Low-angle, range-flank faults in the Panamint, Inyo, and Slate ranges, California: Implications for recent tectonics of the Death Valley region

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ABSTRACT

Four of the mountain ranges near Death Valley, California, display exhumed, low-angle normal faults on their flanks, features originally referred to as turtleback structures. These fault surfaces are smooth, planar to curviplanar, and defined by faceted spurs and coincident interfluve crests. The lowest parts of these faults are overlain in tectonic contact by poorly indurated fanglomerate, and locally by Quaternary volcanic rocks. Steep fault scarps in alluvium are present at the foot of each turtleback-type flank.

Although these may be examples of active low-angle normal faults, it is difficult to establish the dip histories of these faults. The problem with constraining the dip histories is one of missing and concealed information, because the exposed hanging-wall rocks are some of the youngest material cut and displaced by the (currently) shallow-dipping faults. Another important relationship along these range flanks is the intersection between the low-angle faults and steep, scarp-forming faults that cut alluvium at the range fronts. Although this relationship remains unconstrained in most of the ranges, a shallow-dipping fault is cut by one of the steep faults in Panamint Valley, suggesting that, in one area at least, the low-angle faults are not active.

The low-angle faults, and not the steep neotectonic faults, are probably responsible for most of the opening of the present valleys, because each low-angle fault intersects the valley floor at the range front. None of the low-angle faults are perched high in the ranges, as would be the case if the steep faults had uplifted them significantly. Therefore, even if there has been a geologically recent transition from low-angle normal faulting to steep normal (with or without strike slip) faulting, the modern topography still reflects the former regime. Strictly speaking, the

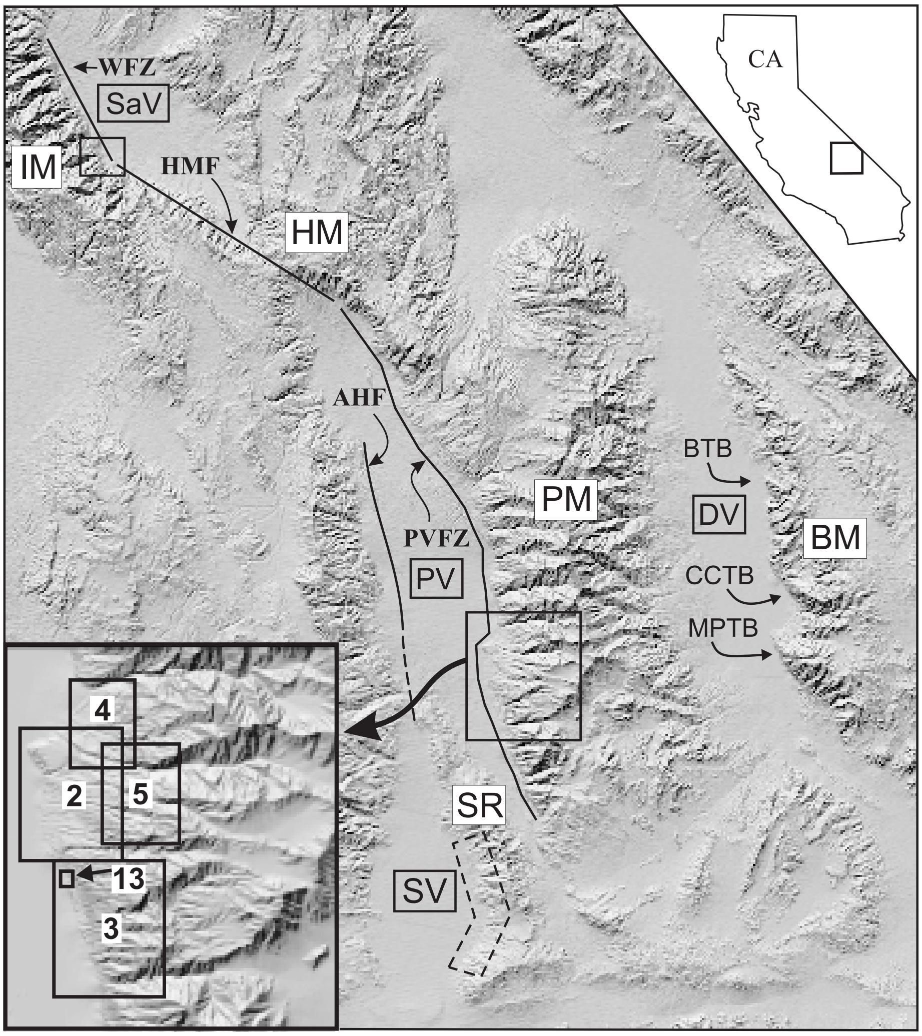

Figure 1. Location map showing ranges, valleys, and faults discussed in text. Valleys (open boxes): SaV—Saline Valley, PV—Panamint Valley, SV—Searles Valley, DV—Death Valley. Ranges: IM—Inyo Mountains, PM—Panamint Mountains, SR— Slate Range, BM—Black Mountains, HM—Hunter Mountain. Faults: WFZ—Western Frontal Zone of Saline Valley (Zellmer, 1980), HMF—Hunter Mountain fault, AHF—Ash Hill fault, PV—Panamint Valley fault zone, BTB—Badwater Turtleback, CCTBB—Copper Canyon turtleback, MPTB—Mormon Point turtleback. Solid-line boxes—range-flank areas mapped as part of this study. Dashed-line polygon—flank of Slate Range described by Smith et al. (1968). Numbers in lower left corner indicate other figures (detailed geologic maps).

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Death Valley region may not be an example of active low-angle normal faults and supradetachment basins.

Keywords: Basin and Range province, basins structural, Inyo Mountains, low-angle faults, normal faults, Panamint Range.

INTRODUCTION

The Basin and Range province of the western United States, and the Death Valley region in particular, are superb natural laboratories for studying continental extension, due to excellent exposure in a desert climate, great structural and topographic relief, and a variety of preextensional and synextensional rocks and structures. One of the most controversial types of structure is the trio of turtlebacks exposed along the western side of the Black Mountains (Fig. 1). The Death Valley turtlebacks are named for the large exhumed fault surfaces that make up a significant portion of the western Black Mountain flank (Curry, 1938). These fault surfaces, originally interpreted as the stripped soles of thrust faults (Curry, 1938, 1954) or the result of gravity sliding on the flanks of growing anticlines (Drewes, 1959), were shown to be late Cenozoic normal faults by Wright et al. (1974). Since this recognition, numerous authors have studied these structures, as well as their hanging-wall and footwall rocks that together compose the Black Mountains. Several studies have used the Black Mountains as a testing ground for hypotheses about large-magnitude extension in the Death Valley region (Stewart, 1983; Wernicke et al., 1988; Asmerom et al., 1990; Holm and Wernicke, 1990; Wright et al., 1991; Topping, 1993; Burchfiel et al., 1995).

Noble (1941) noted a turtleback-like surface at the north end of the Panamint Mountains (Fig. 1). As in the Black Mountains, extensive study of this area has revealed a complicated history of Mesozoic contraction and late Cenozoic extension (e.g., Wernicke et al., 1986, 1993). Curry (1938, p.49) mentioned “similar structure … in the Panamint Mountains” but these have not been investigated, nor have turtleback-like structures been described in other Death Valley–area ranges.

In this paper I document the presence of turtleback-like fault systems at the margins of the Panamint, Inyo, and Slate ranges (Fig. 1), discuss models for the kinematic evolution of these fault systems, specifically the possibility that they are active low-angle normal faults, and discuss the implications of this widespread structural suite for the basin-range morphology of the region.

