Geology of Panamint Valley - Saline Valley Pull-Apart System, California: Palinspastic Evidence for Low-Angle Geometry of a Neogene Range-Bounding Fault

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Geological studies support the interpretation that northern Panamint Valley and Saline Valley, southeast California, form paired pull-apart basins on opposite sides of the right-slip Hunter Mountain Fault Zone. Eight to ten km of late Cenozoic net slip can be established on the Hunter Mountain Fault Zone. Palinspastic reconstruction of northern Panamint Valley indicates that the valley was formed by movement on a shallow crustal, low-angle normal fault of 0-15 degree west dip during the last 3.0 Ma. This interpretation appears to contradict the notions that little extension is accomodated in the uppermost crust by low-angle faulting and that the most recent extension in the Basin and Range Province is accomodated exclusively by high-angle faulting. Saline Valley, however, is interpreted to have formed by extension on closely spaced, rotated planar normal faults. Thus, within one geometric system of paired pull-apart basins, extension appears to have been accommodated in the shallow crust in two different ways.

INTRODUCTION

The structure of the Death Valley Extended Area of southeastern California (Figure 1) is dominated by NNE to NNW-trending normal fault systems and NW-trending wrench fault systems. The late Cenozoic extensional tectonics of this region has been characterized by the interplay of both systems, such that many of the valleys here (e.g., Death Valley itself) are "pull-apart" basins [*Burchfiel and Stewart*, 1966]. Two of these, Panamint and Saline valleys, are linked by the dominantly strike-slip Hunter Mountain fault (Figure 2). This structure maintained strain compatibility between the normal faults responsible for the opening of the valleys, serving much the same functions as tear faults in compressional regions. Simple transfer faults (terminology of *Gibbs*, [1984]) such as this one place important controls on palinspastic reconstructions of extensional regions because the net slip on these structures corresponds to the direction and magnitude of extension in adjoining basins.

We are currently conducting detailed geologic mapping in the area of northern Panamint Valley and Saline Valley. Although our work there is far from complete, it has led to the discovery of a unique linear element (formed by the intersection of a high-angle intrusive contact and an overlapping basalt flow) which occurs on either side of the Hunter Mountain fault and constrains its post-4 Ma net slip. Palinspastic reconstruction of northern Panamint Valley based on these data indicates that the basin was developed by movement on a west dipping low-angle detachment. Coupled with geophysical data presented in a companion paper [*MIT 1985 Field Geophysics Course and Biehler*, this issue], the geological evidence presents a compelling case for the importance of shallow level, low-angle detachments in the development of Basin and Range physiography.

GEOLOGIC FRAMEWORK

The bedrock geology of ranges adjacent to northern Panamint Valley is dominated by (1) upper Precambrian-Triassic sedimentary rocks and their metamorphic

equivalents that are part of the western Cordilleran miogeocline; and (2) Jurassic-lower Tertiary plutonic rocks intruded into the miogeoclinal section during the development of the Sierran batholithic complex at this latitude [*McAllister*, 1956; *Hall* and *McKevitt*, 1962; *Hall*, 1971]. Polyphase compressional deformation of Mesozoic-early Cenozoic age has resulted in complex structural relationships in the ranges [e.g., *Dunne et al.*, 1978; *Dunne*, 1986; *Wernicke et al.*, 1986]. All Precambrian-lower Tertiary rocks were eroded to a surface of relatively low relief before being uncomformably overlain by upper Cenozoic sedimentary and volcanic rocks.

Pre-Cenozoic rocks relevent to this discussion are the Hunter Mountain batholith (Figure 2) of early Jurassic age [*Chen and Moore*, 1982] and its eastern wall rocks. These rocks crop out extensively in the northern Panamint Range and in smaller erosional windows through the extensive Cenozoic basalt cover on the Darwin Plateau. Our detailed mapping of the Panamint Butte area confirms a N7°E striking nearly vertical contact for the southeast side of the Hunter Mountain batholith (Figure 3a). Mapping of part of the Darwin Plateau originally mapped by *Hall and McKevitt* [1962] has revealed a new exposure of this contact near the northeast margin of the plateau. These contacts are similar in orientation, but are offset by the N6°W striking Hunter Mountain Fault Zone (Figures 2 and 3a).

