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EVOLUTION OF EXTENSIONAL BASINS AND BASIN AND RANGE TOPOGRAPHY WEST OF DEATH VALLEY, CALIFORNIA

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Abstract. Neogene extension in the Death Valley region, SE California, has produced a variety of sedimentary basins. Diachronous movements on an array of strike-slip and normal fault systems have resulted in the uplift and preservation of older basins in modern ranges. One of the best exposed of these is the Nova basin on the western flank of the Panamint Mountains. The Nova basin includes over 2000 m of sedimentary and volcanic rocks deposited during denudation of the Panamint Mountains metamorphic core complex in late Miocene (?) – early Pliocene time. The principal growth structure for the basin was the Emigrant detachment, which initiated and moved at a low angle. Modern Panamint Valley, west of the range, developed as a consequence of Late Pliocene – Recent, kinematically linked movement on the right-slip, high-angle Hunter Mountain fault zone and the low-angle Panamint Valley detachment. Detailed mapping of the intersection between the Emigrant and Panamint Valley detachments demonstrates that segments of the earlier system remained active during development of Panamint Valley and, thus, during development of modern Basin and Range topography as well. These results indicate that large-scale extension in the Death Valley region, accommodated by movement on low- to moderate-angle normal fault systems and high-angle strike-slip fault systems, is a continuing process. Basin and Range topography in the Panamint Valley – Death Valley area was generated at least in part by displacements on low-angle detachments rather than high-angle normal faults.

INTRODUCTION

The fact that topography in the Basin and Range Province of the western United States is controlled by normal faulting has been recognized for over a century [e.g., Gilbert, 1875]. Surprisingly, there is still no consensus on the geometric behavior of observed range-bounding faults as they dip beneath the adjacent basins. For many decades the bulk of the geological community believed that the vast majority of these structures are planar and dip steeply (see reviews by Thompson, [1967], and Stewart, [1971, 1978]), even though detailed studies in areas of high relief and good exposure (like the southern Basin and Range) have shown that at least some of the structures that dip steeply at the surface are listric, flattening abruptly beneath the adjacent basin [Longwell, 1945; Hamblin, 1965; Anderson, 1971; Wright and Troxel, 1973].

With the recognition that large-scale extension occurred in the Basin and Range in early to middle Tertiary time [Hamilton and Myers, 1966; Hamilton, 1969; Proffett, 1977] and that much of this extension

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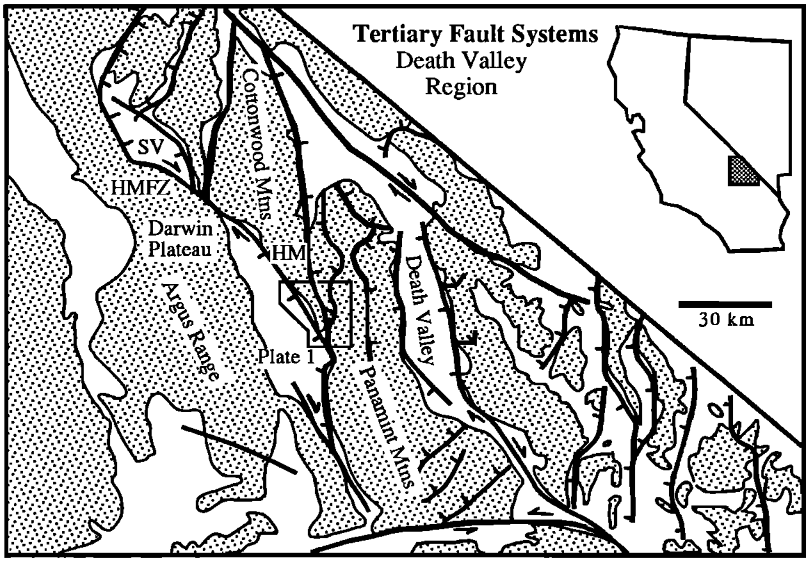


