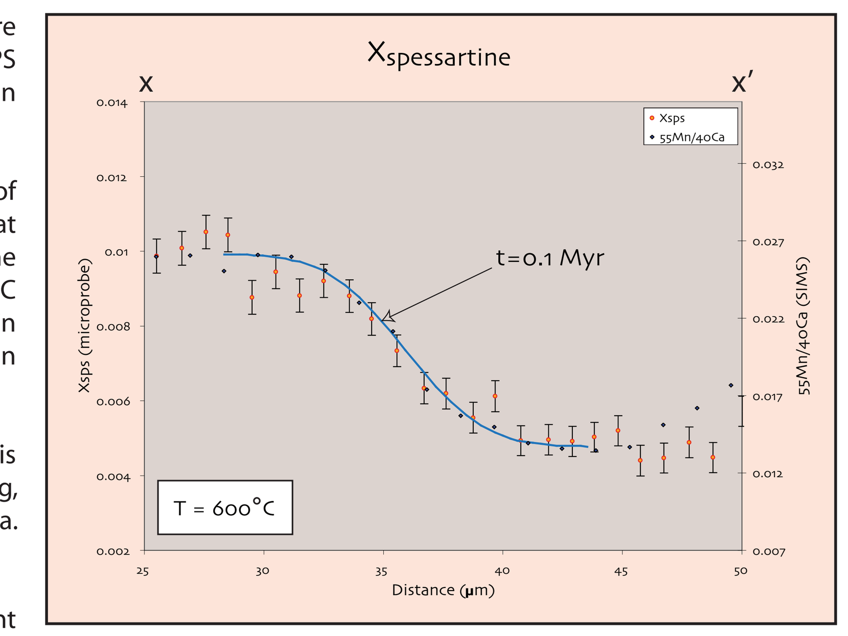
Compositional profiles were collected with Caltech: GPS Division JEOL JXA-8200 electron microprobe and Ion Microprobe.

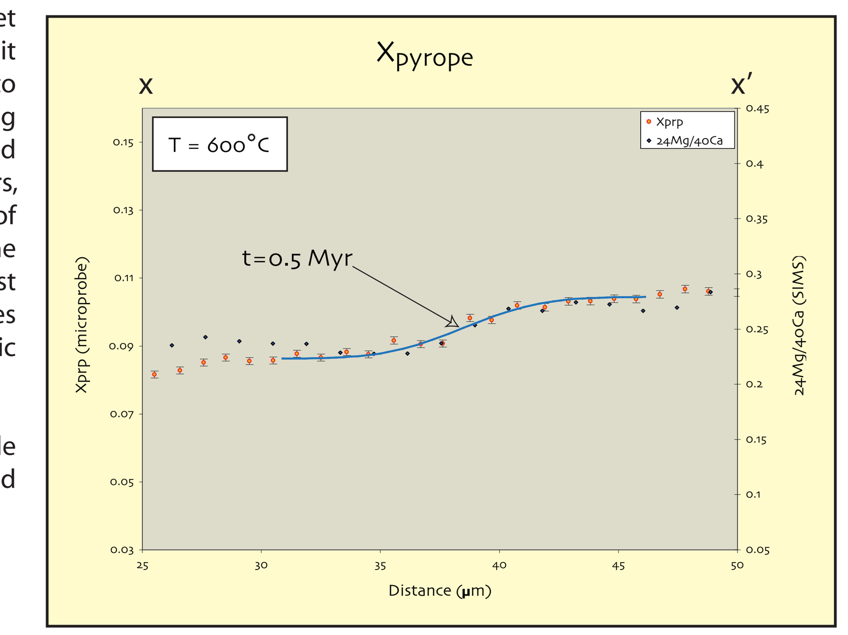
Assuming peak conditions of 600 ˚C / 9 kbar, and that compositional steps across the crack were originally sharp, EBDC modelling of thermal relaxation in Mn yields a time scale of diffusion of ca. 100,000 years.

This compositional step in Mn is being compensated mostly by Mg, which gives a diffusion time of ca. 500,000 years.

Calculated time intervals represent the time necessary to cool garnet from peak conditions to where it becomes effectively frozen to diffusion at around 450 ˚C. Using the longest time interval calculated from Mg profiles of 500,000 years, this represents a cooling rate of ~300 ˚C/Myr. This implies that the onset of exhumation in the schist was quite rapid, with rates comparable to lateral tectonic plate motions (> 5 mm/yr).

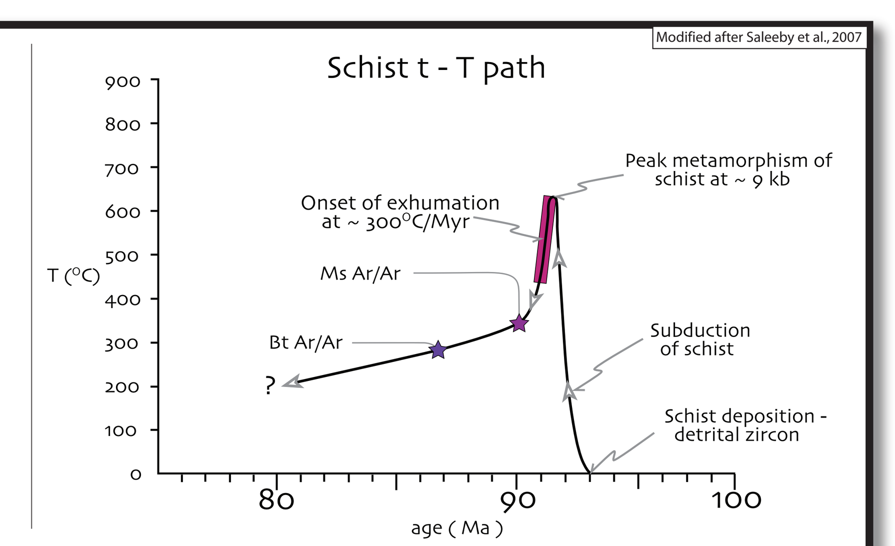
Preliminary results from retrograde rims of upper plate garnets yield remarkably similar data.





7 CONCLUSIONS

- These data corroborate and supplement the existing thermochronologic data of Saleeby et al., 2007 (see diagram at right) and require, in this context, that between 600 - 450 ˚C, cooling rates in the schist reached or exceeded 300 ˚C/Myr and exhumation rates rivaled lateral plate tectonic velocities.
- Garnets from upper plate pendant rocks yield similarly short time intervals of diffusion, suggesting a similar, or common, exhumation history as that of the schist.
- This study documents the birth of the Rand Fault, a crustal-scale extensional structure that crops out in the San Emigdio, Tehachapi, and Rand Mountains and was active from at least 30 km depth until well into the brittle regime. It is thought to have accomodated the majority of schist exhumation-related deformation.
- Brittle failure of garnet at or prior to peak metamorphic conditions in the schist would require exceptionally high critical resolved shear stress. One possibility is that these garnets were broken during subduction-related earthquakes, providing evidence of Cretaceous Farallon - North America shearing.



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