Range-front fault scarps of the Sierra El Mayor, Baja California: Formed above an active low-angle normal fault?

Gary J. Axen* Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA
John M. Fletcher Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, Mexico
Eric Cowgill, Michael Murphy, Paul Kapp, Ian MacMillan — Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA
Ernesto Ramos-Velázquez Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, Mexico
Jorge Aranda-Gómez Unidad de Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, Querétaro, México

ABSTRACT

The Cañada David detachment, a west-dipping low-angle normal fault, juxtaposes Pliocene and Pleistocene(?) sedimentary units over sheared bedrock in the Sierra El Mayor, Baja California. Along the west-central range front, the detachment is overlapped by Quaternary alluvial fans that are, in turn, cut by fault scarps up to 7 m high. Map relationships suggest that scarp-forming faults may sole into the detachment at very shallow depth (<200–300 m). Palinspastic restoration of a topographic profile across 15 north-striking scarps suggests that the ratio of net heave to net throw along scarp-forming faults is ~2, consistent with them soling into a low-angle (~30°) fault. These 15 scarps may have all formed in one earthquake, with rupture propagation from depth to the near-surface aided by clay gouge along the detachment. The detachment is abandoned in the footwall east of the scarps.

INTRODUCTION

Tertiary low-angle normal, or detachment, faults are common in western North America (e.g., Armstrong and Ward, 1991) and worldwide (e.g., Selverstone, 1988; Burchfiel et al., 1992). Many were active at dips < 30° (John, 1987; Axen, 1993; many others). In spite of compelling geologic and seismic reflection evidence for low-angle normal slip, low-angle normal earthquake focal mechanisms are rare (e.g., Jackson, 1987; Wernicke, 1995; Abers et al., 1997).

We present geologic evidence for active slip along a low-angle normal fault in northeastern Baja California, where relative plate motion is partitioned between northwest-striking dextral faults and distributed east-west extension (Gastil et al., 1975; Stock and Hodges, 1989; Savage et al., 1994).

The Sierra El Mayor lies between a principal dextral plate-boundary fault (CP, Fig. 1) and the sub-sea level Laguna Salada basin. The basin is bounded on the northeast by the dextral- and normal-slip (west-down) Laguna Salada fault, which broke in 1892 (Mueller and Rockwell, 1995). The rupture followed the normal, west-down Cañon Rojo fault, ending near Sierra El Mayor range-front fault scarps (Fig. 1). The Laguna Salada fault is inactive southeast of the Cañon Rojo fault.

Two late Miocene-Pleistocene(?) detachment faults divide the Sierra El Mayor into three plates: a lower plate of migmatitic gneiss intruded by Mesozoic granitic rocks, a middle plate of metasedimentary rocks and Mesozoic intrusions depositionally overlain by sedimentary strata, and an upper, sedimentary plate (Fig. 1; Axen and Fletcher, 1998; Axen et al., 1998a). The Cañada David detachment separates the middle and upper plates and dips gently west under Pliocene-Pleistocene(?) strata along the western range front (Carter, 1977; Siem and Gastil, 1994; Vázquez-Hernández et al., 1996; Axen and Fletcher, 1998), rooting west under Laguna Salada (Axen, 1995). The footwall yields latest Tertiary $^{40}Ar/^{39}Ar$, fission-track, and (U-Th)/He cooling ages (Axen et al., 1998b). The Cañada David detachment correlates with a low-angle fault in the northwestern Sierra Cucapá that is east of and cut by the Laguna Salada fault (Isaac, 1987). There and within Sierra El Mayor, the detachments are inactive (Axen et al., 1998a).

