TECTONICS, VOL. 19, NO. 2, PAGES 197-212 APRIL 2000

Thermal evolution of Monte Blanco dome: Low-angle normal faulting during Gulf of California rifting and late Eocene denudation of the eastern Peninsular Ranges

Gary J. Axen,[1] Marty Grove,[1] Daniel Stockli,[2] Oscar M. Lovera,[1] David A. Rothstein,[1]
John M. Fletcher,[3] Kenneth Farley,[4] and Patrick L. Abbott[5]

Abstract. Footwall rocks of the Cañada David detachment fault, northeastern Baja California, record late Eocene-earliest Oligocene and late Neogene cooling events previously unrecognized in the region. Biotite $^{40}Ar/^{39}Ar$ ages of ~65 Ma reflect slow cooling through ~350°C, 5 to 10 m.y. later than is typical in the region. Multiple diffusion domain modeling of K feldspar $^{40}Ar/^{39}Ar$ release spectra shows very slow cooling (~1°C/m.y.) from ~65 to ~45 Ma. Accelerated cooling from ~315°C to ~215°C between ~45 and ~33 Ma records at least 3-4 km of denudation that we relate to east-side-up reactivation of late Cretaceous structures that generally follow the oceanic-continental suture. Previously established rivers flowing west from mainland Mexico apparently became further entrenched during this uplift and continued to supply distinctive rhyolitic detritus to the coast. Ultimately, surface uplift disrupted and rerouted the extraregional rivers some 2 to 6 m.y. before the cooling event ended. Footwall rocks remained nearly isothermal from ~30 to ~15-10 Ma, when renewed rapid cooling (33° ± 17°C/m.y.) began in response to footwall exhumation by top-to-the-west low-angle normal faulting that accommodated rift-related extension in what finally became the Gulf of California. Apatite fission track and (U-Th)/He ages of ~5 Ma and ~4 Ma, respectively, record final detachment-related cooling through ~110°C to ~70°C. Thermal-kinematic modeling suggests that 5-7 km of late Neogene tectonic denudation and 10-12 km of horizontal extension were necessary in order to unroof the samples by 2 Ma. Additional extension, of unknown magnitude, has probably occurred subsequently. Geodetically measured horizontal extension rates are considerably higher than the long-term extension rate that can be attributed to detachment faulting.

[1]Department of Earth and Space Sciences, University of California, Los Angeles.
[2]Department of Geological and Environmental Sciences, Stanford University, Stanford, California. Now at Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena.
[3]Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, México.
[4]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena.
[5]Department of Geological Sciences, San Diego State University, San Diego, California.

Paper number 1999TC001123.
0278-7407/00/1999TC001123$09.00

1. Introduction

Large-magnitude slip (commonly tens of kilometers) on low-angle normal, or detachment, faults has denuded midcrustal rocks in many places, forming metamorphic core complexes that provide tectonic windows into deeper crustal levels than are typically exposed. Study of these windows has led to new insights into crustal formation and architecture and into the structural and metamorphic histories of earlier orogenic events [e.g., *Snoke and Miller*, 1988; *Anderson and Cullers*, 1990; *Axen et al.*, 1998a]. Eocene to late Miocene extension of western North America formed a semicontinuous belt of detachment faults and metamorphic core complexes from Sonora, Mexico, to British Columbia, Canada (Figure 1) [e.g., *Coney*, 1980; *Axen et al.*, 1993]. The Neogene structures of this belt accommodated significant North American-Pacific relative plate motion [*Dickinson and Wernicke*, 1997]. In spite of these facts and the extreme extension within the belt [e.g., *Wernicke et al.*, 1988], continental separation did not follow the core-complex belt, but finally occurred well to the southwest, in the Gulf of California (Figure 1), where detachment faults are uncommon [e.g., *Gastil et al.*, 1975; *Angelier et al.*, 1981; *Dokka and Merriam*, 1982; *Hausback*, 1984; *Stock and Hodges*, 1990; *Umhoefer et al.*, 1994].

In fact, detachment faults do exist west of the Salton Sea and northern Gulf of California (Figure 2) [*Sharp*, 1979; *Siem and Gastil*, 1994], but their importance for gulf rifting has been largely overlooked. These faults generally have been interpreted as mid-Tertiary detachment faults [e.g., *Engel and Schultejann*, 1984] or as reactivated thrust faults [*Sharp*, 1979] that accommodated little horizontal extension (see *Axen and Fletcher* [1998] for a review). However, the detachment faults in the northern Gulf of California and Salton trough are mainly late Miocene to Quaternary and they played a significant role in northern gulf tectonics [*Siem and Gastil*, 1994; *Axen and Fletcher*, 1998].

Monte Blanco in the Sierra El Mayor of northeastern Baja California (Figures 2 and 3) is a structural and topographic dome comprising footwall rocks of the late Neogene-Quaternary Cañada David detachment fault. These rocks are from deeper crustal levels than are typically exposed in the region, and they record some of the youngest cooling ages yet reported from there. For these reasons, Monte Blanco provides unique insights into the histories of late Cenozoic rifting and earlier Cenozoic denudation of the Peninsular Ranges. We present integrated $^{40}Ar/^{39}Ar$, fission track, and (U-Th)/He thermochronometry from footwall rocks. Whereas most eastern

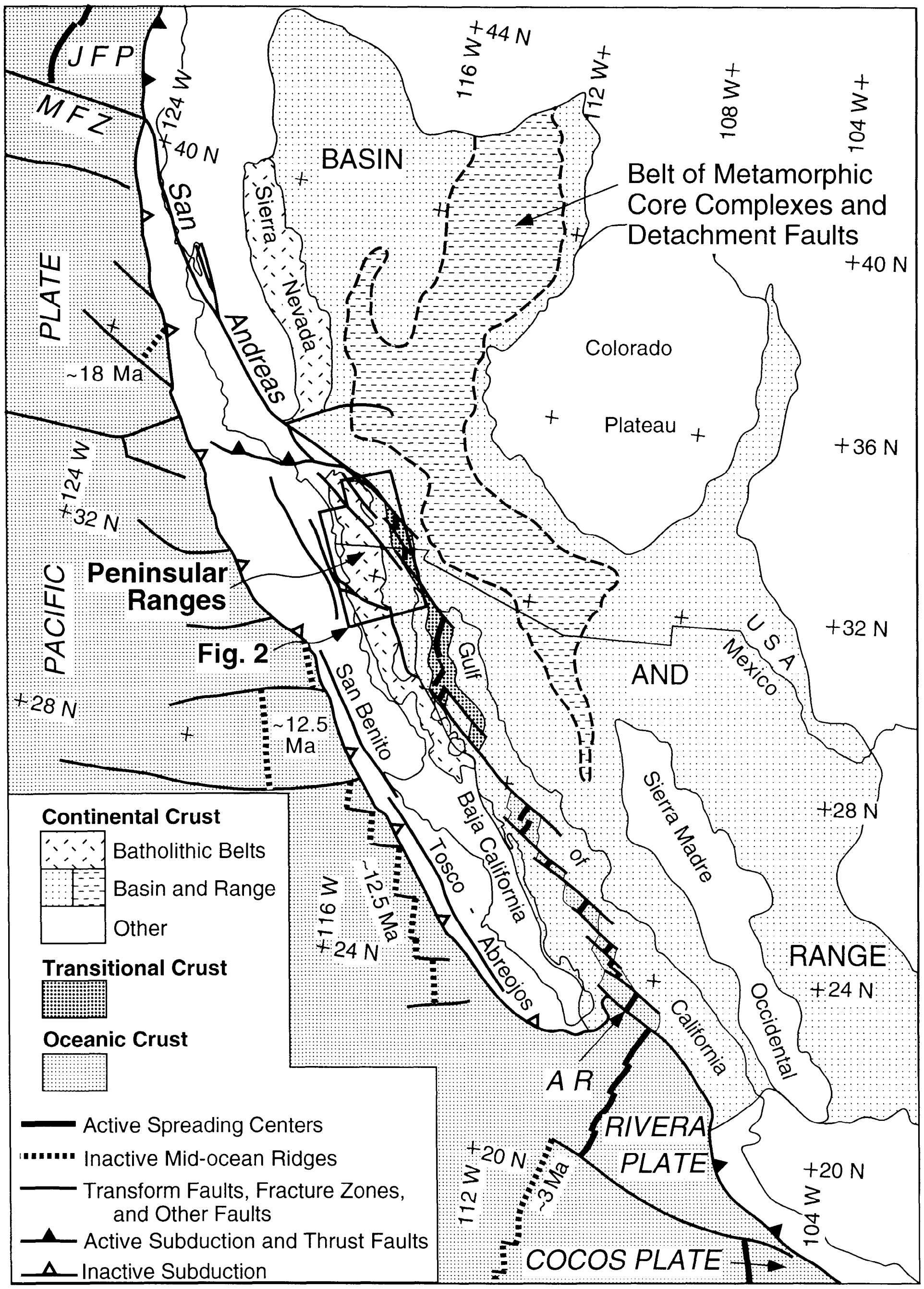


Figure 1. Modern tectonic setting of the study area relative to southwestern North America and the eastern Pacific. In spite of large-magnitude Oligo-Miocene extension in the belt of metamorphic core complexes and detachment faults, continental separation finally occurred in the Gulf of California region. The northern Peninsular Ranges lie west of the only known detachment faults related to Gulf of California rifting (see Figure 2). Abbreviations JFP, Juan de Fuca plate; AR, Alarcón Rise. Modified from *Muehlberger* [1992].

Peninsular Range rocks were unroofed by Paleogene time (Figure 2 and references in the caption), Monte Blanco samples record protracted Tertiary cooling that culminated in Plio-Pleistocene surface exposure.