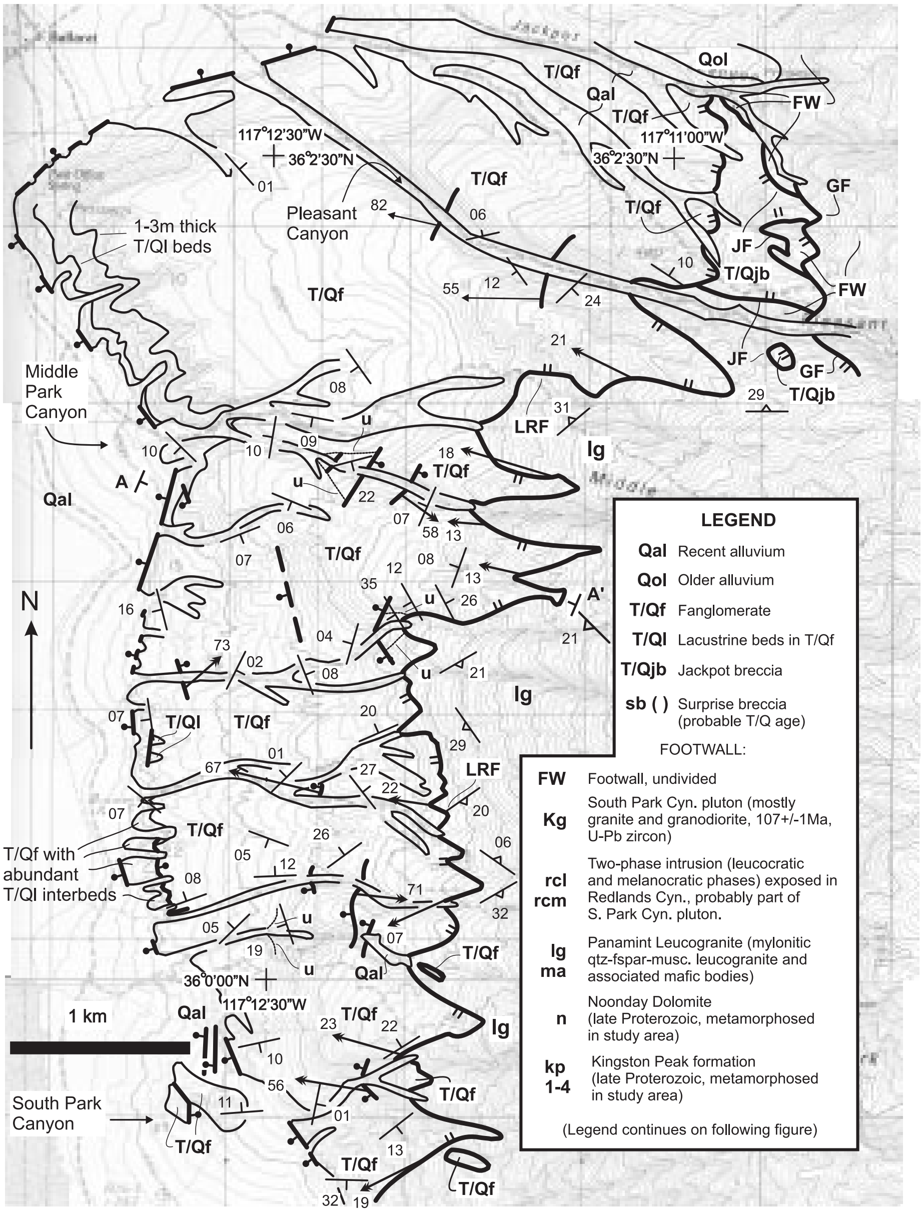


Figure 2. Geologic map of Jackpot Canyon–South Park Canyon segment of Panamint range front. Principal tectonic features are the low-angle, range-flank fault that truncates the base of fanglomerate (T/Qf), and the Panamint Valley fault zone, which is delineated by normal fault scarps at the western ends of the T/Qf exposures. Relationships between older low-angle normal faults (in northeastern corner of this map) are shown in more detail in Figures 4 and 5. Legend for Figures 2–7 is shown on this map and is continued in Figure 3. Topographic base is from U.S. Geological Survey Ballarat and Manly Fall 7.5′ quadrangles. Contour interval north of 36° is 40 ft (12.2 m), south of 36° is 10 m.

Only some of the features observed at the Death Valley turtlebacks are found on the flanks of the Panamint, Inyo, and Slate ranges. These include exhumed fault surfaces, late Neogene hanging-wall rocks, and steep (locally strike slip) scarp-forming faults at the range fronts. In contrast, the turtlebacks of the Black Mountains have tighter, antiformal shapes as compared to the gently curviplanar range-flank faults in the Panamint, Inyo, and Slate ranges, and have associated footwall ductile deformation. Henceforth I use the term low-angle, range-flank fault rather than the more specific term turtleback. (As used here, low-angle refers to a dip of <40°, generally 15°–35°, instead of the more common definition of <30°.) Range flank refers to the entire mountain slope between the range crest and the valley floor. The range front is where the range flank meets the valley floor, and is commonly the site of scarp-forming faults that cut alluvium.

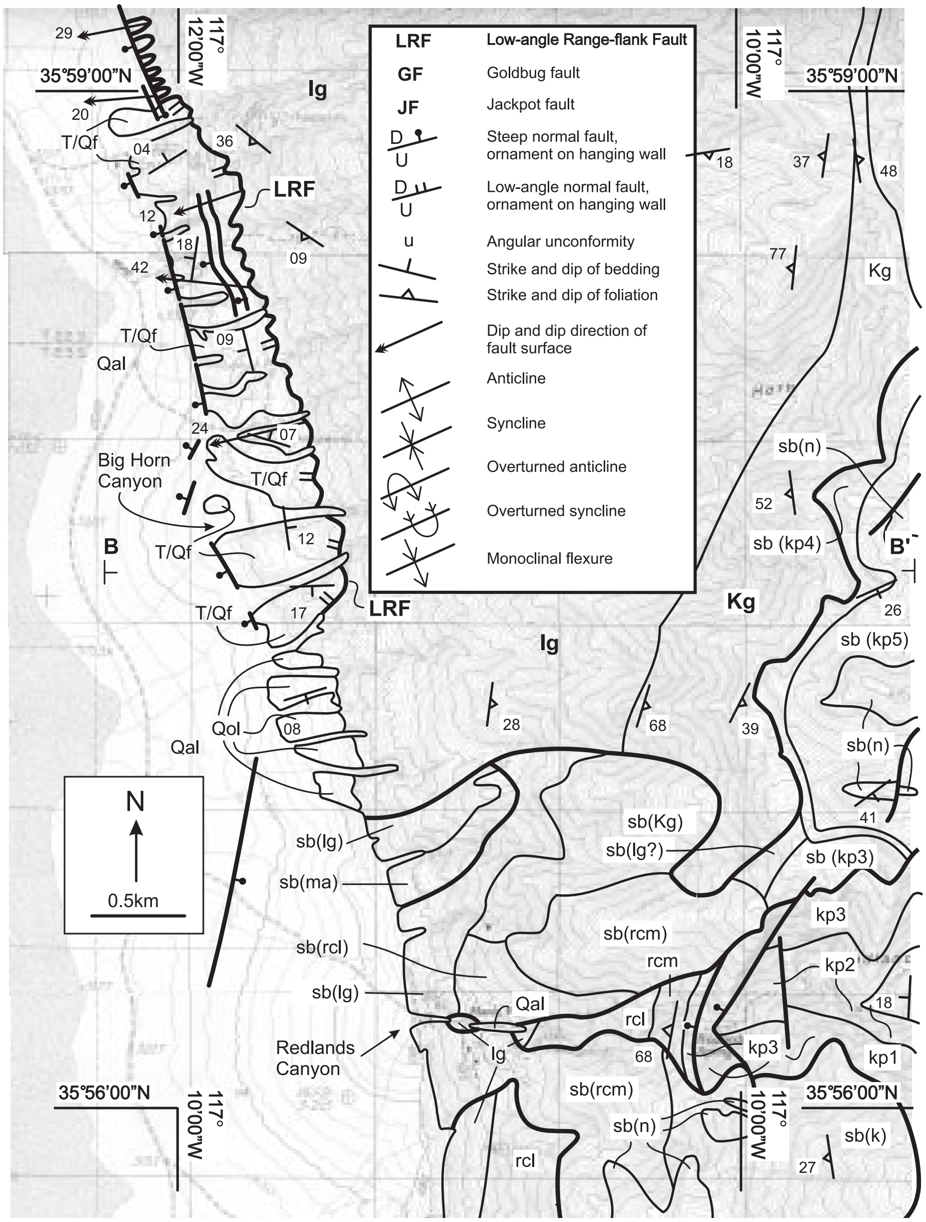


Figure 3. Geologic map of Big Horn Canyon–Redlands Canyon segment of Panamint range front. Principal tectonic features are the low-angle, range-flank fault and the Panamint Valley fault zone, as in Figure 2, as well as Surprise Breccia flanking Redlands Canyon. Legend for Figures 2–7 starts in Figure 2 and continues in this figure. Topographic base is from U.S. Geological Survey Manly Fall 7.5′ quadrangle. Contour interval is 10 m.

Low-Angle vs. High-Angle Faulting in Basin Development

The western flank of the Panamint Mountains was the primary site for this study. It was selected because of its potential to resolve a debate about the roles of low-angle and high-angle faults in opening Panamint Valley. Recognition of similar structures bounding the Inyo and Slate ranges (through mapping and examination of the literature, respectively) motivate the regional discussion of low-angle and high-angle faulting.

While there is no longer any debate about the existence, worldwide, of normal faults that currently have shallow dips, there is much debate about whether such faults are active at shallow dips (see summary by Wernicke, 1995). This debate generally centers around the discrepancy between mechanical models of brittle faulting in the crust, which suggest that normal faults form at steep dips (~45°–60°, e.g., Anderson, 1942), and geological studies that document evidence for fault slip at shallow dips (<~30°, e.g., John, 1987; Davis and Lister, 1988; Fowler and Davis, 1992; Axen, 1993; Axen et al., 1995). Most of the currently known low-angle normal faults are Cenozoic (see summaries, e.g., Crittenden et al., 1980; Armstrong, 1982; Wernicke, 1992, 1995), and a smaller number of Mesozoic and pre-Mesozoic examples have been documented (e.g., Hodges and Walker, 1992; Hoffman, 1998). Modern examples of such structures have been proposed, most notably in the D'Entrecasteaux islands, New Guinea, where Abers (1991) and Abers et al. (1997) documented earthquakes that may have occurred along detachment faults in a series of late Tertiary–Quaternary metamorphic core complexes (Davies and Warren, 1988; Hill et al., 1992). Field studies in the Basin and Range province have suggested that some neotectonic fault scarps in range-front areas are the surface expression of faults that sole into low-angle, range-bounding faults (e.g., Caskey et al., 1996; Axen et al., 1999)

Burchfiel et al. (1987) documented field relationships indicative of post–3.5 Ma low-angle normal faulting under northern Panamint Valley (Fig. 1). The Hunter Mountain fault is continuous with the northern end of the Panamint Valley fault zone. Geologic mapping of a piercing line exposed on both sides of the Hunter Mountain fault constrains the top-to-west-northwest slip line of the Panamint Valley fault zone to a plunge of 0°–15°, with a small right-lateral component. Geophysical surveys suggest that the unconsolidated fill in northern Panamint Valley is shallow, and that 3.5 Ma basalt, which caps the valley's rims, does not underlie the valley (Biehler et al., 1987). In addition, this basalt is involved in an apparent rollover fold on the western rim of the valley. The post–3.5 Ma, low-angle-fault origin for northern Panamint Valley was then incorporated in a model of post–6 Ma extension by Hodges et al. (1989). They proposed that the Panamint Valley fault zone (Fig. 1) is the daylight line of the currently active strand of a west-stepping sequence of detachment faults, the older members of which are exposed east of Panamint Valley.