In the Panamint Butte area, pre-Cenozoic rocks are unconformably overlain by Miocene-Pliocene sedimentary and basaltic volcanic rocks of the Nova Formation [*Hopper*, 1947] These units represent an older extensional basin (which we call the Nova Basin) that has been stranded in the Panamint Range by the subsequent opening of Panamint Valley (Figure 2). Detailed mapping and K-Ar geochronology in the Tucki Mountain area (Figure 1) [*Wernicke et al.*, 1986; *W. Hildreth*, unpublished data, 1985] and SE of Panamint Butte [*K. V. Hodges et al.*, unpublished data, 1985] indicate that the Nova Basin developed in the latest Miocene-early Pliocene time. One of the youngest basalts of the Nova Basin (K-Ar dated at 4.0-4.3 Ma by *Larson* [1979]) lies unconformably directly on miogeoclinal strata and the Hunter Mountain batholith, and caps Panamint Butte itself.

Remnants of the Nova Basin are also present on the west side of northern Panamint Valley in the Argus Range
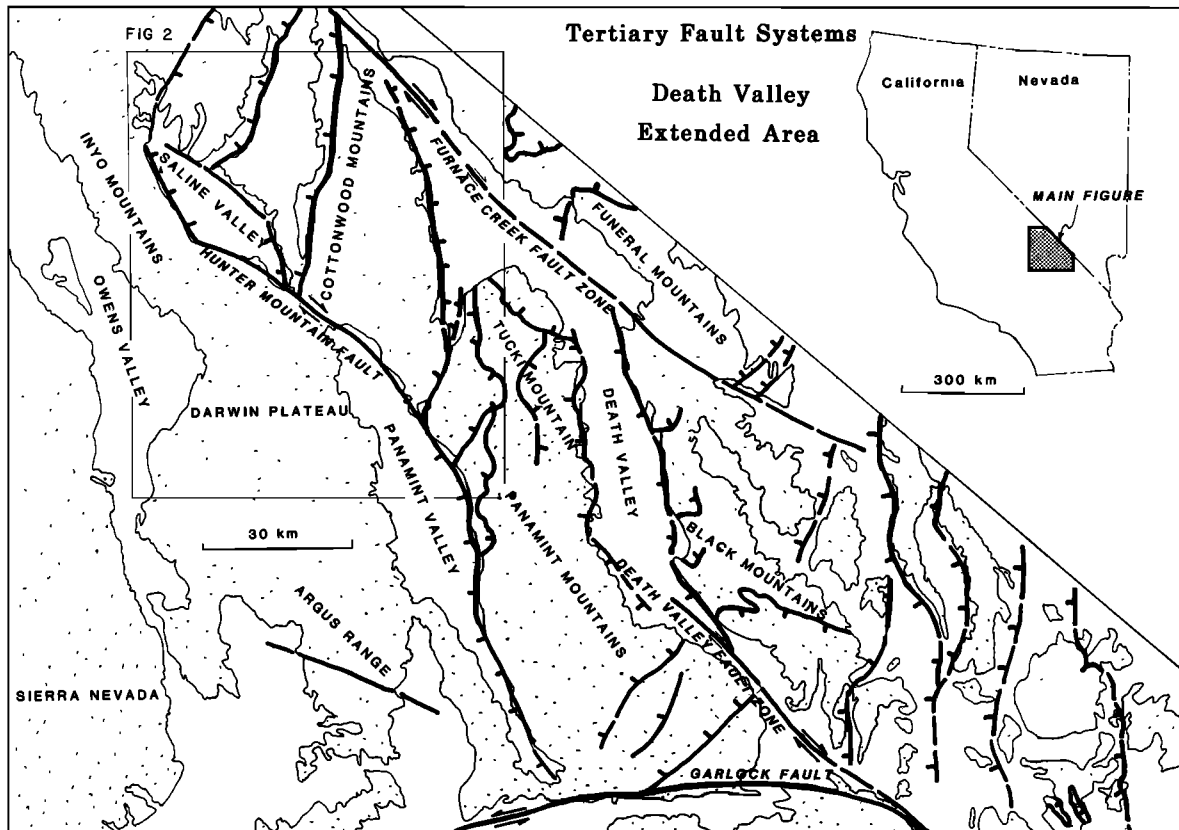
Fig. 1.   Major faults of the Death Valley extended area and location of the northern Panamint Valley and Saline Valley paired pull-apart basins. Location of Figure 2 is shown.

