STRUCTURAL STYLE AND KINEMATIC HISTORY OF THE ACTIVE PANAMINT-SALINE EXTENSIONAL SYSTEM, INYO COUNTY, CALIFORNIA

by

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Abstract

Geologic mapping of faults active during the most recent period of Basin and Range extension in northern Panamint and Saline Valleys, southeastern California, presents a picture of a single extensional system, which is characterized by two different structural styles of uppercrustal extension paired through the right-slip Hunter Mountain Fault zone. Palinspastic reconstructions of faulted pre- to synextensional basalts and Mesozoic structures are used to constrain the magnitude, timing, and structural geometry of extension across the system.

Northern Panamint Valley has experienced 9.3 +- 1.4 km of pull-apart since 4 Ma, essentially contemporaneously with extension across the Saline Range. This amount of extension is equal to the total right-slip offset on the Hunter Mountain Fault. Northern Panamint Valley has formed as a result of the relative westward displacement of an intact Darwin Plateau hangingwall along a listric low-angle normal fault, which splays to the surface at 50-60 degrees, and flattens to less that 5 degrees within the upper 3 km of the crust. Average strain rates for the opening of northern Panamint Valley lie between 2 and 2.7 mm/year, assuming extension began at 4 Ma.

Saline Valley and the Saline Range comprise an extensional system that is more difficult to interpret. The rhombic Saline Valley appears to be a right-lateral oblique pull-apart at the northwest end of the Hunter Mountain Fault, whereas the Saline Range, lying adjacent to and north of the valley, has been extended by numerous north-northeast striking, rotated dip-slip faults. Both areas, however, show the same net extension direction. Palinspastic reconstructions of the Saline Range faults yield about 4.5 +- 0.6 km of extension since 1.4 Ma -- an average strain rate of 2.8 to 3.6 mm/year.

Saline Range-related basalts older than 3.2 Ma that are isolated on Dry Mountain to the east indicate that extension had begun by about 3 Ma, at least on the major western boundary fault of Dry Mountain. These older basalts, where they crop out in the Saline Range, are tilted at the same angle as the extensively exposed 1.4 Ma basalts, suggesting that the earlier period of extension either did not involve rotation, or that rotation did not occur in those areas covered by the older basalts. Normal fault offsets of a Mesozoic thrust across the Saline Range suggest that between 2.5 and 6.4 km of extension occurred there prior to 1.4 Ma. The total amount of extension recoverable from the Saline Range is thus approximately 8.9 +- 2.5 km, which overlaps the amount of displacement measured on the Hunter Mountain Fault. The Panamint-Saline extensional system can therefore be roughly balanced in three dimensions.

Based on the results of this study of the Panamint-Saline extensional system, two distinct styles of upper crustal low-angle detachment faulting appear to have been simultaneously active on either side of the Hunter Mountain Fault. This low-angle fault system is directly responsible for the classic Basin and Range topography of the area, and numerous fault scarps cutting young alluvium suggest that it is still active today. The compatibility of extensional magnitude and timing between northern Panamint Valley, the Hunter Mountain Fault, and the Saline Range indicates that the system has been structurally paired throughout its development. This result further suggests that transfer structures such as the Hunter Mountain Fault accurately reflect the extension that has occurred in adjacent basins, and so may be used to measure the extension in, and thereby constrain the structural geometry of, basins that cannot be independently reconstructed.

Introduction

Many workers have interpreted various extended areas in the Basin and Range Province to be underlain by normal faults that initiated at low angle (eg. Wernicke, 1981; Davis and Lister, 1985; Stewart, 1983; Anderson, 1971; Burchfiel et al., 1987; Davis, 1988). Such faults, commonly referred to as detachments, are inferred to have formed in the brittle upper few kilometers of the crust with initial dips of less than 30 degrees. These interpretations are based on mapping of exhumed normal faults now at very low angles, which juxtapose uppermost crustal rocks on ductilely deformed rocks of the midcrust (eg. Wernicke et al., 1986; Bartley and Wernicke, 1984; Davis et al., 1979; Davis, 1986). Such surface studies, supported by seismic reflection data have led to a concept of thin-skinned extensional nappes, which are bounded at their bases by low-angle decollements that persist as discrete zones of simple shear throughout the upper and middle crust. This conceptual model has extension in the upper crust laterally separated from associated extension in the lower lithosphere (Wernicke, 1981).

Such a concept runs counter to the view of others that continental extension takes place on high-angle faults in the upper crust that may sole into low-angle shear zones only at considerable depth (>> 5 km) (Eyidogan and Jackson, 1985; Jackson, 1986; and others), and that all recent extension in the Basin and Range has occurred on such high-angle faults (Zoback et al., 1981). Many workers favor a two layer model of extending continental crust with brittle uppercrustal extension immediately underlain by pure shear ductile stretching, and possibly lateral accommodational flow in the lower crust (Gans, 1987).

Proponents of "high-angle" extensional tectonics point to the present lack of seismic evidence for shallow, low-angle normal fault motion (Jackson, 1986), and the inherent mechanical problems of moving a thin, but coherent extensional nappe. Low-angle normal faults exposed at the surface are interpreted to have originally been steeper faults that have rotated to low angles during extension, and as low-angle decollements that originated at the mid-crustal depths near the brittle-ductile transition zone (Gans and Miller, 1985).

These two views of Basin and Range extension clearly predict very different types of accommodation to extension at depth, with attendent differences in patterns of heat flow, uplift, and volcanism. While these differences suggest many remote sensing and inferential modelling experiments for testing the two hypotheses, the results of such efforts to date remain ambiguous.

Figure 1. Location of the Panamint-Saline area within the Death Valley extensional region. The location of figure 2 is indicated.

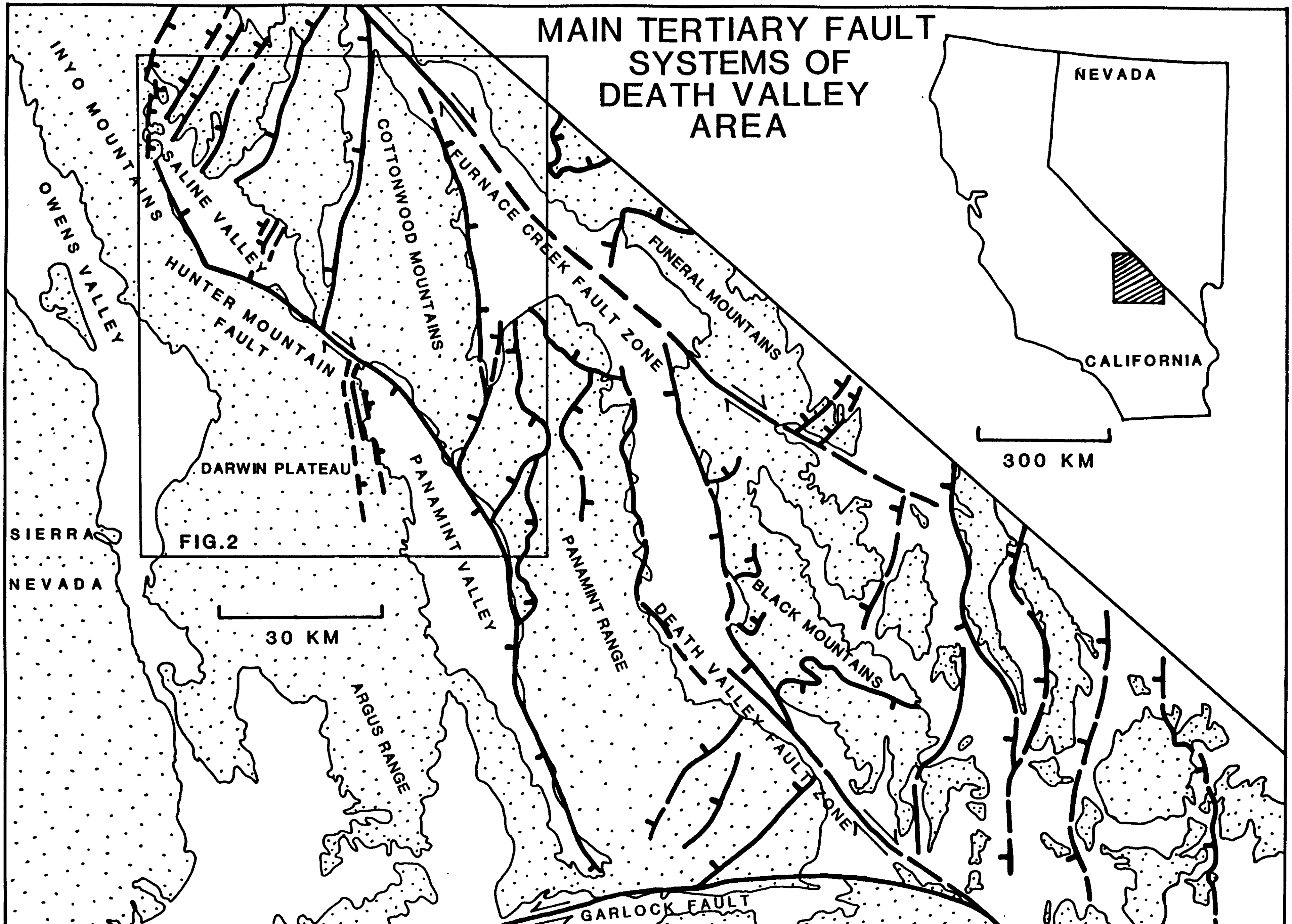

MAIN TERTIARY FAULT SYSTEMS OF DEATH VALLEY AREA
NEVADA
CALIFORNIA
300 KM
INYO MOUNTAINS
OWENS VALLEY
SALINE VALLEY
HUNTER MOUNTAIN FAULT
COTTONWOOD MOUNTAINS
FURNACE CREEK FAULT ZONE
FUNERAL MOUNTAINS
DARWIN PLATEAU
PANAMINT VALLEY
PANAMINT RANGE
FIG.2
SIERRA NEVADA
30 KM
ARGUS RANGE
BLACK MOUNTAINS
DEATH VALLEY FAULT ZONE
GARLOCK FAULT

FIGURE 1

Purpose

The two primary purposes of this study are: 1) to examine the geological evidence for active low-angle normal faulting in the Panamint-Saline extensional system of the southwestern Basin and Range (figure 1), and 2) to test the common assumption that extensional "transfer" faults (Gibbs, 1984) reflect both the direction and magnitude of the extension present, but often unrecoverable in the adjacent basins that they link together. The Panamint-Saline area provides an excellent opportunity to address these questions because it circumvents two common field problems: (1) that exposed and inactive extensional structures are sufficiently ambiguous to permit opposing interpretations of the same available data (amply obvious from the controversy described above), and (2) that many of the faults in active extensional areas are buried under sedimentary deposits.

The Panamint-Saline area is extensionally active, exhibiting classic Basin and Range topography and containing abundant fault scarps that cut recent alluvial deposits. The area is also capped with extensive Plio-Pleistocene basalt flows, which are everywhere cut and displaced by the extensional faults. These basalts comprise a datable paleosurface that provides a datum for palinspastically reconstructing the developing basins, solving for extensional rates, and constraining active fault geometries at depth. The area is not affected by significant post-extensional uplift, which hampers the study of older, exhumed structures elsewhere.

The two extensional basins are joined by the right-slip Hunter Mountain Fault, from which can be measured an amount, direction, and approximate timing of displacement. The widespread, extensionally tilted basalt flows of the Saline Range, which are exposed across the northern edge of Saline Valley, provide a means of measuring the extension in the system independently from the Hunter Mountain Fault. Such a system can potentially be balanced in three dimensions.