These models, in which northern Panamint Valley is a shallow supradetachment basin and the Panamint Valley fault zone is the surface expression of this detachment, contrast sharply with evidence for high-angle faulting in both northern and southern Panamint Valley. Detailed mapping of scarp-forming faults along the Panamint Valley and Ash Hill fault zones (Fig. 1) suggests that the currently active faults, which cut unconsolidated alluvial fan and lacustrine deposits, are steep and primarily right lateral (Hopper, 1947; Smith, 1976, 1979; Zhang et al., 1990; Lemmer and Schweig, 1991; Densmore and Anderson, 1997).

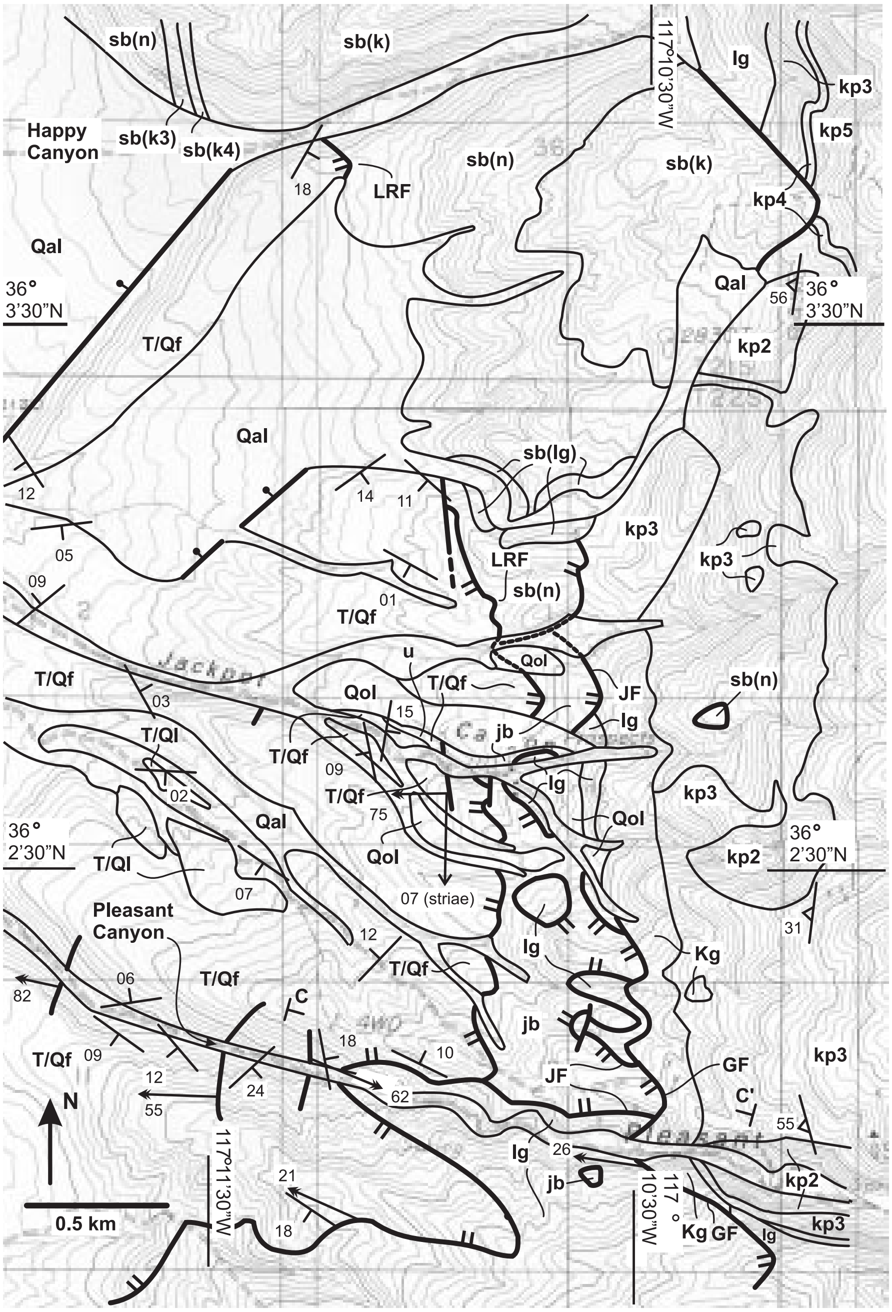


Figure 4. Geologic map of Ballarat embayment, Panamint range flank. Adjoins northeast corner of Figure 2; this figure is at a larger scale. Principal tectonic features are the low-angle, range-flank fault (LRF) and the Panamint Valley fault zone (as in Figs. 2 and 3), as well as the Jackpot (JF) and Goldbug (GF) low-angle normal faults, and the Surprise Breccia. Legend is shown in Figures 2 and 3. Topographic base is from U.S. Geological Survey Ballarat 7.5′ quadrangle. Contour interval is 40 ft (12.2 m).

For this study, the southern portion of the Panamint range was selected as a place to search for low-angle, range-flank faults, and to evaluate their intersection with steep, scarp-forming faults at the range front. The study was extended to Saline Valley in order to examine the possibility of a similar tectonic history in that area, because Burchfiel et al. (1987) suggested that Panamint and Saline Valleys are genetically linked rhombochasms.

RANGE-FLANK FAULT SYSTEM IN THE PANAMINT STUDY AREA

Overview of the Results of This Study

For this study, the western flank of the Panamint Mountains between Happy and Redlands Canyons was mapped at scales ranging from 1:4800 to 1:24 000 (Figs. 2–7). Important results, discussed in detail in the following and summarized in Figure 8, are as follows. (1) The southern portion of the western flank of the range is a fault surface, dipping 15°–35° to the west. The fault separates metamorphic footwall rocks from late Cenozoic fanglomerate of the hanging wall. Bedding in the hanging wall is, on average, horizontal. (2) Two older low-angle faults, as well as the basal contact of a large breccia mass, are in the footwall of the main low-angle fault. (3) Scarp-forming faults of the Panamint Valley fault zone cut the low-angle range-flank fault.

Low-Angle, Range-Flank Fault

The southern portion of the western flank of the Panamint Mountains is interpreted as an exhumed and slightly incised fault surface. Morphologically, it is formed by interfluve crests on its lower part. Several major canyons cut deeply into the range, but the range flank between these canyons is dissected only by small gullies. The crests between these gullies define a curviplanar surface dipping ~15°–35°W (Fig. 9; especially the area between Pleasant and Big Horn Canyons). Noble (1926) and Maxon (1950) first noted the presence of this surface.

At the range front, the fault is preserved, overlain by coarse, upper plate fanglomerate gravel (Fig. 10). The base of the fanglomerate is extremely sharp, and locally exhibits striations (see following). The fanglomerate is underlain by 10 cm to a few meters of fault gouge. The gouge is soft and made of clay-sized material, and commonly exhibits layering, defined by orange, red, and yellow, more rarely gray or green. Fragments of footwall rock are locally present in the gouge layer. In a zone 10–200 m thick below the gouge, the footwall rock is highly fractured, and stained red with opaque minerals (probably iron oxides).

The footwall is composed of metamorphic rock. Leucogranite orthogneiss predominates, with intermingled amphibolite. These two lithologies make up the lower part of the range flank, and thus underlie the preserved portions of the low-angle, range-flank fault. In the low-angle, range-flank fault zone, mafic minerals in the amphibolite are commonly altered to red oxides, and are the likely source of the fault-zone staining. Metamor-

