Refrigeration of the western Cordilleran lithosphere during Laramide shallow-angle subduction

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ABSTRACT

The Laramide orogeny has generally been attributed to a shift from normal-angle to shallow-angle subduction beneath the western margin of the North American plate. In addition to important mechanical effects, this shift may have had important thermal effects on the lithosphere in the western Cordillera. Before the Laramide, geothermal gradients in the western Cordillera were probably normal to high because of the presence below of a hot asthenospheric wedge. With the shift to shallow subduction, the wedge was probably expelled and replaced by a cold subducting slab that extended just below the Cordilleran lithosphere. This would shift the western Cordillera into a cold, forearc-like thermal setting dominated by the refrigeration effects of the subducting slab. Thermochronologic data from the Sierra Nevada, Great Basin, Mojave Desert, western Arizona, and perhaps the Colorado Plateau record latest Cretaceous–early Tertiary cooling that may be evidence of such refrigeration. If regional refrigeration occurred, it would have several important implications: (1) metamorphism in the western Cordillera would have waned with the start of the Laramide orogeny; (2) the crust in the western Cordillera would have strengthened and become much more resistant to deformation (e.g., gravitational collapse and extension of thickened crust in the Sevier hinterland would have been impeded); and (3) latest Cretaceous–early Tertiary isotopic cooling ages may not be valid indicators of a period of major regional uplift and unroofing.

INTRODUCTION

The latest Cretaceous to early Tertiary (ca. 75–45 Ma) Laramide orogeny involved a major shift in the location of magmatism and deformation in the central and southern parts of the U.S. Cordillera. Before the Laramide, a subduction-related magmatic arc was located close to the North American plate margin in the Sierra Nevada, and back-arc deformation was concentrated in the Sevier fold-thrust belt and Sevier hinterland (Fig. 1). At 80 Ma, magmatism stopped in the Sierra and deformation and magmatism began to migrate as much as 1000 km east into the interior of the North American plate. This migration into the plate interior has generally been attributed to a shift from normal-angle to shallow-angle subduction beneath the western margin of the North American plate (Fig. 2) (e.g., Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Bird, 1988). With the shallowing, the subducting slab no longer penetrated into the asthenosphere beneath the Sierra Nevada, causing magmatism to wane and shift inland. Coupling of the top of the slab with the base of the Cordilleran lithosphere caused deformation far in the North American interior.

The thesis of this paper is that the postulated shift from normal to shallow subduction probably also had major thermal effects on parts of the Cordilleran lithosphere (cf. Henry and Pollack, 1988; Dumitru, 1990). During pre-Laramide normal subduction, the Sierra Nevada resided in an arc position and the Cordillera east of the Sierra resided in a back-arc position. Geothermal gradients in these settings were probably moderate to high. With the shift to shallow subduction, the western Cordillera should have developed a much colder, fore-arc–like thermal structure where no hot asthenospheric wedge was present, but rather the lithosphere was refrigerated by the underlying cold subducting slab (Fig. 2). Such a shift from a warm to a cold lithosphere would have very important consequences for rheology and metamorphic conditions in the western Cordillera.

MECHANICS OF REFRIGERATION

Heat flows and thermal gradients are high in magmatic arcs such as the pre-Laramide Sierra Nevada because of the transfer of heat upward from the underlying asthenospheric wedge (Fig. 2). Surface heat-flow data and mineral assemblages in metamorphic country rocks suggest that regional thermal gradients in arcs are moderately high but not extreme, in the general range 25–50 °C/km (e.g., Barton and Hanson, 1989, p. 1055, and references therein). Gradients are higher near active centers of magmatism, but this is a local, ephemeral situation. Backarc areas similarly have moderate to high thermal gradients (e.g., Henry and Pollack, 1988).

