Heterogeneous Neogene cooling and exhumation of the Los Cabos block, southern Baja California: Evidence from fission-track thermochronology

John M. Fletcher* Centro de Investigación Científiica y de Educación Superior de Ensenada, Baja California, México
Barry P. Kohn Victorian Institute of Earth and Planetary Sciences, School of Earth Sciences, University of Melbourne, Parkville, Victoria 3052, Australia
David A. Foster Department of Geology, University of Florida, Gainesville, Florida 32611, USA, and Department of Earth Sciences, La Trobe University, Melbourne, Australia
Andrew J. W. Gleadow Victorian Institute of Earth and Planetary Sciences, School of Earth Sciences, University of Melbourne, Parkville, Victoria 3052, Australia

ABSTRACT

The Los Cabos block is a massif of Mesozoic crystalline basement at the southern tip of the Baja California Peninsula and has long been considered a distinct tectonostratigraphic terrane separated from the rest of the peninsula by the La Paz fault along its western margin. Although the region is cut by an extensive array of active north-northwest–striking normal faults, none of them correspond to the proposed La Paz fault. The largest fault in the array and arguably one of the dominant Neogene structures in the Gulf extensional province is the San José del Cabo fault, which is an east-dipping normal fault that has a strike length of ~150 km, a topographic escarpment in excess of 1000 m, and forms the eastern limit of the Los Cabos block.

Apatite and zircon fission-track data demonstrate a marked difference in Neogene tectonism between the two margins of the Los Cabos block. Samples from the western margin, in the footwall of the proposed La Paz fault, indicate rapid Paleocene cooling (~20 °C/m.y.), followed by essentially slow monotonic cooling (~2–3 °C/m.y.) through the Tertiary. In contrast, samples from the eastern margin, in the footwall of the San José del Cabo fault, record rapid cooling (to ~45 °C/m.y.) related to tectonic exhumation across the fault commencing in the mid-Miocene (~10–12 Ma), when the sampled rocks were at ~150 °C. The San José del Cabo fault accommodated ~5.2–6.5 km of exhumation at rates as high as ~1.5–2 mm/yr, but averaged 0.4–0.7 mm/yr.

Continental rifting in the southern Gulf extensional province postdated the southward passage of the Rivera triple junction (ca. 12 Ma), which implies that driving forces were likely dominated by far-field plate kinematics and coupling between the Pacific, Farallon, and North America plates. This continental rifting has persisted through many inferred reconfigurations of plate motion: northward rotation of relative-motion vector (8 Ma), eastward migration of wrenching from the Pacific to the Gulf extensional province (6 Ma), and onset of sea-floor spreading (3.6 Ma).

Keywords: Gulf of California, fission-track dating, Los Cabos block, La Paz fault, San José del Cabo fault.

INTRODUCTION

The peninsula of Baja California is a 1200-km-long sliver of continental crust that has been undergoing transfer from the North American plate to the Pacific plate since the Miocene. This separation has largely occurred across the Gulf extensional province, which is principally defined by an axial array of en echelon transforms linked by narrow spreading centers, but also includes a broader network of faults distributed throughout the Gulf extensional province (Fig. 1). According to the modified NUVEL-1A (DeMets and Dixon, 1999), Euler vectors of relative plate motion are oriented only 12°–17° more westerly than the axis of the Gulf of California, making the Gulf extensional province unrivaled as the most highly oblique rift in the world.

Numerous processes, like those suggested for the rest of western North America, could have contributed to produce extension in the Gulf extensional province, including (1) gravitational collapse of crust that was overthickened by contractional orogenesis and emplacement of the Late Cretaceous batholith (e.g., Coney and Harms, 1984), (2) the Oligocene decrease in convergence rates and removal of the shallowly subducted Farallon slab (e.g., Severinghaus and Atwater, 1989), (3) backarc extension associated with early to middle Miocene volcanism (e.g., Karig and Jensky, 1972), and (4) microplate coupling that resulted from the termination of Pacific-Farallon spreading (e.g., Nicholson, 1994; Bohannon and Parsons, 1995), which occurred around 12 Ma in southern Baja California. Each of these processes likely would have affected the Gulf extensional province at different times. Therefore, our understanding of the driving forces of highly oblique extension depends on knowledge of the onset of extension in the Gulf extensional province. However, because the transtensional deformation is ongoing, it is difficult to isolate critical crosscutting relationships that define the onset of extension in the Gulf extensional province. Commonly, mid-Tertiary rocks showing key crosscutting relationships have been stripped from the uplifted footwalls or buried in the hanging-wall basins.