and on the Darwin Plateau [*Smith*, 1976; *Schweig*, 1985]. Much of the northern Darwin Plateau consists of basaltic volcanic rocks of Miocene-Pliocene age which rest unconformably on bedrock identical to that in the Panamint Butte area.   Petrology and K-Ar ages of the Darwin Plateau volcanics [*Larson*, 1979; *Schweig*, 1985] indicate that the uppermost basalts on the plateau are correlative to the capping basalt on Panamint Butte.

These data indicate that the northern end of Panamint Valley opened after development of the Nova Basin and eruption of the lower Pliocene basalts, and fault scarps cutting the alluvium on both sides of the valley indicate continuing extension.   These latest structures show both right-slip and normal-slip components of displacement (see *Smith* [1976] and our mapping).   The valley ends abruptly in the north against a steep topographic slope, trending N6°W and having 1.0-1.5 km of relief, that corresponds to the Hunter Mountain Fault Zone.   Active subsidiary scarps along this margin of the valley also attest to modern extension.

Saline Valley appears to have formed during the same time period as northern Panamint Valley.   Although parts of the Saline Range may have been involved in earlier basin development [*Blakely and McKee*, 1985], the Saline Range to the north of the Saline Valley contains basalts that date from 3.8 to 1.7 Ma [*Larson*, 1979].   Mapping in the Saline Range and adjacent areas suggests that Saline Valley did not begin to form until after extrusion of the oldest (3.8-2.8 Ma) basalts [*Burchfiel*, 1969; *Ross*, 1967, 1968; *Larson*, 1979].   Saline Valley is bounded on its south side by the westward continuation of the Hunter Mountain Fault Zone [*Zellmer*, 1980, 1983]   The faults along the east side of the valley are marked by active

normal-slip faults, some of which also have right-slip displacement.   NE-trending normal-slip faults are abundant in the Saline Range [*Ross*, 1967] and present in the Dry Mountain area [*Burchfiel*, 1969].   These faults are parallel to active normal fault scarps along the east side of Saline Valley [*Zellmer*, 1980, 1983].

We believe that formation of northern Panamint Valley and Saline Valley was the result of development of a late Pliocene to Recent extensional system that consists of paired pull-apart basins connected by the Hunter Mountain transfer Fault.   This interpretation of the kinematic significance of the Hunter Mountain fault Zone is supported by the following: (1) the zone does not extend eastward beyond the eastern boundary of Panamint Valley, nor does it extend westward beyond the western margin of Saline Valley, and (2) there is no evidence for pre-late Cenozoic movement on the zone.

EXTENSION GEOMETRY IN NORTHERN PANAMINT VALLEY

Given the transfer fault interpretation for the Hunter Mountain Fault Zone, we argue that the displacement on the central segment of the structure is equal to the amount of extension in both northern Panamint Valley and Saline Valley.   The intersection between the steep eastern wall of the Hunter Mountain batholith and the unconformity at the base of the Miocene-Pliocene basalt sequence produces a N7°E, subhorizontal line that is offset by the Hunter Mountain Fault Zone.