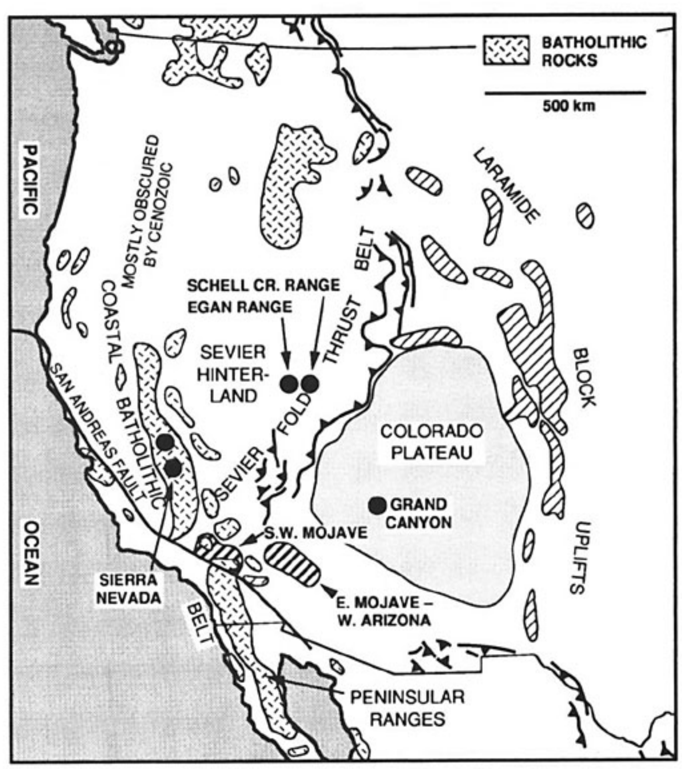

Figure 1. Map showing areas of pre-Laramide arc magmatism (Sierra Nevada and Peninsular Ranges) and deformation (Sevier fold-thrust belt and hinterland), areas of Laramide deformation, and locations where thermochronologic data record cooling around beginning of Laramide orogeny (modified from Haxel et al., 1984).

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Again, the presence of a hot asthenospheric wedge beneath the area is the ultimate controlling factor.

In contrast, thermal gradients in fore-arc areas are commonly low because the subducting slab is much colder than the asthenospheric material that would otherwise reside beneath the fore arc. One notable consequence of the low gradients is the common development of blueschist facies metamorphic rocks, which indicates gradients lower than about 15–20 °C/km. In California, the Franciscan accretionary prism and Great Valley fore-arc basin accumulated in a fore-arc setting, and Early Cretaceous to early Tertiary gradients in these units were ~7–13 °C/km (summarized in Dumitru, 1991). If the Laramide shallowing of subduction expelled the asthenospheric wedge from beneath the Cordillera, the Cordillera should have developed the thermal characteristics of a very wide fore arc (Fig. 2).

The timing of the shift to shallow-angle subduction can be inferred from magmatic and deformational ages in the Cordillera. Plutons emplaced between 120 and 80 Ma form the bulk of the Sierra Nevada batholith (Chen and Moore, 1982), indicating that the Sierra was the site of a subduction-related magmatic arc during that time. Magmatism in the Sierra ceased at 80 Ma; this suggests that the shift to shallow subduction started at about that time. Classic Laramide deformation in the interior of the North American plate occurred 75 to 45 Ma (Fig. 1) (e.g., Dickinson et al., 1988); this suggests that sufficient shallowing had occurred in some areas by ca. 75–70 Ma to bring the top of the subducting slab into contact with the base of the lithosphere in the North American interior.

There would be an important time lag between the shift of shallow subduction and cooling of shallow levels in the crust because of the time needed for heat to conduct through the lithosphere. For example, the beginning of substantial cooling in the Sierra Nevada, as inferred from fission-track data, lagged 5–10 m.y. behind the 80 Ma cessation of magmatism, and then took about another 10 m.y. to complete (see below). Calculations show that the time for thermal equilibration to the new conditions of shallow subduction is proportional to the square of the thickness of the lithosphere above the top of the subducting slab (Fig. 3). If isotopic ages (fission-track, K-Ar, $^{40}Ar/^{39}Ar$) record shallow-subduction–induced lithospheric cooling, they would lag behind the shift to shallow subduction by several million to many tens of million years, depending mainly on the depth to the top of the subducting slab in the area of interest (see Bird, 1988, for a discussion of controls on these depths). Where the lithosphere was thick, ⩾100 km, cooling at shallow levels would probably be so slow as to leave no clear signature in isotopic ages (e.g., C in Fig. 3). Cooling ages would also be influenced by the time of establishment of shallow subduction, the depths of the rocks at that time, and the closure temperatures of the isotopic systems (e.g., Dumitru, 1990). Therefore, cooling ages reflecting the shift to shallow subduction might range from about 80 Ma to middle Tertiary.