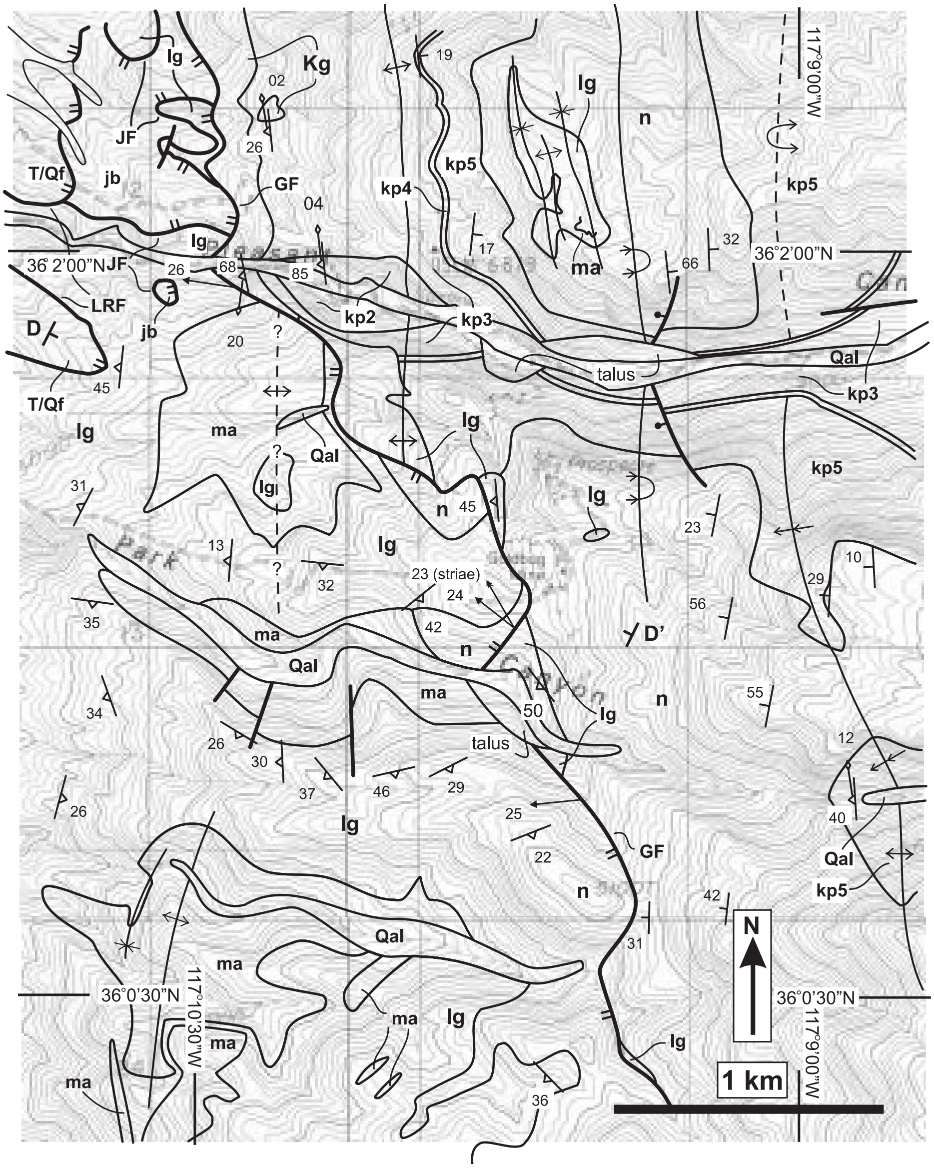


Figure 5. Geologic map of central Pleasant Canyon–Goldbug mine area, Panamint Mountains. Principal tectonic feature is the Goldbug low-angle normal fault, crossing the map from northwest to southeast. Offset on Goldbug fault is probably <0.5 km, as shown by offset of anticline axis and the contact between Noonday Dolomite marble (n) and leucogranite orthogneiss (lg). Legend is shown in Figures 2 and 3. Topographic base is from U.S. Geological Survey Ballarat 7.5′ quadrangle. Contour interval is 40 ft (12.2 m).

phosed Late Proterozoic sedimentary rocks are exposed at higher elevations, primarily the Kingston Peak Formation and the Noonday Dolomite.

The hanging-wall fanglomerate (unit T/Qf, Figs. 2–7) is poorly sorted, and closely resembles the modern alluvial fans in the area. Clasts consist exclusively of footwall rock units. At one locality, a sheet-like body of Noonday Dolomite breccia is exposed in unit T/Qf, and thin beds of silt and clay (unit T/Ql) are locally intercalated with the fanglomerate gravels (Figs. 2–7). Some of the fanglomerate is indurated by calcite cement in a 1–5-m-thick zone parallel to, and immediately above, the low-angle, range-flank fault.

The hanging wall of the low-angle, range-flank fault moved down to the west relative to the footwall, at least during the period of slip that produced the currently exposed striae and fault gouge. The fault places poorly consolidated, apparently young fanglomerate atop metamorphic bedrock, a relationship of higher crustal levels over lower crustal levels that is common to most normal faults. Striae are exposed on the low-angle, range-flank fault at several localities, and on slip surfaces within the gouge zone (Fig. 9). Most of these fault striae plunge nearly downdip, although they commonly exhibit a small right-lateral component. Only three exposures showed sinistral components of slip, and these exposures were all on slip surfaces within the gouge zone, not on the low-angle, range-flank fault.

Deformation of the hanging-wall fanglomerate is relatively minor. Bedding attitudes in unit T/Qf rarely exceed 30°, and are horizontal on average (Fig. 11, A and B). The fanglomerate is cut by high-angle faults, exposed on the steep walls of drainages that dissect the unit T/Qf exposures. A thin layer of colluvium, composed of slightly reworked T/Qf rocks, mantles the exposures and prevents most of the faults from being traced more than several meters in map view. The faults are planar fractures, rarely curviplanar, and commonly display apparent normal separation. Poles to faults cutting unit T/Qf define two distinct domains. An average pole was determined for each domain (Fig. 11, C and D), and the average poles are consistent with a set of conjugate fracture planes. Normal slip is probably predominant, because three of the four striated fault surfaces display steep striae (Fig. 11E).

Pre-Low-Angle, Range-Flank Faults

Two pre-low-angle, range-flank faults are exposed in the study area (Fig. 8): (1) the Jackpot fault, a shallow-dipping fault that cuts the base of the monolithologic Jackpot Breccia, and (2) the west-dipping Goldbug fault, the easternmost of the low-angle faults. In addition to these faults, the footwall of the low-angle, range-flank fault also consists in part of a second breccia unit, the Surprise Breccia.

The Jackpot Breccia is characterized by clasts that have clearly been displaced, and in some cases rotated, with respect to one another. This breccia resembles large rockfall-avalanche deposits (e.g., Yarnold and Lombard, 1989). It is distinguishable from the Surprise Breccia (Figs. 2–7, named by Labotka et al., 1980) because the latter generally consists of highly fractured bedrock with little interclast displacement and rotation. The base of the Jackpot Breccia is very similar to the low-angle, range-flank fault: it is a sharp fault contact, with a gouge zone and fractured, stained footwall rock. Striae on the Jackpot fault show orientations similar to those on the low-angle, range-flank fault. The upper plate of the Jackpot fault has been disrupted by high-angle faults that end downward at the Jackpot fault. These faults have back-rotated the layering in the Jackpot Breccia (Fig. 12).

The Goldbug fault is a 25°, west-dipping normal to oblique fault. The best exposures of the fault are in Middle Park Canyon, in the vicinity of the Goldbug mine (Fig. 5). There, both the hang-

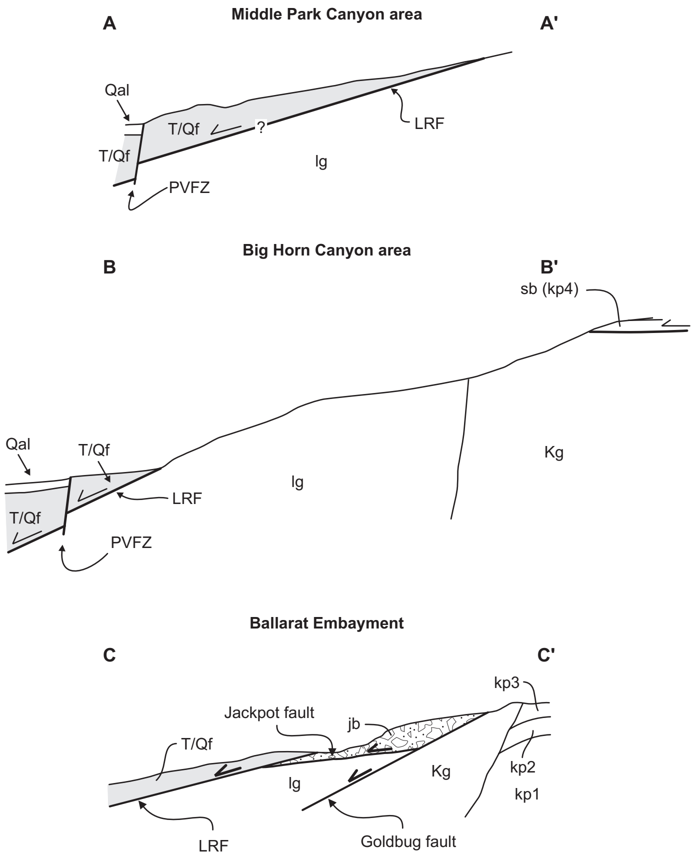


Figure 6. Cross sections to accompany Figures 2 (A–A′), 3 (B–B′), and 4 (C–C′).

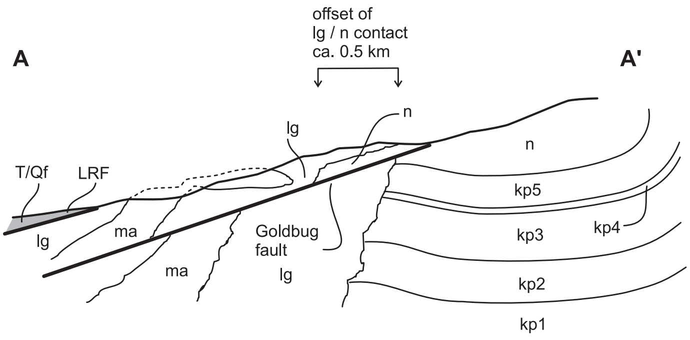


Figure 7. Cross section to accompany Figure 5. Slip on the Goldbug fault is probably not more than ~0.5 km, as determined by the offset of the leucogranite orthogneiss (lg)–Noonday Dolomite (n) contact.