2. Geologic and Tectonic Setting

Our study area lies immediately east of the Sierra Juárez, one of the Peninsular Ranges of northern Baja California, Mexico, and southern California. Basement rock types of the Peninsular Ranges comprise a subduction-related batholith and older metamorphic country rocks. A western assemblage of Jurassic-Early Cretaceous arc rocks and older oceanic crust was sutured against the North American marginal flysch basin to the east before and during emplacement of batholithic rocks from 120 to 90 Ma [*Gastil et al.*, 1975; *Gastil*, 1993; *Silver and Chappell*, 1988; *Todd et al.*, 1988; *Busby et al.*, 1998; *Dickin-*

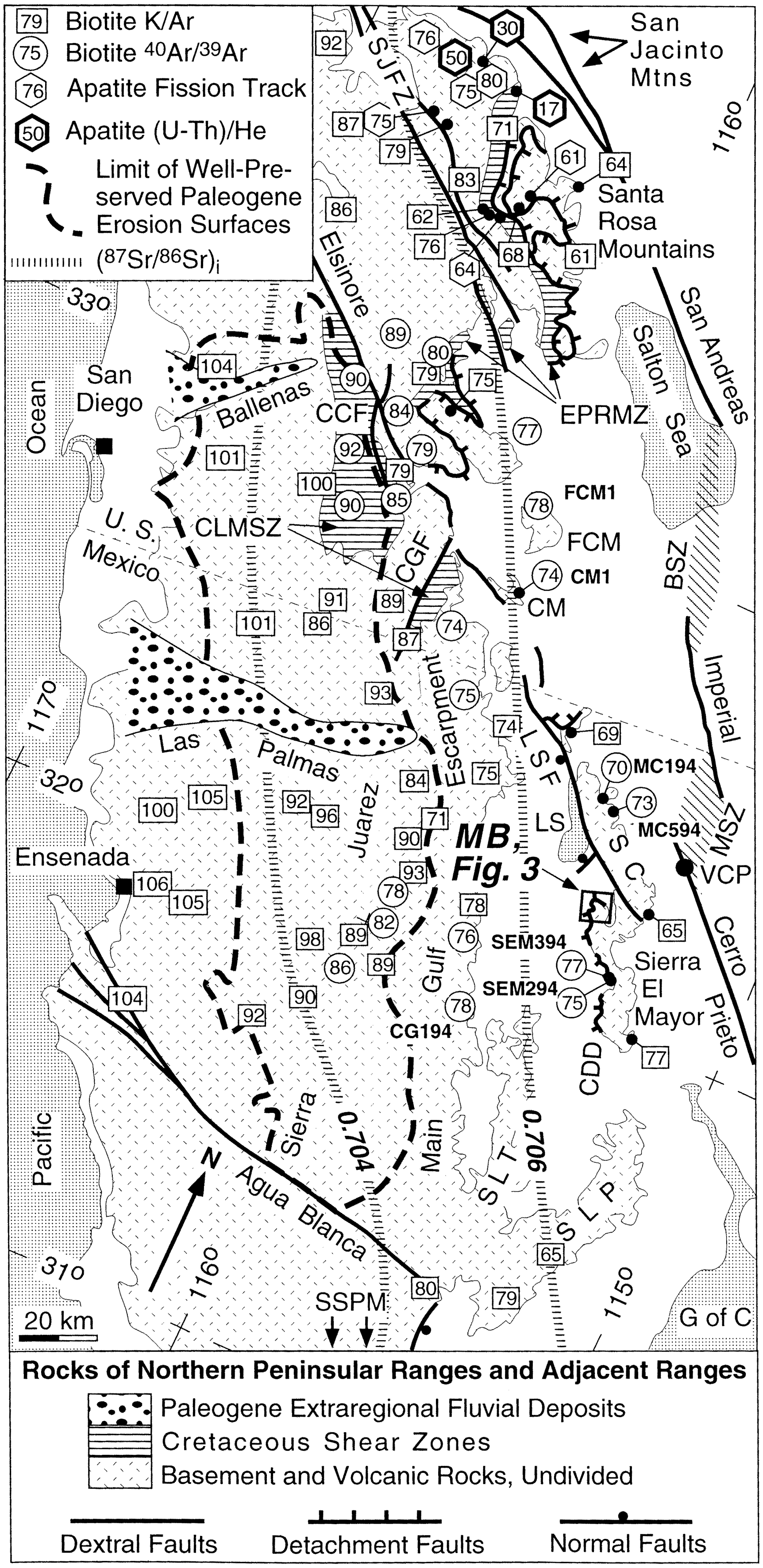

Biotite K/Ar
Biotite 40Ar/39Ar
Apatite Fission Track
Apatite (U-Th)/He
Limit of Well-Preserved Paleogene Erosion Surfaces
(87Sr/86Sr)i
San Jacinto Mtns
Santa Rosa Mountains
San Andreas
Salton Sea
SJFZ
Elsinore
EPRMZ
San Diego
Ocean
Ballenas
CCF
CLMSZ
U. S.
Mexico
CGF
FCM1
FCM
CM1
CM
BSZ
Imperial
Las Palmas
Juarez
Main Gulf Escarpment
LSF
LS
MC194
MC594
MSZ
VCP
MB, Fig. 3
SC
Cerro Prieto
Sierra El Mayor
SEM394
SEM294
CG194
CDD
Ensenada
Pacific
Agua Blanca
Sierra
0.704
0.706
SLT
SLP
SSPM
G of C
N
20 km
Rocks of Northern Peninsular Ranges and Adjacent Ranges
Paleogene Extraregional Fluvial Deposits
Cretaceous Shear Zones
Basement and Volcanic Rocks, Undivided
Dextral Faults
Detachment Faults
Normal Faults

Figure 2.

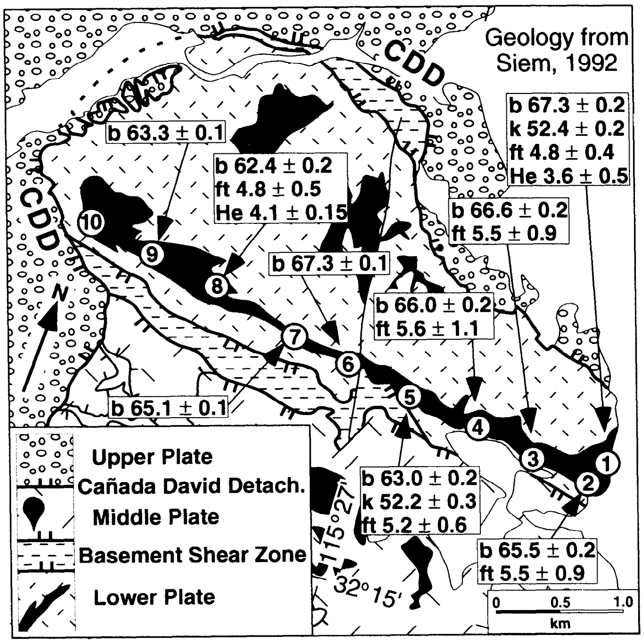


Figure 3. Simplified geologic map of Monte Blanco dome, showing location of samples MX96-001 to MX96-010 (circled numbers are final digits of sample number; see Table 1 for latitude/longitude of samples). Different types of ages indicated are $^{40}Ar/^{39}Ar$ total-gas ages of biotite (b) and K feldspar (k), and fission track (ft) and (U-Th)/He (He) ages of apatite. Major intrusions are shown as solid areas; heavy lines are detachment faults (ticks on the upper plates); CDD is Cañada David detachment.

son and Butler, 1998]. Basement rocks of the study area originated in the eastern assemblage but now lie in the Sierra El Mayor, separated from the Peninsular Ranges by the Neogene Laguna Salada basin (Figure 2).

A shallowing angle of subduction in Late Cretaceous to early Tertiary time caused the arc to migrate east to central Mexico [*Coney and Reynolds*, 1977; *McDowell and Mauger*, 1994]. During this time the eastern batholith was deeply denuded (12-20 km), largely by east-side-up structures such as the eastern Peninsular Ranges mylonite zone, the Cuyamaca-Laguna Mountains shear zone, and the Chariot Canyon and Carrizo Gorge faults (Figure 2) [*Todd et al.*, 1988; *Grove*, 1994; *Lovera et al.*, 1999]. This is reflected by abundant K/Ar, $^{40}Ar/^{39}Ar$, fission track, and (U-Th)/He cooling ages that become progressively younger and more discordant eastward (Figure 2 and references in the caption; also *Snee et al.* [1994] and *Schmidt et al.* [1998]).

In Late Cretaceous time the ancestral Peninsular Ranges of California and Baja California were drained by west flowing, steep gradient, short-length streams that built numerous alluvial fan/submarine fan masses on and across the narrow coastal plain [*Bottjer and Link*, 1984]. As the magmatic arc migrated eastward from Late Cretaceous into Early Tertiary time, the rivers grew eastward becoming longer, fewer in number, and larger in discharge [*Minch*, 1979; *Kies and Abbott*, 1983].

By late Paleocene time, regional erosion was beveling the ancestral Peninsular Ranges and large west flowing rivers were eroding the Jurassic rhyolitic arc in Sonora, Mexico, and carrying gravel-sized sediments across the Cretaceous Peninsular Ranges arc, to the Pacific coast (Figure 2) [*Minch*, 1979; *Abbott and Smith*, 1989]. Deposition of distinctive, extraregional Jurassic rhyo-dacitic clast assemblages (known as Poway clasts) by these rivers ended in late Eocene time [*Kies and Abbott*, 1983], an event that we relate to east-side-up reactivation of late Cretaceous structures.

Incised into the Peninsular Ranges are two west-southwest trending, parallel, conglomerate-filled river valleys of Eocene age (Figure 2) [*Fairbanks*, 1893]. These large rivers dominated their regional landscape during Eocene time. Their origin is understood and their flow characteristics and provenance are known, but it has never before been understood why they stopped flowing to the Pacific Coast. The Ballena Gravels in San Diego County are up to 110 m thick and 3 km wide lying in a paleovalley of 1.1 to 1.3 sinuosity [*Minch*, 1979; *Steer and Abbott*, 1984]. Just 60 km to the south in northern Baja California lie the Las Palmas Gravels, which are up to 240 m thick and 6 km wide [*Minch*, 1979; *McDonough and Abbott*, 1989]. Paleohydrologic reconstructions of the two Eocene rivers suggest river lengths >300 km with 100-year flood discharges around 27,000 m^3/s. Modern analogues flow eastward off the Andes Mountains in southern Argentina and into the Atlantic Ocean.