In this study we use apatite and zircon fission-track thermochronology to define the cooling history over the last ~250 °C of rocks exposed in the Los Cabos block, a massif of Mesozoic crystalline rocks located in southernmost Baja California of the southern Gulf extensional province, Mexico (Fig. 1). The regional distribution of our sample suite allows temperature to be used as a proxy for relative depth and thus the reconstructed thermal histories provide an effective approach for elucidating rock-exhumation histories. We report the discovery of strongly heterogeneous Neogene cooling and uplift of the complex. Moreover, our geologic and thermochronologic data help constrain the timing of the onset of extension, and challenge well-developed ideas on the Neogene slip history of faults in the southern Gulf extensional province. This study demonstrates the power of low-temperature thermochronology to identify important fault zones, define limits of highly extended regions, and address process-oriented tectonic problems in the Gulf extensional province.

LOS CABOS BLOCK

The Los Cabos block is found at the southern extreme of the Baja California Peninsula and is composed of Mesozoic batholithic rocks that form mountains as high as 2000 m (Fig. 1). Plutonic rocks range from orthopyroxene-bearing

*E-mail: jfletche@cicese.mx.

*Data Repository item 200016 contains additional material related to this article.

gabbro to peraluminous granite and prebatholithic metasedimentary rocks have been extensively migmatized and metamorphosed at upper amphibolite facies conditions. The geochronology of the plutonic rocks is poorly known, but a large tonalite pluton yielded a hornblende K-Ar age of 115 Ma (Hausback, 1984), and the Los Cabos block is generally thought to represent an isolated exposure of the Cretaceous batholith found throughout the Cordillera of western North America.

Western Margin

The uplifted granitic basement of the Los Cabos block contrasts markedly with the rest of Baja California Sur, which is dominated by gently dipping strata of the Miocene volcanic arc and rarely exceeds 500 m in elevation (Fig. 1). This radical change in geology and physiography has led numerous workers to propose that a major fault, called the La Paz fault by Beal (1948), exists along the western margin of the Los Cabos block (Fig. 1). More recently, workers have assigned to the La Paz fault a major role in the Neogene tectonic evolution of the Gulf of California. In addition to separating distinct tectonostratigraphic terranes (Sedlock et al., 1993), the La Paz fault is thought to have accommodated a suturing of the Los Cabos block to the Baja California Peninsula (Hausback, 1984). In addition, much of the offshore seismic activity around southern Baja California has been proposed to be associated with the northern and southern extensions of the La Paz fault (e.g., Molnar, 1973; Munguía, 1995). Hausback (1984) correlated the La Paz fault with a prominent lineament in satellite images and suggested that it was a long-lived structure that created a topographic buttress, which diverted paleodrainages, inhibited deposition of Miocene volcanic material to the east, and accommodated 50 km of sinistral displacement of Miocene arc facies.

Geologic studies along the western margin of the Los Cabos block have not confirmed the existence of the La Paz fault as defined by Hausback (1984). Along most of its length, the prominent satellite lineament is a Mesozoic igneous contact between strongly foliated tonalitic gneisses to the west and a large pluton of megacrystic K-feldspar granite to the east (Aranda-Gómez and Pérez-Venzor, 1988; Ramos-Velázquez, 1998). Given the general lack of faulting along the lineament, Aranda-Gómez and Pérez-Venzor (1988) inferred that the main strand of the La Paz fault must be beneath the alluvial fans to the west of the range front. However, the geomorphic expression of the western range front is very sinuous, with wide arroyos and discrete alluvial fans that penetrate many kilometers into the range, which indicates that the range front is not controlled by a Neogene fault (Fig. 1). In addition, volcanic flows and epiclastic deposits have been found in depositional contact on crystalline basement in two locations along the western margin of the Los Cabos block (Hausback, 1984; Ramos-Velázquez, 1998). Strata found west of Sierra El Novillo are inferred to be early Miocene (Schwennicke et al., 1996) and thus there need not be any significant uplift of the granitic basement relative to the main exposure of the west-dipping Miocene volcanogenic sequence found to the west of the range front (Fig. 1).