Figure 3*b* is a cross section drawn parallel to the Hunter Mountain Fault Zone (N6°W) and depicts relevant geological data projected from both sides of the structure. The linear element described above is shown as two
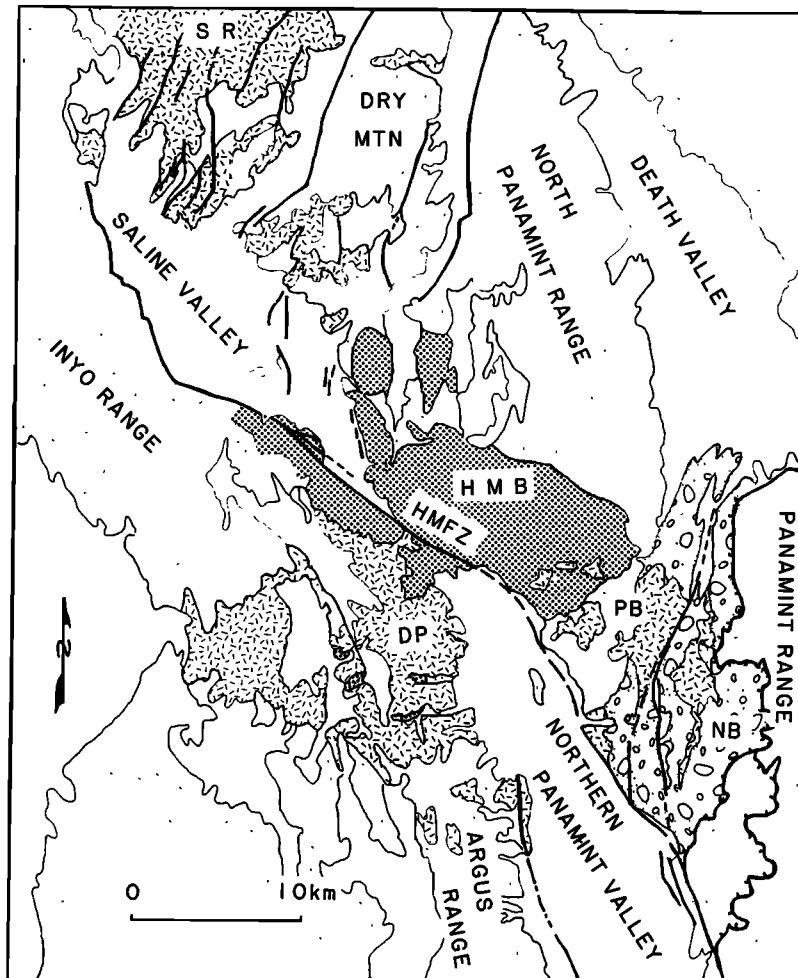
Fig. 2 General geological framework of the northern Panamint Valley and Saline Valley area. HMB, Hunter Mountain batholith; HMFZ , Hunter Mountain Fault Zone; DP, Darwin Plateau; PB, Panamint Butte; SR, Saline Range; NB, Nova Basin. Random dash pattern covers area of late Cenozoic volcanic rocks.

piercing points in the section. The net slip indicated by the offset of this element is 8-10 km of right-lateral strike-slip accompanied by 0-2 km of down-to-the-south dip slip. The range of slip vectors shown on Figure 3 reflects uncertainties in the projection of the linear element onto the section. If we assign the maximum age of Saline Valley (3.0 Ma) to the age of inception of the Hunter Mountain Fault Zone, the minimum average slip rate on the fault is 2-3.2 mm/y. Presumably, this figure also corresponds to the minimum rate of extension in northern Panamint Valley and Saline Valley.