Subduction-related volcanism migrated back to the Gulf area by about 24 Ma; it ended in the northern Gulf ~16 Ma

Figure 2. (opposite) Simplified map of the northern Peninsular Ranges and adjacent desert ranges (granite pattern), showing limits of well-preserved Paleogene erosion surfaces (heavy dashed line), of Paleogene river deposits (conglomerate pattern), and of oceanic-continental transition zone as imaged by the initial $^{87}Sr/^{86}Sr$ ratios between 0.704 and 0.706. Representative basement biotite and apatite cooling ages (in Ma) are shown by numbers in boxes (K/Ar), circles ($^{40}Ar/^{39}Ar$ total gas), and hexagons (fission track and (U-Th)/He). Labeled samples are listed in Table 1; others are from references below. K feldspar thermal history results from FCM1, CM1, SEM394, and CG194 are shown in Figure 7. Heavy solid lines are faults, with detachments shown by ticks on the upper plates. Abbreviations BSZ, Brawley seismic zone; CCF, Chariot Canyon fault; CGF, Carrizo Gorge fault; CLMSZ, Cuyamaca-Laguna Mountains shear zone; EPRMZ, eastern Peninsular Ranges mylonite zone; G of C, Gulf of California; LS, Laguna Salada; LSF, Laguna Salada fault; MB, Monte Blanco area; MSZ, Mexicali seismic zone; SC, Sierra Cucapá; SLP, Sierra Las Pintas; SSPM, Sierra San Pedro Mártir; VCP, volcán Cerro Prieto. Compiled from *Strand* [1962], *Krummenacher et al.* [1975], *Minch* [1979], *Dokka* [1984], *Gromet and Silver* [1987], *Todd et al.* [1988], *Abbott and Smith* [1989], *Frez and González* [1991], *Goodwin and Renne* [1991], *Germinario* [1993], *Grove* [1993], *George and Dokka* [1994], *Rothstein* [1997], *Wolf et al.* [1997], and *Axen and Fletcher* [1998].

and was replaced by rift-related volcanism by about 12 Ma [*Sawlan*, 1991; *Martín-Barajas et al.*, 1995]. From 30 to 8 Ma the Pacific-North American relative plate velocity was ~33 mm/yr toward 300°. At 12 Ma the velocity increased to ~52 mm/yr, but the direction did not change significantly. At 8 Ma the direction rotated clockwise to ~323°, but the rate remained ~52 mm/yr [*Atwater and Stock*, 1998]. The Pacific and North American plates came into contact at ~28 Ma; before then, they were separated by the intervening Farallon-Vancouver plates, which were subducting under North America faster than the Pacific plate was spreading away [*Atwater*, 1989]. As the mid-ocean ridge approached the subduction zone, the Farallon plate broke into small oceanic plates. These commonly stalled in the subduction zone, causing spreading to cease and leading to their "capture" by the Pacific plate [e.g., *Nicholson et al.*, 1994]. Several of these inactive ridge segments are preserved in the eastern Pacific (Figure 1). They are progressively younger southward (Figure 1), so record the piecemeal demise of the subduction zone.

Early gulf rifting began ~12 Ma, in response to waning oceanic spreading and capture of a long series of Farallon microplates by the Pacific plate (inactive ridge segments labelled "~12.5 Ma" in Figure 1). Roughly synchronously, subduction slowed and then stopped, and the margin of the overriding North American plate became coupled to the captured microplates, causing divergent wrench tectonics at the plate boundary and within western North America [*Stock and Hodges*, 1989; *Sawlan*, 1991; *Nicholson et al.*, 1994; *Lee et al.*, 1996]. Full continental separation in the southern Gulf of California had occurred by Pliocene time (~3.6 Ma), the age of the oldest discernible magnetic lineations that record Baja California-North America motion (formed at the Alarcón rise, Figure 1) [*DeMets*, 1995]. Farther north, deep rhombic basins are probably floored by oceanic crust but are not magnetically lineated [*Lonsdale*, 1991]. In the northern gulf and Salton trough, rifting has formed bathymetrically and/or sedimentologically deep basins that are underlain by transitional crust (Figure 1) [e.g., *Elders et al.*, 1972; *Fuis and Kohler*, 1984; *Fuis et al.*, 1984].

The gulf rift is highly oblique [e.g., *Umhoefer and Dorsey*, 1997] but otherwise shares many characteristics with narrow rifts, such as common listric master fault systems, along-strike segmentation, and flank uplifts [e.g., *Dokka and Merriam*, 1982; *Stock and Hodges*, 1990; *Axen*, 1995]. In large part, these similarities probably stem from strong plate margin strain partitioning that began in early gulf history, when dextral slip was concentrated on the San Benito-Tosco-Abreojos fault system west of the Baja California peninsula (Figure 1) and extension within the gulf region was roughly perpendicular to its margins [*Spencer and Normark*, 1979; *Stock and Hodges*, 1989]. Slip on the western faults has slowed or stopped, but strain within the gulf region is still complexly partitioned among strike-slip faults, normal faults, vertical axis rotations, and incipient spreading centers [e.g., *Fenby and Gastil*, 1991; *Lewis and Stock*, 1998].

The Sierra El Mayor lies immediately west of the dextral Cerro Prieto fault and the Mexicali seismic zone (Figure 2), a transform fault–spreading center pair of the Pacific-North America plate margin [*Frez and González*, 1991] that accommodates most of the modern plate motion at this latitude [*Bennett et al.*, 1996]. The Sierra is separated from the Peninsular Ranges by the actively extending, subsea level Laguna Salada basin [*Savage et al.*, 1994; *Mueller and Rockwell*, 1995; *Axen et al.*, 1999]. Dated volcanic rocks and dikes in nearby areas are 20 to 8 Ma old [*Barnard*, 1968; *Gastil et al.*, 1979; *Lee et al.*, 1996].

Monte Blanco dome (Figures 2 and 3) was mapped by *Siem* [1992] and forms the lower plate of a brittle detachment fault system that roots west under Laguna Salada [*Axen and Fletcher*, 1998]. The Cañada David detachment is a sharp fault marked by a layer of clay gouge <25 cm thick. It follows the north and west sides of the dome (Figure 3), cutting upper plate strata that include faulted and tilted Pliocene Imperial Formation and Pleistocene Palm Spring Formation [*Siem and Gastil*, 1994; *Stock et al.*, 1996]. Striae in sheared basement rocks and clay gouge trend west and shear sense indicators yield top-west transport [*Siem and Gastil*, 1994; *Axen and Fletcher*, 1998], highly oblique to the ~323° direction of relative plate motion. The south side of the dome is bounded by a structurally lower detachment fault that merges westward with the Cañada David detachment fault (Figure 3). The lower detachment is overlain by tectonically slivered metasedimentary rocks of the middle plate; southward, the middle plate thickens and is structurally more coherent. The detachment faults at Monte Blanco have been cut and deactivated by the Laguna Salada and related faults, but the southern continuation of the Cañada David detachment along the range front is likely still active [*Axen and Fletcher*, 1998; *Axen et al.*, 1998b; *Axen et al.*, 1999].

Lower plate rocks of Monte Blanco are mainly high-grade and migmatitic biotite gneiss, calc-silicate, and amphibolite [*Siem*, 1992] of the prebatholithic flysch sequence [*Todd et al.*, 1988; *Gastil*, 1993]. These are intruded by unfoliated Cretaceous granodiorite, pegmatite dikes, and small plutons (Figure 3) [*Siem and Gastil*, 1994], indicating that the foliation is at least Cretaceous in age and not related to the detachment history. Pelitic assemblages (garnet + sillimanite + biotite + potassium feldspar + quartz + graphite) lack prograde muscovite, indicating upper amphibolite-grade recrystallization at >12 km depth [*Axen et al.*, 1998a]. Subhorizontal to gently tilted foliation and compositional layering of the prebatholithic rocks are domed concordantly with the detachment surfaces [*Siem and Gastil*, 1994]. The upper 10-100 m of lower plate rocks are brittlely sheared, highly faulted, and chloritically altered. Middle plate rocks are of lower metamorphic grade, typically greenschist facies. Where the middle plate is structurally coherent, they commonly have steep foliation, are isoclinally folded, and are intruded discordantly by dikes and irregular to stock-like plutons that are typically larger and more widely spaced than intrusions in the lower plate.

3. Sampling and Analytical Methods

At Monte Blanco, 10 samples spaced ~0.5 km apart were taken from an ~90 Ma granodiorite dike in the lower plate [*Siem and Gastil*, 1994]. The dike strikes about parallel to the transport direction of the detachment fault (Figure 3 and Table 1). Topographic relief among these samples is <100 m. The westernmost sample was too altered to be of use. Biotite, K feldspar, and apatite were separated using conventional den-

Table 1. Summary of Cooling Ages for Monte Blanco Dome and Surroundings

Sample	Location Latitude/Longitude	Biotite* $^{40}Ar/^{39}Ar$ ± 1σ, Ma	K feldspar* $^{40}Ar/^{39}Ar$ ± 1σ, Ma	Apatite FT ± 1σ, Ma	Apatite (U-Th)/He ± 1σ, Ma
FCM1 †	33°01'49"/116°05'02"	75.5 ± 0.2	75.9 ± 0.3		
CM1 †	32°46'59"/116°00'58"	73.5 ± 0.2	72.1 ± 0.4		
MC194†	32°32'00"/115°38'54"	69.8 ± 0.8			
MC594†	32°32'00"/115°38'42"	73.2 ± 0.4			
CT594†	32°15'48"/115°50'42"	75.9 ± 1.1			
CG194†	32°15'18"/115°47'24"	78.2 ± 0.3	76.8 ± 0.6		
SEM294 †	32°00'00"/115°14'48"	74.8 ± 0.2			
SEM394 †	32°00'48"/115°14'06"	76.6 ± 0.3	73.5 ± 0.2		
MX96-001‡	32°15'51"/115°25'47"	67.3 ± 0.3	52.4 ± 0.2	4.8 ± 0.4	3.6 ± 0.5
MX96-002‡	32°15'45"/115°25'52"	65.5 ± 0.3		5.5 ± 0.9	
MX96-003‡	32°15'46"/115°26'08"	66.6 ± 0.3		5.5 ± 0.9	
MX96-004‡	32°15'48"/115°26'30"	66.0 ± 0.3		5.6 ± 1.1	
MX96-005‡	32°15'53"/115°26'54"	63.0 ± 0.3	52.2 ± 0.3	5.2 ± 0.6	
MX96-006‡	32°15'54"/115°27'12"	67.3 ± 0.2			
MX96-007‡	32°16'00"/115°27'32"	65.1 ± 0.2			
MX96-008‡	32°16'06"/115°27'56"	62.4 ± 0.3		4.8±0.5	4.1 ± 0.2
MX96-009‡	32°16'10"/115°28'13"	63.3 ± 0.2			

* Integrated Ages (K-Ar equivalent).
† Map location on Figure 2.
‡ Map location on Figure 3.

sity and magnetic techniques followed by hand selection. Biotite and K feldspar were analyzed by $^{40}Ar/^{39}Ar$ (University of California, Los Angeles), and apatite was examined by fission track (Stanford University) and (U-Th)/He (California Institute of Technology). Irradiation constants, experimental conditions, complete Ar data tables, and fission track length plots are available in Appendices A and B (supporting materials available from AGU[1] or from http://www.oro.ess.ucla.edu).