Fig. 1. Tertiary fault systems of the Death Valley region. Ranges are stippled. Normal and strike-slip faults are shown by heavy lines; hatchures are on the hanging wall side of normal faults, and arrows indicate relative motion on strike-slip faults. HM, Hunter Mountain; HMFZ, Hunter Mountain fault zone; SV, Saline Valley. The area shown in the tectonic map (Plate 1) is outlined.

may have been accommodated by movement on low-angle normal faults of regional extent [Armstrong, 1972; Wernicke, 1981, 1985; Allmendinger et al., 1983], some workers postulated that the late Cenozoic development of Basin and Range topography was a fundamentally different process from earlier extension on low-angle faults [e.g., Zoback et al., 1981; Eaton, 1982]. This view was challenged by Hamilton [1982], who suggested that Neogene – Recent Basin and Range topography formed concurrently with movement on large detachment systems; by Dickinson et al. [1987], who argued that characteristic Basin and Range topography of mid-Tertiary age was controlled by low-angle faulting in the Galiuro Mountains, southeastern Arizona; and by Burchfiel et al. [1987], who demonstrated that the modern fault bounding the Panamint Mountains, southeastern California, must have initiated at an angle of less than 15°.

The Panamint Mountains (Figure 1) constitute an especially interesting case for the study of extensional basin evolution because they contain an uplifted, upper Miocene(?) – Pliocene basin, developed during the extensional evolution of a "metamorphic core complex," that lies immediately adjacent to a modern Basin and Range basin: Panamint Valley. In this paper we discuss the age and structural evolution of each basin and argue that they formed as part of a continuous extensional process in which low-angle faulting played a dominant role.

GEOLOGIC SETTING

The Death Valley area of southeastern California has been the site of large-scale extension since at least middle Miocene time [Cemen et al., 1982]. This extension was accommodated by listric and planar normal faults and by NW-trending, right-lateral strike-slip faults which served as transfer structures between normal fault systems. The interplay between normal and strike-slip fault systems has led to the development of two spectacular examples of "pull-apart" [Burchfiel and Stewart, 1966] or rhombhedral basins: Panamint Valley and central Death Valley itself. These valleys are separated by the Panamint Mountains, a metamorphic core complex which evolved over the middle Miocene - Recent interval (Figure 1).

It is convenient to think of the northern and central Panamint Mountains in terms of four tectonic plates distinguished by metamorphic grade and structural history (Figure 2). The structurally lowest plate (or "Parautochthon") consists of Precambrian crystalline basement intruded by Miocene (?) granite porphyry dikes [Hunt and Mabey, 1966; Stern et al., 1966]. The "Lower Allochthon" is composed of middle and lower Proterozoic crystalline basement and upper Proterozoic strata, which were metamorphosed at greenschist to lower amphibolite facies conditions between middle Mesozoic and early Tertiary time [Labotka et al., 1985] and have been intruded by Cretaceous granites. Several phases of ductile to