Eastern Margin

The eastern limit of the Los Cabos block has not been clearly defined by previous workers and Mesozoic granitic rocks extend to the easternmost outcrops on the Baja California Peninsula (Fig. 1). However, a principal result of this study is the discovery of the dominant role of the San José del Cabo fault in the Neogene tectonic evolution of the region, and we consider it to be an important tectonic boundary that best defines the eastern limit of the Los Cabos block. The San José del Cabo fault extends 80 km from the Pacific Ocean to the Gulf of California and controls an abrupt range-front escarpment, with more than 1000 m of relief (Fig. 1). Natural cross sections of the fault can be found in numerous arroyos and canyons that cut into the range front (Fig. 2). The fault zone ranges to 200 m thick and is typically defined by an east-dipping high-angle fault that places alluvial deposits against strongly brecciated crystalline basement. Crystalline rocks in the immediate footwall are penetratively fractured and foliated clay gouge defines zones of high shear strain. Pliocene-Pleistocene boulder conglomerates deposited in high-gradient alluvial fans are consistently cut by the fault and dip 10°–20° toward the range. A distinctive yellowish sandstone unconformably overlies the back-rotated conglomerates and commonly postdates faulting. However, even this deposit and its upper alluvial terrace are cut by a Quaternary fault scarp that extends more than 10 km along the fault trace, north of San José del Cabo (Fig. 1). In April 1969, two earthquakes ($M_s > 5.0$) occurred east of Isla Cerralvo (Molnar, 1973), which we interpret to be the offshore extension of the San José del Cabo fault. Fault striae, offset geomorphologic features, and earthquake focal mechanisms all indicate that the San José del Cabo fault has accommodated a protracted history of normal displacement with almost no strike-slip component.

APATITE AND ZIRCON FISSION-TRACK RESULTS AND THERMAL MODELING

In order to more fully evaluate the significance of the radical differences in tectonic and geomorphologic character of the margins of the Los Cabos block, six samples were collected for apatite and zircon fission-track analyses: three from the western margin in what is considered to be footwall of the proposed La Paz fault and three from the eastern margin in the immediate footwall of the San José del Cabo fault (Fig. 1). Sample locations, radial grain-age plots, track-length histograms and other analytical details are available (Figs. Ia and Ib, Table I)[1].

The western margin samples yield zircon and apatite fission-track ages, which for each mineral are concordant (within analytical error at ±1 σ) and range between 62 and 63 Ma and 48 and 53 Ma, respectively (Table 1). Mean track lengths for apatite are between 12.74 and 13.02 μm and standard deviations of the track-length distributions are between 1.58 and 1.88 μm. Samples from the eastern margin yield zircon and apatite fission-track ages, which are also concordant for each mineral type (within analytical error at ±1 σ), but are considerably younger, i.e., 43–46 Ma and 9–10 Ma, respectively (Table 1). Mean apatite track lengths, between 13.69 and 14.02 μm, are longer than those recorded for the western margin, and standard deviations of their track-length distributions range between 1.46 and 1.92 μm.

Combining apatite fission-track age and confined-track length data with geologic information permits rigorous constraints to be placed on the low-temperature thermal histories of rocks in the Los Cabos block. The annealing model and algorithms of Laslett et al. (1987) and the approach of Gallagher (1995) were employed to derive time-temperature paths for the western and eastern blocks for the portion of the cooling history <110 °C. Zircon closure-temperature estimates of 240 ± 15 °C and 220 ± 10 °C were used for the western and eastern blocks, respectively (e.g., Hurford, 1986; Brandon et al., 1998). These reflect the different cooling rates that the blocks underwent when they passed through the zircon closure temperature (Fig. 3).