GEOLOGY OF THE WEST-CENTRAL SIERRA EL MAYOR

We mapped ~9 km of the west-central range front (Fig. 2). Alluvial deposits are lumped into

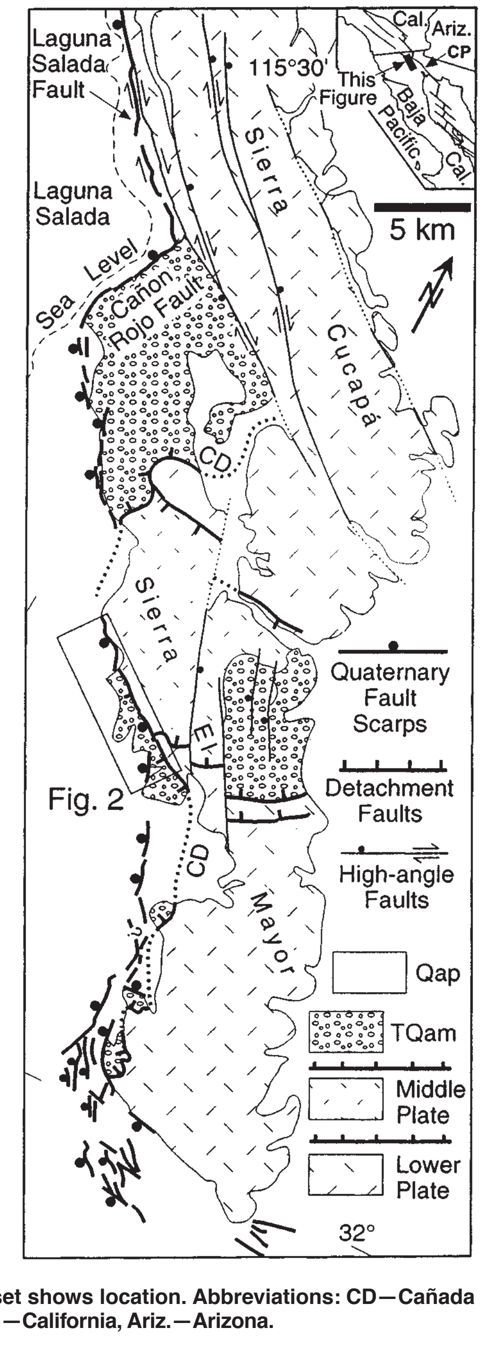

Figure 1. Geologic sketch map of Sierras El Mayor and Cucapá, showing detachment faults, major fault scarps, and location of Figure 2. Abbreviations: Qap—Quaternary alluvium and playa-lake deposits; TQam—Upper Miocene(?), Pliocene, and Pleistocene alluvial and marine strata. From Carter (1977), Mueller and Rockwell (1995), Axen et al. (1998a), and thematic mapper satellite-image analysis. Inset shows location. Abbreviations: CD—Cañada David detachment; CP—Cerro Prieto fault, Cal.—California, Ariz.—Arizona.

*E-mail: gaxen@ess.ucla.edu.