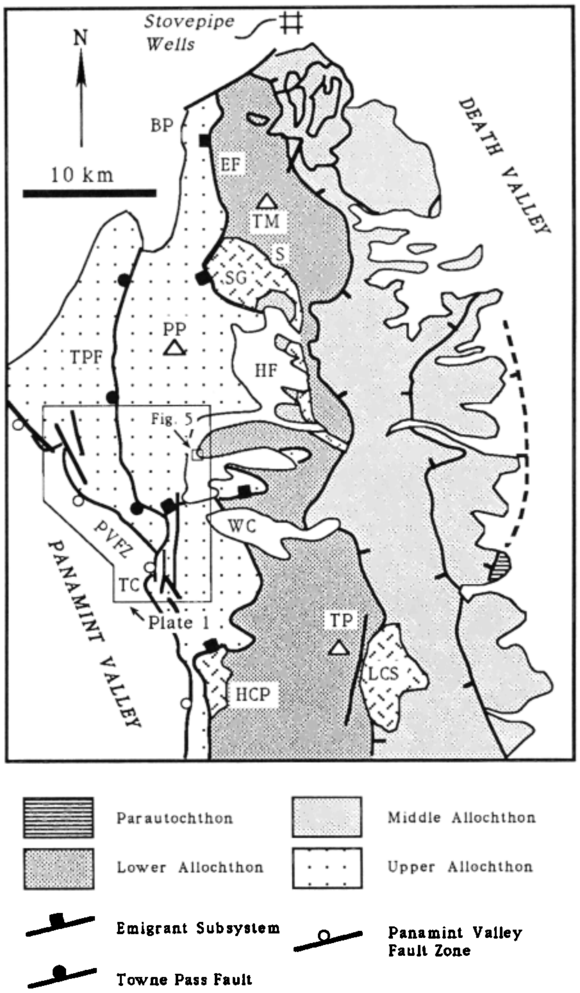


Fig. 2. Location and fault map of the Panamint Range. Key indicates pattern and fault ornamentation; fault barbs are on the hanging wall side of low-angle structures. BP, Black Point; EF, Emigrant fault; HF, Harrisburg Flats; HCP, Hall Canyon Pluton; LCS, Little Chief Stock; PB, Panamint Butte; PP, Pinto Peak; PVFZ, Panamint Valley fault Zone; S, Skidoo townsite; SG, Skidoo Granite; TC, Tuber Canyon; TM, Tucki Mountain; TP Telescope Peak; TPF, Towne Pass fault; WC, Wildrose Canyon. The locations of Plate 1 and Figure 5 are shown by the labeled boxes.

brittle-ductile deformation affected this plate in Mesozoic-Cenozoic time [Hodges et al., 1987].

The "Middle Allochthon" contains lower greenschist facies to unmetamorphosed, upper Precambrian to Permian strata, which are unconformably overlain by upper Tertiary alluvial basin deposits and intercalated volcanic flows in the northeastern Panamint Mountains. The structurally highest "Upper Allochthon" includes the following: (1) some small (< 1 km^2) structural slices of Lower Allochthon and Middle Allochthon lithologies at its easternmost exposures; (2) a thick section of Paleozoic rocks of Middle Allochthon affinity at Panamint Butte (Figure 2); and (3) synextensional, Pliocene sedimentary and volcanic rocks of the Nova Formation [Hopper, 1947; Hall, 1971; Walker and Coleman, 1987].

The contacts between the four plates in the central Panamint Mountains are temporally distinct, consistently top-to-the-northwest, generally low-angle normal faults. The structures that separate the Lower Allochthon from the Parautochthon are part of the Eastern Panamint fault system [Hodges et al., 1989]. This fault system is exposed near the eastern foot of the Panamint Mountains and presently dips shallowly westward. Palinspastic reconstruction of a sequence of Upper Miocene volcanic rocks erupted synchronously with development of the fault system indicates that its original dip must have been 45°-60° westward [McKenna and Hodges, 1989].

The family of structures that separates the Lower Allochthon from structurally higher plates is defined as the Tucki Mountain detachment system. The oldest fault in this system (> 10.7 Ma; Hodges et al., [1989]) is the Harrisburg detachment, which presently dips eastward beneath the Middle Allochthon due to Pliocene doming of the range but is inferred to have initially dipped westward [Hodges et al., 1987]. The youngest fault in the system is the west-dipping Emigrant detachment, which served as the principal growth fault for the Nova Basin.

THE NOVA BASIN

Hopper [1947] proposed the name "Nova Formation" for a thick section of alluvial fan deposits ("fanglomerates") and intercalated volcanic rocks exposed along the west flank of the northern Panamint Range. Hall [1971] abandoned use of the term "Nova Formation" because Hopper had been vague about its definition; instead, he preferred to distinguish a variety of upper Miocene (?) – Recent alluvial packages, based on their degree of induration, clast composition, and position in the sequence relative to volcanic horizons. We believe that the "Nova Formation" nomenclature serves a useful purpose by distinguishing the more indurated upper Miocene (?) – Pliocene deposits from the poorly consolidated upper Pliocene – Recent alluvium associated with the development of Panamint Valley. Throughout this paper we will refer to the ancient sedimentary basin represented by the Nova Formation as the "Nova Basin."