Biotite and K feldspar were irradiated for 45 hours in the L67 position of the Ford reactor (University of Michigan) using Fish Canyon sanidine (27.8±0.3 Ma) as a flux monitor. Procedures for laser fusion, furnace step heating, and $^{40}Ar/^{39}Ar$ are presented by *Quidelleur et al.* [1997]. The heating schedule employed for K feldspar analysis facilitated correction of age spectra for Cl-correlated excess ^{40}Ar [*Harrison et al.*, 1994] and, for thermal history calculations, allowed estimation of multiple diffusion domain model parameters (E and D/r^2, where E is activation energy, D is diffusivity, and r is diffusion-domain radius) [*Lovera et al.*, 1989, 1997; *Quidelleur et al.*, 1997].

Fission track dating of apatite is based on the decay of trace ^{238}U nuclei by natural nuclear fission [e.g., *Fleischer et al.* 1975; *Green et al.*, 1989; *Dumitru*, 1999]. Fission of a single nuclei creates two highly charged ions which mutually repel and create a 17-μm-long damage track through the crystal lattice. Fission occurs at an essentially constant rate, so track numbers and grain U contents may be used to calculate fission track ages. In apatite, tracks are almost totally stable at temperatures below 60°C, are totally erased by recrystallization at temperatures above about 125°C, and are partially stable between 60 and 125°C. Within the partial stability zone, recrystallization shortens tracks and reduces their apparent number to a degree directly dependent on the temperature. Thus fission track data may be used to reconstruct sample time-temperature histories within the temperature window 60-125°C [*Gallagher*, 1995; see also *Dumitru*, 1999]. For each sample in this study, 15 to 30 individual grains were dated and 43 to 100 track lengths were measured, following methods identical to those of *Dumitru et al.* [1995].

(U-Th)/He dating is based on the production of ^4He by alpha decay of U and Th [*Zeitler et al.*, 1987; *Wolf et al.*, 1996]. In apatite, He is retained at temperatures below ~45°C, entirely lost by diffusion above ~85°C, and partially retained between ~45° and ~85°C [*Wolf et al.*, 1996, 1998]. The ^4He and U-Th extracted from 5 to 20 inclusion-free apatite grains were measured using isotope dilution quadrupole and inductively coupled plasma mass spectrometry, respectively. (U-Th)/He ages are corrected for alpha particle emission during radioactive decay [*Farley et al.* 1996].

4. Thermal History Results

4.1. Likelihood of Monotonic Cooling

Interpretation of $^{40}Ar/^{39}Ar$, fission track, and (U-Th)/He results presented below presumes monotonic cooling. Transient reheating of the Monte Blanco dome rocks could alter our interpretations significantly. We feel confident that reheating may be ruled out for the following reasons. (1) Because the magmatic arc was well removed to the east in early Tertiary time, the ambient geothermal gradient was likely maintained at a low value due to shallow-angle subduction [e.g., *Dumitru*, 1990]. (2) Although arc magmatism was reestablished in the early Miocene and *Siem* [1992] mapped a few thin (~1 m) Miocene(?) andesitic dikes at Monte Blanco (as have others in the surrounding areas), volumetrically significant plutonic bodies of this age have not been recognized in the vicinity of the Sierra El Mayor [e.g., *Barnard*, 1968; *Gastil et al.*, 1979; *Mendoza-Borunda et al.*, 1995; *Lee et al.*, 1996; *Romero-Espejel and Delgado-Argote*, 1997; *Romero-Espejel and Martín-*

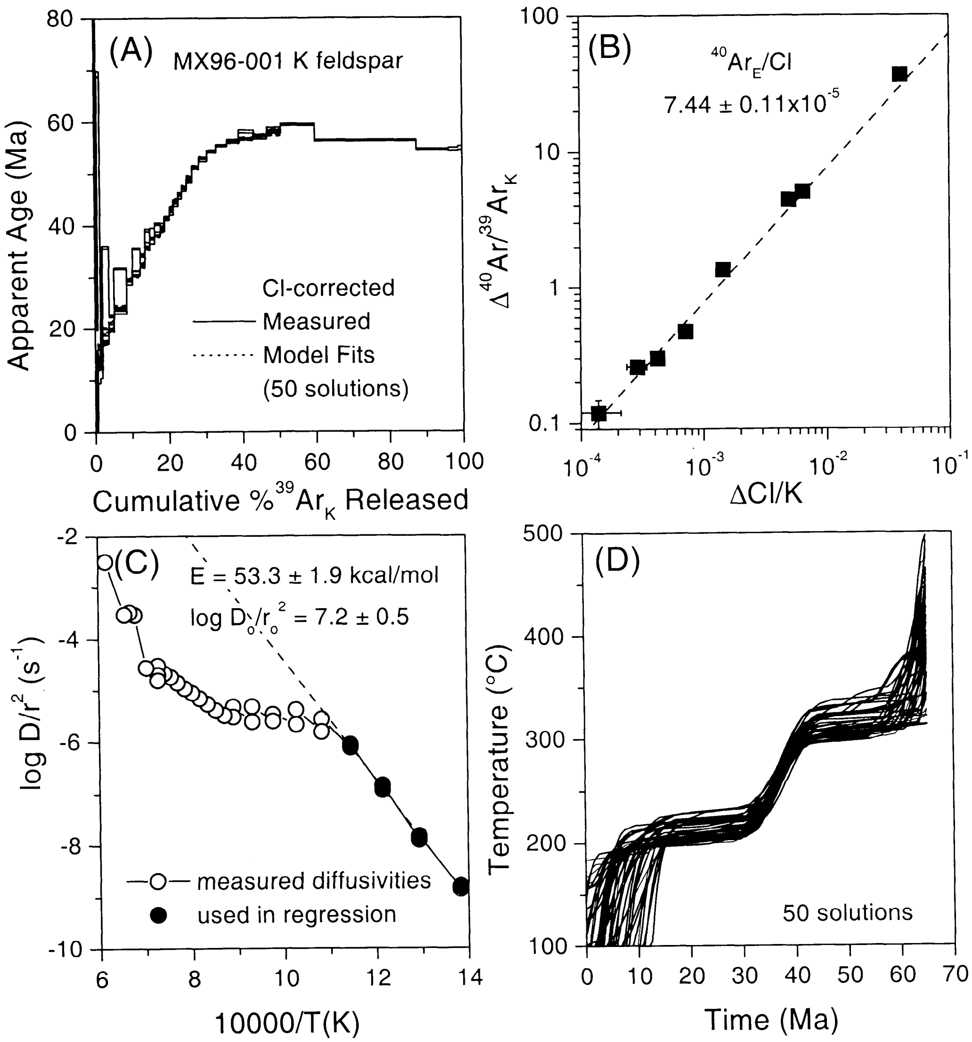


Figure 4. Multidiffusion domain (MDD) model results for MX96-001 K-feldspar. (a) Measured and Cl-corrected age spectrum. Correction for Cl-correlated excess radiogenic ^{40}Ar (^{40}Ar^{E}) performed according to *Harrison et al.* [1994]. Model fits produced from thermal history calculations are also displayed. (b) Correlation between ^{40}Ar/K and Cl/K that forms basis for correcting the age spectrum. (c) Measured ^{39}Ar diffusivities with diffusion parameters (activation energy or E and frequency factor or D_0/r_0^2) employed in thermal history calculations. Values of E and D_0/r_0^2 are allowed to vary randomly within uncertainty to produce 10 equivalent sets of MDD parameters [see *Lovera et al.*, 1997]. (d) Calculated monotonic cooling histories capable of reproducing the Cl-corrected age spectrum (see Figure 4a). Five best fit solutions were obtained from each set of MDD parameters.

Barajas, 1998]. (3) The nearest large Miocene volcanic center is in the Sierra Las Pintas, ~50 km south (Figure 2) [*Gastil et al.*, 1979]. Biotite and K feldspar from both this region and from the southern Sierra El Mayor show no abnormal Ar loss. (4) Elevated heat flow, hydrothermal activity, and Quaternary magmatism occur near Cerro Prieto [*de Boer*, 1979; *Lippmann*, 1983] and locally in Laguna Salada [*Venegas and Alvarez*, 1994], but are aerially restricted and probably are late Pleistocene-Holocene phenomena, almost certainly younger than ~3.5 Ma, the age of oldest oceanic crust in the gulf [*DeMets*, 1995]. (5) Consistent age results over the detailed 5-km sample transect (Figure 3) argue against a nearby localized heat source. Thus we interpret our results in terms of monotonic cooling that was driven by unroofing, which agrees well with the known geological history.