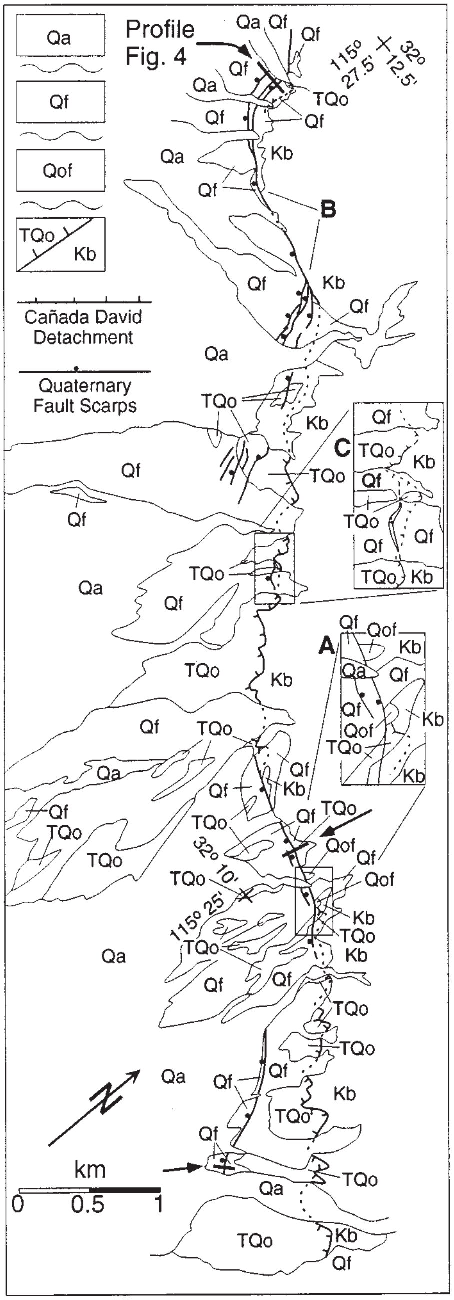

Figure 2. Geologic map of west-central front of Sierra El Mayor. Fault scarps are shown the same whether essentially unmodified, largely eroded, or depositionally onlapped by younger alluvial fans. Arrows point to detailed topographic profiles. Abbreviations: Qa—modern alluvium; Qf—Pleistocene alluvial fans; Qof—older alluvial fans; TQo—Pliocene(?)-Pleistocene(?) fluvial strata, Kb—crystalline basement. Mapped at ~1:8000 scale on enlarged aerial photograph 41B R-347 17-27; hand-rectified (by using drainages) to 1:50,000-scale Guardianes de la Patria topographic map I11D85 (both available from the Instituto Nacional de Estadística Geografía e Informática, Mexico).

three map units. Modern alluvium (Qa) floors channels cut into older deposits and is not faulted. Incised alluvial fans (Qf, Fig. 2) are intermediate in age. Their surfaces are cut by fault scarps. These fans typically are < 10 m thick and depositionally overlap the trace of the detachment. Fans of at least four different ages were mapped on the basis of relative elevation and surface morphology. Bar-and-channel morphology, desert pavement in channels, desert varnish on bars, and caliche-coated bottoms of surface clasts indicate ages between 15 and 500 ka (Christenson and Purcell, 1985). Similar fans in the southern Sierra El Mayor are probably younger than ca. 60 ka U-series minimum ages from a soil carbonate beneath the fans (Carter, 1977). Similar fans along the western Sierra Cucapá are ca. 15–50 ka (Mueller and Rockwell, 1995). Older, high-standing alluvial-fan(?) deposits (Qof, shown only near point A, Fig. 2) are present locally and also overlap the detachment trace. Their surfaces are not preserved, and they are recognized by abundant marble boulders in float along elongate ridge crests that stand higher than the incised fans.

The oldest deposits (TQo, Fig. 2) are conglomerate and minor sandstone that are exposed in arroyo walls and that support float-covered hills above the alluvial fans. Their depositional base is not exposed. This unit forms the upper plate of all exposures of the Cañada David detachment in the study area (Figs. 2 and 3A). It is cut by many high-angle normal faults (Fig. 3C) and is gently to steeply tilted. Clast content changes upsection from middle-plate to lower-plate dominated, recording exhumation of the lower plate (Axen et al., 1998a). We correlate this unit with strata of the Plio-Pleistocene(?) Lopez Mateos growth-fault basin (Axen and Fletcher, 1998; Axen et al., 1998a).

Hanging walls of detachment faults in the region generally moved west (Axen and Fletcher, 1998). In the study area (Fig. 2), the detachment is typically marked by foliated brown clay gouge derived from the upper plate. Both the detachment itself and shears in the gouge show striae that trend generally southwest (Fig. 3A). The immediate footwall of the detachment is a "basement shear zone" (Siem and Gastil, 1994): ~10–50 m of chloritic breccia, black foliated gouge, and powdery white gouge. These are cut by many low- and high-angle faults and shears and generally grade down into coherent basement. Both foliated gouge types display composite S-C fabrics that are typically west-directed.

Alluvial-fan deposits and surfaces (Qf) are both cut by, and in buttress unconformity against, discontinuous systems of fault scarps (simplified on Fig. 2). Field observations and three detailed topographic profiles (Figs. 2 and 4) show that scarps become steeper, more planar, and probably younger northward. There is also a general northward increase in maximum scarp height and in the width and complexity of north- to northwest-striking scarp systems. These systems are linked by west-northwest-striking faults that locally form scarps. We interpret the latter faults as dextral or dextral-oblique, based on sparse striae (Fig. 3b), and on their geometry linking left-stepping systems of more northerly striking scarps.