Previous Work

Northern Panamint Valley low-angle normal fault

Burchfiel et al. (1987) interpreted northern Panamint Valley to have formed as the result of the nearly complete removal of hanging wall rocks from the footwall by 8 to 10 kilometers along a shallow, low-angle, west-dipping detachment. They base the magnitude of the displacement, and the geometry of the detachment fault on the offset of a linear geologic feature across the Hunter

Mountain Fault. The offset lineament is defined by the intersection of a high-angle intrusive contact with a subhorizontal basalt flow on either side of the fault.

Their interpretation was supported by geophysical data presented in a companion paper by Biehler et al. (1987). Biehler et al. found that a "seismic basement" of rocks apparently undisturbed by the extension lies only about one kilometer below the present valley floor. Their magnetic profile across the valley also suggests that the basalts, abundant on either side of the valley, are absent from beneath as much as 9 km of the width of the valley floor..

Mapping

The Panamint-Saline area has been mapped at about 1 inch to the mile by Ross (1967 a,b), Burchfiel (1969), Merriam (1963), McAllister (1956), Hall and McKevitt (1962) and Hall (1971). Some additional mapping of fault scarps, as well as general geological interpretations have been presented by Smith (1975), Zellmer (1980), Schweig (1984), and Burchfiel (unpublished).

Geochronology

Potassium-Argon ages for the Pliocene basalt flows in the region have been published by Elliot et al. (1984), Larson (1979), Schweig (1984), and Ross (1970).

Geological Framework

The area discussed in this report lies within the Death Valley extended region of the southwestern Basin and Range Province (Figure 1). Saline Valley lies to the north of northern Panamint Valley and is joined to it by the N55W-trending Hunter Mountain Fault, which cuts through the abrupt intervening topographic high underlain by the Hunter Mountain Batholith (Figure 2). The Hunter Mountain Fault does not extend beyond the eastern boundary of Panamint Valley, or beyond the western boundary of Saline Valley, and thus can be interpreted as a transfer structure between the two extensional basins. The two to three kilometers of rugged relief between the basins and ranges reflect the youthfulness of the extensional faulting.

Lithologies

The entire Death Valley Region is underlain by thrust faulted and folded Paleozoic rocks of the western Cordilleran miogeocline, Jurassic to Tertiary felsic intrusive rocks, and a variably thick cover of Neogene sediment and volcanic rocks (eg. see McAllister, 1956; Ross et al., 1967a; Burchfiel, 1969; Burchfiel and Davis, 1975; Dunne et al., 1978; Schweig, 1984). This study of the Panamint-Saline area is based primarily on the Plio-Pleistocene basalts. They formed a laterally extensive subhorizontal volcanic unit overlying the deformed Paleozoic and intrusive rocks,

Figure 2. General geologic map of the Panamint-Saline area showing major lithologies, Tertiary extensional structures, and geographic landmarks.

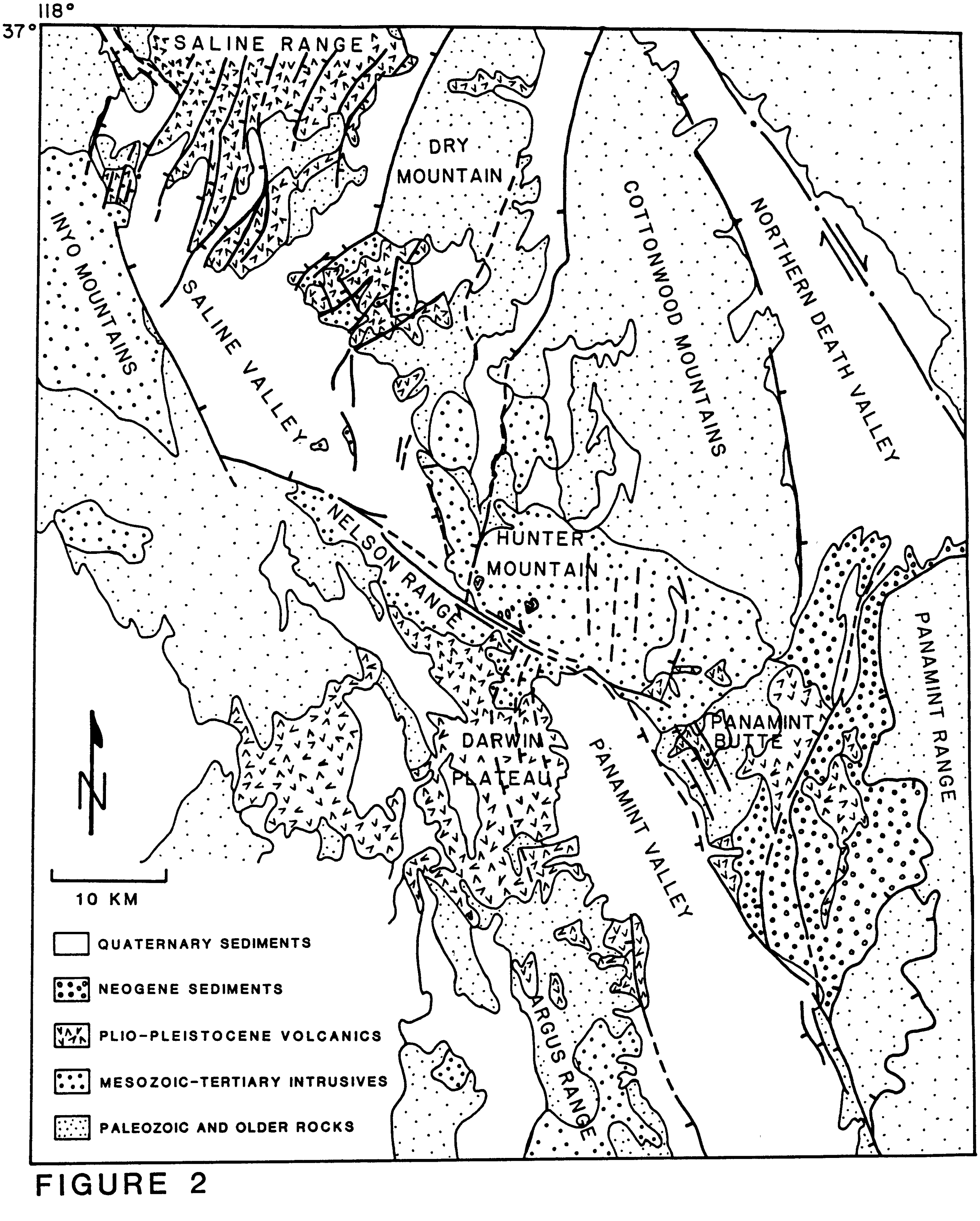

118°
37°
SALINE RANGE
DRY MOUNTAIN
INYO MOUNTAINS
SALINE VALLEY
COTTONWOOD MOUNTAINS
NORTHERN DEATH VALLEY
NELSON RANGE
HUNTER MOUNTAIN
DARWIN PLATEAU
PANAMINT VALLEY
PANAMINT BUTTE
PANAMINT RANGE
ARGUS RANGE
N
10 KM
QUATERNARY SEDIMENTS
NEOGENE SEDIMENTS
PLIO-PLEISTOCENE VOLCANICS
MESOZOIC-TERTIARY INTRUSIVES
PALEOZOIC AND OLDER ROCKS

FIGURE 2

and can therefore be used in their present configuration to reconstruct the extensional evolution of the area. The basalts are pre-extensional to early synextensional in age, and clearly extruded onto a landscape of limited topographic relief. The basalts crop out at high elevations in all the surrounding ranges except the Inyo Mountains, which may have had 1 to 1.5 km of relief at the onset of volcanism (Plates A and B).

Structure

The central portion of the Hunter Mountain Fault shows almost pure right-slip. The sense of slip is clearly demonstrated by right-slip stream offsets, and shutter ridges with no significant component of dip-slip. The N55W strike of the fault is interpreted to represent the overall extension direction within the two basins since their inception (Burchfiel et al., 1987). At the northwest and southeast ends of the Hunter Mountain Fault, where it bounds the southern end of Saline Valley and the northern end of Panamint Valley, respectively, the fault shows components of both right-slip and dip-slip displacement. Active faults in the aluvium on the eastern side of northern Panamint Valley, which trend obliquely to the Hunter Mountain Fault and parallel to the range bounding faults of Panamint Butte, consistently show both normal and right-slip offsets (Plate A). Fault scarps in the alluvium of Saline Valley also show oblique right-slip and dip-slip offsets, depending on their orientations. The northeast-striking normal faults in the Saline Range show predominantly dip-slip offsets, and independently yield an extension direction of approximately N60W.

Northern Panamint Valley is a half-graben with most of the active faults concentrated on its eastern side. The faults in Panamint Butte to the east of the valley dip 50-60 degrees west (Plate A). The basalts of the Darwin Plateau to the west of the valley are horizontal up on the plateau and dip moderately eastward into the valley, forming a classic hangingwall rollover (Hamblin, 1965; Gibbs, 1984). There are no major faults bounding the basalt-alluvium contact. The rollover structure is interrupted only by 40-45 degree east-dipping antithetic faults with relatively small displacements. There is no evidence for strike-slip displacement along these antithetic faults in the Darwin Plateau, even though they are oriented obliquely to the Hunter Mountain Fault.

Saline Valley has a distinctly rhombic shape (Zellmer, 1980) bounded on the south, east and west by steeply dipping range front faults of the Nelson Range, Inyo Mountains, and Ubehebe Peak area, respectively (Figure 2). These faults probably have large cumulative offsets, as the ranges stand more than 3 km above the valley floor. Saline Valley does not have the extensive peripheral covering of basalts found around northern Panamint Valley. At the northern edge of the valley, however, the basalts of the Saline Range plunge into the basin near its lowest point (~365 m), and crop out across most of its width. These basalts are tilted consistently to the east-southeast at about 20 degrees along closely spaced, northeast-trending, west-dipping normal faults. The regional consistency of basalt dips suggests that the extensional style closely resembles idealized rotated planar normal faulting (Wernicke and Burchfiel, 1982). The amount of rotation and fault offset decreases, while the number of faults increases to the north as the Saline Range rises to a maximum elevation of over 2,130 m. Several of these faults show well developed scarps extending south, well into the alluvium of Saline Valley.

Based on the transfer interpretation of the Hunter Mountain Fault, Burchfiel et al. (1987) have suggested that northern Panamint Valley, Saline Valley, and the Saline Range constitute a single unified extensional system with the Hunter Mountain Fault separating zones of different uppercrustal extensional style and distribution, but similar timing and magnitude of net extension.

Methodology

Mapping

During this study geologic mapping at scales from one to three inches to the mile was undertaken over certain key areas of the extensional system, particularly across the Saline Range and Dry Mountain south of 37 degrees north latitude, and the northeastern Darwin Plateau and northwestern Panamint Butte areas surrounding northern Panamint Valley. Fieid mapping was augmented by photogeological mapping of faults and lithologic contacts using 1982 USGS GS-VFDT 1:24,000 series photos. The mapping effort concentrated on the basalts and on all the faults that are demonstrably part of the latest extensional episode. All mapping has been compiled at 1 : 62,500 (Plates A and B).

Geochronology

Key basalt units were sampled for conventional K-Ar dating. The general ages of the various volcanic sequences had already been determined (Elliot et al., 1984; Larson, 1979; Ross, 1970), but more specific dating was necessary to firmly establish the timing of extension, and also whether a continuous basalt field was present prior to extension.