Northern Panamint Valley may be palinspastically reconstructed by aligning the two piercing points in Figure 3b. This exercise completely restores the uppermost basalt flows on the Darwin Plateau against the correlative caprocks of Panamint Butte, strongly suggesting that opening of the basin was principally accommodated by movement on a detachment fault dipping $0°-15°$ westward. The range-bounding fault along the eastern margin of Panamint Valley (which is presumably the surface expression of this detachment) dips approximately $42°W$, indicating a broadly listric geometry. This conclusion is supported by the gently curved, convex-upward geometry of the Darwin Plateau basalts, indicating "rollover" in the hanging wall of a curved fault [Hamblin, 1965].

If a low-angle detachment fault underlies northern

Panamint Valley, then the valley fill cannot be very deep. A drill hole in the central part of the valley encountered 370 ft (113 m) of Cenozoic valley fill before entering Paleozoic rocks [Smith and Pratt, 1957]. In addition, the low-angle normal fault would have removed all the Tertiary and Paleozoic rocks of the hanging wall from the footwall in the valley: the valley fill must have been deposited directly onto a progressively broader expanse of the footwall rocks as the valley formed. Subsequently, the valley fill must have moved relatively westward with the hanging wall. Geophysical data gathered by the Massachusetts Institute of Technology (MIT) Geophysics Field Camp in 1985 in connection with our geological work [MIT 1985 Field Geophysics Course and Biehler, this issue] indicate that the valley fill is only a few hundred feet thick and that no basalt underlies the valley. The latter interpretation is important because it supports the interpretation that hanging wall rocks of the postulated low-angle normal fault were completely removed from footwall rocks beneath the valley.

TECTONIC IMPLICATIONS

Structural relationships around northern Panamint Valley and geophysical data for the valley itself strongly indicate that low-angle detachment faulting has played a major role in the development of this Pliocene-Recent basin.
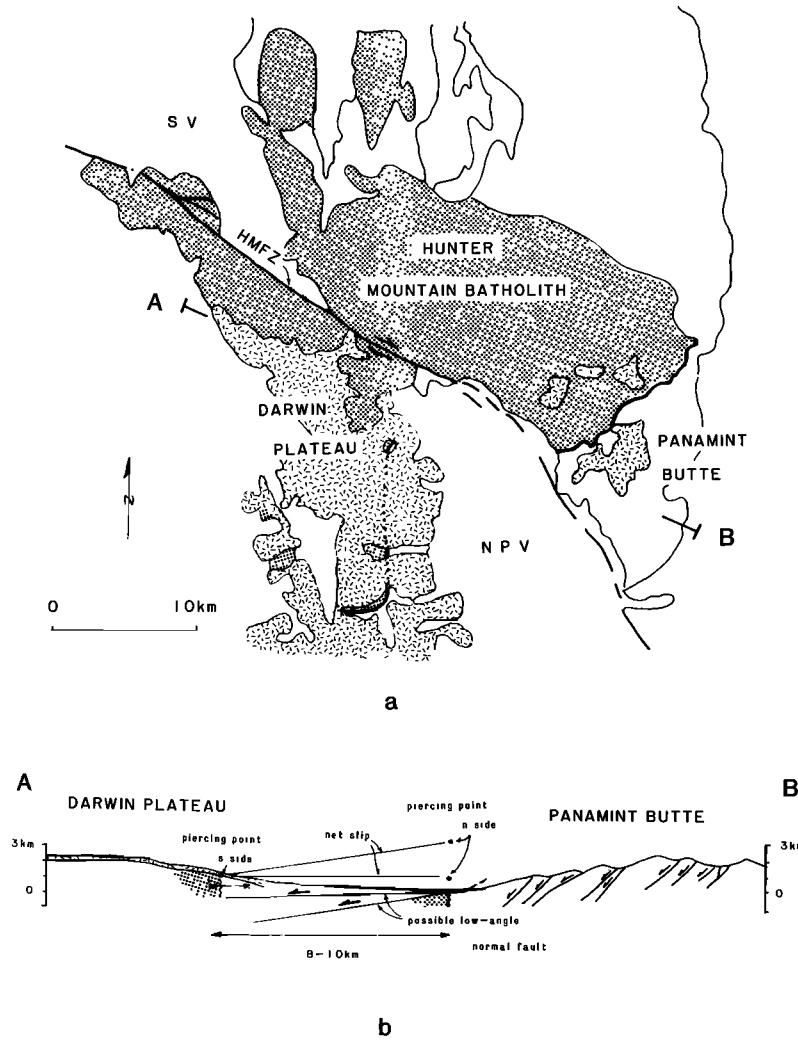
a