4.2. Biotite

Reconnaissance K/Ar and ^{40}Ar/^{39}Ar total-gas biotite ages from basement surrounding the Sierra El Mayor establish Cretaceous to early Tertiary regional cooling trends (Figure 2 and Table 1) [*Krummenacher et al.*, 1975; *Grove* 1993; *Rothstein*, 1997]. Step-heating ^{40}Ar/^{39}Ar results from Monte Blanco dome biotites (63-67 Ma; Figure 3 and Table 1) indicate that these rocks cooled through ~350°C 5-10 m.y. later than most basement rocks of the eastern Peninsular Ranges and adjacent areas (Figure 2 and references in the caption; *Ortega-Rivera*

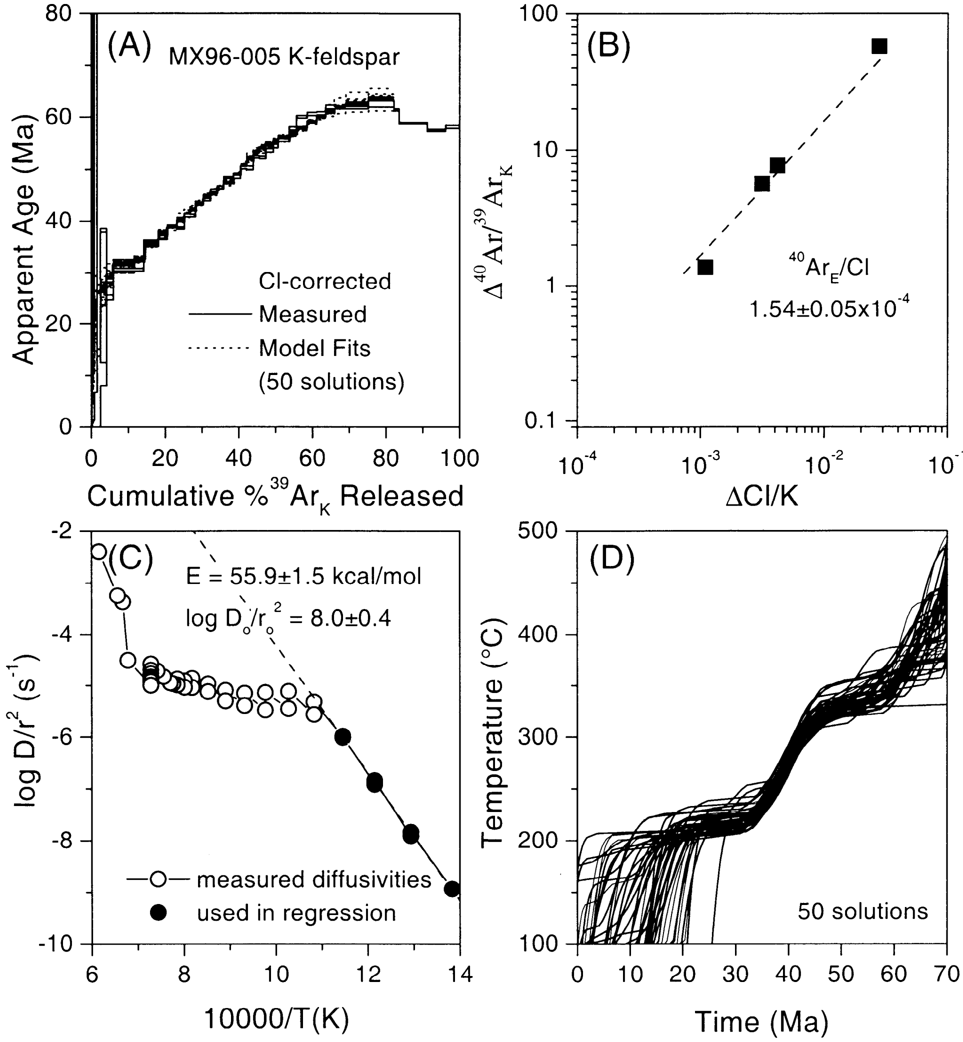


Figure 5. Multidiffusion domain (MDD) model results for MX96-005 K-feldspar (see Figure 4 for explanation).

et al. [1997]; Table 1; biotite closure temperature calculated using diffusion parameters of *Grove and Harrison* [1996], a cylindrical diffusion radius of 350 µm, and a mean cooling rate of 30°C/m.y.). Rocks of the Sierra Cucapá yield similar biotite ages to Monte Blanco dome, but biotites from the southern Sierra El Mayor yield similar $^{40}Ar/^{39}Ar$ ages to the Sierra Juárez to the west and Coyote Mountains and Fish Creek Mountains to the north (Figure 2 and Table 1). This contrast is consistent with the deeper crustal exposures represented by the Monte Blanco dome and Sierra Cucapá rocks by virtue of their position in the lower plate of the detachment system (Figures 2 and 3).

4.3. K Feldspar

Measured $^{40}Ar/^{39}Ar$ age spectra yielded by samples MX96-001 and MX96-005 are shown in Figures 4a and 5a, respectively. Minor excess radiogenic ^{40}Ar ($^{40}Ar^{E}$) evident in the low-temperature release of both samples is well correlated with Cl-derived ^{38}Ar (Figures 4b and 5b, respectively). The corrected age spectra shown in Figures 4a and 5a were obtained following procedures outlined by *Harrison et al.* [1994]. Diffusivities calculated from ^{39}Ar release are displayed in the Arrhenius plots of Figures 4c and 5c. Both the diffusion properties (activation energy E and frequency factor D_o/r_o^2) and the form of the Arrhenius plots are typical for K feldspars derived from basement terranes [*Lovera et al.*, 1997]. In modeling the diffusion properties of these samples we calculated 10 equivalent sets of multiple diffusion domain (MDD) parameters. In each iteration we allowed E and D_o/r_o^2 to vary randomly within the limits imposed by their 1σ uncertainties (see Figures 4c and 5c) and then employed a least squares approach to calculate the domain distribution required to fit the measured Arrhenius array [*Lovera et al.*, 1997].

From each set of MDD parameters we then calculated five monotonic cooling histories (Figures 4d and 5d) which produced the best fit to the age spectra corrected for Cl-correlated $^{40}Ar^{E}$. This yielded a total of 50 solutions for each sample. To better represent the statistical properties of the thermal history results, we have calculated the 90% confidence intervals of both the overall distribution and the median for each of the samples (Figures 6a and 6b). The similarity of these results is striking, particularly when the contrast in the age and Ar diffusion properties is taken into account. In order to increase the robustness of the K feldspar thermal history results for further calculations, we combined data for both samples in Figure 6c.

Temperature-time paths from Monte Blanco K feldspars (Figure 6c) show that those rocks were still above 300°C at ~65 Ma. Subsequently, very slow cooling persisted until ~45 Ma, followed by more rapid cooling to ~200°C between ~45 and 33 Ma and by a subsequent return to very slow cooling until ~15 Ma. This contrasts markedly with the temperature-time paths yielded by K feldspars from surrounding areas (samples FCM1, CM1, SEM394, and CG194; Figures 2 and 7 and Table 1) that indicate cooling to <200°C between 75 and 65 Ma) [*Grove*, 1993; *Rothstein*, 1997].

4.4. Apatite

Final cooling is best constrained by the apatite results, which indicate rapid cooling (~30°C/m.y.) through ~110-70°C at ~5-4 Ma (Figure 8). Monte Blanco apatites yield the youngest known fission track ages in the region (Tables 1 and 2 and Figures 2 and 8), which are statistically concordant ages with a weighted mean of 5.0 ±0.2 Ma, 40-65 m.y. younger than is typical of the eastern Peninsular Ranges (Figure 2 and references therein) [see *Cerveny et al.*, 1991; *Snee et al.*, 1994; *Ortega-Rivera et al.*, 1997; *Schmidt et al.*, 1998]. Fission track length histograms exhibit long mean lengths and unimodal distributions (Appendix B). The consistency of the ages and the simple track length distributions indicate that the ages can be interpreted as directly dating the time the samples cooled below ~110°C [e.g., *Gallagher*, 1995]. Apatite (U-Th)/He ages of ~4 Ma (Tables 1 and 3) are also much younger than similar ages in the eastern Peninsular Ranges (Figure 2) [*Wolf et al.*, 1997]. Cooling rate determined from comparison of apatite fission track and (U-Th)/He ages is 33° ± 17° C/m.y. At this rate, bulk closure of apatite to He loss is 70° ± 8°C, taking grain size effects into account [*Wolf et al.*, 1996; *Farley*, unpublished data, 1998]. This cooling rate (33° ± 17° C/m.y.) compares favorably with the rate determined from modeling of fission track length distributions [e.g., *Gallagher*, 1995], which gives 25° ± 10°C/m.y.

5. Late Eocene-Early Oligocene Denudation

We attribute late Eocene-early Oligocene cooling to tectonic uplift of an as-yet poorly defined belt along the eastern Peninsular Ranges and infer that uplift may not have been limited to the Sierra el Mayor. For example, young biotite cooling ages similar to those from the Sierra el Mayor, are recorded immediately west of the Salton trough (Figure 2) [*Krummenacher et al.*, 1975; *Goodwin and Renne*, 1991]. Denudation of at least 3-4 km is implied by the ~100°C cooling recorded at Monte Blanco from 45 to 33 Ma, assuming geothermal gradients of 25°-33°C/km, which are likely higher than existed during Eocene flat subduction [e.g., *Dumitru*, 1990]. Apatite fission track ages in the Sierra San Pedro Mártir, over 100 km to the south, decrease eastward from Cretaceous ages to values as low as 35.6 ± 3.7 Ma at the eastern base of the range [*Cerveny et al.*, 1991; *Ortega-Rivera et al.*, 1997; *Schmidt et al.*, 1998]. Thus the late Eocene-early Oligo-