Dating was carried out at the Isotope Geology Branch of the U.S. Geological Survey in Menlo Park, California using the techniques outlined in Dalrymple and Lanphere (1969). These new data, as well as relevant ages published by other workers, are summarized in table 1. Approximate sample locations are shown in

Table 1
New K-Ar age determinations from the Panamint-Saline area
(mean ages from two separate determinations)

Sample loc. (figure 1)	Sample no.	Material dated	Apparent age (Ma) *
1	SV-1-87[1]	basalt whole rock	1.75 +- .04*
2	SR-2-87	andesite whole rock	3.29 +- .09*
3	SR-3-87	basalt whole rock	1.38 +- .04
4	SR-6-87	basalt whole rock	1.35 +- 0.09*
5	SR-7-87	basalt whole rock	1.36 +- 0.06
6	DMH-1-87	andesite whole rock	3.34 +- 0.03
7	SV-2-87	andesite/basalt wr.	3.22 +- 0.13*
8	DM-2-87	basalt whole rock	3.17 +- 0.12*
9	SR-4-87	basalt whole rock	1.35 +- 0.09
10	DP-3-87	basalt whole rock	4.63 +- 0.06
11	PB-3-87	basalt whole rock	5.02 +- 0.25
		other relevant age data	
12	ES102[1]	latite -- biotite	3.4 +- 0.2
13	ES179[1]	andesite whole rock	2.5 +- 0.3
14	ES219[1]	andesite whole rock	3.7 +- 0.7
15	ES458[1]	basalt whole rock	4.6 +- 0.5
16	7[2]	andesite - K feldspar	3.6 +- 0.1
17	F158[2]	andesite whole rock	2.9 +- 0.5
18	14[2]	andesite whole rock	3.1 +- 1.2
19	DV-16[3]	basalt whole rock	1.8 +- 0.3
20	DV-17[3]	basalt whole rock	1.7 +- 0.2
21	DV-25A[3]	basalt whole rock	4.0 +- 0.2
22	WH-68-1[4]	basalt whole rock	4.05 +- 0.15

* The (+-) value is one standard deviation based on the two separate age determinations.
**The (+-) value is the root-mean-square average of the estimated analytical uncertainties at one standard deviation for the two determinations, where this value was larger than *.
[1] Data from Elliot et al. (1984).
[2] Data from Ross (1970), recalculated by Elliot et al. (1984).
[3] Data from Larson (1979).
[4] Data from Hall (1971).

Figure 3. Petrographic descriptions, exact sample locations, and details of the spectrometry results for the newly dated samples are given in the appendix.

Northern Panamint Valley: evidence for an active low-angle normal fault half-graben

Basalt Distribution, Age, and morphology

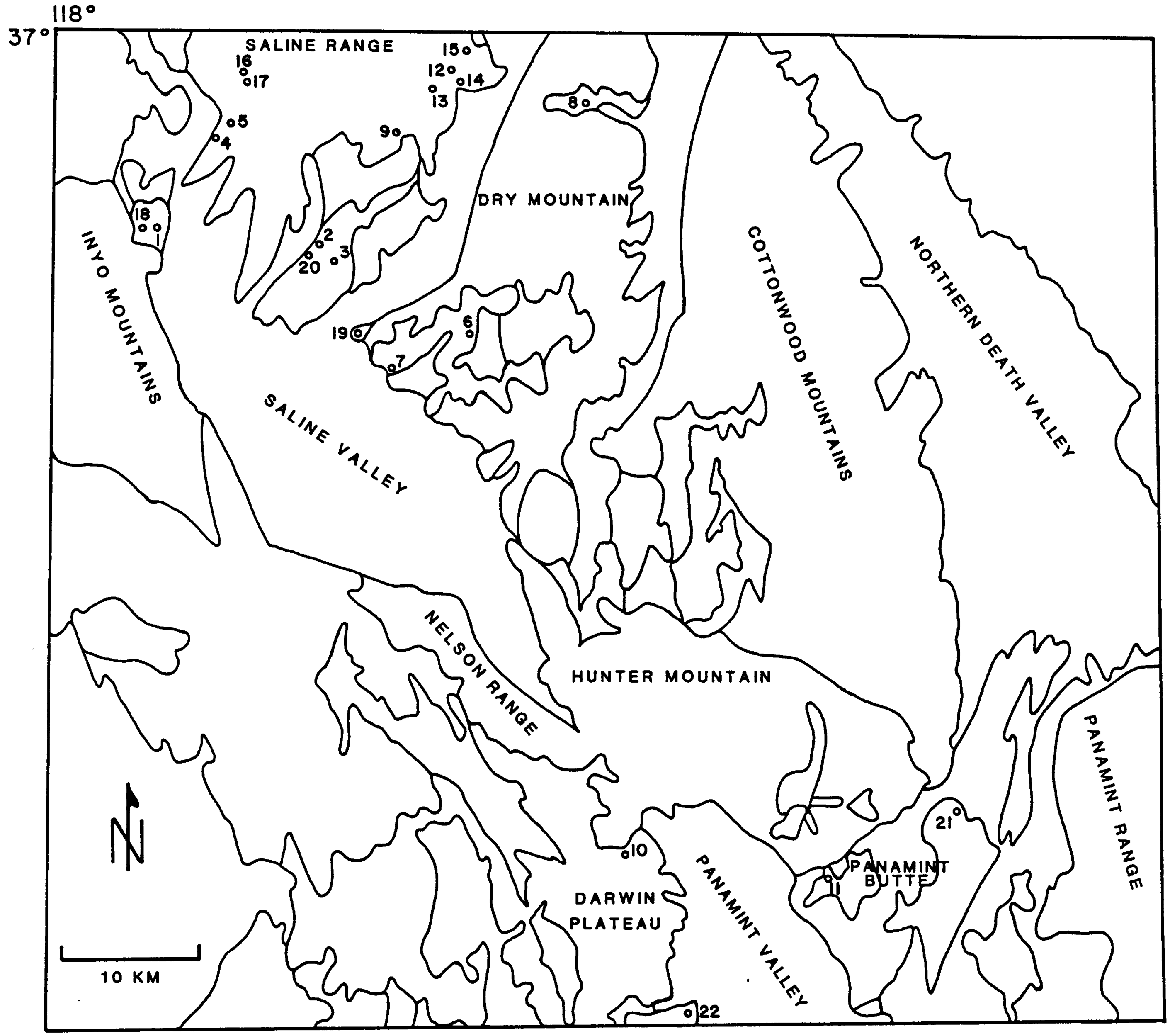
Flows from the thick sequence of basalt exposed on the Darwin Plateau have been dated from about 7 Ma to 4 Ma, and basalts on Panamint Butte, Hunter Mountain, and Townes Pass -- all to the northeast of the Hunter Mountain Fault -- yield similar dates (Schweig, 1984; Larson, 1979; this paper) (Figure 3). Potassium-Argon ages of 4.0 Ma from Larson (1979) on a flow from Townes Pass, which appears to have been faulted down from the capping basalts on Panamint Butte, and 4.05 Ma from Hall (1971) on a sample from the eastern edge of Darwin Plateau, suggest that Panamint Butte and Darwin Plateau stood at essentially the same elevation 4 Ma ago, and were covered by a continuous sequence of basalts prior to the onset of extension. Walker and Coleman (1988) have found that the basalts capping these areas are "chemically identical", further supporting this conclusion.

As the basalts on Darwin Plateau are at virtually the same elevation as those on Panamint Butte (Plate A), either a small amount of extension has occurred on a high-angle fault extending westward from Panamint Butte, or the fault at Panamint Butte flattens to near horizontal, regardless of the depth, beneath the Darwin Plateau. The amount of extension on such a low-angle fault could potentially be much greater than that permissible on a high-angle fault.

Piercing point reconstruction of the Hunter Mountain Fault

Remapping of the "unique linear element" described by Burchfiel et al. (1987) confirmed their finding for 8 to 10 km of offset on the Hunter Mountain Fault. Northeast of the Hunter Mountain Fault, the near vertical intrusive contact between the Hunter Mountain pluton and the Paleozoic rocks is exposed for more than 10 km, striking N50-60E (Figure 2). On the western slope of Panamint Butte, the contact is overlapped by a subhorizontal basalt flow dated in this study at 5.02 +- 0.25 Ma. South of the Hunter Mountain Fault on Darwin Plateau, the offset intrusive contact is exposed in a single outcrop 4 km southwest of the fault, where it is overlain by a gently east-dipping basalt dated in this study at 4.63 +- 0.06 Ma. This southwestern exposure of the basalt-capped intrusive contact strikes N45-65E, essentially the same as that north of the Hunter Mountain Fault. Given a maximum total basalt thickness on Darwin Plateau of about 120 m (Hall and McKevitt, 1962), the pre-extensional elevations at the bases of the basalts in the two exposures could

Figure 3. Locations of K-Ar wholerock dated basalt-andesite samples, see table 1 for data relevant to each location number. Exact locations for newly dated samples included in the appendix.


118°
37°
SALINE RANGE
DRY MOUNTAIN
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COTTONWOOD MOUNTAINS
NORTHERN DEATH VALLEY
SALINE VALLEY
NELSON RANGE
HUNTER MOUNTAIN
PANAMINT RANGE
PANAMINT BUTTE
DARWIN PLATEAU
PANAMINT VALLEY
10 KM
N
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FIGURE 3

not have differed by more than 30 to 60 m. The intersection of the subhorizontal basalts with the subvertical intrusive contact defines a line which has apparently been offset by the Hunter Mountain Fault. The piercing points defined by the projection of these offset linear elements onto the plane of the fault indicates that 9.3 +- 1.4 km of strike-slip, and from 0 to 1 km of dip-slip displacement have occurred on the Hunter Mountain Fault since about 4.0 Ma (Figure 4). The averaged strain rate during this period was a minimum of 2.0 to 2.7 mm/year, assuming that extension began at 4 Ma. Evidence from recent fault offsets in northern Panamint Valley indicate that the strain rate may have slowed to about 1-2 mm/year during the last 10,000 to 20,000 years, averaged over several separate earthquake slip events (Smith, 1979).

The analysis presented above represents the only available total strain measurement for the Hunter Mountain Fault. The error in the strike-slip offset results primarily from uncertainty in the projection of the piercing point from south of the fault, and the error in the throw comes mostly from uncertainty in the reconstruction of footwall faults in Panamint Butte (Figure 4). It is interesting to note that realining the topographically similar high ridges of the Nelson Range and Hunter Mountain across the Hunter Mountain Fault yields about the same amount of total offset as the piercing point reconstruction (8 to 11 km) (Figure 2).

The total offset on the Hunter Mountain Fault occurs right at the northern end of Panamint Valley and must therefore also represent the amount of extension across the basin. No independent reconstruction across northern Panamint Valley can be made without speculating on the extent of basalt buried within it. Magnetic evidence from Biehler et al. (1987) suggests that basalt is indeed absent beneath much of the valley, as would have to be the case since the valley is hardly wider than the 9 km of measured offset on the Hunter Mountain Fault.

Darwin Plateau Rollover

The basalts of the Darwin Plateau dip gently to the east beneath the floor of northern Panamint Valley without any major fault bounding their contact with the alluvium. The valley floor itself dips to the east until it reaches the high-angle faults on the west side of Panamint Butte. Thus the valley is interpreted here to be a half-graben, with the down-warped basalts of the Darwin Plateau interpreted to represent a rollover structure that has accommodated movement along a west-dipping listric fault (Hamblin, 1965; Gibbs, 1984).

The north-striking faults in Darwin Plateau dip 40-45 degrees and have relatively small displacements. They are interpreted to be faults accommodating shape changes in the hangingwall of a listric fault (White et al., 1986). The strike of these faults suggests that the axis of listric curvature on the main detachment is also oriented north-south, although the faults do curve to the northeast in the immediate vicinity of the Hunter Mountain Fault and approach it at high angle.

The shape and position of a rollover structure, coupled with the geometry of accommodation faults within it, place strong constraints on both the shape of, and depth to the main listric detachment fault (Williams and Vann, 1987; White et al., 1986). Most specific fault reconstructions based on hanging wall rollover require small net displacements and no footwall deformation. Northern Panamint Valley clearly violates both of these conditions, yet qualitative applications of the same arguments still suggest a restricted range of detachment geometries, all of them shallow low-angle normal faults (see below).