Intersections of the detachment and scarp-forming faults are not exposed, but the detachment appears to control the location of the scarp-forming faults for these reasons (see Fig. 5a). First, no scarps or scarp-forming faults were traceable into the bedrock of the range, as might be expected if the scarp-forming faults were unrelated to the detachment. Second, scarps typically mimic the trace of the detachment and are generally <0.5 km west of its trace (Fig. 2), suggesting a genetic relationship. Third, straight scarps >1 km long are rare, and many curve at least 10°/km, an unusual geometry for major, range-bounding, high-angle faults. Fourth, one curved, scarp-bounded graben ~200 m long is nearly aligned with the trace of the detachment at either end (C, Fig. 2). The east-facing scarp dies out north and south. The west-facing scarp projects toward the detachment footwall in both directions, but its controlling fault could not be clearly identified in either place. These four map relationships would not be expected if the scarp-forming faults simply crosscut the detachment. However, steep faults at two sites (A and B, Fig. 2) drop alluvial fan deposits (Qf or Qof) against the basement shear zone, so the detachment is apparently cut there. This is inconsistent with our hypothesis but may be explained if those faults sole into the basement shear zone.

PROFILE RECONSTRUCTION

Surficial geology can elucidate subsurface normal fault geometry. Beanland et al. (1990, Fig. 7) obtained comparable dips in three ways for a 1987 normal-fault event: 45° at ~8 km depth

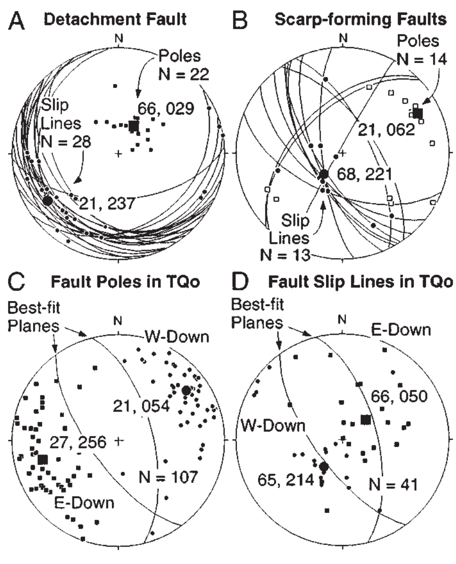

Figure 3. Lower-hemisphere, equal-area stereonets showing structural orientation data collected in this study, which show local northeast to east-northeast extension direction.

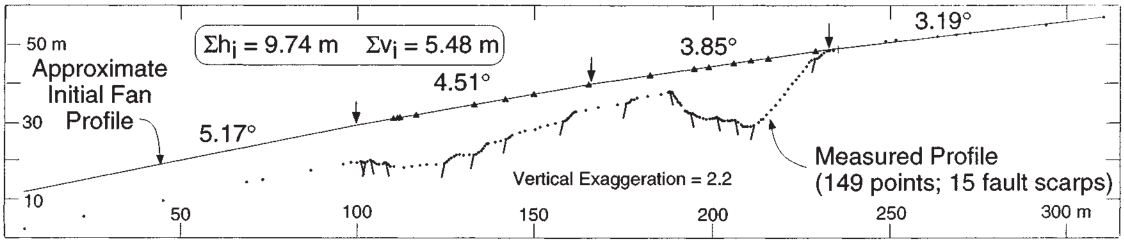

Figure 4. Detailed topographic profile used in reconstruction (see text) and based on 149 measurements via laser distance meter (small black dots). Arrows mark ends of line segments that approximate initial alluvial-fan profile; slope of each segment is shown. Heavy short lines show dip and unreconstructed locations of scarp-forming faults, and triangles show intersections of reconstructed faults with initial fan profile. Location shown in Figure 2. Σh_i = total heave, Σv_i = total throw.

from focal mechanisms, 39° ± 3° from ~0.5 to 6 km depth from geodetic modeling, and 55° from offset alluvial surfaces. King et al. (1985) combined scarp measurements with fault dips from focal mechanisms of two earthquakes to deduce the dip of a nonseismogenic master fault at depth. In both examples, the surficially determined fault dips were steeper than the dips estimated by other means, a common result for normal faults (Yeats et al., 1997).