Stratigraphy

The Nova Formation includes more than 3 km of sedimentary and volcanic rocks. It can be divided

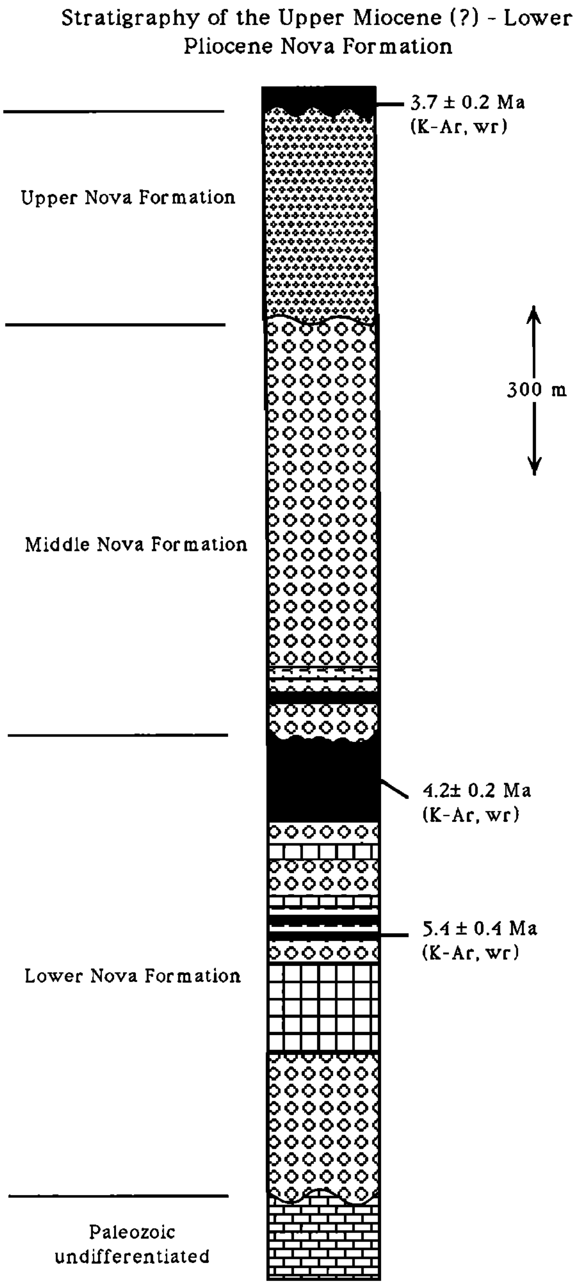


Fig. 3. Stratigraphy of the upper Miocene to lower Pliocene Nova Formation, with radiometric age constraints as indicated. Other consistent K-Ar ages are available for the sequence (e.g., W. Hildreth, unpublished data), but the stratigraphic positions of the dated units are less certain than those noted here.

into lower, middle, and upper parts, based on lithology and contact relations (Figure 3). The lower part of the Nova Formation attains a thickness of over 1000 m. It consists of the initial deposits in the Nova Basin and is characterized by coarse, poorly bedded conglomerates with localized monolithologic and polylithologic megabreccia horizons which we interpret as landslide deposits. Volcanic flows, ranging in composition from calc-alkaline basalt to rhyolite, occur sporadically within the middle part of the unit and become more abundant near the top. Major and trace element geochemistry, as well as Sr and Pb isotopic signatures, indicate that these flows are part of the thick Darwin Plateau sequence to the west (Figure 1), which was adjacent to the northern Panamint Mountains prior to Plio-Pleistocene opening of Panamint Valley [Coleman et al., 1987; Walker and Coleman, 1987]. An apparent unroofing sequence for the Panamint Mountains is recorded in the lower Nova Formation; unmetamorphosed Paleozoic units of the Middle Allochthon characterized the source area for clasts and megabreccias within the basal Nova Formation, but metamorphic rocks of the Lower Allochthon become abundant in conglomerates and breccia sheets near the top of the lower Nova Formation [Walker and Coleman, 1987].