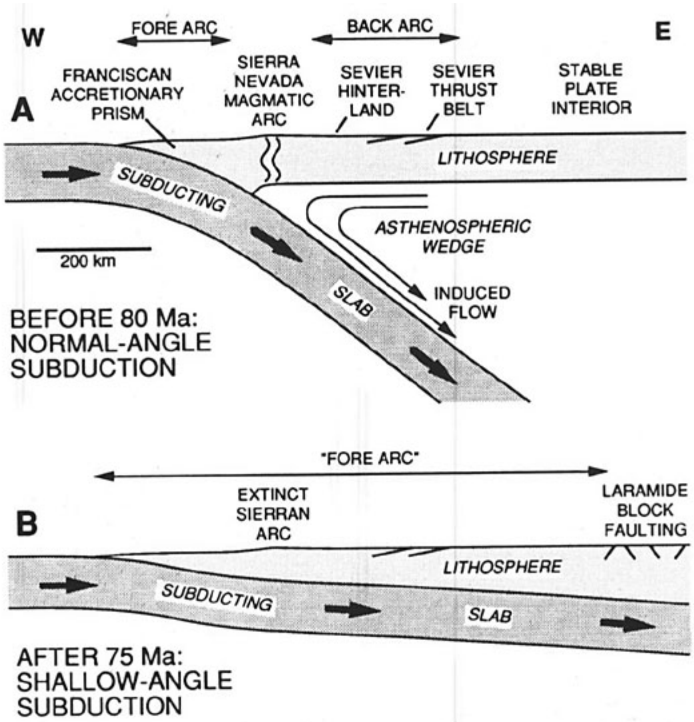

Figure 2. Cross sections showing postulated shallowing of subduction during Laramide orogeny. Before Laramide, asthenospheric wedge was present beneath Sierra Nevada and areas to east, causing moderate to high geothermal gradients. With shift to subhorizontal subduction, wedge was expelled and thermal regime of Cordilleran lithosphere came to be dominated by refrigeration effects of cold subducting slab.

Favorable circumstances would be needed to preserve evidence of Laramide refrigeration. Much of the western Cordillera was affected by Basin and Range extension in post-Laramide time with attendant high thermal gradients, volcanism, and deformation. The higher temperatures would reset isotopic systems unless earlier uplift and unroofing had brought these rocks to shallower levels. Therefore, evidence of refrigeration should be fragmentary. Below we summarize several areas that may retain evidence of Laramide refrigeration (Fig. 4).

EVIDENCE FOR REFRIGERATION

Sierra Nevada

Arc magmatism in the Sierra Nevada ceased at 80 Ma (Chen and Moore, 1982). Biotite K-Ar ages of most currently exposed plutons in the Sierra are older than 80 Ma, indicating that most areas cooled below ~350 °C before regional magmatism stopped. Sphene and apatite fission-track data indicate that rocks currently exposed in canyon walls in the central Sierra (Yosemite Valley and Kings River Canyon) cooled below 270 ±50 °C at ca. 72 Ma, cooled below 95 °C at ca. 67 Ma, and then continued to cool to 60 °C or colder (Fig. 4). This suggests that thermal gradients in the Sierra remained relatively high (~50 °C/km) for 5–10 m.y. after the cessation of arc magmatism at 80 Ma, and then decreased to about one-fifth or less of previous values over about the next 10 m.y. (discussed in detail in Dumitru, 1990). Variations in fission-track lengths with sample elevation suggest that Tertiary gradients were in the range 5–15 °C/km, similar to gradients in the more typical fore-arc areas to the west (Francis-