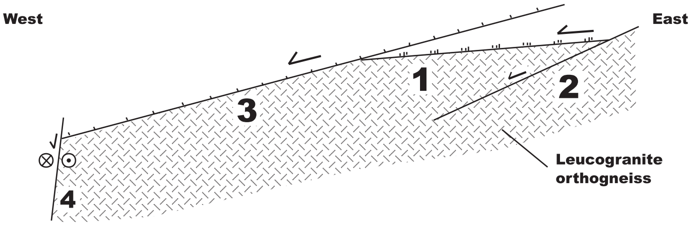


Figure 8. Diagrammatic composite cross section of the western Panamint range flank. Faults are numbered in order of activity, as determined by crosscutting relationships and by other characteristics of the faults (discussed in text). This cross section is most applicable to the central portion of the Panamint study area (Fig. 2 and the north half of Fig. 3). Faults (in order of activity). 1—Jackpot fault. Similar to low-angle, range-flank fault (LRF), truncates base of Jackpot Breccia. At the northern and southern edges of the study area, fault 1 is not present, but the basal contact of another breccia mass (Surprise Breccia) occupies the same structural position as fault 1 (see text for details). 2—Goldbug fault. Cuts Jackpot fault, and is probably older than low-angle, range-flank fault (see text). 3—Low-angle, range-flank fault.

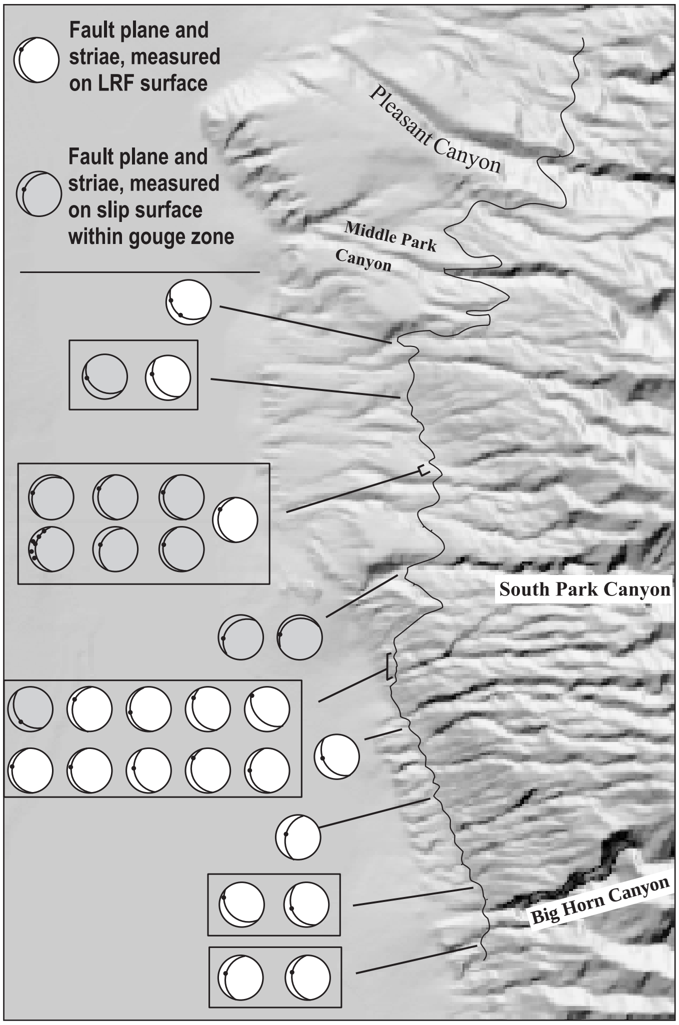
ing wall and the footwall contain exposures of the deformed intrusive contact between the leucogranite orthogneiss and Noonday Dolomite marble (intrusive contact originally mapped as a thrust fault; Johnson, 1957; Albee et al., 1981). Two factors suggest that the displacement on the fault has probably not been greater than several hundred meters (Figs. 5 and 7). (1) A roughly domiform sheet of mafic intrusive rock in the hanging wall may correlate with an anticline in metasedimentary rocks in the footwall. (2) The map-view offset of the Noonday Dolomite–orthogneiss contact is ~0.5 km.

Both the low-angle, range-flank fault and the Goldbug fault cut the Jackpot fault, as exposed on the north wall of Pleasant Canyon (Fig. 4). Because there is no exposed intersection between the low-angle, range-flank fault and Goldbug faults, their relative timing must be determined indirectly. Because the low-angle, range-flank fault cuts young fanglomerate, and displays a large, little-eroded fault surface (two characteristics not shared by the Goldbug fault), the low-angle, range-flank fault is probably younger. Given this assumption, the order of pre-low-angle, range-flank fault events is inferred to have been: (1) emplacement of the Jackpot Breccia, probably as a landslide or rockfall avalanche from exposures of Noonday Dolomite high on the range flank; (2) truncation of the base of the Jackpot Breccia by the Jackpot fault; and (3) slip on the Goldbug fault.

The footwall of the low-angle, range-flank fault also includes portions of the Surprise Breccia (Labotka and Albee, 1980; Albee et al., 1981). The origin of these extremely large masses of monolithologic breccia is enigmatic, and is not explored in detail here. They consist of highly fractured rock; the predominant Surprise units are the Kingston Peak and Noonday formations. Some of the low-angle, range-flank fault footwall near the mouth of Redlands Canyon (Fig. 3) consists of previously unmapped breccia, which has a highly fractured appearance similar to the Surprise Breccia.

Panamint Valley Fault Zone and its Relationship to the Low-Angle Range-Flank Fault

The Panamint Valley fault zone was named by Hopper (1947), and extends the full length of the



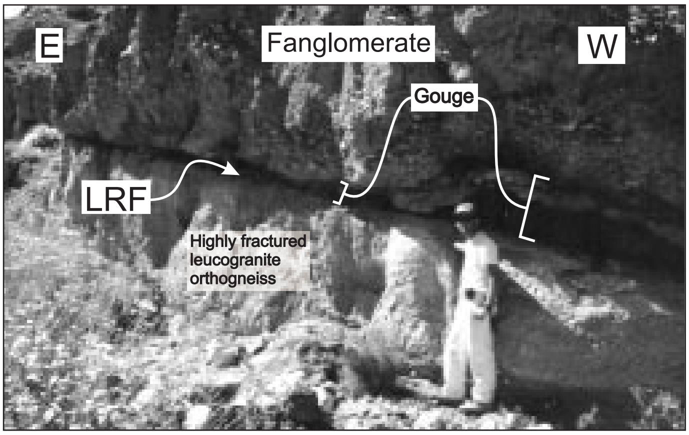


Figure 10. Photograph of Panamint low-angle, range-flank fault (LRF) between South Park and Big Horn canyons, looking south. Zone of fault gouge is immediately behind and above the author's head. Light-colored material below the gouge is highly fractured metaigneous footwall rock.

Figure 9. Lower hemisphere stereonets showing orientations of fault planes and striae in the Panamint low-angle, range-flank fault zone. White stereonets show data collected from slip surfaces within the gouge zone.

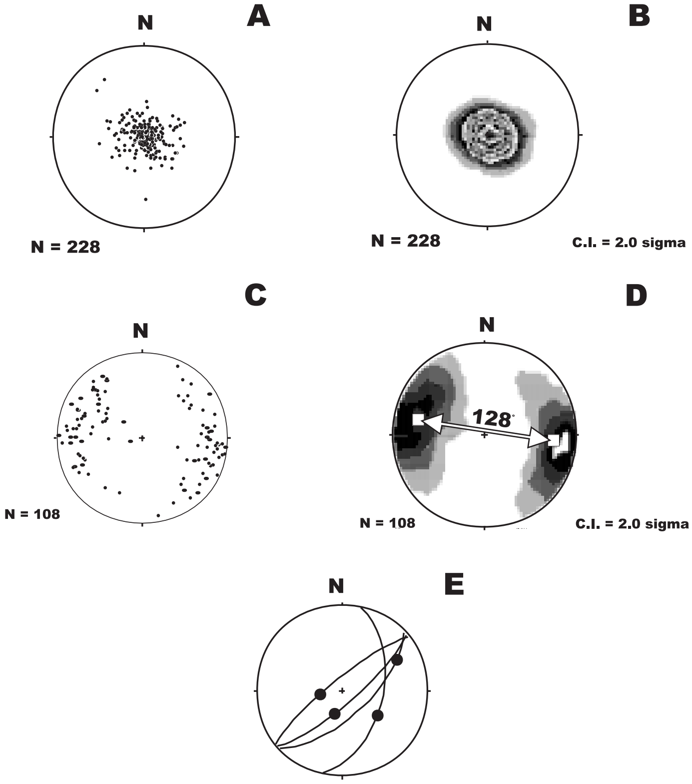


Figure 11. Summary of structural data for the hanging wall of the Panamint low-angle, range-flank fault (LRF). (A) Poles to bedding in unit T/Qf. (B) Kamb contour plot of data from A, showing that the hanging-wall beds are horizontal on average. (C) Poles to faults that cut unit T/Qf. (D) Kamb contour plot of data from D, showing that the faults define two steeply dipping domains. The average poles for each domain are 128° apart, consistent with a set of steeply dipping (~60°) conjugate fractures. (E) Orientations of the rare faults that both cut T/Qf and display striations. Great circles—faults, dots—striations.

eastern side of Panamint Valley (Fig. 1). Different investigators have emphasized different aspects of the zone. Johnson (1957) referred to the fractured and stained rock below unit T/Qf as the product of an earlier, steep Panamint Valley fault zone, and referred to the scarp-forming faults at the range front as the modern Panamint Valley fault zone. Smith (1976) mapped these scarps in detail, and noted dextral offsets along some of them. He also mapped a sheet of monolithologic breccia ~25 km north of the area described in this paper, and suggested that it had been offset 4 ± 1 km dextrally from a proposed source location. The low-angle fault model of Burchfiel et al. (1987) and Hodges et al. (1989) interpreted the scarps of the northern Panamint Valley fault zone as either the surface exposure of a low-angle normal fault, or as an upper plate fault. Zhang et al. (1990) documented dextrally offset stream channels along the youngest segments of the Panamint Valley fault zone. They also divided the scarp-forming faults into two classes: those that cut unit T/Qf but not unit Qal (and show only normal displacement), and those that cut unit Qal and show a component of dextral displacement. They suggested that the strike-slip faults postdate the most recent Pleistocene pluvial lake, based on the fresh appearance of the scarps and the fact that the scarps cut across subaerially deposited material located below the level of this pluvial lake.