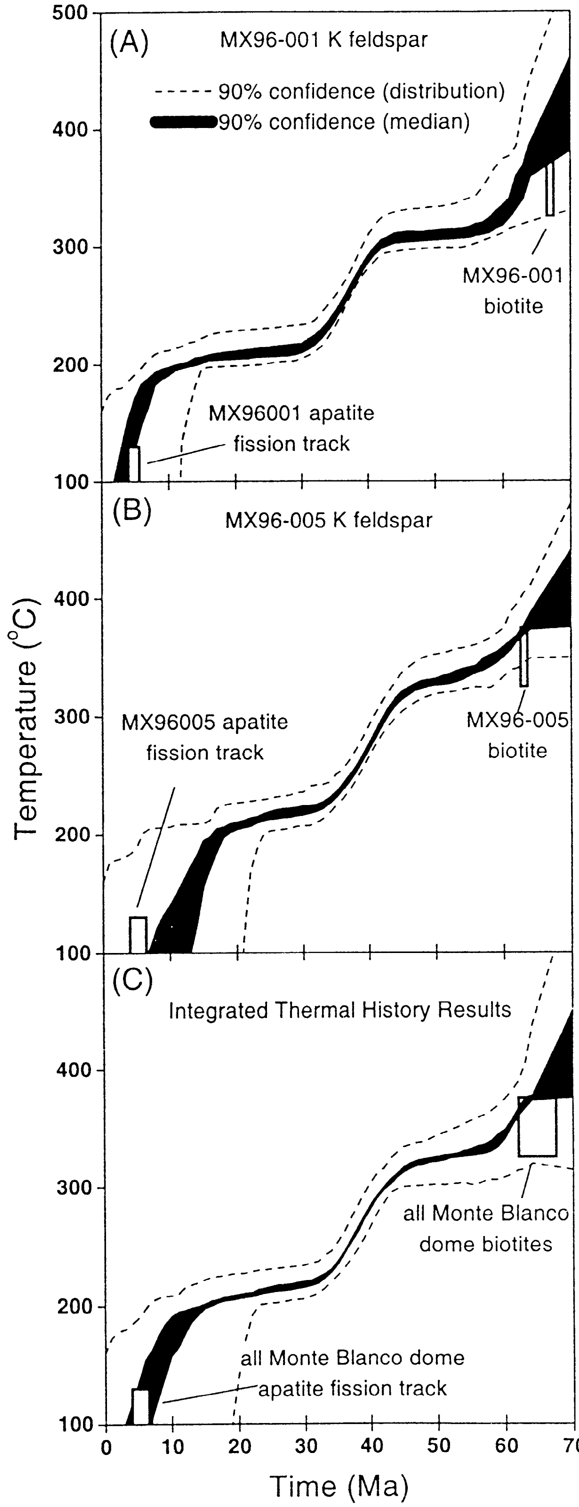


Figure 6. Thermal history results for Monte Blanco dome. (a) Confidence intervals (90% level) for distribution and median of MX96-001 K feldspar thermal history (see Figure 4d). Biotite (~350 ± 25°C for 350 μm grains assuming 30°C/m.y. cooling [see *Grove and Harrison*, 1996]) and apatite (~110 ± 20°C [see *Fitzgerald and Gleadow*, 1990]) closure conditions employ bulk ages from Tables 1 and 2. (b) Same as in Figure 6a for MX96-005 K feldspar (Figure 5). (c) Integrated thermal history results for all Monte Blanco dome samples.

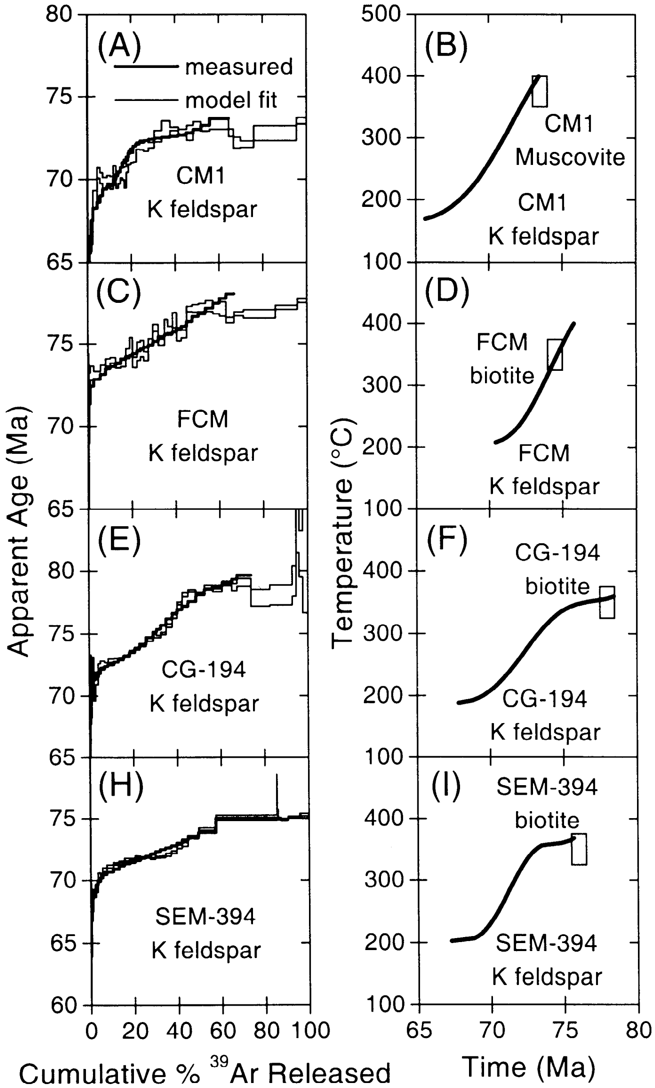


Figure 7. Thermal history results for adjacent basement rocks of the Peninsular Ranges batholith (see Figure 2 for localities and Table 1 for mica bulk ages). (a) Measured and representative MDD model age spectra for CM1 K feldspar. (b) Representative monotonic cooling history calculated for CM1 K feldspar as described in Figure 4 with constraint from coexisting muscovite. (c) and (d) Results for FCM K feldspar and biotite. (e) and (f) Results for CG-194 K feldspar and biotite. (g) and (h) Results for CG-194 K feldspar and biotite. Note that temperatures inferred for all samples at 70-65 Ma are ~200°C or about 150°C lower than temperatures recorded by Monte Blanco dome rocks at this time (see Figure 6).

cene denudation event may also be recorded there in rocks that were shallower and cooler than those at Monte Blanco.

Other lines of evidence suggest that late Eocene-early Oligocene denudation recorded by footwall rocks at Monte Blanco was restricted to a belt along or east of the present-day Peninsular Ranges escarpment. For example, strata older than late Oligocene or early Miocene are not preserved along the escarpment in northern Baja California [*Gastil et al.*, 1975], suggesting that a relict topographic high existed there (see also *Romero-Espejel and Martín-Barajas* [1998], but note that we disagree with their interpretation that the age of the erosion surface decreases progressively eastward, from Paleogene in the west to Miocene along the escarpment). Similarly, only rocks east of the well-preserved Paleogene erosion surfaces and Eocene channel deposits (Figures 2 and 9b) could have been affected strongly by this denudation event.

Eocene-Oligocene paleogeography also suggests uplift of eastern parts of the Peninsular Ranges basement. The age of denudation recorded by Monte Blanco samples correlates well with time of demise of the powerful Eocene Ballena river system that flowed west from Sonora, in mainland Mexico [*Abbott and Smith*, 1989]. Eocene rivers were well established by 45 Ma. Thus they were antecedent and probably became entrenched in the rising uplift. The percentages of extraregional rhyodacitic clasts increase stratigraphically upward in the river deposits, from their appearance in latest Paleocene time up to middle Eocene when they comprised 72% of the conglomerate clasts [*Kies and Abbott*, 1983]. The stratigraphically highest fan deposits straddle the middle-upper Eocene boundary; these highest preserved beds yield rodent fossils of Chadronian age, about 37±2 Ma [*Walsh*, 1998]. By that time, the extraregional clast content had dropped to 55%. The sediments of the Eocene fan record the waning delivery of rhyodacitic debris, which then ceased abruptly. Subsequently, the Eocene alluvial fan was never buried, and it suffered surprisingly little erosion: the extrapolated gradient of the Ballena river deposits is concordant with that of the Poway fan. Upper Eocene and lower Oligocene strata adjacent to the Poway fan in southern San Diego show no primary deposits of Poway rhyodacitic debris [*Walsh and Demere*, 1991]. Uppermost Eocene and Oligocene strata in San Diego and northern Baja California were supplied from local sources only, presumably including local rivers draining and beveling the uplift.

Thus the mystery of why the Eocene rivers stopped flowing to the coast is apparently now partially solved: the rivers were ultimately disrupted and diverted by the uplift recorded at Monte Blanco. The cooling, and presumably the uplift also, began in the Sierra el Mayor ~45 Ma, but Ballena river erosion was able to keep pace with uplift until ~37±2 Ma, when it no longer flowed to the coastal plain. The rivers were diverted before cooling ended at ~33 Ma.

Late Eocene-early Oligocene denudation probably occurred in response to reactivation of east dipping reverse-sense structures along the eastern Peninsular Ranges (Figure 9). This deformation probably reactivated Late Cretaceous east-side-up structures, which are common in the eastern Peninsular Ranges and include the eastern Peninsular Ranges mylonite zone, Cuyamaca-Laguna Mountains shear zone, Chariot Canyon fault, a fault in Carrizo Gorge, and a foliation fan in the Sierra San Pedro Mártir (Figure 2) [*Sharp*, 1979; *Engel and Schultejann*, 1984; *Todd et al.*, 1988; *Goodwin and Renne*, 1991; *Germinario*, 1993; *Grove*, 1994; *Thomson and Girty*, 1994; *Schmidt et al.*, 1998]. These Cretaceous structures formed both during and after emplacement of local plutonic rocks and range from ductile to brittle in nature. Examples of reactivation include brittle thrust faults that overprint the eastern Peninsular Ranges mylonite zone [*Sharp*, 1979; *Engel and Schultejann*, 1984] and that may be responsible for age discontinuities there [e.g., *Goodwin and Renne*, 1991]. It is likely that similar structures lie west of the Sierra el Mayor but have

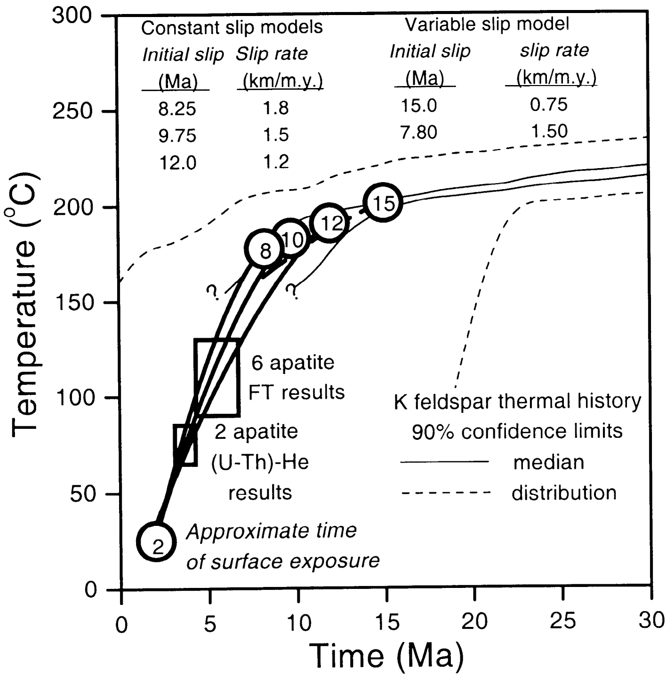


Figure 8. Thermokinetic model results for normal slip on 30° dipping fault (see *Harrison et al.* [1995] and text for additional details). Thermal history constraints are taken from Figure 7 (see also Tables 1 and 3 for (U-Th)/He constraints). Temperature-time histories calculated for three constant slip models indicated by bold curves. Dashed curve corresponds to variable slip model described in text.