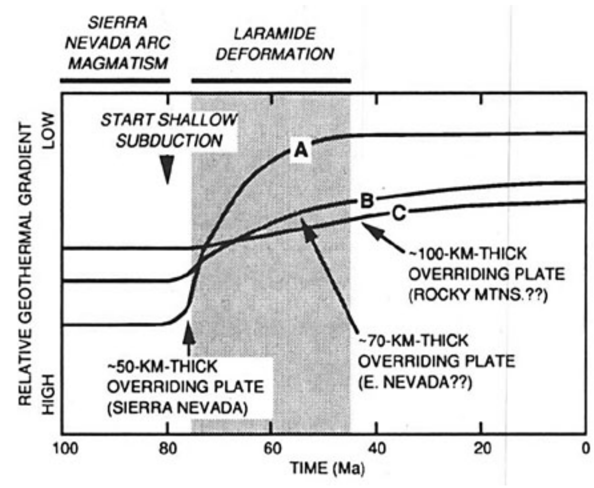

Figure 3. Schematic near-surface lithospheric cooling curves (A, B, and C) for different parts of Cordillera illustrate effect of thickness of overriding lithosphere on time scale of cooling (extrapolated from modeling results of Dumitru, 1990, Figs. 6, 7, and 8). Curves are also drawn to suggest that gradients during refrigeration were lower nearer plate margin, as suggested by comparison of Sierra Nevada and eastern Nevada data, but this is a tentative inference. Reheating after shallow subduction stopped in middle(?) Cenozoic is ignored.

can accretionary prism and Great Valley fore-arc basin). Thermal modeling suggests that the top of the subducting slab must have risen to a depth of 35–60 km beneath the Sierra to produce the observed time lag of cooling. This is much less than the likely 120 km depth during pre-Laramide arc magmatism and thus supports the shallow-subduction model (Dumitru, 1990; see also Bird, 1988).

The evidence for Laramide cooling is especially distinct in the Sierra Nevada because pre-Laramide gradients were particularly high due to regional arc magmatism, whereas Laramide gradients were apparently particularly low (A in Fig. 3). Furthermore, the Sierra has not undergone the elevated Cenozoic thermal gradients that affected the Basin and Range region of the Cordillera.

Great Basin

Cenozoic fault blocks in the east-central Basin and Range province expose tilted stratigraphic or crustal sections as thick as 15 km, offering a unique opportunity for establishing the thermal history of rocks at known depths prior to extensional faulting. Geochronologic and structural data summarized by Gans and Miller (1983) and Miller and Gans (1989) indicate that peak temperatures in virtually all the exposed sections were reached in the Late Cretaceous (ca. 90–75 Ma), while the Paleozoic miogeoclinal succession was approximately flat lying. Because upper Eocene to Oligocene sedimentary and volcanic rocks were deposited only on the upper part of this succession (generally with little angular discordance) and, more important, on rocks that have never been hotter than 50–80 °C (conodont alteration indices of 1–1.5), pre-Oligocene uplift and erosion must have been minor. Preliminary thermochronologic data from the deeper parts of the succession indicate pronounced cooling throughout the area during the latest Cretaceous and early Tertiary (74–45 Ma); in light of the structural arguments above, this must reflect a lowering of thermal gradients at that time. For example, rocks from the deepest structural levels in the Schell Creek Range (paleodepths of 10–12 km) yield muscovite and biotite $^{40}Ar/^{39}Ar$ ages of 63 and 55 Ma and a zircon fission-track age of ~52 Ma, indicating cooling from ~450 to <~230 °C and a lowering of the upper crustal gradient from >40 to ~20 °C/km (Fig. 4). At higher structural levels (paleodepths of ~6–8 km) in the Schell Creek, Egan, and southern Snake ranges, detrital microcline consistently yields $^{40}Ar/^{39}Ar$ age spectra indicative of slow cooling from ~250–300 °C to ~150 °C over the period 80 to 40 Ma. This also suggests that thermal gradients decreased from ~40 to ~20 °C/km. Subsequent Cenozoic extensional faulting starting as early as Oligocene preserved the evidence of these gradients in the upended parts of large tilt blocks. The low early Tertiary temperatures inferred for deep-seated rocks help to explain another observation from this region. Late Eocene to early Oligocene granites that intruded at depths of 7–10 km in the Egan, Schell Creek, and Deep Creek ranges are typically hypabyssal in appearance; they have strongly quenched (locally glassy) margins and very narrow (hornfelsic) contact-metamorphic aureoles (Gans and Miller, 1983). These relations contrast strongly with the more mesozonal appearance of Mesozoic plutons in the same areas, despite their similar compositions and emplacement depths, suggesting that mid-crustal temperatures in the early Tertiary were substantially lower than in the Mesozoic.