Footwall extension in Panamint Butte: an underlying detachment(?)

Panamint Butte is cut by a series of closely spaced, west-dipping, high-angle (50-60 degrees) normal faults, which account for a small amount of horizontal extension, but more than 600 m of cumulative vertical throw (Plate A, Figure 4). These faults can be divided into two groups: those which appear to be a part of the Hunter Mountain Fault system, and those which do not. The group of faults that drop basalts down towards the basin and define the steep, west face of Panamint Butte cannot be traced northward onto Hunter Mountain beyond the southeasternmost projection of the Hunter Mountain Fault. These faults are interpreted as splays related to the main detachment. The faults farther east, within the higher part of Panamint Butte, do extend to the north and are parallel to a group of major west-dipping normal faults that connect Panamint and Death Valleys. These faults are not directly linked to the Hunter Mountain Fault, but they do displace the basalt down to its present position on the western front of Panamint Butte. These faults are interpreted as rooting into a separate, lower detachment than the one responsible for the formation of northern Panamint Valley.

Geophysical evidence

Gravity data for the Death Valley area indicate that northern Panamint Valley does not have the negative gravity anomaly associated with it that would be expected for a basin containing thick alluvial deposits (Chapman et al., 1973). Data from Biehler et al. (1987) support the interpretation of a thin valley fill based on the results of gravity, seismic refraction, electrical resistivity, and magnetotelluric studies. They concluded that northern Panamint Valley is underlain by an average of about 200 m of sediment, and that relativley undeformed basement rocks (presumably Paleozoic miogeoclinal rocks) lie only about 840 m beneath the alluvial surface in the center of the basin. Their magnetic data also indicate that the basalts of Darwin Plateau and Panamint Butte are absent beneath as much as 9 km of the valley floor, corroborating the interpretation presented above. In addition, a drill hole near the central playa encountered no basalt, and only 113 m of Quaternary and Neogene sediments before entering Paleozoic rocks (Smith and Pratt, 1957).

Cross-section interpretations

The evidence presented above constrains the formation of northern Panamint Valley to be the result of the relative westward movement of a coherent hanging wall block along a west-dipping detachment that lies no deeper than 5 km beneath Darwin Plateau and has a regional dip of no more than 5 degrees. This fault must have a listric geometry, as evidenced by the high-angle splays through the west side of Panamint Butte. The detachment is apparently very shallow along the eastern edge of northern Panamint Valley and may not extend any further east than the west side of Panamint Butte.

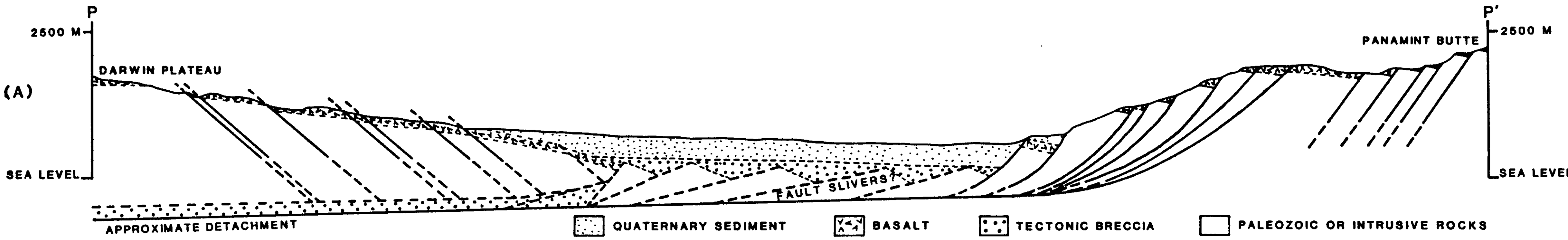
Cross-section P-P' (Figure 4) is based on the following information: 9.3 km of horizontal and 670 m of vertical displacement across the Hunter Mountain Fault; a rudimentary depth to detachment calculation based on the ratio of the "negative area" of the basin cross-section to the amount of extension (Figure 5); the geophysical evidence for very shallow basin fill; and the shape and location of the hangingwall rollover, as well as the attitude of antithetic faults within it. The most westerly of the hangingwall accommodation faults on Darwin Plateau would have originally intersected the underlying detachment at the inflection between its listric and essentially planar segments. With the Darwin Plateau restored to its pre-extensional position, the projection of this fault down at a 45 degree east dip intersects the regional depth calculated for the detachment at this inflection point. Cross-section P-P' is drawn such that the high-angle splays along the west side of Panamint Butte flatten into a planar, gently west-dipping detachment at this point (Figure 4).

The material between the detachment and the base of sediment is presumed to comprise a complicated zone of tectonic breccia and piggy-backed fault slivers derived from both the footwall and the hangingwall. Similar brecciated fault slivers have been documented in other exhumed terranes of the southwestern Basin and Range thought to represent low-angle normal faults (eg. Harding, 1987; Wright and Troxel, 1984).

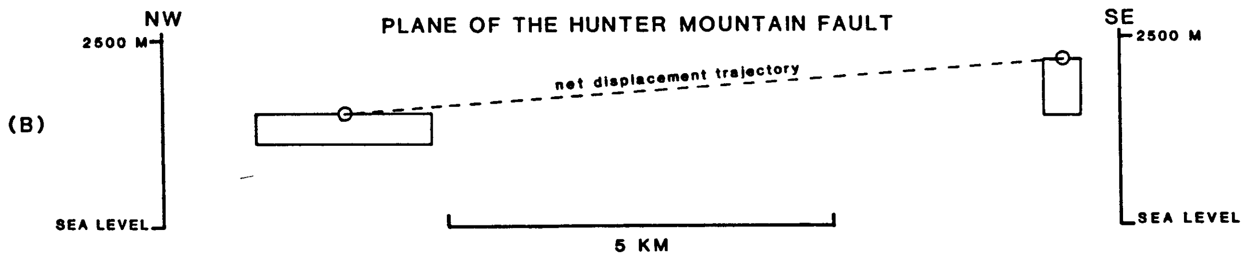
The section line P-P' is oriented to N80W, roughly perpendicular to the fault trends on the sides of the valley and 25 degrees from the N55W trend of the Hunter Mountain Fault. Thus only 8.4 km of apparent extension appears in the

Figure 4. (A) Cross-section of northern Panamint Valley illustrating the low-angle detachment interpretation presented in the text.

(B) Piercing points defined by the projections of the offset basalt-capped intrusive contacts from the Darwin Plateau and Panamint Butte onto the plane of the Hunter Mountain Fault. The boxes show the uncertainties in the projections. The net displacement trajectory shows preferred total offset.



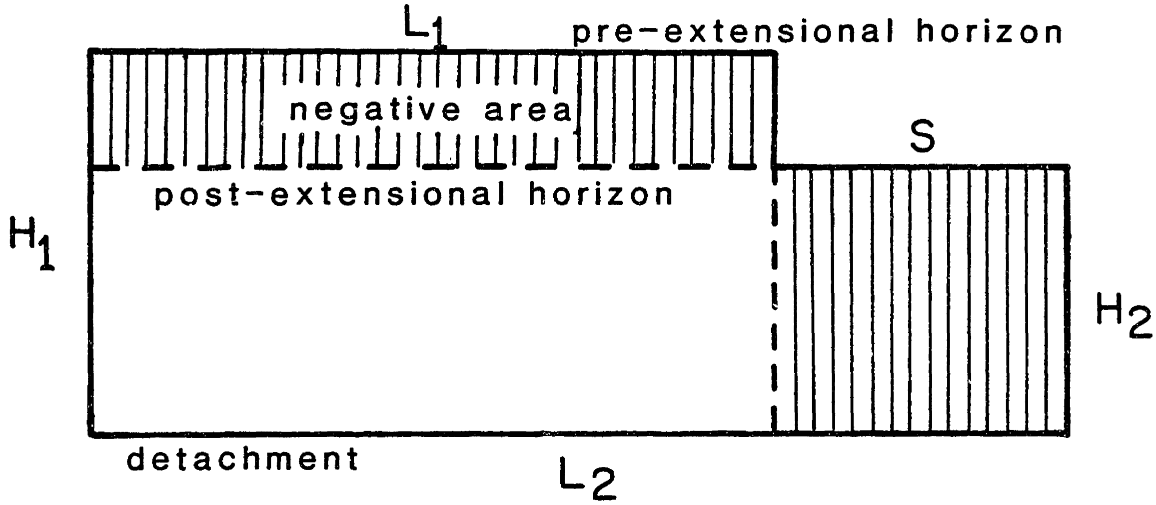
(A)
P
P'
2500 M
SEA LEVEL
DARWIN PLATEAU
PANAMINT BUTTE
FAULT SLIVERS?
APPROXIMATE DETACHMENT
QUATERNARY SEDIMENT
BASALT
TECTONIC BRECCIA
PALEOZOIC OR INTRUSIVE ROCKS



(B)
NW
SE
2500 M
SEA LEVEL
PLANE OF THE HUNTER MOUNTAIN FAULT
net displacement trajectory
5 KM

FIGURE 4

Figure 5. The simplified depth-to-detachment calculation used in this study. The extended terrane is approximated as a block that retains its cross-sectional area during deformation above a fixed, horizontal detachment. The negative area corresponds to the cross-sectional area of the extensional basin measured between the pre-extensional horizon (presumably represented in the bounding ranges) and the post-extensional horizon (represented by the basin floor).



$(L_1)(H_1-H_2)$ = negative area = $(S)(H_2)$

the negative area and s, the amount of extension, are known from the reconstructable cross-section, and so H_2 can be calculated.

As area is assumed to be conserved during extension,

$$(L_1)(H_1) = (L_2)(H_2),$$

or

$$H_1 = (L_2/L_1)(H_2),$$

giving H_1, the depth to detachment from the pre-extensional level of the reconstructed horizon.

FIGURE 5

cross-section. The separation of basalt across northern Panamint Valley exceeds this amount, which suggests that a significant amount of basalt must be involved in the breccia and sediments of the basin. South of the section line, basalt and Paleozoic breccias crop out in and around Lake Hill and are presumably representative of the brecciated masses lying beneath the alluvial sediments and above the detachment surface. It should be noted that the basalts on Darwin Plateau actually correlate to an area south of Panamint Butte when restored parallel to the Hunter Mountain Fault.

Alternative cross-section interpretation

The range of uncertainties in the data presented still do not allow for any other than a low-angle normal fault interpretation for northern Panamint Valley. The simplified cross-section in figure 6 ignores several important elements of the data to present the broadest possible interpretation of the basin configuration. It depends only on the orientations of visible faults, the obvious half-graben nature of the basin, and the assumption that the Darwin Plateau rollover structure continues to the high-angle faults that bound the west side of Panamint Butte. This cross-section greatly underestimates the amount of extension as indicated by the Hunter Mountain Fault offset, and greatly overestimates the depth of sediment in the basin as indicated by geophysical evidence.

The profile of the cross-section thus constructed lends itself to graphical and analytical methods for determining the shape and depth to the detachment fault (Gibbs, 1983, 1984; White et al., 1986; Williams and Vann, 1987). Three such fault constructions are shown in figure 6. The most realistic of these, which takes into account hangingwall extension and accommodation along 45 degree east-dipping antithetic faults with a "modified chevron" construction, predicts a detachment which flattens to a low regional dip at 4.6 km below the pre-extensional landsurface. This section still requires 4.4 km of total horizontal extension and, while it predicts a detachment some 2 km deeper than shown in cross-section P-P', it does not significantly change the character of the argument for an active, uppercrustal, low-angle normal fault beneath northern Panamint Valley. Only a very unrealistic conventional chevron construction, which assumes that accommodation in the hangingwall takes place by vertical shear thereby allowing for no hangingwall extension, places the subhorizontal detachment near a mid-crustal depth reasonable for brittle-ductile decoupling.