To test the idea that scarp-forming faults sole into the detachment, we reconstructed an east-west topographic profile (Figs. 2 and 4) that runs perpendicular to 15 recognizable scarps. The profile is subparallel to the regional direction of detachment transport (Axen and Fletcher, 1998) and to the geodetically determined direction of maximum extensional strain rate in northern Laguna Salada (080° ± 2°; Savage et al., 1994), but is ~30° off of the local extension direction (Fig. 3). The largest scarp is ~7 m high and the smallest is ~0.2 m high. The trace of the detachment is only ~100 m to the east (Fig. 2).

We algebraically determined heave and throw across the 15 scarps as follows (Fig. 4). First, we used linear least-squares fits to points on the unfaulted fan surfaces east and west of the scarp array to obtain their surface slopes (3.19° and 5.17°, respectively). (The profile is an oblique conical section, not radial to the fan, so the western segment is steeper than the eastern one.) Next, the central line segments were constructed. Each is half the horizontal length of the faulted section, and their slopes (3.85° and 4.51°) are intermediate between those of the end segments. The eastern segment was left in its best-fit location, and the other segments were sequentially added, approximating the prescarp fan profile as four line segments. We assume that scarp-forming faults dip 65° and have normal slip in the profile plane. This dip is similar to average measured dips of both scarp-forming faults and of faults in unit TQo, but the dip direction is more westerly than the average trends of measured slip lines (Fig. 3, B-D). West-dipping faults were located at the base of west-facing scarps, and east-dipping faults at the top of east-facing scarps. The exact fault positions within their scarps are unknown, but these positions facilitated reconstruction and introduced insignificant error. Finally, faults were restored sequentially from east to west by aligning the measured fan surface immediately west of each fault with the reconstructed fan profile, yielding heave and throw for each. The remaining, unreconstructed profile to the west was translated by the amount of the heave and throw for each step. Horizontal-axis rotations were ignored.

Summing across all faults yields a net heave of 9.74 m and net throw of 5.48 m. The high ratio of heave to throw, ~1.8, reflects the fact that each of the seven antithetic faults increases the net heave but decreases the net throw. If all scarp-forming faults sole into one master fault at depth (Fig. 5B), then this ratio reflects the in-profile slip line of the master fault (i.e., its dip, if it strikes north). Our reconstruction gives a master fault dip of 29°, in accord with measured detachment dips (Fig. 3A). Assuming unacceptably large, conspiring errors in the heave and throw (20% greater or less), yields upper and lower limits of 40° and 21°, respectively, for the master fault dip. Using listric or domino geometry or lower dip for scarp-forming faults would all lower the calculated detachment dip, so 40° is a very conservative upper limit.

DISCUSSION

The scarps probably did not form as a result of subsidence or gravity sliding on a weak sedimentary layer. Subsidence is common where ground water is rapidly withdrawn, but this is not significant in Laguna Salada. Also, many of the mapped scarps west of the laguna face west, away from it (Gastil et al., 1975; Axen and Fletcher., 1998) and the only scarp we identified between the study area and the Laguna faces east; such geometry would be unusual for subsidence-related faults. Weak layers (i.e., gypsum or clay) that might serve as glide surfaces are not known within definite (TQo) or inferred (Qf, Qof) upper-plate units, and a free, west-facing slope, needed for gravity glides, is absent in Laguna Salada.

Instead, our observations are consistent with detachment geometries observed elsewhere. Steep upper-plate faults (e.g., Fig. 3C) are common above the shallow parts of detachments (Axen, 1993, many others). Similarly, supradetachment depocenters are typically farther from footwalls than are half-graben depocenters (Friedmann and Burbank, 1995). The lowest point of Laguna Salada is adjacent to the Laguna Salada fault, but the low point west of our study area is 5–8 km from the range front, consistent with a southward change to detachment-controlled deposition. In fact, these north-to-south differences may simply reflect the depth of low-angle normal faulting: If geodetically measured strain in northern Laguna Salada is due to slip on the Laguna Salada fault, then its slipping portion dips <45° at depth, maybe much less (Savage et al., 1994).