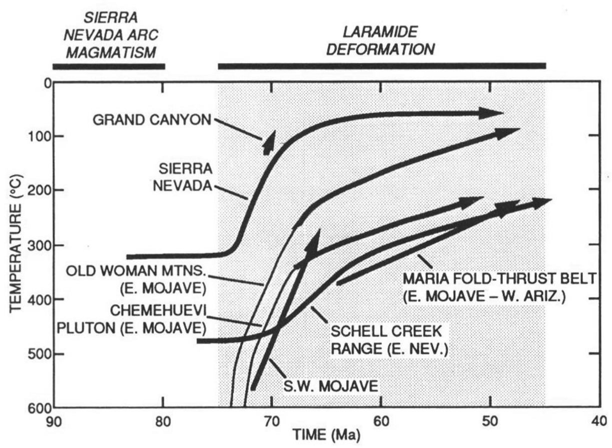

Figure 4. Schematic temperature-time plots for various locations in Cordillera based on K-Ar, $^{40}Ar/^{39}Ar$, fission-track, and other data, showing cooling around beginning of Laramide orogeny. Cooling shown by heavy lines is attributed to subduction-induced refrigeration. Early cooling in eastern Mojave Desert shown by fine lines is attributed to initial cooling of plutons and movement on western Old Woman Mountains shear zone rather than refrigeration.

Mojave Desert and Western Arizona

Hornblende and biotite from an area ~50 by 150 km in the southwestern Mojave Desert and San Bernardino Mountains have nearly concordant K-Ar ages that cluster between 75 and 65 Ma. These ages are generally substantially younger than igneous emplacement ages and are evidence of latest Cretaceous cooling from above ~530 °C to below ~330 °C. Most ages in the San Gabriel Mountains are similar, even though this area is west of the San Andreas fault and so formerly was farther south (Miller and Morton, 1980). Most $^{40}Ar/^{39}Ar$ ages from the Pelona schist and related rocks are 75–48 Ma, indicative of the same general time of cooling (Jacobson, 1990).

In the eastern Mojave Desert and western Arizona, $^{40}Ar/^{39}Ar$ data suggest somewhat later regional cooling between ca. 65 and 50 Ma. Rocks in the Maria fold-thrust belt that were not overprinted by mid-Tertiary heating retain evidence of cooling from >350–400 °C at ca. 65 Ma to <200 °C by ca. 45 Ma (Knapp and Heizler, 1990; Richard et al., 1990). Areas of the western Chemehuevi Mountains that did not undergo major Tertiary overprinting cooled from >330 to <220 °C between 65 and 55 Ma (Foster et al., 1990). Apatite fission-track ages from rocks that were in the upper crust during Late Cretaceous time in the Marble, Clipper, Ship, and Turtle mountains are 66–62 Ma, suggesting a similar time of cooling (Foster et al., 1991).