Figure 6. Alternative reconstructions of the listric northern Panamint Valley detachment fault using graphical methods based on the shape of the hangingwall rollover (from Williams and Vann, 1987). The rollover profile is obtained by projecting the east tilted basalts of the Darwin Plateau beneath the valley to intersect a projection of the western boundary fault of Panamint Butte. This simplistic interpretation ignores the evidence for 9.3 km of offset on the Hunter Mountain Fault, shallow basin fill, and the absence of basalts beneath the basin to present the cross-section least likely to involve a shallow, low-angle detachment fault. The standard chevron construction, which unrealistically assumes vertical faulting in the deforming hangingwall, predicts a deep, broadly listric detachment, but both the preferred modified chevron construction (adapted here from Williams and Vann, 1987) and the slip-line construction predict shallow, low-angle detachments.

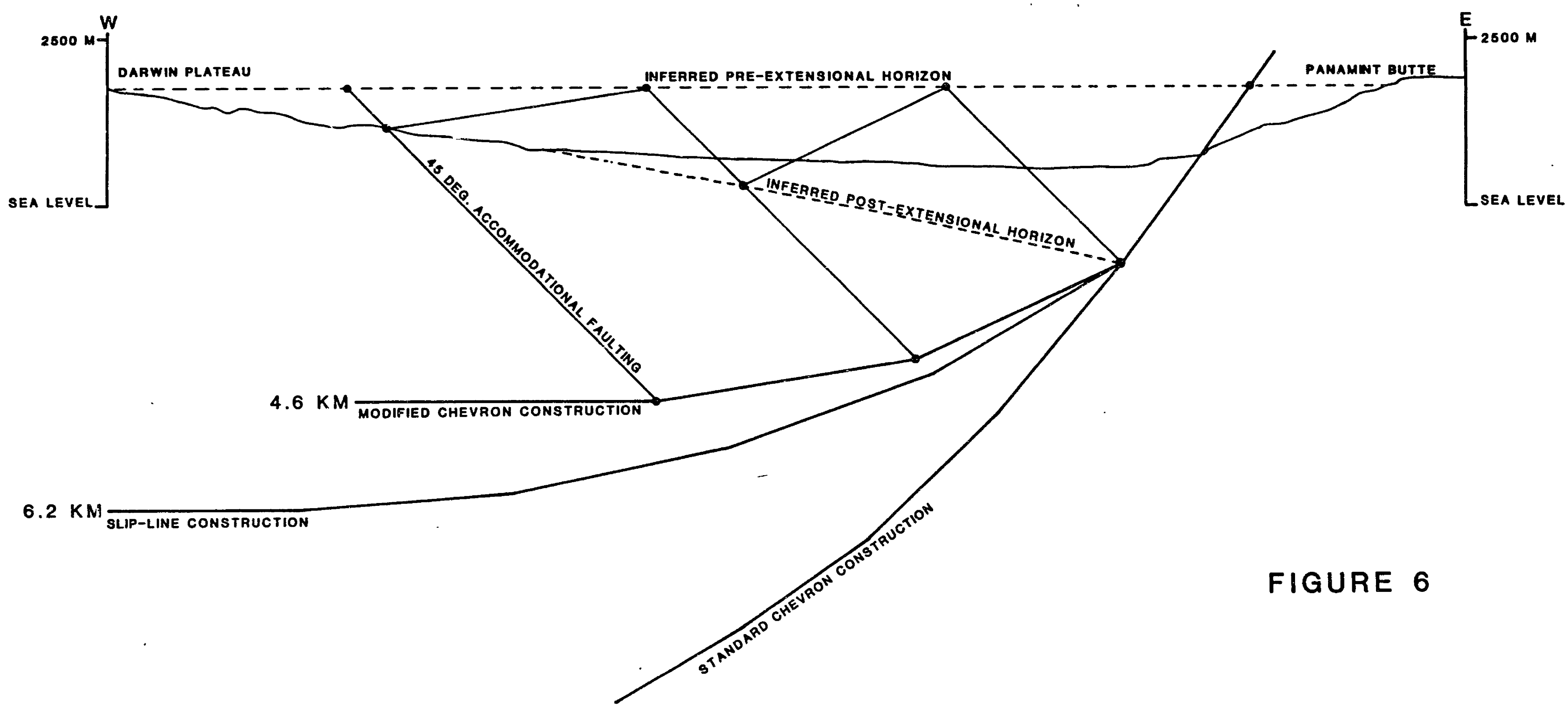

W
2500 M
DARWIN PLATEAU
SEA LEVEL
INFERRED PRE-EXTENSIONAL HORIZON
E
2500 M
PANAMINT BUTTE
SEA LEVEL
45 DEG. ACCOMMODATIONAL FAULTING
INFERRED POST-EXTENSIONAL HORIZON
4.6 KM
MODIFIED CHEVRON CONSTRUCTION
6.2 KM
SLIP-LINE CONSTRUCTION
STANDARD CHEVRON CONSTRUCTION

FIGURE 6

Saline Valley and the Saline Range

The purpose in studying the Saline area was two fold:

(1) to see if the timing and amount of extension there agreed with the results from northern Panamint Valley, and

(2) to place constraints on the structural geometry of the Saline area and compare this to the interpretation of nappe-like extension along a low-angle fault in northern Panamint Valley.

Saline Valley

Gravity data suggest that Saline Valley is underlain by a thick sedimentary sequence (Chapman et al., 1973). The basin is more than twenty kilometers across measured parallel to the Hunter Mountain Fault (twice as wide as northern Panamint Valley), and there are numerous fault scarps present in the alluvium. Basalt is exposed only along the northern flanks of the valley defined by the Saline Range and the southwestern edge of Dry Mountain.

Geomorphology

The most striking feature of Saline Valley is its pronounced rhombic shape (Figure 2) (Zellmer, 1980, others). Its southwestern and western boundaries are defined by the Hunter Mountain Fault zone and a north-trending fault zone that forms the eastern boundary of the Inyo Mountains, respectively. The northern and eastern boundaries of Saline Valley are slightly more irregular, and are not obviously fault controlled. These boundaries are simply defined by the contact between the basin sediments and either Paleozoic rocks, Mesozoic intrusive rocks, or Plio-Pleistocene volcanic rocks.

The floor of the valley slopes gently west, and the partially spring fed playa lies close to the western and southwestern boundary faults. A large, steep fan originating in Grapevine Canyon dominates the morphology of the southern portion of the valley. Well developed alluvial fans also characterize the eastern and northwestern parts of the valley, whereas fans are less well developed along its western margins.

Structure

Faults at the base of the Inyo Mountains that delineate the western and southwestern boundaries of Saline Valley make scarps within alluvium and at alluvium-bedrock contacts. Fault planes can also be found within the Paleozoic bedrocks. Kinematic study of the bedrock faults along these sides of the valley show them to have oblique right-slip to dip-slip displacements, depending on their orientation (Zellmer, 1980; this study), and indicates that all of the displacements are consistent with a net regional extension direction of N55W, parallel to the Hunter Mountain Fault.

Although the faults along the western and southwestern sides of the valley are marked by the most active scarps, the valley appears to be more structurally complex than the relatively simple half-graben of northern Panamint Valley. Fault scarps present in the alluvium along the east side of the valley trend north-northeast, oblique to the bounding range, and show predominantly down-to-the-northwest dip-slip offset (Zellmer, 1980, 1983). These faults parallel faults in the Saline Range farther to the north. The structure of the mountains along the northeastern part of Saline Valley is marked by a complex downwarp into the basin reminiscent of a rollover. The warp is defined by basalt flows that are horizontal at 1,830 m in the range and which dip more than 20 degrees to the southeast at the valley floor. This dip-slope of basalt is cut by northeast trending, down-to-the-northwest normal faults that show increased displacement southward into the valley. The north side of the valley is defined by the southernmost exposures of basalt in the Saline Range and adjoining ranges, which together form a topographic boundary parallel to the Hunter Mountain Fault. The north-northeast trending dip-slip faults of the Saline Range have displacements that parallel the displacement on the Hunter Mountain Fault. Some of the Saline Range faults have scarps that extend into the alluvium of the valley, but none of these extend south beyond the southernmost limit of basalt outcrops. Surprisingly there is no evidence of strike-slip faulting along this northwest trending boundary, as might have been expected from its orientation and the abrupt change in fault trends that takes place across it.

Saline Range

The Saline Range contains a thick sequence of basaltic to andesitic lava flows, and related volcanic and sedimentary deposits (Ross, 1970) overlying complexly deformed Paleozoic rocks that are exposed in erosional windows through the volcanics (Figure 2 and Plate B). The Saline Range rises northward from Saline Valley to an elevation of 2,150 m, but is lower than the surrounding mountain ranges from which it is separated by narrow sediment filled valleys on both its eastern and western flanks. The Saline Range and its boundaries trend north-northeast, roughly perpendicular to the Hunter Mountain Fault.

Structure

The Saline Range is characterized by north-northeast trending, west-dipping normal faults that appear to have accommodated extension by "domino-style" fault block rotation (Wernicke and Burchfiel, 1982). The faults are spaced at intervals of a few hundred meters and are present across the entire range. Where the faults have well exposed scarps they dip 40-50 degrees west. The southern end of the range is dominated by a few large faults with dip-slip displacements of tens to hundreds of meters, whereas the higher, northern parts of the range contain more numerous closely spaced faults with offsets of generally only tens of meters. The tilt of the structural blocks was measured from the attitudes of flow contacts and from planes of flattened vesicles within the volcanic rocks. The tilts are uniformly to the east-southeast across the entire range, and are somewhat steeper (20-25 degrees) at the southern end of the range than at the northern end (10-20 degrees) (Plate B).

A major graben in the south central part of the range contains blocks tilted to the west along an active east-dipping fault. This area is surrounded by blocks with the regional east-southeast tilt. Other east-dipping normal faults are present within the range, although they are minor, and appear to be superimposed onto the overall west-dipping trend.

The Saline Range, and the trough in which it lies are bounded on the east by a west-dipping fault that is also the western range bounding fault for the Dry Mountain block to the east. Neither this fault, nor the Dry Mountain block appear to have been tilted along with the Saline Range during the extension. Breccia sheets of Paleozoic rocks derived from Dry Mountain crop out in places along the eastern edge of the Saline Range and may be evidence for either brittle detachment faulting, or large scale landsliding along that boundary.

There is no correspondingly well defined boundary fault along the western side of the Saline Range. The north-northwest-striking, east-dipping oblique-slip fault which bounds the west side of Saline Valley ends at the southwesternmost basalt exposures in the Saline Range. To the north of this point a disconnected set of north-striking, east-dipping faults separate the high Inyo Mountains from the Saline Range.

The Saline Range slopes southward into Saline Valley, but the same stratigraphic level of basalt is exposed across the entire range. The basalts appear to have the same general thickness throughout the range, and so this slope apparently formed after the basalts were extruded. The slope must therefore be the result of either greater extension across the range to the south, or a deeper level of extensional detachment to the south (see below).

Distribution and Age of Basalts

Isolated areas of basalt related to those of the Saline Range crop out along the eastern flank of the Inyo Mountains and in places on Dry Mountain, but the great mass of volcanics is concentrated within the Saline Range trough (Figure 2,

Plate B). The total accumulation of volcanic rocks within the trough has been estimated to be as much as 1,000 m (Blakely and McKee, 1985), however the average thickness is closer to about 500 m.