The middle Nova Formation rests unconformably on the lower Nova and is exposed continuously from the east side of Pinto Peak northward to Black Point (Figure 2). Conglomerates in the middle Nova are similar in appearance to those in the lower Nova, but the clasts reflect a mixed provenance of both Middle Allochthon unmetamorphic and Lower Allochthon metamorphic bedrock. Megabreccias are less common in the middle Nova than in the lower Nova, and volcanic flows and tuffs are only locally present.

The upper Nova Formation lies entirely within a restricted subbasin that is exposed west of Pinto Peak. It rests with angular unconformity on both lower and middle Nova Formation rocks near the eastern edge of Panamint Valley, but it is fault bounded elsewhere. The upper Nova is composed primarily of conglomerate derived by reworking of other parts of the Nova Formation, and it is characteristically well bedded compared to the lower and middle parts of the section. No volcanic units have been identified in the upper Nova.

Depositional environments for the Nova Formation range from alluvial fans to playas. All variations from proximal to distal alluvial fan facies have been observed. We do not yet know whether this wide range of facies represents fan switching and progradation or responses to changes in the rate and style of syndepositional faulting [cf., Bilodeau and Blair, 1986; Blair, 1987]. We are working presently with the notion that faulting variations were important because of the active nature of the basin and because of the presence of abundant unconformities in the section which do not have regional significance.

Structural Evolution

We are fortunate in the Panamint Mountains to have excellent three-dimensional exposures of the

Tectonic Cross Section of the Nova Basin

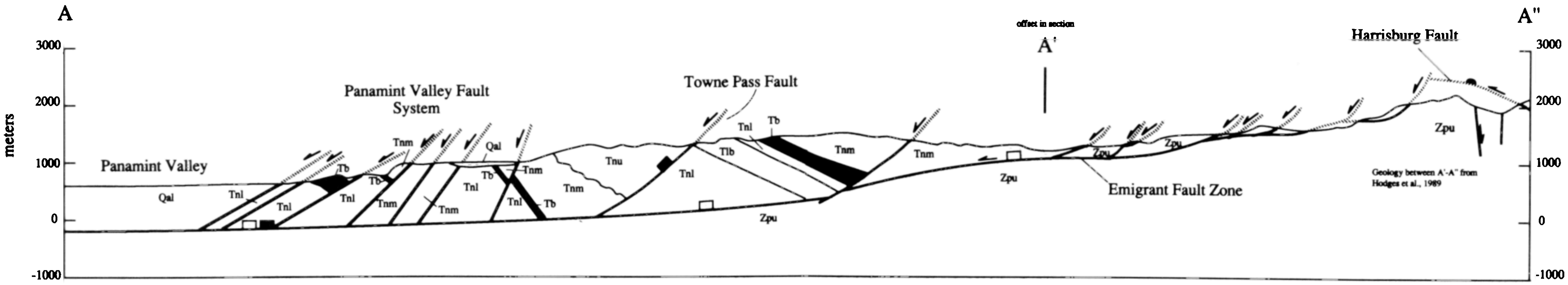
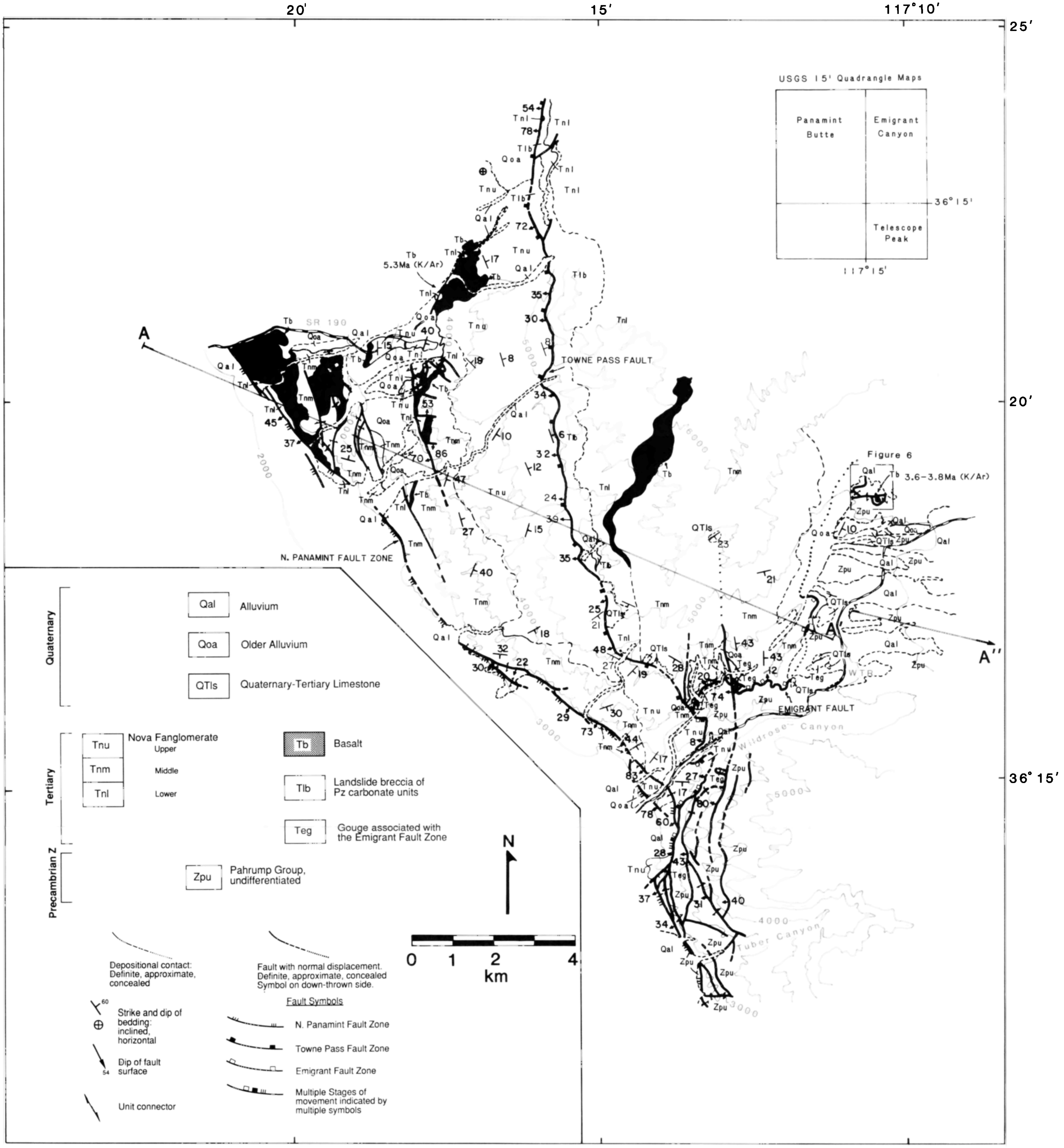