The fission-track data suggest strongly contrasting cooling histories for the western and eastern margins of the Los Cabos block (Fig. 3), the latter representing rocks recently exhumed from a significantly deeper crustal level. The western block underwent relatively rapid cooling during the Paleocene (ca. 61–63 Ma), from paleotemperatures of at least ~240 ± 15 °C. Modeling of the apatite fission-track data suggests two possible cooling paths below ~110 °C (1a and 1b, Fig. 3). However, it is clear that the rocks had cooled to at least ~95 ± 5 °C by ca. 56 Ma, at an average rate of ~20 °C/m.y. Cooling may then have continued into the early Eocene (path 1b) to paleotemperatures <50 °C, followed by middle Eocene heating and subsequent continued slow cooling to the present. Alternatively, model 1a suggests that the Paleocene cooling episode was followed by a period of middle Eocene stability and slow cooling through the Tertiary at an average rate of ~2–3 °C/m.y., with a possible phase of slightly

[1] GSA Data Repository item 200016, Fission-track data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org or at www.geosociety.org/pubs/drpint.htm.

accelerated cooling in the early-middle Miocene. The eastern margin apatite fission-track data indicate that samples resided at paleotemperatures >110 °C prior to an episode of rapid middle Miocene cooling (Fig. 3) in the middle to late Miocene. Zircon fission-track data show that during the middle Eocene (ca. 43–46 Ma) rocks of the eastern margin resided at a paleotemperature of ~220 ± 10 °C, which was at least 125 °C hotter than rocks from the western margin.

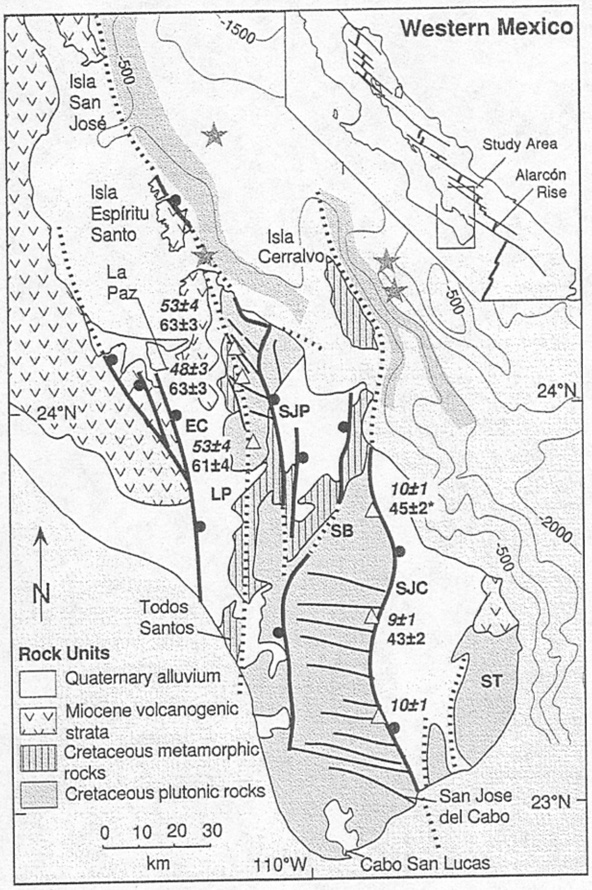

Figure 1. Schematic geologic map of La Paz–Los Cabos region showing distribution of fission-track samples (triangles) and ages (apatite = italic, zircon = regular, asterisk = mean of two measurements) from Los Cabos block. Stars are epicenters of earthquakes with Ms > 5. Bathymetric contour interval is 500 m and fault-controlled bathymetric escarpments are darker blue. EC = El Carrizal fault, LP = proposed La Paz fault, SB = San Bartolo fault, SJP = San Juan de los Planes fault, SJC = San José del Cabo fault, ST = Sierra Trinidad.

DISCUSSION AND CONCLUSIONS

Regional Cooling Paths

Rapid Paleocene cooling indicated by western margin samples is most likely attributed to in situ cooling of the Cretaceous batholith and/or post-plutonic tectonism. In the Los Cabos block, greenschist facies mylonite zones crosscut the youngest plutons related to the Cretaceous batholith. These shear zones typically dip shallowly to the east and accomplish normal displacement, but left-lateral east-striking mylonite zones also have been observed (Ramos-Velázquez, 1998). Although the shear zones are not widespread, deformation mechanisms indicate that they were active over the correct temperature range and could have contributed to the Paleocene cooling.