The base of the volcanic sequence is only locally exposed, and is underlain by Paleozoic sedimentary rocks. Small, isolated exposures of these basement rocks are present across the Saline Range. In the southeastern part of the range a several square kilometer window of Paleozoic rocks is exposed, capped only by the uppermost basalt flows. These youngest basalts appear to mantle the entire area Saline Range. The isolated basalts on the western side of the trough are not faulted to higher elevations within the Inyo Mountain block, however basalts on top of the Dry Mountain block have been isolated by movement on its western boundary fault and therefore must have been extruded prior to, or soon after the initiation of extension.

The K-Ar ages of basalts sampled from the Saline area are shown in table 1. Details of the analyses and the petrography of the samples appear in the appendix.

The most significant result of the geochronological study was the discovery that the uppermost basalts that cap the Saline Range are only 1.4 Ma old, whereas the horizontal flows isolated on the Dry Mountain block are 3.2 Ma and older. Based on these results, and the K-Ar basalt ages reported in Elliot et al. (1984) and Larson (1979), it appears that the area experienced two main periods of volcanic activity: an initial period of sporadic eruptions prior to 3 Ma and roughly synchronous with the onset of extension, and a period of voluminous extrusion between about 1.7 and 1.4 Ma that occurred within a developing extensional trough. These younger volcanic rocks have since been extended by fault block rotation during the last 1.4 Ma. There are outcrops of the older basalt within the Saline Range and on the west side of the trough (Ross, 1970; Elliot et al., 1984; Larson, 1979; this paper), but these older flows did not necessarily constitute a continuous pre-extensional basalt layer, nor are they tilted any more than the younger basalt flows. Thus the amount of extension measured from the faulting and tilting of volcanics in the Saline Range records only the extension since 1.4 Ma. The amount of extension that occurred before 1.4 Ma can only be assessed through an examination of the Paleozoic rocks.

Cross-sections

The configuration of basalt capped fault blocks in the Saline Range provides a basis for the construction of cross-sections that can be used to calculate the magnitude of extension, and thereby constrain the structural geometry beneath the range. Cross-sections S S' and N N' were drawn perpendicular to the faults in the

Saline Range, and parallel to the regional extension direction of N55W (Plate C). The amount of extension can be determined by comparing the cumulative widths of the fault blocks, measured along the tops of the tilted basalts, with the current width of the range. In so doing three assumptions are made: (1) the dip of the basalts is entirely due to extensional rotation, (2) during extension the faults have remained essentially planar near the surface, and (3) the 1.35 Ma horizontal basalt exposed at 1,830 m in the east-central part of the range (location 9, Figure 3) represents the initial pre-extensional position of the capping basalts throughout the entire area.

Section S-S' yields 4.65 +- 0.6 km of extension, and section N-N' gives 4.35 +- 0.5 km. The uncertainties reflect corresponding uncertainty in the dips of the faults, and in the projections into buried or eroded areas, particularly in the sedimentary troughs on either side of the range. The magnitude of extension across the Saline Range appears to have been uniform from north to south during the last 1.4 Ma at about 4.5 +-0.6 km, yielding a minimum average strain-rate of between 2.8 to 3.6 mm/year.

Wernicke and Burchfiel (1982) calculated that for 40-50 degree dipping faults and bedding dips of 20 degrees, extension by idealized rotated planar normal faulting would yield from 23% to 34% extension. Idealized rotated planar faulting yields the theoretical maximum amount of extension, any configuration of listric faults would necessarily yield less (Wernicke and Burchfiel, 1982). The Saline Range cross-sections yield 20% to 25% extension and so, although the faults might curve into the underlying detachment, the extensional style must be close to the ideal rotated planar normal fault case. This interpretation is further supported by the fact that all the fault blocks have been tilted by about the same amount, as variable tilts would be evidence of the presence of variously shaped listric faults.

The main difference between the northern and southern parts of the Saline Range is that the current elevation of the uppermost basalts, relative to the pre-extensional level represented by the 1.35 Ma horizontal remnant at 1830 m, is much lower to the south. In the northern part of the range these basalts lie only a few hundred meters below their pre-extensional level, whereas basalts of the same age lie as low as 500 m at the southern tip of the range. If this downwarping is entirely due to extension, and the amount of extension is uniform from north to south (as it appears to be), then the detachment along which the fault blocks are tilted must be deeper to the south. A simple negative area calculation for the depth to detachment (Figure 5) indicates that a detachment lies about 2 km beneath section N-N', and as much as 8 km beneath section S-S'. The detachment thus about 20 degrees to the south (a direction roughly perpendicular to the net north-northwest movement of the fault blocks across it) and probably lies even deeper beneath the lowest parts of Saline Valley. These calculations place the detachment within the brittle upper crust as a low-angle normal fault above which the extended hangingwall has broken into blocks bounded by high-angle faults.

Extension in the Saline Range prior to 1.4 Ma

The 4.5 km of extension across the Saline Range since 1.4 Ma represents about one half of the total measured along the Hunter Mountain Fault over about one half of the time (9 km since after 4 Ma). The isolated remnants of basalts older than 3 Ma within the Dry Mountain block indicates that some extensional faulting occurred between 1.4 Ma and 3 Ma. Extrapolating the strain rate for the latest period of extension recorded in the Saline Range back to 3 Ma yields 9.6 km of extension measured in northern Panamint Valley. This result suggests that there may have been 4.5 to 5 km of extension across the Saline Range area prior to 1.4 Ma. The older basalts, where they are exposed in the Saline Range, dip the same amount as the youngest capping basalts, suggesting that the extension from 3 Ma to 1.4 Ma either did not involve domino-style fault block rotation, or that currently exposed areas of older basalts were not involved in the earlier period of extension.

The Paleozoic rocks exposed in the Saline Range show segments of the early Mesozoic, east-vergent Last Chance Thrust, which placed lower Cambrian rocks above the Mississippian-Pennsylvanian Rest Spring Shale (see maps of Ross, 1967b; and Burchfiel, 1969). Along its easternmost exposure in the Saline Range this thrust fault dips eastward between 30 and 40 degrees (Burchfiel, 1969), projecting beneath the narrow alluvial trough that separates the Saline Range from Dry Mountain. The bedrock of the Dry Mountain block is composed entirely of rocks from the lower plate of the Last Chance Thrust and, based on regional geological considerations, it is inferred that the upper plate rocks lay above the western part of Dry Mountain prior to erosion. Bedding in the Dry Mountain block indicates that the essentially bedding-parallel thrust was originally horizontal to gently west-dipping. Thus the thrust has been offset along the western boundary fault of Dry Mountain.

Cross-section X-X' (see Plate B) is an east-west section constructed using data from the maps of Ross (1967b) and Burchfiel (1969). It shows the eastern edge of the Saline Range, where the Last Chance Thrust is exposed, and the western edge of Dry Mountain (Figure 7). This cross-section yields different amounts of extension depending on the dip of the thrust fault and the geometry assumed for the west-dipping Dry Mountain boundary fault. A maximum extension estimate of 6.8 km comes from assuming that the boundary fault dips 30 degrees west, the same dip as the present slope of the mountain's flank, and that the thrust dips 40 degrees east. A minimum estimate of 2.2 km comes from assuming that the boundary fault dips 60 degrees west, and that the thrust dips 30 degree east. Part of the extension measured on this cross-section occurred after 1.4 Ma. The capping basalts near the thrust fault exposure dip about 10 degrees east. Subtracting this amount from the tilt of the thrust gives a pre-1.4 Ma range of extension on the Dry Mountain bounding fault of 5.4 to 1.5 km.

The large window of Paleozoic rocks in which the Last Chance Thrust is exposed has 1.4 Ma basalts resting on footwall rocks of the thrust. Everywhere in the Saline Range to the west of this window the few exposures of Paleozoic rocks through the 1.4 Ma basalts must be considered as hanginwall to the thrust, based on regional geological considerations (Ross, 1967b; Burchfiel, 1969). Thus one or more down-to-the-west faults similar to the Dry Mountain boundary fault must have also offset the Last Chance Thrust before 1.4 Ma, and probably accommodated at least an additional kilometer of pre-1.4 Ma extension. The above estimates for pre-1.4 Ma extension are poorly constrained, but do suggest that between 2.5 and 6.4 km of extension occurred across the Saline Range prior to the extrusion of the youngest 1.4 Ma basalts, and that the total amount of extension since has been approximately 8.9 +- 2.5 km.

A Paired Panamint-Saline Extensional System? -- Summary and Discussion

Several lines of evidence strongly support the interpretation that the formation of northern Panamint Valley during the last 4 Ma has involved the relative westward movement of a coherent hangingwall block 9.3 +- 1.4 km along a west-dipping low-angle normal fault lying less than 5 km beneath Darwin Plateau. The evidence consists of: the offset of the basalt capped subvertical intrusive contact across the southeastern end of the Hunter Mountain Fault; the hangingwall rollover geometry of Darwin Plateau; the limited elevation difference between similar aged basalts on Darwin Plateau and Panamint Butte; and the geophysical evidence for very thin sedimentary fill in the valley, shallow depth to seismically undisturbed basement, and the absence of basalts beneath most of the basin. Even ignoring all but the most obvious geomorphologic and structural evidence, and allowing for the least amount of extension possible requires the presence of a listric detachment fault which flattens to subhorizontal within the upper 5 km of the

Figure 7. Various interpretations of section X-X' demonstrating the full range of possible horizontal offsets on the western boundary fault of Dry Mountain based on realistic limits for the geometry of the fault, and the dip of the offset Mesozoic thrust exposed in the Saline Range.

(A) A 60 degree west-dipping extensional fault, both planar and listric (flattening at ~4 km). Letters A through F give the horizontal offset from the corresponding point of the hangingwall side of the fault to point Z on the footwall side.

(B) A 30 degree west-dipping extensional fault. Letters G, H, and I give the horizontal offset from the corresponding point on the hangingwall side of the fault to point Z on the footwall side.

In both figures the range between 30 and 40 degrees of east dip on the offset thrust represents the total movement on the extensional fault. The range between 20 and 30 degrees represents the offset that occurred prior to 1.4 Ma and the10 degrees of eastward tilting of the young basalts exposed near the western end of the section. The level of the offset thrust east of the extensional fault is an approximation based on the apparent thickness of rocks footwall to the thrust missing from Dry Mountain.