Plate 1. (continued)

Tectonic Map of the Nova Basin
and Surroundings, Inyo County, California



faults that controlled the development of the Nova Basin. Those which served as the growth faults for the lower and middle Nova Formation belong to the youngest family of structures in the Tucki Mountain detachment system, the Emigrant subsystem [Wernicke et al., 1986; Hodges et al., 1989]. In collaboration with Brian Wernicke at Harvard University we have mapped the exposed trace of the Emigrant fault zone from the northern foot of Tucki Mountain to the mouth of Wildrose Canyon (Figure 2), a distance of over 30 km, at a scale of 1:10,000. Between Tucki Mountain and Skidoo townsite the fault zone is characterized by fault gouge and breccia up to 50-m thick. Lithologies within the zone are predominantly upper Precambrian metasedimentary rocks and upper Cretaceous granitic intrusive rocks of the Lower Allochthon. The zone consistently dips less than 20°NW. South of Skidoo the zone gradually widens to become an extensional duplex [Gibbs, 1984]. The sole fault of the duplex climbs near the crest of the Panamint Range and its dip steepens to greater than 70°NW, while the roof fault maintains a shallow northwest dip. Much of the Harrisburg Flats area (Figure 2), between the roof and sole faults, consists of east-tilted fault blocks (or "riders" in the terminology of Gibbs, [1984]).