b

Fig. 3 (a) Detailed map of the area of the Hunter Mountain batholith. Unique line used to establish to piercing points is the intersection of the vertical southeast contact of the Hunter Mountain batholith (heavy dark line) and the late Cenozoic volcanic rocks of the Darwin Plateau and Panamint Butte. HMFZ, Hunter Mountain Fault Zone; SV, Saline Valley; NPV, Northern Panamint Valley. Irregular line segment pattern covers area of late Cenozoic volcanic rocks. (b) Cross section A-B parallel to the Hunter Mountain Fault Zone. Piercing points form both south side (left side of section) and north side (right side of section) are projected onto the line of section. Corresponding lines of net slip and possible low-angle normal faults are shown. The uncertainty of the piercing point on the north side is due to a normal fault at the range front which drops the contact down. We suggest that the highest piercing point is the correct one, but the lower one is also possible. Uncertainty of horizontal offset is mainly due to a 2-km uncertainty in projecting the unique line to the line of section on the south side of the fault zone. Faults in the Panamint Butte area are from more detailed maps than that of Figure 3a.

Although many geologists have stressed the importance of low-anlge normal faults to Cenozoic extension in the North American Cordillera (e.g., Anderson, 1971; Armstrong, 1972; Wernicke, 1981], some controversy exists concerning the initial geometry of these structures. Few examples demonstrate an initial low-angle geometry as convincingly as the northern Panamint Valley situation. Reconstruction of the basin along a low-angle detachment fault results in the restoration of an early Pliocene volcanic plateau; no alternative reconstruction involving large-scale rotation of an initially high-angle structure produces an acceptable initial orientation of the volcanic units.

The geology of northern Panamint Valley seems to contradict two widely held notions conerning Cenozoic extension in the western United States: (1) that little of the extension in the uppermost crust is accommodated by low-angle faulting [e.g., Eyidogan and Jackson, 1985;

Jackson, 1987], and (2) that the most recent extension is accommodated exclusively by high-angle "Basin and Range" faults [e.g., Zoback et al., 1981] The northern Panamint Valley detachment fault clearly initiated in the upper 5 km of the crust and apparently is still active at a shallow level. Moreover, the detachment is directly responsible for the present Basin and Range topography that characterizes the Panamint Butte-Darwin Plateau area.

We do not, however, wish to imply that all Basin and Range topography is a consequence of low-angle range bounding structures. Immediately to the north, in Saline Valley, extension appears to have been accommodated differently. In the Saline Range and parts of Dry Mountain, there are numerous northeast striking, west dipping normal faults which project into Saline Valley, and Pliocene volcanic rocks are exposed continuosly across the ranges [Ross, 1967, 1968; Burchfiel, 1969; Larsen, 1979]. Moreover, gravity data [Chapman et al.,

1973] indicate that Saline Valley is an extremely deep basin. These lines of evidence preclude a single low-angle detachment model for extension in Saline Valley; instead they favor a model based on closely spaced rotated planar faults [*Wernicke and Burchfiel*, 1982]. These faults may end at depth at a low-angle normal fault, but such a low-angle fault would not be directly responsible for the shallow crustal extension. Thus, within one geometric system of paired pull-apart basins, extension appears to have been accommodated in the shallow crust in markedly different ways.

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