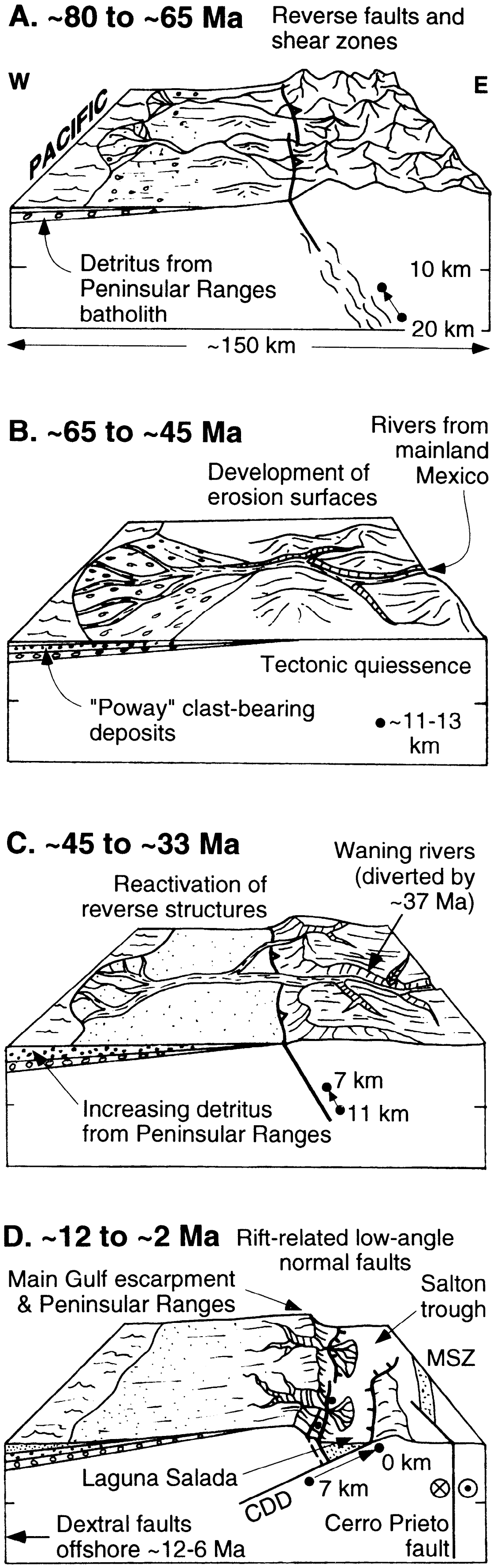
not yet been identified [*Gastil et al.*, 1975; *Romero-Espejel and Delgado-Argote*, 1997; *Romero-Espejel and Martín-Barajas*, 1998]. We believe that a significant structural break in the batholith follows the steep age gradient of biotite cooling ages that separates ages >88 Ma, to the west, from ages <78 Ma to the east (Figure 2) [e.g., Grove, 1994]. This age gradient locally coincides with the Chariot Canyon fault and a fault in Carrizo Gorge [*Grove*, 1994] (Figure 2). Furthermore, all of the above structures, as well as the age gradient, follow strong gradients in $\delta^{18}O$, $^{87}Sr/^{86}Sr$ initial ratios (Figure 2), and $^{143}Nd/^{144}Nd$ values. These chemical gradients, along with pre-batholithic trends, are thought to mark the eastern part of the transition zone between oceanic crust in the west and North American basement in the east [*Gromet and Silver*, 1987; *Silver and Chappel*, 1988, and references therein; *Gastil*, 1993]. Presumably, this zone is a weak lithospheric boundary underlying the Peninsular Ranges batholith.

Potential tectonic causes of late Eocene-early Oligocene denudation along the eastern Peninsular Ranges include (1) northward passage of the Mendocino and Pioneer fracture zones beneath the area [*Stock and Molnar*, 1988, Figures 2e to 2h], (2) the approach of the East Pacific Rise and arrival at the trench of progressively younger, more buoyant lithosphere, (3) global plate reorganizations reflected in the bend of the Hawaiian-Emperor seamount chain, (4) an Eocene decrease in Vancouver/Farallon-North American plate velocity, and (5) passage under the area of the Vancouver-Farallon plate boundary. Presently, there are too few relevant data to choose confidently among these, but we favor a combination of the first two options, both of which would lead to passage of younger, more buoyant subducted lithosphere beneath the region, potentially causing uplift. The Eocene decrease in plate velocities at ~50 Ma [*Stock and Molnar*, 1988] is too old to explain a 45-33 Ma event. Similarly, the Pacific hotspot velocity change that caused the bend in the seamount chain at ~43 Ma [*Clague and Dalrymple*, 1989] is not reflected in the Farallon/Vancouver-North American convergence rates, which did not change significantly in the interval of cooling from 45 to 33 Ma [*Stock and Molnar*, 1988]. Too little is known about

Table 2. Apatite Fission Track Data for Monte Blanco Dome

Sample	Elev., m	n	ρd	Nd	ρs	Ns	ρi	Ni	Age, Ma ±1 σ	$P(X^2)$, %	Mean track length, μm ±1 σ (number)
MX96-001	200	30	1.869	5573	0.068	137	4.960	9953	4.8±0.4	14	13.49±0.20 (53)
MX96-002	215	25	1.869	5573	0.047	41	2.856	2490	5.5±0.9	87	13.56±0.23 (43)
MX96-003	230	25	1.891	5573	0.023	35	1.438	2148	5.5±0.9	93	13.31±0.19 (55)
MX96-004	230	15	1.891	5573	0.062	27	3.753	1627	5.6±1.1	72	—
MX96-005	240	25	1.912	5573	0.072	89	4.747	5838	5.2±0.6	98	13.24±0.17 (100)
MX96-008	280	20	1.912	5455	0.096	82	7.204	6142	4.8±0.5	84	13.68±0.15 (100)

Abbreviations are Elev., sample elevation; n, number of crystals; ρd, induced track density in external detector adjacent to dosimetry glass (x 10^6 tracks per square centimeter); Nd, number of tracks counted in determining ρd; ρs, spontaneous track density (x 10^6 tracks per square centimeter); Ns, number of spontaneous tracks counted; ρi, induced track density in external detector (muscovite) (x 10^6 tracks per square centimeter); Ni, number of induced tracks counted; $P(\chi^2)$, χ^2 probability [*Galbraith*, 1981; *Green*, 1981]. Age is the sample central fission track age; central age given [*Galbraith and Laslett*, 1993] and calculated using zeta calibration method [*Hurford and Green*, 1983]. The following is a summary of key laboratory procedures. Samples were analyzed by D. F. Stockli (zeta value 356±8). All apatites were etched for 20 s in 5 N nitric acid at room temperature. Grains were dated by external detector method with muscovite detectors. The CN5 dosimetry glass was used as a neutron flux monitor. Samples were irradiated in well thermalized positions at the Oregon State University reactor. External detectors were etched in 48% HF. Tracks were counted with Zeiss Axioskop microscope with 100x air objective, 1.25x tube factor, 10x eyepieces, transmitted light with supplementary reflected light as needed; external detector prints were located with Kinetek automated scanning stage [*Dumitru*, 1993]. Confined tracks lengths were measured only in grains with *c* axes subparallel to slide plane; only horizontal tracks measured (within ±5-10°), following protocols of *Laslett et al.* [1982]. Lengths were measured with computer digitizing tablet and drawing tube, calibrated against stage micrometer [e.g., *Dumitru*, 1993].



the Vancouver-Farallon plate boundary to constrain its potential effects.

6. Late Miocene-Pliocene Exhumation

We attribute late Miocene-Pliocene cooling at Monte Blanco to tectonic exhumation of the footwall of the west directed Cañada David detachment (CDD) (Figure 9c). The detachment was active as recently as Plio-Pleistocene time, during deposition of Imperial and Palm Spring Formations [*Siem and Gastil*, 1994; *Stock et al.*, 1996; *Axen and Fletcher*, 1998]. The acceleration of cooling at ~15-10 Ma coincides with initial extension and rift-related volcanism nearby [*Martín-Barajas et al.*, 1995; *Lee et al.*, 1996] and with acceleration of the Pacific-North American plate rate at ~12 Ma [*Atwater and Stock*, 1998].

A thermokinetic finite difference model of normal faulting (modified from *Harrison et al.* [1995]) allows us to interpret the T-t history (Figure 8) in terms of the magnitude and duration of detachment slip. The model is two-dimensional, with a length of 100 km and a depth of 40 km. The upper surface is held at a constant temperature (20°C) and has an initial heat flux of 70 mW/m^2, the lower surface has constant heat flux (30 mW/m^2), heat production decays exponentially with depth over a scale length of 10 km, and lateral boundaries have zero heat flux, yielding an average geotherm of ~25°C/km in the upper 10 km [e.g., *Turcotte and Schubert*, 1982]. Modern surface heat flux ranges from 80 to >200 mW/m^2 in the Salton trough, and from 20 to >200 mW/m^2 in Laguna Salada, with both typically averaging around 100 mW/m^2 except locally; surface heat flux in the Peninsular Ranges is typically 50-80 mW/m^2 [*Lachenbruch et al.*, 1985; *Venegas and Alvarez*, 1994] and is probably representative of the initial conditions at Monte Blanco.

The fault is modeled using Couette flow in a 1-km-thick zone [*Turcotte and Schubert*, 1982]. We assume a constant 30° fault dip [*Axen and Fletcher*, 1998; *Axen et al.*, 1999] and

Figure 9. (opposite) Schematic block diagrams, viewed to the north, of the upper crust of peninsular California, showing the regional paleogeographic and structural evolution of Monte Blanco samples (solid circles). Surficial relief and thicknesses of sedimentary deposits and are exaggerated. (a) Reverse faults and ductile shear zones unroof the Peninsular Ranges batholith, while the subduction-related arc is far to the east due to low-angle subduction. (b) Tectonic quiessence prevails along the west coast as large rivers carry resistant cobbles from mainland Mexico, while the arc completes its eastward sweep across mainland Mexico. (c) Rejuvenated uplift, probably on older reactivated structures, raises the basement of Monte Blanco an additional 4+ km, disrupting extraregional rivers. By ~33 Ma, contraction in eastern Mexico had waned and was replaced by extension as the arc began its return migration westward. By ~24 Ma, the arc was reestablished in the region of the present gulf. Subduction along Baja California ended by 12 Ma. (d) Low-angle normal faulting related to proto-gulf and gulf rifting unroofs the Monte Blanco area. Strain was partitioned between normal faults of the rift and dextral faults offshore until about 6 Ma, when dextral faulting shifted into the gulf. CDD, Cañada David detachment; MSZ, Mexicali seismic zone.