The relationship between scarp-forming faults of the Panamint Valley fault zone and the low-angle, range-flank fault was investigated in detail in this study, because of its relevance to the question of which fault is active. The intersection of the low-angle, range-flank fault and the Panamint Valley fault zone is generally not exposed, being 200–500 m below the surface of Panamint Valley in most of the study area. One segment of the Panamint Valley fault zone system, however, is very close to the low-angle, range-flank fault (northern edge of Fig. 3; see also Fig. 13). Although the high-angle, scarp-forming fault that forms the western end of most of unit T/Qf spurs does not intersect the low-angle, range-flank fault, faults of similar orientation (located only tens of meters to the east) cut the low-angle, range-flank fault, and displace it a few meters down to the west. These smaller faults are probably part of the Panamint Valley fault zone, and thus the fault zone is interpreted to cut the low-angle, range-flank fault. It is likely that the larger scarp-forming faults of the Panamint Valley fault zone cut the low-angle, range-flank fault and displace it by more than a few meters in areas currently buried under alluvium.

Another steep fault cuts the low-angle, range-flank fault in Jackpot Canyon (Fig. 4). The fault that cuts the low-angle, range-flank fault there does not exhibit striae, but a parallel fault 0.125 km to the west exhibits striae that plunge 7° to the south. This suggests that high-angle strike-slip faults probably cut the low-angle, range-flank fault.

RANGE-FLANK FAULT SYSTEM IN THE INYO STUDY AREA

The eastern flank of the Inyo Mountains (Fig. 1) was studied in order to search for similarities to the western flank of the Panamint Mountains. Zellmer (1980) and Burchfiel et al. (1987) suggested that Panamint and Saline Valleys opened at essentially the same time, with strike-slip displacement between the two hanging-wall (valley) blocks taken up along the Hunter Mountain fault zone. Zellmer (1980) described the eastern edge of the Inyo Mountains (the Western Frontal Zone of Saline Valley, Fig. 1) as a steep, east-down normal fault.

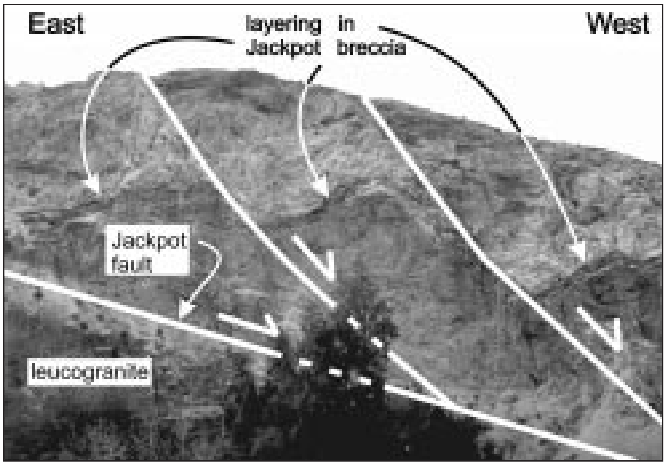


Figure 12. Exposure of Jackpot fault in Jackpot Canyon, looking south. Height of exposure is ~15 m. Layering in the Jackpot breccia has been back-rotated by upper plate faults, which sole into the Jackpot fault. The Jackpot fault is marked by light-colored talus that has fallen onto the fault ledge from the upper plate.

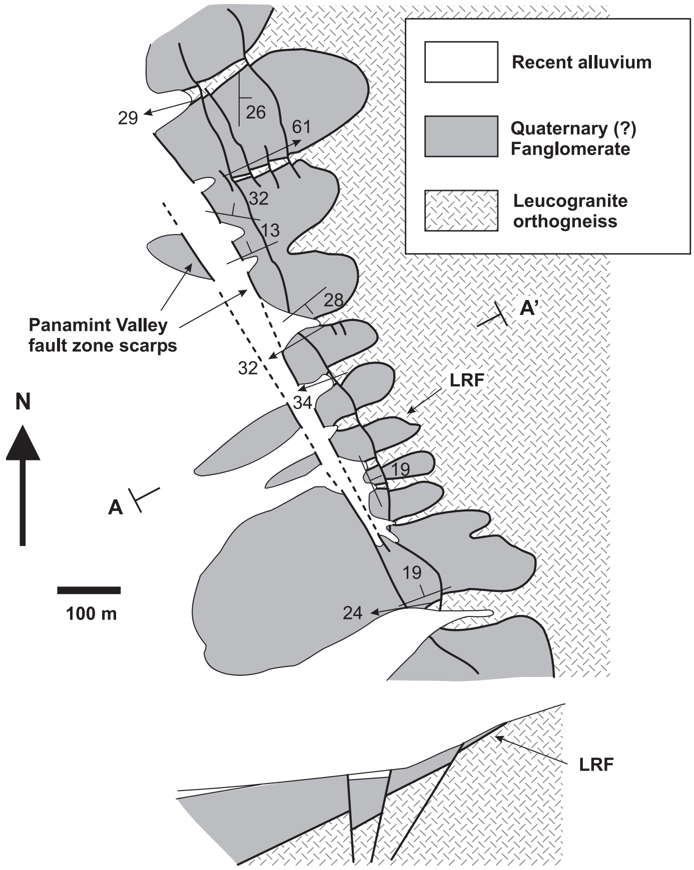


Figure 13. Detailed map of an area ~1 km south of South Park Canyon, Panamint range front. Arrows indicate dip and dip directions of faults. Faults that cut the low-angle, range-flank fault are Probably part of the Panamint Valley fault zone, based on proximity to the Panamint Valley fault zone, and based on similar orientation.

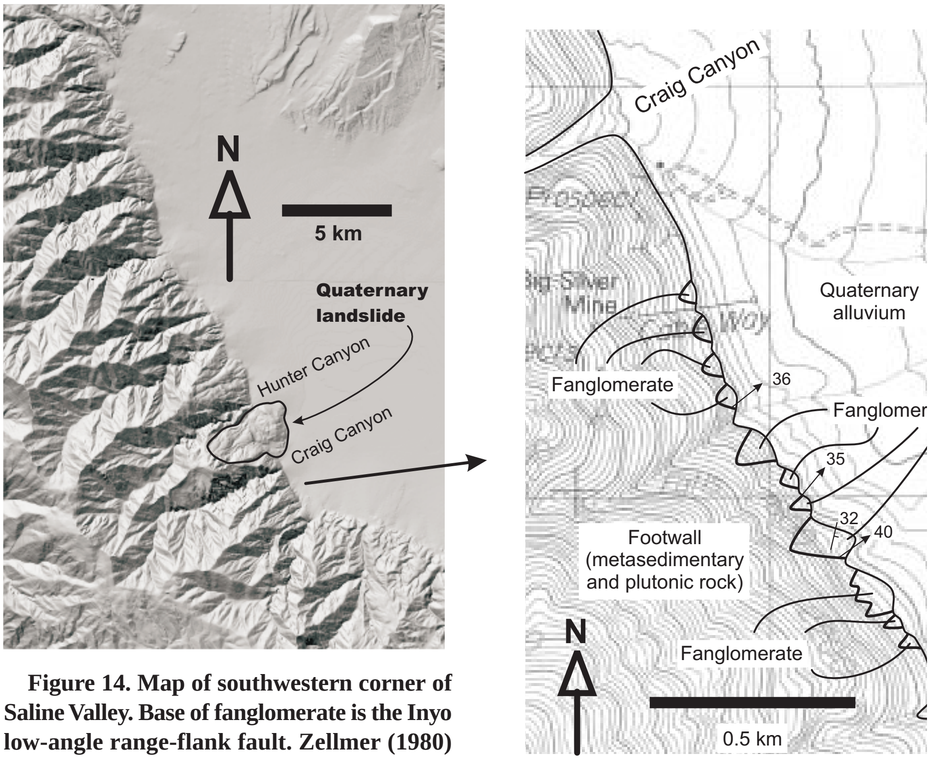


Figure 14. Map of southwestern corner of Saline Valley. Base of fanglomerate is the Inyo low-angle range-flank fault. Zellmer (1980) documented small east-facing scarps in alluvium along the range front, although they are not visible at the scale of the topographic map or the digital shaded relief image.