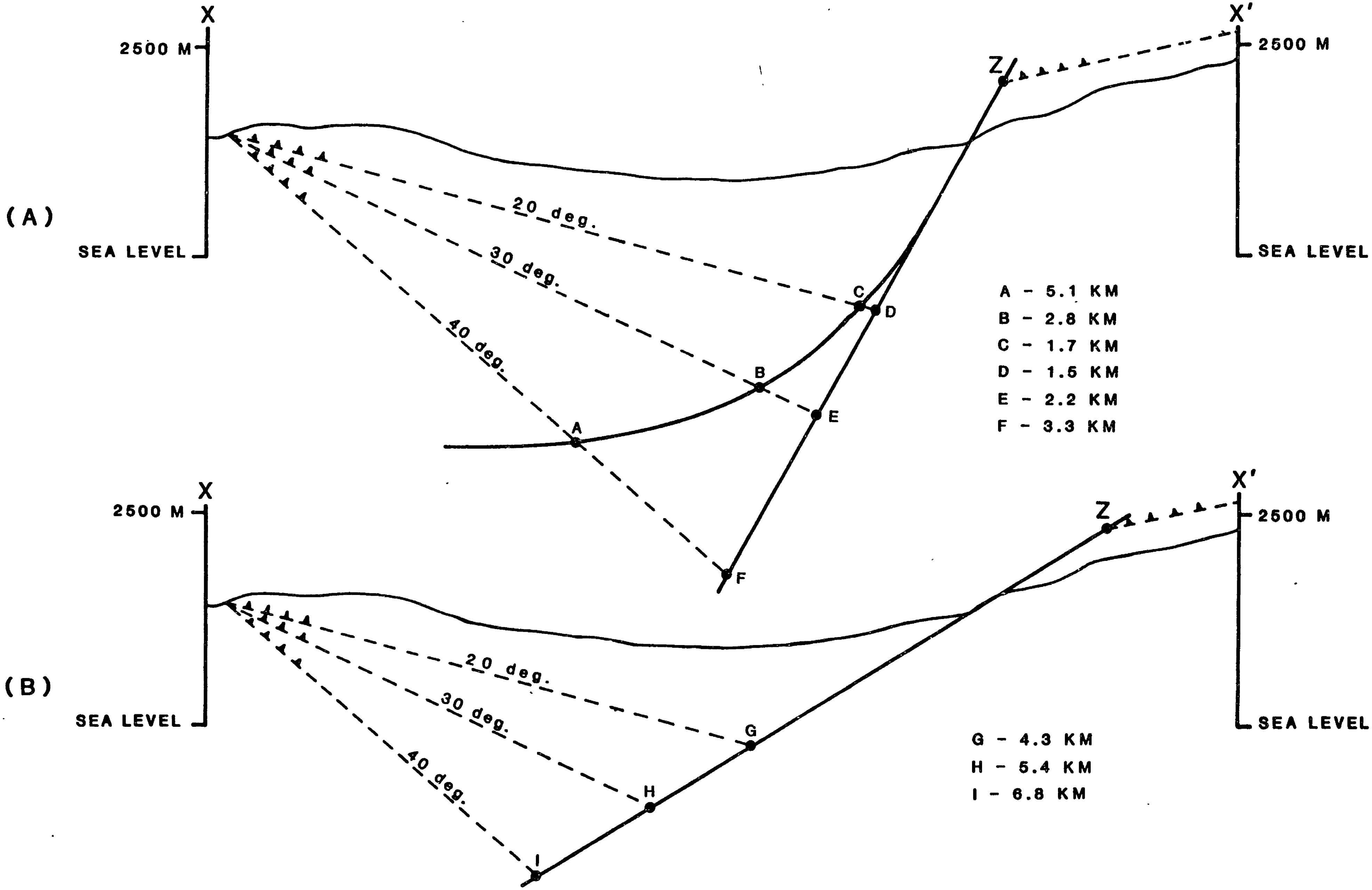

(A)
X
X′
2500 M
2500 M
SEA LEVEL
SEA LEVEL
Z
20 deg.
30 deg.
40 deg.
A
B
C
D
E
F
A - 5.1 KM
B - 2.8 KM
C - 1.7 KM
D - 1.5 KM
E - 2.2 KM
F - 3.3 KM
(B)
X
X′
2500 M
2500 M
SEA LEVEL
SEA LEVEL
Z
20 deg.
30 deg.
40 deg.
G
H
I
G - 4.3 KM
H - 5.4 KM
I - 6.8 KM

FIGURE 7

crust. This result supports the conclusion that low-angle normal faults are presently active in the Basin and Range. Dates on basalts near Darwin Plateau and Panamint Butte constrain the extension across northern Panamint Valley to have begun sometime after 4 Ma (Larson, 1979; Hall, 1971), yielding a minimum average strain rate of between 2 and 2.7 mm/year.

The central part of the Hunter Mountain Fault exhibits strike-slip offset with no significant component of compression or extension across its trace, and therefore its N55W trend represents the net direction of regional extension. The sections of the Hunter Mountain Fault immediately adjacent to Saline and northern Panamint Valleys are oblique-slip, with a significant dip-slip component. The sense of offset on alluvial scarps within northern Panamint Valley and Saline Valley, as well as kinematic data from other extensional faults in the area, including the attitude of faulting in the Saline Range, all support this conclusion. The Hunter Mountain Fault appears to transfer virtually all of the extension present in northern Panamint Valley into Saline Valley -- there are no extensional structures along the central portion of the Hunter Mountain Fault which could divert any significant amount of extensional strain away from Saline Valley. Unfortunately neither the amount of extension, nor the structure beneath Saline Valley can be easily determined from the surface data. There is no way to confirm that it represents 9 km of pull-apart. At present it is known only that gravity data suggest Saline Valley is underlain by a deep sedimentary basin.

The geology of the Saline Range can be used to measure the amount of extension just north of Saline Valley. The thick sequence of basalt flows obscures the amount and nature of extension which took place prior to 1.4 Ma, but reconstruction of the 1.4 Ma basalt yields 4.5 +- 0.6 km, for a strain rate of 2.8 to 3.6 mm/year. The extension across the Saline Range, and probable related extension in Saline Valley, can account for all of the strain transmitted through the Hunter Mountain Fault since 1.4 Ma, as the average strain rates for the two basins are about the same. Calculating the amount of extension that occurred across the Saline Range prior to 1.4 Ma is more difficult. Using an estimate based on the extensional offset of the Mesozoic Last Chance Thrust, the total amount of extension across the area related to the Hunter Mountain Fault is between 6.4 and 11.5 km. As the extensional tilting of the Paleozoic rocks and Mesozoic structures that took place before 1.4 Ma has the same essential geometry and trend as the post-1.4 Ma tilting, it is not unreasonable to assume they are parts of the same extensional episode.

Although the magnitude of extension measured from the Saline Range is not exactly the same as the offset on the Hunter Mountain Fault and related extension in northern Panamint Valley, the range of magnitudes do overlap and the system can be considered roughly balanced in three dimensions. This result, coupled with the consistency of the other structural, kinematic, and geochronological data, strongly supports the hypothesis of paired extensional basin evolution. It further suggests that transfer structures such as the Hunter Mountain Fault accurately reflect the extension that has occurred in adjacent basins, and so may be used to measure the extension in, and thereby constrain the structural geometry of, basins that cannot be independently reconstructed.

The Hunter Mountain Fault clearly separates two areas of upper crustal extension that are similar in magnitude and timing, but completely different in terms of their structural style. Whereas northern Panamint Valley formed as the result of coherent hangingwall movement on a single shallow, west-dipping, listric, low-angle detachment fault, the Saline area is underlain by a complicated mosaic of high-angle fault bounded blocks above a detachment that dips southward beneath Saline Valley, roughly perpendicular to the regional N55W extension direction. Based on the results of these basic field studies of the Panamint-Saline extensional system, two varieties of upper crustal low angle detachment faults have been active simultaneously on either side of the Hunter Mountain Transfer Fault for the past 3 to 4 Ma. This low angle system is directly responsible for the classic Basin and Range topography of the area.

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Appendix: Details of Potassium-Argon Wholerock Dated Samples

SV-1-87: (36 deg. 51'13" N, 117 deg. 54'44" W: Waucoba Wash 15' quadrangle, Inyo County, California). Basalt -- mildly porphyritic, holocrystalline, unaltered; phenocrysts of plagioclase (labradorite), clinopyroxene (augite), and olivine (chrystolite): groundmass of same minerals and minor opacques with diabasic to locally sub-ophitic texture; mildy trachytic.

Analytic Data:
K2O (wt.%) 1.59225 +- 9.17886E-3 or .576471% (n=4)
Run 1: radiogenic Ar-40 = 34.5659% -- 3.92779E-12 moles/gram
age = 1.71237 Ma +- .0379938 Ma or 2.21878% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 56.2541% -- 4.09992E-12 moles/gram
age = 1.78757 Ma +- .0270133 Ma or 1.51117% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

SR-2-87: (36 deg. 51'24" N, 117 deg. 46'36" W: Waucoba Wash 15' quadrangle, Inyo County, California). Andesite -- aphanitic, hypocrystalline, mildly altered; some phenocrysts of iddingsite (after olivine), actinolite (after clinopyroxene ?), and anorthoclase; groundmass of sodic placioclase, opacques, and glass; some calcite present.

Analytic Data:
K2O (wt.%) 2.889 +- 7.78881E-3 or .269043% (n=4)
Run 1: radiogenic Ar-40 = 36.3363% -- 1.3372E-11 moles/gram
age = 3.20532 Ma +- .0378349 Ma or 1.18038% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 43.0969% -- 1.41047 moles/gram
age = 3.38092 Ma +- .0362538 Ma or 1.07231% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

SR-3-87: (36 deg. 51'00" N, 117 deg. 46'36" W: Waucoba Wash 15' quadrangle, Inyo County, California). Trachybasalt -- porphyritic, aphanitic, relatively unaltered; phenocrysts of olivine (some rims of iddingsite), euhedral clinopyroxene (partially resorbed); groundmass of plagioclase (andesine-labradorite) with some devitrified glass and very sparse opacques; pronounced trachytic texture; some vesicles with calcite present.

Analytic Data:
K2O (wt.%) 1.3365 +- .0118181 or .884255% (n=4)
Run 1: radiogenic Ar-40 = 18.2165% -- 2.61918E-12 moles/gram
age = 1.36051 Ma +- .0413726 Ma or 3.04097% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 15.2451% -- 2.69978E-12 moles/gram
age = 1.40254 Ma +- .0422442 Ma or 3.01197% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

SR-6-87: (36 deg. 56'06" N, 117 deg. 51'27" W: Waucoba Wash 15' quadrangle, Inyo County, California). Basalt -- porphyritic, holocrystalline; phenocrysts of plagioclase (andesine-labradorite), olivines and clinopyroxenes both in subophitic relationships with plagioclase; some plagioclase also contain inclusions of pyroxene; groundmass of same mineralogy with opacques.

Analytical Data:

K2O (wt.%) .77925 +- 2.87227E-3 or3.69235E-3% (n=4)

Run 1: radiogenic Ar-40 = 14.89978% -- 1.616848E-12 moles/gram
age = 1.440714 Ma +- 4.485922E-2 Ma or 3.113681% (est. analyt. 1 sigma)

Run 2: radiogenic Ar-40 = 8.279932% -- 1.421451E-12 moles/gram
age = 1.266651 Ma +- 6.169788E-2 Ma or 4.870946% (est. analyt. 1 sigma)

Collected by K. Sternlof, 1987.

SR-7-87: (36 deg. 55'54" N, 117 deg. 52'01" W: Waucoba Wash 15' quadrangle, Inyo County, California). Basalt -- porphyritic, vesicular, hypocrystalline; phenocrysts of olivine, plagioclase (labradorite), orthopyroxene (hypersthene?), generally diabasic relationship between plagioclase and pyroxene; groundmass of plagioclase, pyroxene, sparse, small opacques, partially devitrified glass; occasional vesicles with some calcite lining.

Analytical Data:

K2O (wt.%) .772 +- 3.464086E-3 or 4.487158E-3% (n=4)

Run 1: radiogenic Ar-40 = 14.86569% -- 1.536078E-12 moles/gram
age = 1.38162 Ma +- 4.565537E-2 Ma or 3.304481% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 7.393282% -- 1.489132E-12 moles/gram
age = 1.339286 Ma +- .0705497 Ma or 6.267709% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

DMH-1-87: (36 deg. 48'22" N, 117 deg. 39'09" W: Dry Mountain 15' quadrangle, Inyo County, California). Trachyandesite -- porphyro-aphanitic, hypocrystalline; phenocrysts of orthopyroxene (hypersthene); groundmass of plagioclase (andesine), some pyroxene and olivine, and sparse opacques; sparse, clean vesicles; mild trachytic texture to plagioclase microlites.

Analytical Data:

K2O (wt.%) 3.2075 +- 1.258305E-2 or 3.92301% (n=4)

Run 1: radiogenic Ar-40 = 42.53286% -- 1.554521E-11 moles/gram
age = 3.363311 Ma +- .0353095 Ma or 1.049841% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 45.52254% -- 1.534224E-11 moles/gram
age = 3.319307 Ma +- 3.389031E-2 Ma or 1.021006% (est. analyt. 1 sigma)

Collected by K. Sternlof, 1987.