Table 3. Apatite (U-Th)/He Data for Monte Blanco Dome

Sample	He, nmol/g	U, ppm	Th, ppm	F_t	Age ± 1σ, Ma
MX96-001	0.28	19.34	1.99	0.72	3.58 ± 0.50
MX96-008	0.63	35.29	0.96	0.80	4.12 ± 0.20

Apatite (U-Th)/He ages. F_t is the fraction of alpha particles retained, as calculated using the technique described by *Farley et al.* [1996]. The apatites in sample MX96-001 had mean prism diameter and length of 85 and 145 μm, respectively. Comparable values for MX96-008 were 120 and 165 μm.

neglect frictional heating. Material is instantaneously eroded from the uplifting footwall so that no topography is created. The sample was positioned 2 km horizontally from the fault, but model cooling histories are all very similar within 5 km horizontal distance from the fault.

Starting temperature of each model run was determined from the upper limit given by the 90% confidence interval calculated for the median of the distribution of acceptable thermal histories from K feldspar MDD results (Figure 8). The cooling paths were required to pass through the apatite fission track and (U-Th)/He data, and to arrive at 20°C at about 2 Ma (Figure 8). Runs were not considered that began after 8 Ma, when the most recent major change in Pacific-North American relative plate rates occurred [*Atwater and Stock*, 1998], nor before 15 Ma, when the K feldspar model results show slow cooling. Three models were run with single, constant fault slip rates of 1.8, 1.5, and 1.2 km/m.y. beginning at 8.25, 9.75, and 12 Ma, respectively. One model was run using two slip rates: 0.75 km/m.y. from 15 to 7.8 Ma and 1.5 km/m.y. after 7.8 Ma. It was impossible to start at 15 Ma and fit all the data with a single-rate model.

About 11-14 km of detachment slip is required between 15-8 Ma and 2 Ma in order to fit the available T-t data, equivalent to ~10-12 km of horizontal extension and ~5-7 km of unroofing of the Monte Blanco samples. (Larger amounts correspond to slower slip rates and longer model run duration.) Additional extension may have occurred after the samples reached the surface and the apatite thermochronometers were closed, but it is poorly constrained and not required. Thus, Monte Blanco probably restores ~12 km west, under present central Laguna Salada basin. The preextension conditions of the Monte Blanco rocks (~5-7 km depth at ~175-200°C) are consistent with the brittle nature of the detachment faults.

Horizontal extension rates during the last few million years of the thermal-kinematic models are ~1 to 1.6 mm/yr, consistent with less well constrained extension rates determined for the past 60 ka [*Axen et al.*, 1999]. These rates are only ~25% to 40% of the ~4 mm/yr extension rate across Laguna Salada, based upon 13 years of geodolite measurements [*Savage et al.*, 1994]. If our modeled, long-term average rates for CDD-related extension are correct, then it seems likely that other active faults may make up the difference. Locally, faults along the west side of the Laguna Salada basin cut Quaternary deposits [*Gastil et al.*, 1975; *Axen and Fletcher*, 1998]; also, faults mapped within the Sierra Juárez escarpment and the Sierra Las Tinajas [*Gastil et al.*, 1975; *Mendoza-Borunda et al.*, 1995; *Romero-Espejel and Delgado-Argote*, 1997] may be active; the former are recognizable largely due to fault-related morphologies such as triangular facets. These faults may lie entirely within the hanging walls of the CDD (south) and Laguna Salada (north) "master" faults and so may indicate that slip rate on the latter faults increases with depth, corresponding to larger net slip on the master faults at depth. The Laguna Salada fault east of Monte Blanco did not break in the 1892 earthquake [*Mueller and Rockwell*, 1995] but does cut Quaternary deposits; its effect on the geodetic strain rate budget is unclear.

It is possible that the horizontal extension rates increased significantly after ~2 Ma, from the long-term, detachment-model rate (~12 to ~2 Ma) to the geodetically determined modern rate. Our results also allow, but do not require, an earlier increase of detachment-related cooling rate, slip rate, and horizontal extension rate at ~8 Ma. At that time, the Pacific-North American plate motion vector rotated clockwise from ~300° to ~323° with no corresponding change of speed [*Atwater and Stock*, 1998], so the extensional (margin-perpendicular) component of the relative plate velocity decreased, while the slip rate on the detachment either increased or remained constant.

The following mutually compatible mechanisms may explain this contradictory relationship between decreasing extensional (margin-perpendicular) component of the relative plate motion vector and constant or increasing extension rate in Laguna Salada. (1) There was no simple causative relationship between the plate margin velocity change and the detachment slip rate, in spite of the facts that the Cañada David detachment is the westernmost major extensional structure at this latitude and is rooted beneath the stable continental margin. This conclusion seems unavoidable. (2) The mechanical coupling between the Pacific plate and Baja California was not fully established until ~8 Ma. However, by ~12 Ma the extensional component of relative plate velocity was at its maximum, and to date, there is no evidence of strong, late Miocene extension in western offshore Baja California. Lacking such evidence, it is probably valid to assume that the continental margin, at least outboard of the San Benito-Tosco-Abreojos fault system, was coupled to the Pacific plate. (3) Local boundary conditions (e.g., changing local strain partitioning [see *Lewis and Stock*, 1998]) may have overridden plate margin control of detachment slip rate. Too few data are available to evaluate this fully, but some considerations favor its importance. Strong dextral plate margin slip may have started to shift into the gulf by 8 Ma and may have been fully established there by 6 Ma [*Dickinson*, 1996; *Ingersoll and Ru-*

melhart, 1999], at which time the transfer of Baja Califonia to the Pacific plate was probably essentially complete. However, spreading centers were not likely to have been well developed in the gulf at that time, so other structures, such as the Cañada David detachment, would necessarily have accommodated the extensional strain. (4) On the scale of the entire southern Basin and Range, strain became concentrated into the gulf region, causing the extension rate to increase there. This seems likely because strain rates in much of the Basin and Range of southeastern California [e.g., *Davis*, 1988] and western Arizona [e.g., *Spencer et al.*, 1995], and probably northern Mexico as well [e.g., *Gans*, 1997], had slowed dramatically by 8 Ma. This would also accentuate the effects described in mechanism 3.

7. Conclusions

Integrated $^{40}Ar/^{39}Ar$, fission track, and (U-Th)/He dating of samples from Monte Blanco dome reveals the following thermal tectonic history. Slow cooling (~1°C/m.y.) from ~330° to ~315°C at 65-45 Ma reflects tectonic quiescence also recorded by Paleogene erosional surfaces and extraregional river deposits. Cooling from ~315°C to ~215°C occurred at an increased rate of ~10°C/m.y. between 45 and 33 Ma, which we relate to at least 3-4 km of uplift. This uplift may have affected a belt of rocks presently along the eastern Peninsular Ranges and adjacent desert regions and was probably caused by east-side-up reactivation of preexisting structures. During the early part of this event, deposition of extraregional clasts in the western Peninsular Ranges waned, ending about 37±2 Ma [*Walsh*, 1998]. Subsequent deposition on the coastal plain was of sediment derived from local, Peninsular Ranges rock types only. This probably reflects incision of the uplift by the beheaded large rivers along with local streams. Cooling returned to very low rates until ~10-15 Ma, when detachment faulting began to exhume deep crustal rocks of the Monte Blanco dome at vertical rates of the order of 1 mm/yr and horizontal rates of ~1 to 1.6 mm/yr, less than half of the geodetically measured extension rate across Laguna Salada [*Savage et al.*, 1994]. Final unroofing occurred in the Pleistocene. The horizontal extension accommodated by detachment faulting was ~10-12 km, with a vertical component of ~5-7 km.

It is interesting to note that the coastal plain stratigraphy of San Diego and northern Baja California shows little in the way of tectonic uplift or downdrop. Shoreline deposits are found in Upper Cretaceous, Paleocene, Eocene, Oligocene, Miocene, Pliocene, and Pleistocene sedimentary rocks. This relative stability of the coastal plain stands in marked contrast to the prodigious uplifts that occurred just 60 km to the east during Late Cretaceous, Eocene, and Miocene-Pliocene time.

The Cañada David detachment unroofed basement rocks from an unusually deep crustal level, thus providing a unique record of Tertiary thermal events along the continental margin. Thermochronologic results reveal a late Eocene-early Oligocene uplift event along the eastern Peninsular Ranges and underscore the importance of detachment faulting in northern Gulf of California tectonics. We tentatively relate late Eocene-early Oligocene uplift to subduction of buoyant oceanic lithosphere. It appears likely that constant or increasing slip rate on the Cañada David detachment between ~12 and ~2 Ma, which was ultimately caused by the transfer of Baja California to the Pacific plate [e.g., *Stock and Hodges*, 1989], was accentuated by local strain partitioning effects and by regional concentration of extensional strain from the width of the Basin and Range into the narrower Gulf of California region.

[1]Supporting Appendices A and B are available on diskette or via Anonymous FTP from kosmos.agu.org, directory APEND (Username = anonymous, Password = guest). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009 or by phone at 800-966-2481; $15.00. Payment must accompany order.

Acknowledgments. Funded by grants from UC MEXUS and UCLA Committee on Research to Axen, from DOE to T.M. Harrison (DE-FG-03-89ER14049), from CONACYT to Fletcher (4345-PT), and a Stanford University McGee grant to Stockli. We thank T. Dumitru for helpful discussions and E. Campbell-Stone and P. Umhoefer for thoughtful reviews.

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P. L. Abbott, Department of Geological Sciences, San Diego State University, San Diego, CA 92181-1020 (pabbott@geology.sdsu.edu).

G. J. Axen, M. Grove, O. M. Lovera, and D. A. Rothstein, Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095-1567 (gaxen@ess.ucla.edu; marty@argon.ess.ucla.edu; lovera@argon.ess.ucla.edu).

K. Farley and D. Stockli, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125 (farley@gps.caltech.edu; stockli@gps.caltech.edu).

J. M. Fletcher, Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, México (jfletche@cicese.mx).

(Received April 19, 1999;
revised September 30, 1999;
accepted October 29, 1999.)