The eastern flank of the Inyo Mountains resembles the western flank of the Panamint Mountains; it is a planar to gently curviplanar, partially incised fault surface. It is slightly steeper than the Panamint flank, having an average dip of 35°–40°, as opposed to 20°–30°. For the current study, the smoothest and most planar portion of the flank was examined near the mouth of Craig Canyon (Fig. 14). This is immediately north of the intersection between the west-northwest–trending Hunter Mountain fault and the west-northwest–trending Inyo range front (Fig. 1).

In the Craig Canyon area, fanglomerate spurs are exposed at the range front, separated from underlying granitic bedrock by a fault zone. The spurs are smaller than most of the upper plate spurs in the Panamint area, with a height of 20–60 m in most cases (Fig. 15). The fault zone at the base of the fanglomerate displays characteristics similar to the Panamint low-angle, range-flank fault. (1) The base of the fanglomerate is sharply truncated. (2) There is a 5–10-m-thick zone of dark gray to black fault gouge. The gouge is soft and friable, and composed of clay-sized material. It contains fragments of altered granitic rock, commonly lenticular, and exhibits a scaly foliation parallel to the range flank. (3) Underneath the gouge zone, there is a 10–20-m-thick zone of very highly fractured granitic and metacarbonate rock. This zone gives way downward to much less fractured granitic bedrock.

The Western Frontal Zone of Zellmer (1980) is a zone of east-facing, scarp-forming faults that cut unconsolidated fanglomerate and colluvium, much like the Panamint Valley fault zone, but without any measured strike-slip offset described to date.

RANGE-FLANK FAULT SYSTEM OF THE WESTERN SLATE RANGE

Smith et al. (1968) mapped a portion of the southern Slate Range (Fig. 1), an area currently part of a restricted military reservation. The western flank of the southern Slate Range resembles the smooth range-flank fault surfaces of the Black, Panamint, and Inyo ranges. Like the turtlebacks and the Panamint and Inyo fault surfaces, the curviplanar western flank of the Slate Range is defined by interfluve crests separating small gullies (noted by Smith et al., 1968 in their Figs. 6, 10, and 11). These authors also mapped a thrust fault (Sand Canyon thrust) that separates two suites of Precambrian rocks, and noted that the range-flank surface coincides with the trace of this thrust. Thus, they interpreted the range-flank surface as the exhumed sole of the thrust fault.

Smith et al. (1968) also described field relationships along the western flank of the Slate Range that are similar to the turtleback-like fault systems in nearby ranges. On one portion of the low-angle fault surface, Tertiary rocks are described as lying in depositional contact on fault gouge. Steep fault scarps, both east and west facing, are also present in alluvium at the range front.

The similarities between the western flank of the Slate Range and the turtleback-like structures in nearby ranges suggest that the flank is an exhumed low-angle normal fault. That this surface may be the sole of a pre-Cenozoic thrust is not questioned here, but it is likely that normal slip (with or without strike slip) subsequently occurred on the fault, a possibility raised by Smith et al. (1968). The hypothesis that the Tertiary rocks were deposited on exposed fault gouge is unlikely for two reasons. (1) Erosion would have had to cease just as the hanging wall was removed, but before the gouge was eroded, which would be fortuitous. (2) Deposition of the Tertiary rocks might strip away the friable gouge. This gouge zone is probably part of a late Cenozoic normal (with or without strike slip) fault zone, similar to the Death Valley turtlebacks and the Panamint and Inyo low-angle range-flank faults.

DISCUSSION

The presence of low-angle range-flank faults in several Death Valley–area basins raises two main questions. (1) Were the low-angle range-flank faults active at shallow dips, as was suggested for the range-flank fault in the northern Panamints (Burchfiel et al., 1987)? If so, the Death Valley region provides well-exposed, accessible examples of what low-angle normal faults and associated supradetachment basins look like while still active, or at least recently active. (2) Can models for low-angle, basin-bounding faults (Burchfiel et al., 1987, 1995; Hodges et al., 1989) and currently active, high-angle, locally strike slip faults (Miller, 1991; Keener et al., 1993; Ellis et al., 1995; Densmore and Anderson, 1997) be integrated? If so, what implications would a synthesis of these models have for the recent (and future) tectonic evolution of the region?

Difficulties in Constraining Initial Dips of Range-Flank Faults

Despite the importance of establishing the dip histories of the currently low angle faults, these histories are difficult to constrain, as shown by the Panamint low-angle, range-flank fault. The hanging wall consists of subhorizontal fanglomerate (Fig. 11, A and B), suggesting that it did not rotate significantly during the time interval required for deposition of the currently exposed unit T/Qf. The simplest model for deformation of unit T/Qf is west-northwest–directed extension

Figure 15. View of eastern flank of Inyo Mountains, Saline Valley, immediately south of Craig Canyon. Relatively smooth appearing, rilled material at base of flank is upper plate fanglomerate. The largest fanglomerate spurs are ~40 m high. The range-flank surface above the spurs dips 35°–40° toward the camera.

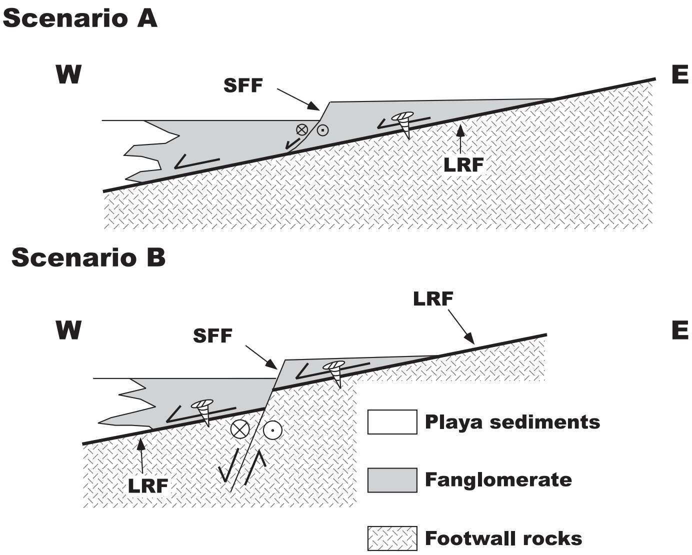


Figure 16. Alternative models for the intersection of a steep, scarp-forming fault (SFF) and a low-angle range-flank fault (LRF). Scenario A depicts the SFF as an upper plate fault to an active LRF at depth. Scenario B depicts an inactive LRF cut by a throughgoing SFF. Screw fastener symbol indicates inactive faults and inactive segments of faults.

above a shallow-dipping low-angle, range-flank fault (Fig. 11, B and C). The currently exposed T/Qf beds are only the youngest material cut and displaced by the low-angle, range-flank fault, however. It is possible that the fault initiated at a steeper dip and rotated to a shallow dip, and that the older, east-tilted hanging-wall beds are buried underneath Panamint Valley.

Another approach to constraining the dip history of a range-flank fault is to use data from the footwall. In the Panamint Mountains, the eastern half of the footwall block consists of Late Proterozoic and Paleozoic miogeoclinal strata dipping 20°–40°E (Hunt and Mabey, 1966). McKenna and Hodges (1990) documented 20°–40° of eastward rotation of volcanic strata in the eastern Panamints since 9.0 ± 0.4 Ma. These data allow for significant eastward rotation of the Panamint block during the evolution of its western flank.

Treating the footwall as a single rigid block may not be a safe assumption, however, for two reasons. (1) McKenna and Hodges (1990) documented a west-dipping normal fault cropping out on the east side of the Panamint Mountains. They suggested that a generally north trending, range-scale anticline in the Panamint Mountains is, in part, a rollover fold above this fault system. (2) The northern end of the Panamint block is enveloped by a Cenozoic detachment fault system, which has the shape of a gently north plunging antiform. Detailed mapping of this area (summarized in Wernicke et al., 1986, 1993) has shown that all segments of this fault system probably dipped west initially, but that older segments of the system now dip east, due to warping of the detachment system during its evolution. The footwall of the system is thus decoupled from the hanging wall, which is in part a syntectonic basin (Hodges et al., 1989). Footwall structure, therefore, may not document the dip history of either the hanging wall or the fault. Although the low-angle faults in the southern Panamints are not continuous with the northern Panamint fault system, they are similar in position, age, and orientation to the youngest components of the northern system. Thus, issues of decoupling raised in the north need to be considered in the south.

Low-Angle vs. High-Angle Faulting: Regional Discussion

The most important issue raised by range-flank studies like this one is the nature of the intersection between the low-angle and high-angle faults. Two end-member models are possible (Fig. 16). In scenario A, the scarp-forming faults at the range fronts are upper plate faults that end downward at the low-angle faults. In this case, the Death Valley–area basins are the type locality for modern examples of detachment faults and supradetachment basins. In scenario B, the low-angle faults are no longer active, and have been cut by the scarp-forming faults. However, the transition to high-angle faulting may have been so recent that the basins may appear virtually the same as they did during their supradetachment histories.

Truncation of low-angle faults by high-angle faults has been demonstrated geologically in the southern Panamint range (this study), and inferred geophysically at Mormon Point (Keener et al., 1993). The range-flank fault systems of the Inyo and Slate ranges are similar to the Panamint and Death Valley systems, consisting of low-angle normal faults that form the range flanks, and scarp-forming faults that cut alluvium at the range fronts. At present, it is unknown if the steeper, scarp-forming faults cut the low-angle faults at depth, but an analogy to the truncations in the Panamint and Mormon Point systems may be reasonable, given their similar appearance at the surface.