Regional geologic relations strongly favor the slow near-monotonic cooling path 1a over 1b (Fig. 3). First, no evidence for the middle Eocene heating of path 1b, which would require magmatism and/or burial (tectonic or depositional), has been identified. Early Tertiary marine sedimentation of the Tepetate Formation is observed 70 km to the west of La Paz, but this unit thins rapidly to the east and is not present in the region of the Los Cabos block (Gastil et al., 1979; Hausback, 1984). The Tepetate Formation is composed of interbedded mudstone and fine-grained sandstone and typically lacks synorogenic conglomerates, which is consistent with sedimentation during slow monotonic uplift of its source area to the east. In addition, the presence of early Miocene strata depositionally overlying crystalline basement suggests that rocks of the western margin had reached the surface by the early Miocene. Therefore, both field relations and thermal modeling strongly indicate that no Neogene fault is required to explain the exhumation history of the western margin of the Los Cabos block. This is consistent with the high range-front sinuousity and lack of geomorphologic evidence for a transpeninsular fault, such as the proposed La Paz fault, along the western margin of the Los Cabos block.

In contrast, rocks of the eastern margin resided at depths below the partial annealing zone of apatite, where temperatures exceeded 110 °C, until as late as the middle Miocene, at which time they were cooling rapidly in response to uplift in the footwall of the San José del Cabo fault. Path 2 indicates that the eastern margin samples underwent cooling rates as high as ~45 °C/m.y., but the rates greatly diminished by latest Tertiary–Qua-

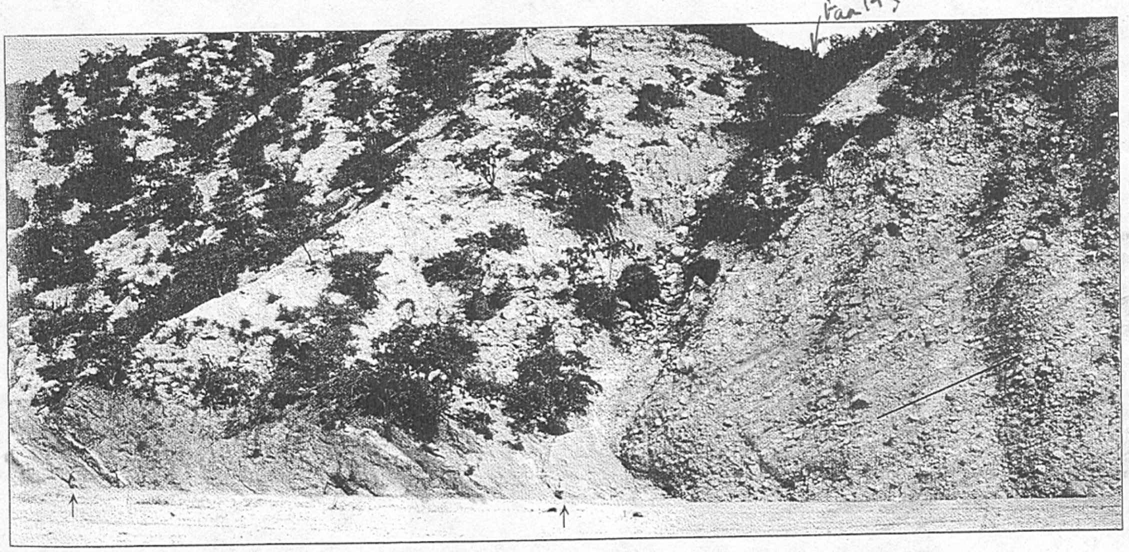

Figure 2. San José del Cabo fault looking north-northwest. Pliocene-Pleistocene boulder conglomerates, dipping 15°, are faulted against cataclastic crystalline basement. Darker laminated rock in footwall is foliated clay gouge. Upper yellow deposit is late Quaternary sandstone that overlaps fault at this locality. Arrows identify geologists on arroyo floor. Black line defines stratification of boulder conglomerate and is ~15 m.