SV-2-87: (36 deg. 47'51" N, 117 deg. 43'50" W: Dry Mountain 15' quadrangle, Inyo County, California). Andesite/basalt -- vesicular, aphanitic, holocrystalline; mostly plagioclase (andesine-labradorite) with some orthopyroxene (?); sparse opacques and devitrified glass; sparse, small. clean vesicles.

Analytical Data:

K2O (wt.%) 2.216 +- 6.78236E-3 or .306063% (n=4)

Run 1: radiogenic Ar-40 = 43.611% -- 1.0725E-11 moles/gram
age = 3.35848 Ma +- .0372105 Ma or 1.10796% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 47.8198% -- 9.87779E-12 mles/gram
age = 3.09337 Ma +- .0348035 Ma or 1.1251% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

DM-2-87: (36 deg. 56'14" N, 117 deg. 34'38" W: Dry Mountain 15' quadrangle, Inyo County, California). Basalt -- porphyro-aphanitic, holocrystalline; abundant phenocrysts of iddingsite psuedomorphs of olivine with occasional large olivines rimmed with iddingsite, also sparse, large clinopyroxene (augite); groundmass of plagioclase, pyroxene, and abundant, small opacques.

Analytical Data:

K2O (wt.%) .98125 +- 3.685559E-3 or 3.75598% (n=4)

Run 1: radiogenic Ar-40 = 13.71568% -- 4.645476E-12 moles/gram
age = 3.28539 Ma +- 9.245756 Ma or 2.814203% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 13.28301% -- 4.310948E-12 moles/gram
age = 3.049032 Ma +- 8.860499 Ma or 2.906004% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

SR-4-87: (36 deg. 56'14" N, 117 deg. 43'14" W: Dry Mountain 15' quadrangle, Inyo County, California). Trachybasalt -- porphyro-aphanitic, vesicular, hypocrystalline; phenocrysts of plagioclae (labradorite) in diabasic relationship with clinopyroxene; groundmass of plagioclase, abundant small opacques, some olivine, some pyroxene, and mostly devitrified glass; some vesicles; pronounced trachytic texture to plagioclase microlites.

Analytical Data:

K2O (wt.%) 1.08325 +- 2.629969E-3 or2.42785E-3% (n=4)

Run 1: radiogenic Ar-40 = 5.338013% -- 1.991035E-12 moles/gram
age = 1.276231 Ma +- 9.348825E-2 Ma or 7.324821% (est. analyt. 1 sigma)

Run 2: radiogenic Ar-40 = 6.177655% -- 2.21663E-12 moles/gram
age = 1.420729 Ma +- .0896681 Ma or 6.311413% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

DP-3-87: (36 deg. 27'15" N, 117 deg. 31'58" W: Darwin Plateau 15' quadrangle, Inyo County, California). Basalt -- porphyro-aphanitic, hypocrystalline; phenocrysts of clinopyroxene (augite), olivine, and plagioclase (labradorite); groundmass of plagioclase, opacques, iddingsite, and minor glass.

Analytical Data:

K2O (wt.%) 1.47175 +- 5.56027E-3 or .3773% (n=4)

Run 1: radiogenic Ar-40 = 35.6541% -- 9.79698E-12 moles/gram
age = 4.61762 Ma +- .0590003 Ma or 1.27772% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 34.2473% -- 9.86827E-12 moles/gram
age = 4.65131 Ma +- .0612316 Ma or 1.31644% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

PB-3-87: (36 deg. 27'08" N, 117 deg. 21'37" W: Panamint Butte 15' quadrangle, Inyo County, California). Basalt -- aphanitic, sparsely porphyritic, holocrystalline; phenocrysts of plagioclase (labradorite), olivine, and clinopyroxene (augite); groundmass of plageioclase, iddingsite, interstitial pyroxene (?), and opacques; some small vesicles.

Analytical Data:

K2O (wt.%) .6945 +- 1.29098E-3 or .18586% (n=4)

Run 1: radiogenic Ar-40 = 8.31957% -- 5.07358E-12 moles/gram
age = 5.0669 Ma +- .235857 Ma or 4.65486% (est. analytical 1 sigma)

Run 2: radiogenic Ar-40 = 7.37864% -- 4.97266E-12 moles/gram
age = 4.96643 Ma +- .261359 Ma or 5.26251% (est. analytical 1 sigma)

Collected by K. Sternlof, 1987.

Descriptions for Plates A, B, and C

Plate A. Geologic map of northern Panamint Valley, the northeastern edge of the Darwin Plateau, and the northwestern edge of Panamint Butte focusing on post-early Pliocene extensional faults.

Plate B. Geologic map of the southern Saline Range, northern Saline Valley, and areas on the Dry Mountain structural block focusing on post-early Pliocene extensional faults.

Plate C. Cross-sections N-N' and S-S' across the Saline Range and Dry Mountain. Extension measurements are based on a comparison of the cumulative width of the rotated blocks, measured along the upper basalt surface (real of inferred), with the present width of the extended terrane. The two lines A-B for each cross-section show the original, and extended widths of the terrane. Basalts are shown with the "v" pattern.

Map Legend for Plates A and B

Lithologic Units

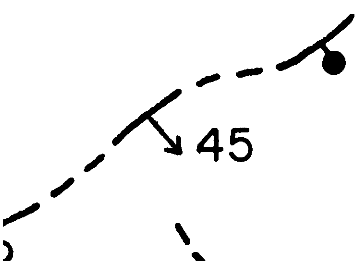
Q Quaternary sediments, may in cases include older sediments.

b Plio-Pleistocene undifferentiated basalts, andesites, other volcanic rocks, and intravolcanic sediments.

g Mesozoic and early Tertiary granitic to quartz monzonitic intrusive rocks.

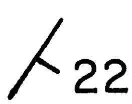
P Late Precambrian thru Paleozoic undifferentiated miogeoclinal sedimentary rocks, complexly deformed by Mesozoic thrusting and mildly to unmetamorphosed.

Map Symbols



Normal fault, dashed where approximated or buried. Ball on down-thrown side--hollow ball denotes fault which makes a scarp in Quaternary alluvium. Arrow indicates fault dip measurement.

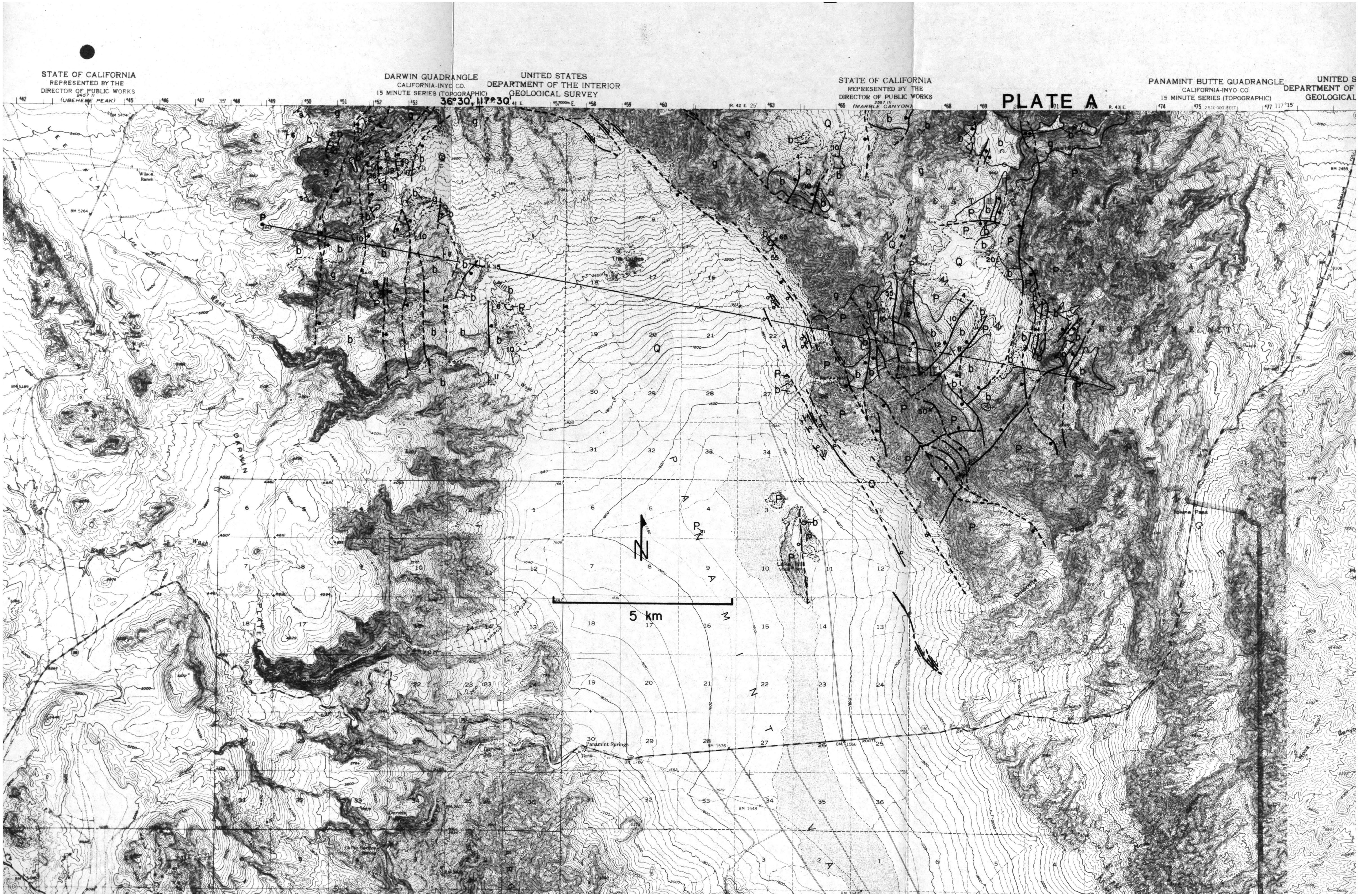
Fault with right-slip component of displacement.



Strike and dip of volcanic flow layering, planes of flattened vesicles within flows, or bedding in intravolcanic sediments.

Horizontal layering.

Lithologic contact, dashed where approximate, or with Quaternary sediment.


STATE OF CALIFORNIA
REPRESENTED BY THE
DIRECTOR OF PUBLIC WORKS
(UBEHEBE PEAK)
DARWIN QUADRANGLE
CALIFORNIA-INYO CO.
15 MINUTE SERIES (TOPOGRAPHIC)
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
36°30', 117°30'
STATE OF CALIFORNIA
REPRESENTED BY THE
DIRECTOR OF PUBLIC WORKS
(MARBLE CANYON)
PLATE A
PANAMINT BUTTE QUADRANGLE
CALIFORNIA-INYO CO.
15 MINUTE SERIES (TOPOGRAPHIC)
117°15'
5 km
Panamint Springs

TOP

PLATE B

Base from U.S.G.S. topo series 1: 62,500
WAUCOBA WASH, DRY MTN., TIN MTN., CALIF.
Compiled in BWTR (3/15/88)
Michael Carr   Scale 1:62,500

PLATE C


N
NW
N'
SE
B
PRE-EXTENSIONAL LENGTH
A
2500 M
B
RECONSTRUCTION LEVEL (1830 M)
A'
2500 M
SEA LEVEL
SEA LEVEL
(?)
DETACHMENT
(?)
S
NW
A
PRE-EXTENSIONAL LENGTH
B
S'
SE
2500 M
A
RECONSTRUCTION LEVEL (1830 M)
B
2500 M
SEA LEVEL
SEA LEVEL
(?)
DETACHMENT
(?)