The Old Woman Mountains in the eastern Mojave Desert apparently retain evidence of both a local Late Cretaceous unroofing event and subsequent regional crustal refrigeration (e.g., Foster et al., 1991). In this area, plutons were emplaced at depths of ~15 km at 73 Ma. $^{40}Ar/^{39}Ar$ and fission-track data indicate that after the plutons initially cooled to below 350 °C during thermal equilibration with the country rocks, they continued to cool at a rate >30 °C/m.y. until ca. 68 Ma, then at a rate of 10–30 °C/m.y. until well after 60 Ma. The rapid cooling before ~68 Ma probably reflects cooling during uplift along the western Old Woman Mountains shear zone, which was active at this time. The slower cooling after ~68 Ma, in some areas continuing to below 100 °C, is very similar to the cooling seen elsewhere in the eastern Mojave Desert and probably reflects refrigeration.

No major latest Cretaceous normal faults are known in the area of 75–65 Ma K-Ar ages in the southwestern Mojave Desert. Aside from the Old Woman Mountains, latest Cretaceous–early Tertiary extension has not been identified in the eastern Mojave Desert and western Arizona, but latest Cretaceous–early Tertiary cooling there has generally been attributed to uplift (e.g., John and Mukasa, 1990). We think it is a reasonable alternative that the regional cooling in these areas resulted from reduced thermal gradients rather than great uplift and unroofing. Most of the reduction in thermal gradients apparently occurred ca. 75–65 Ma in the southwestern Mojave and ca. 65–50 Ma farther east in the eastern Mojave and western Arizona.

Colorado Plateau

Apatite fission-track data from the Colorado Plateau at the Grand Canyon indicate cooling at ca. 70 Ma (Naeser et al., 1989). Rocks at the bottom of the canyon near Phantom Ranch were probably around 130 °C before this time and cooled at least 40 °C. This is a relatively small amount of cooling, and it is quite reasonable that it resulted from uplift and unroofing during Laramide folding of the familiar Colorado Plateau monoclines. However, given the coincidence in time of cooling with the predictions of the shallow-subduction model, refrigeration should be considered an alternate possibility.

DISCUSSION

There are good theoretical grounds to suggest that the Laramide shift to shallow subduction should have caused widespread refrigeration of the lithosphere in the western Cordillera (Fig. 2). The thermal-history data from the Sierra Nevada strongly suggest refrigeration, and the data from the other areas, though not so definitive, are certainly suggestive of a regional refrigeration event. We reiterate that the rate of cooling is controlled mainly by the thickness of the Cordilleran lithosphere above the top of the shallowly subducting slab. Where the lithosphere was thicker than ~100 km (perhaps in the Rocky Mountains?), cooling may have been so slow at shallow levels as to have left no clear signature in isotopic ages (C in Fig. 3).

If refrigeration did occur, it would have important consequences for metamorphism in the western Cordillera. Available metamorphic data from the Great Basin suggest that the Laramide was a time of waning metamorphism (e.g., Snoke and Miller, 1988, Fig. 23-10; Miller et al., 1988), as would be expected if thermal gradients decreased. Refrigeration would also have important consequences for lithospheric rheology, causing pronounced strengthening and impeding deformation. Several authors have suggested that Mesozoic crustal thickening during the Sevier orogeny was followed by a period of gradual crustal heating and weakening that ultimately led to gravitational collapse and Basin and Range extension (e.g., Glazner and Bartley, 1985; Sonder et al., 1987). Refrigeration during the Laramide would interfere severely with such a gradual heating process. In contrast, Gans et al. (1989) argued that the onset of major Basin and Range extension was caused by a new (post-Laramide) pulse of voluminous mantle-derived magmatism that rapidly heated and weakened the lithosphere, a model more compatible with an abnormally cold lithosphere during the Laramide.

This model of low Laramide gradients also has obvious implications for the interpretation of isotopic cooling ages from the Cordillera. Cooling ages are usually interpreted as dating uplift and unroofing events. Aside from the Old Woman Mountains, however, no large normal-fault systems to accommodate major Laramide-age uplift have been identified in the areas we have discussed. Rather than uplift and unroofing, many latest Cretaceous–early Tertiary cooling ages in the western Cordillera probably reflect decreased thermal gradients, obviating the need to postulate a period of major regional uplift, erosion, and/or tectonic denudation.

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