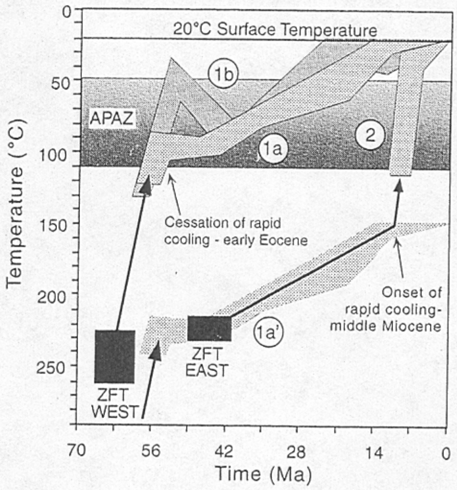

Figure 3. Time-temperature cooling envelopes for eastern and western blocks as determined from modeled apatite fission-track (FT) data and zircon FT ages. Two possible cooling paths (1a and 1b) are compatible with apatite FT data derived for western margin. Path 2 is compatible with apatite FT data from eastern margin. Path 1a′ is not direct result of modeling, but is simply path 1a projected through eastern margin zircon data. APAZ is apatite FT partial-annealing zone. Cooling history is poorly constrained for temperatures below 50 °C due to slow FT annealing rates. ZFTs represent estimated range of closure temperature for fission tracks in zircons in western and eastern blocks.

ternary time. The total magnitude and onset of the rapid middle Miocene cooling can be estimated by assuming that samples from both margins of the Los Cabos block followed the same relative cooling trajectory during the middle Eocene to the middle Miocene, albeit at different crustal depths. That is, the intersection between cooling path 2 and 1a′, which is the projection of path 1a through the zircon data from the eastern margin, gives a paleotemperature of ~150 °C prior to the onset of rapid middle Miocene cooling (Fig. 3). Assuming a regional geothermal gradient of 20–25 °C/km (and a surface temperature of ~20 °C), we estimate that the footwall of the San José del Cabo fault has accommodated ~5.2–6.5 km of Neogene uplift at a maximum rate of ~1.5–2 mm/yr and an average rate of 0.4–0.7 mm/yr.

Tectonic Implications

Continental rifting along the western margin of the southern Gulf extensional province has produced an array of north-northwest–striking normal faults that are currently active. Zircon and apatite fission-track data indicate that the onset of continental rifting coincided approximately with the southward passage of the Rivera triple junction (ca. 12 Ma), which implies that crustal extension most likely was triggered by far-field stresses generated by lithospheric-plate kinematics and coupling between the Pacific and North America plates through partially subducted microplates of the former Farallon slab (e.g., Bohannon and Parsons, 1995). The Gulf margin normal faults accomplish east-northeast extension at a high angle to the rift margin, and the kinematics of faulting have not changed throughout many inferred reconfigurations of plate motion, including the northward rotation of the relative-motion vector at 8 Ma (Atwater and Stock, 1998), the eastward migration of Pacific–North America wrenching from the Tosco-Abreojos fault to the Gulf extensional province ca. 6 Ma (Lonsdale, 1989), and the onset of sea-floor spreading at 3.6 Ma (DeMets, 1995). However, the Pliocene-Pleistocene reduction in cooling rate and inferred tectonic exhumation, as defined by path 2 of the thermal modeling, may mark the onset of sea-floor spreading at the Alarcón rise (Fig. 1).

ACKNOWLEDGMENTS

This work was funded by Consejo Nacional de Ciencia y Tecnología (grants 4345PT, 26750T), the Australian Research Council, and the Australian Institute of Nuclear Science and Engineering. Joann Stock and Brian Hausback provided insightful reviews. Ernesto Ramos-Velázquez and Ramón Mendoza-Borunda assisted in field work. José Mojarro and Luis Gradilla assisted in figure preparation. José Antonio Pérez-Venzor, Jorge Aranda-Gómez, and Gerardo Gonzales-Barba helped focus the study.

REFERENCES CITED

Aranda-Gómez, J. J., and Pérez-Venzor, J. A., 1988, Estudio Geologico de Punta Coyotes, Baja California Sur: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 7, p. 1–21.

Atwater, T., and Stock, J. M., 1998, Pacific–North America plate tectonics of the Neogene southwestern United States: An update: International Geology Reviews, v. 40, p. 375–402.