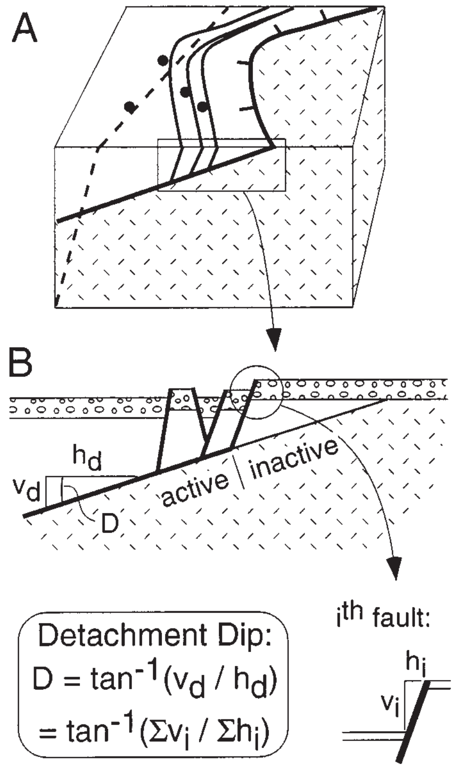

Figure 5. A: Block diagram showing scarp-forming faults (solid) soling into a detachment at depth and mimicking its map pattern, versus a steep, rooted fault (dashed) cutting detachment (considered unlikely here). B: Inferred cross-section geometry showing detachment slip diverging onto scarp-forming faults and abandonment of overlapped, uppermost detachment. For this geometry, throw (Σv_i) and heave (Σh_i) summed across scarp array should equal those of detachment (v_d and h_d).

Death Valley has many similarities to Laguna Salada and may also be floored by an active detachment fault. Miocene to Pleistocene strata east of Death Valley lie above metamorphic basement on a detachment, and Quaternary scarps closely mimic its curvature (Burchfiel et al., 1995), suggesting that the detachment may be active at shallow depth. As in our study area, back-rotation of the footwall has probably stranded the detachment in the range (e.g., Burchfiel et al., 1995).

Similar relationships have also been inferred west of the Ruby Mountains, Nevada, on the basis of seismic reflection data (Wernicke, 1995, and references therein). All three localities may represent active "rolling-hinge" tectonics (e.g., Axen and Bartley, 1997).

The conclusion that the dip of ruptures in surficial sediments is a poor indicator of normal-fault dip relative to focal mechanisms or geodetic modeling of postseismic deformation (Yeats et al., 1997) may be overstated. Much may be learned about subsurface fault geometries from studies of coseismic surface ruptures that try to characterize the strain contribution from all scarps rather than focusing on only the main scarp(s).

If one earthquake caused the ~10 m of inferred detachment slip, consistent with the uniform slopes of scarps (Fig. 4), then it would likely have been a strong event with a hypocenter at several kilometers depth beneath Laguna Salada. Along-strike correlation of fans and scarps that cut them or are onlapped by them (not shown in Fig. 2) requires at least two or three scarp-forming events—that is, earthquakes—in the past 15 to 60 ka. Three such events (30 m east-west extension) in 60 ka would give an average east-west extension rate of only 0.5 mm/yr, well below the ~2–4 mm/yr rates measured across Laguna Salada (Savage et al., 1994). Clay gouge along the low-angle detachment may have allowed rupture propagation to very shallow depth (~100 m).

CONCLUSIONS

The west-central Sierra El Mayor is likely bounded by an active low-angle normal fault, the Cañada David detachment. Detailed mapping of Quaternary (< 60 ka?) alluvial fans and fault scarps along the west-central range front suggests that many such scarps formed along faults that sole into the detachment. Reconstruction of a detailed topographic profile, measured across 15 scarps and in the regional direction of detachment transport and geodetically measured extension, suggests that the scarp-forming faults sole into a fault that dips ~30° in the shallow subsurface. Within the range, detachment faults are inactive, having been transferred, rolling-hinge style(?), to the footwall of the active, range-front detachment.

ACKNOWLEDGMENTS

Supported by grants awarded to G. J. Axen from the University of California Mexico-United States program and the University of California, Los Angeles Committee on Organized Research and to J. Fletcher from the Consejo Nacional de Ciéncias y Tecnología. F. Sabins graciously provided a thematic mapper satellite image. Helpful reviews were provided by E. Duebendorfer and B. John.

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Manuscript received June 23, 1998
Revised manuscript received October 22, 1998
Manuscript accepted November 10, 1998