Transition from Low-Angle to High-Angle Faulting

Although timing constraints for both low-angle and steep faults are scarce, the existing data permit a geologically recent transition between the two regimes, at least in the Panamint Valley and Death Valley, where evidence for such transitions has been documented. Evidence for the recent nature of this transition comes from the ages of the hanging walls of the low-angle faults, and the youthful appearance of the steep, scarp-forming faults.

Geologically young rocks are scarce in the footwalls of the range-flank fault systems. These footwalls consist mostly of Paleozoic miogeoclinal sediments, commonly metamorphosed, and intrusive igneous rocks, mostly Mesozoic. The Death Valley turtleback terrane, however, contains

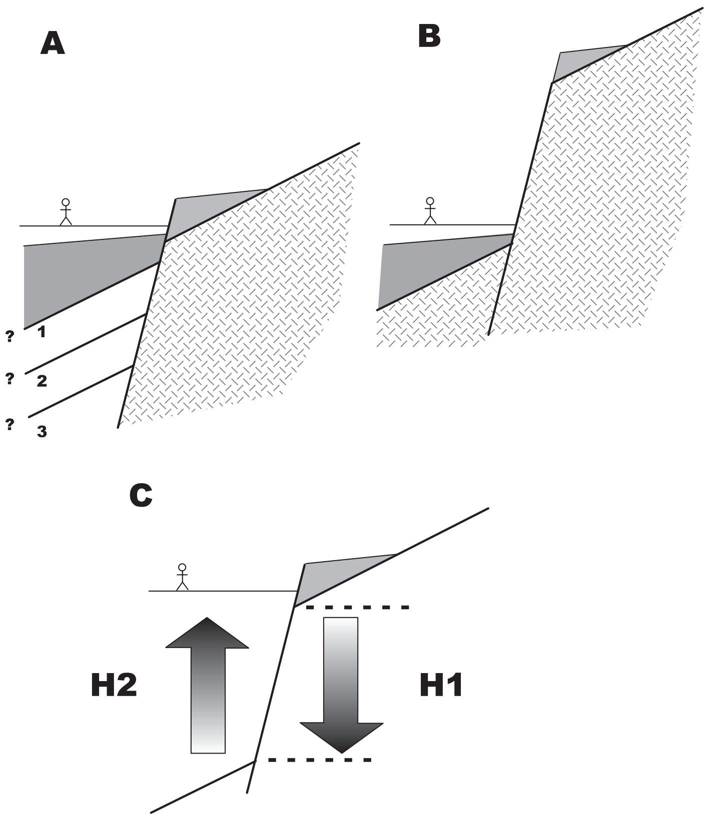


Figure 17. Diagrammatic cross sections showing observed geometry of a typical Death Valley–area range flank, and models for the evolution of that geometry. (A) Observed geometry. Low-angle fault is exposed at the range front. Range flank is the exhumed surface of the low-angle fault. Position of offset low-angle fault in subsurface is uncertain (1–3). (B) Not observed—low-angle faults and their hanging walls perched high in the range. (C) Conditions necessary to produce A, assuming significant throw on the high-angle fault, H2—vertical accumulation of sediment in the basin. H1 would have to equal H2 (or nearly so) in order to produce the observed geometry.

11.6 Ma diorite, which cooled through 500 °C at 10 Ma and was exposed by 5 Ma (Asmerom et al., 1990). Although the uplift and unroofing of these rocks was not necessarily due to the currently exposed turtleback faults, extension-related uplift was probably occurring by late Neogene time, at least in the Black Mountains.

The exposed portions of the hanging walls are apparently young, consisting mostly of unconsolidated fanglomerate. In the Panamint low-angle, range-flank fault hanging wall, clasts in the fanglomerate consist entirely of lithologies exposed above it on the range flank. Stratigraphically higher miogeoclinal rocks, which might have been exposed on this flank at earlier times, are not present; therefore the fanglomerate is probably geologically young, possibly Quaternary age. The Badwater turtleback fault cuts volcanic rocks as young as 700 ka in the hanging wall (Knott et al., 1996). It is therefore likely that the Badwater and Panamint normal-fault systems were contributing to the opening of Death and Panamint Valleys as recently as mid-Quaternary time. The relatively fresh appearance of scarp-forming faults at all of the range fronts supports the notion of a late Quaternary age for these steeper faults.

Zhang et al. (1990) and Densmore and Anderson (1997) presented evidence consistent with a late Quaternary age for the dextral shear in Panamint Valley. Zhang et al. (1990) noted that the dextral offsets on the Panamint Valley fault zone occurred in apparently subaerial sediments, which are exposed at elevations below that of the most recent Pleistocene lake (13 ka; Smith, 1976). Densmore and Anderson (1997) documented warping of a pluvial shoreline, probably 120–150 ka, along the Ash Hill fault. The dextral faults in Panamint Valley (which cut unit Qal) were probably preceded by steep normal faults, because normal fault scarps of the Panamint Valley fault zone cut unit T/Qf but not unit Qal (Figs. 2–7).

Relative Importance of Low-Angle and High-Angle Faults in Creating Basin-Range Topography

A geometric argument demonstrates that most of the opening of the valleys probably occurred along the (currently) low-angle range-flank faults, and not along the steeper scarp-forming faults. In all four valleys, the exposures of the low-angle faults have not been uplifted very far relative to the valley floors. They are still located at the range front (Fig. 17A), not high in the mountain block (Fig. 17B). This shows that normal slip on the steep faults has been small, due to their young age, a low slip rate, a predominance of strike slip, or a combination of these factors. It might be argued that the valley block could have been downdropped a great distance (H1, Fig. 17C), while basin sedimentation and erosion of the hanging wall kept pace (H2, Fig. 17C), in order to produce the configuration exposed in all four valleys. Such an argument seems fortuitous, because there is no mechanism that would require sediment to fill each basin to such a level as to produce the observed geometry. For example, no obvious link exists between the low-angle, range-flank–type faults and the heights of the drainage divides that enclose each basin. These divides have a variety of heights above the valley floors: 150 m in the case of Searles Valley, 250 m in the case of Panamint Valley, 1200 m in Saline Valley. Death Valley has no outlet, and yet, like the other valleys, the turtlebacks display the same geometry shown in Figure 17A.

In Panamint Valley, the strike-slip component of the scarp-forming faults may be indirectly responsible for topography even younger than that created by the low-angle range-flank faults. Smith (1976) proposed that a zone of crushed granitic bedrock on the south face of Hunter Mountain (Fig. 1) may be the site of a south-directed, Quaternary thrust fault. In his model, the transition from west-northwest–east-southeast–directed extension to north-northwest–oriented dextral shear changed the Hunter Mountain fault from a dextral accommodation structure to a restraining bend in a strike-slip fault system, thus leading to contraction in the Hunter Mountain area. Ellis et al. (1995) suggested through computer modeling that much of the high topography of Hunter Mountain may be due to this contractile deformation.

Two-Stage Model for Evolution of Death Valley–Area Basins

A two-stage model appears to be the most reasonable explanation for the variety of observations from the range flanks of the Death Valley region. First, multiple generations of predominantly normal faults, which now dip shallowly, accomplished most of the uplift of the mountain blocks relative to the valleys. Second, steep faults uplifted portions of the low-angle faults and their hanging walls a short distance. In Panamint Valley, natural exposures demonstrate that these steep faults are not upper plate faults, but cut the low-angle faults. In Panamint Valley, a dextral-shear component of the second phase is currently active, and may be causing local contractile orogenesis at the north end of the valley.

The two-stage basin evolution has probably occurred in the context of the Eastern California shear zone, a broad zone of northwest- to north-striking dextral shear that may have accommodated as much as 25% of Pacific–North America motion since the late Miocene (Dokka and Travis, 1990). Recent studies integrating space geodesy and geological data suggest that dextral shear on northwest-striking faults has decreased during the last few million years, while increasing on more north-trending faults (Dixon et al., 1995; Reheis and Dixon, 1996). This is generally consistent with the two-stage model for Death Valley–area basins, in which dextral shear during the first phase occurs on the northwest-trending Hunter Mountain fault, and later occurs on the north-northwest–trending Panamint Valley fault zone. Geological and geomorphic studies in the White Mountains (a northern continuation of the Inyo Mountains, Fig. 1) suggest that very young, north-northwest–plunging turtleback-like faults are currently forming in response to this latest phase of Eastern California shear zone activity (Guth, 1996, 1997; Guth et al., 1996).

CONCLUSIONS

The turtleback-like faults in four mountain ranges and the truncation of a low-angle fault by a high-angle fault in at least one range are best explained by a two-stage model for late Cenozoic tectonics in the Death Valley area. A major remaining question is the applicability of this model to the entire region. In southern Panamint Valley and possibly at Mormon Point, low-angle faults are truncated by high-angle faults, lending credence to the two-stage model. The other range flanks do not expose such a truncation, nor is there any shallow geophysical data from these areas at present. If a similar truncation exists along the other range flanks, it implies that much of the topography of the Death Valley region is relict, having been caused by low-angle faults that are no longer active. The cessation of this activity may have been so recent, however, that when coupled with low Holocene erosion rates, the topography is essentially unchanged. If a Panamint Valley–type, two-stage model is applicable to the region as a whole, it grants geologists an excellent view of two phases of tectonic geomorphology. The Death Valley region may not be an example of active detachment faulting and supradetachment basins, but it provides a detailed view of recently active models of these features.

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