Beal, C. H., 1948, Reconnaissance geology and oil possibilities of Baja California, Mexico: Geological Society of America Memoir 31, 138 p.

Bohannon, R. G., and Parsons, T., 1995, Tectonic implications of post-30 Ma Pacific and North American relative plate motions: Geological Society of America Bulletin, v. 107, p. 937–959.

Brandon, M. T., Roden-Tice, M. K., and Garver, J. I., 1998, Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State: Geological Society of America Bulletin, v. 110, p. 985–1009.

Coney, P. J., and Harms, T. A., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550–554.

DeMets, C., 1995, A reappraisal for seafloor spreading lineations in the Gulf of California: Implications for the transfer of Baja California to the Pacific plate and estimates of Pacific–North America plate motion: Geophysical Research Letters, v. 22, p. 3545–3548.

DeMets, C., and Dixon, T., 1999, New kinematic models for Pacific–North America motion from 3 Ma to present: Evidence for steady motion and biases in the NUVEL-1A model: Geophysical Research Letters, v. 26, p. 1921–1924.

Gallagher, K., 1995, Evolving temperature histories from apatite fission-track data: Earth and Planetary Science Letters, v. 136, p. 421–435.

Gastil, R. G., Krummenacher, D., and Minch, J., 1979, The record of Cenozoic volcanism around the Gulf of California: Geological Society of America Bulletin, v. 90, p. 839–857.

Hausback, B. P., 1984, Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico, *in* Frizzell, V. A., ed., Geology of the Baja Peninsula: Society of Economic Paleontologists and Mineralogists Special Paper 39, p. 219–236.

Hurford, A. J., 1986, Cooling and uplift patterns in the Lepontine Alps, south-central Switzerland, and an age of vertical movement on the Insubric fault line: Contributions to Mineralogy and Petrology, v. 92, p. 413–427.

Karig, D. E., and Jensky, W., 1972, The Proto-Gulf of California: Earth and Planetary Science Letters, v. 17, p. 169–174.

Laslett, G. M., Green, P. F., Duddy, I. R., and Gleadow, A. J. W., 1987, Thermal annealing of fission tracks in apatite 2. A quantitative analysis: Chemical Geology, v. 65, p. 1–13.

Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California, *in* Winterer, E. L., et al., eds., The eastern Pacific Ocean and Hawai: Boulder, Colorado, Geological Society of America, Geology of North America, v. N, p. 499–521.

Molnar, P., 1973, Fault plane solutions of earthquakes and direction of motion in the Gulf of California and on the Rivera Fracture Zone: Geological Society of America Bulletin, v. 84, p. 1651–1658.

Munguía, L., 1995, El temblor de La Paz, Baja California Sur, del 30 de Junio de 1995: Informe Técnico, Centro de Investigación Científica y de Educación Superior de Ensenada, 23 p.

Nicholson, C., 1994, Microplate capture, rotation of the Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system: Geology, v. 22, p. 491–495.

Ramos-Velázquez, E., 1998, Características de la deformación en las rocas cristalinas cretácicas al este sureste de la ciudad de La Paz, BCS México [Master's thesis]: Ensenada, CICESE–Centro de Investigación Científica y de Educación Superior de Ensenada.

Schwennicke, T., Gonzales-Barba, G., and DeAnda-Franco, N., 1996, Lower Miocene marine and fluvial beds at Rancho La Palma, Baja California Sur: Boletin del Departamento Geologico de la Universidad de Sonora, v. 13, p. 1–14.

Sedlock, R. L., Ortega-Gutierrez, F., and Speed, R. C., 1993, Tectonostratigraphic terranes and tectonic evolution of Mexico: Geological Society of America Special Paper 278, 153 p.

Severinghaus, J., and Atwater, T., 1989, Cenozoic geometry and thermal condition of the subducting slabs beneath western North America, *in* Wernicke, B., ed., Basin and Range extensional tectonics near the latitude of Las Vegas: Geological Society of America Memoir 176, p. 1–22.

Manuscript received August 3, 1999
Revised manuscript received November 10, 1999
Manuscript accepted November 17, 1999

Printed in U.S.A.