Harding [1987] and Hodges et al. [1989] concluded that the steep segment of the sole fault at the range crest marks the near-surface "breakaway" zone of the Emigrant subsystem. Field relationships in the Harrisburg Flats area clearly demonstrate continuity between shallowly dipping western exposures of the sole fault and steeply dipping eastern exposures. Palinspastic reconstruction of the extensional riders in this area indicates that the sole fault dips less than 15°NW beneath the Nova Formation [Hodges et al., 1989]. Detailed mapping of the structurally lowest portions of the Nova Basin south of Panamint Butte (Figure 2; K.V. Hodges and others, unpublished data, 1989) suggests that a complex landslide of Lower Allochthon and Middle Allochthon lithologies, shed partially off the Emigrant scarp, may have marked the earliest stage of basin evolution.

The upper Nova Formation was deposited in a subbasin generated by movement on the Towne Pass fault (Figure 2). This structure was described by Hall [1971] as a NNW-trending, 45°-80°W–dipping normal fault with a minimum of 2400 m displacement. We have mapped this fault along its entire trace at a scale of 1:24,000 (Plate 1). From north to south the fault orientation changes from a NNW trend with steep to moderate dip to a NW trend with moderate to shallow dip. Along much of its length the immediate footwall of the fault is an immense landslide deposit of upper Paleozoic strata that lies within the lower Nova Formation. South of this landslide the Towne Pass footwall consists of lower and middle Nova units.

Our interpretation of the structural and stratigraphic evolution of the Nova Basin is illustrated in Figure 4.

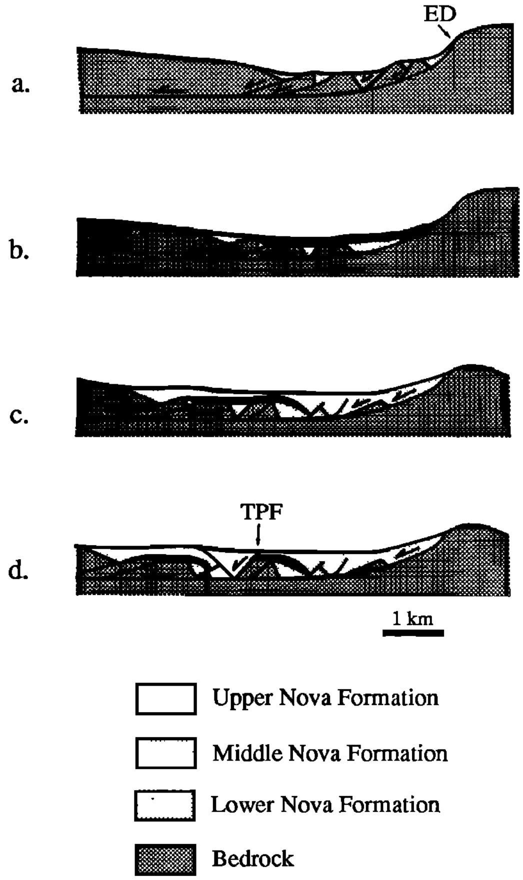


Fig. 4 . Schematic cross sections illustrating evolution of the Nova basin. (a): Initiation of the Emigrant detachment (ED) and lower Nova Formation deposition, (b): eruption of the upper Miocene – lower Pliocene (?) volcanic sequence that marks the top of the Lower Nova Formation, (c): deposition of the middle Nova Formation, (d): initiation of the Towne Pass fault (TPF) and deposition of the upper Nova Formation.

Although the synextensional Nova strata presently dip eastward at low to moderate angles, there is no evidence to suggest that the Emigrant detachment itself initiated at high angle and was subsequently rotated to a shallower dip. Reconstruction of the Precambrian strata in the Emigrant riders to their pre-Emigrant configuration as part of the Lower Allochthon indicates stratal rotations of about 45° associated with the curvature of the sole fault at the breakaway [Hodges et al., 1989]. This rotation is sufficient to restore observed dips in middle and lower Nova strata, deposited near the breakaway zone, to horizontal. Thus we infer that the Emigrant detachment initiated and moved at a low angle. There is similarly no evidence that the Towne Pass fault has been rotated substantially since initiation.

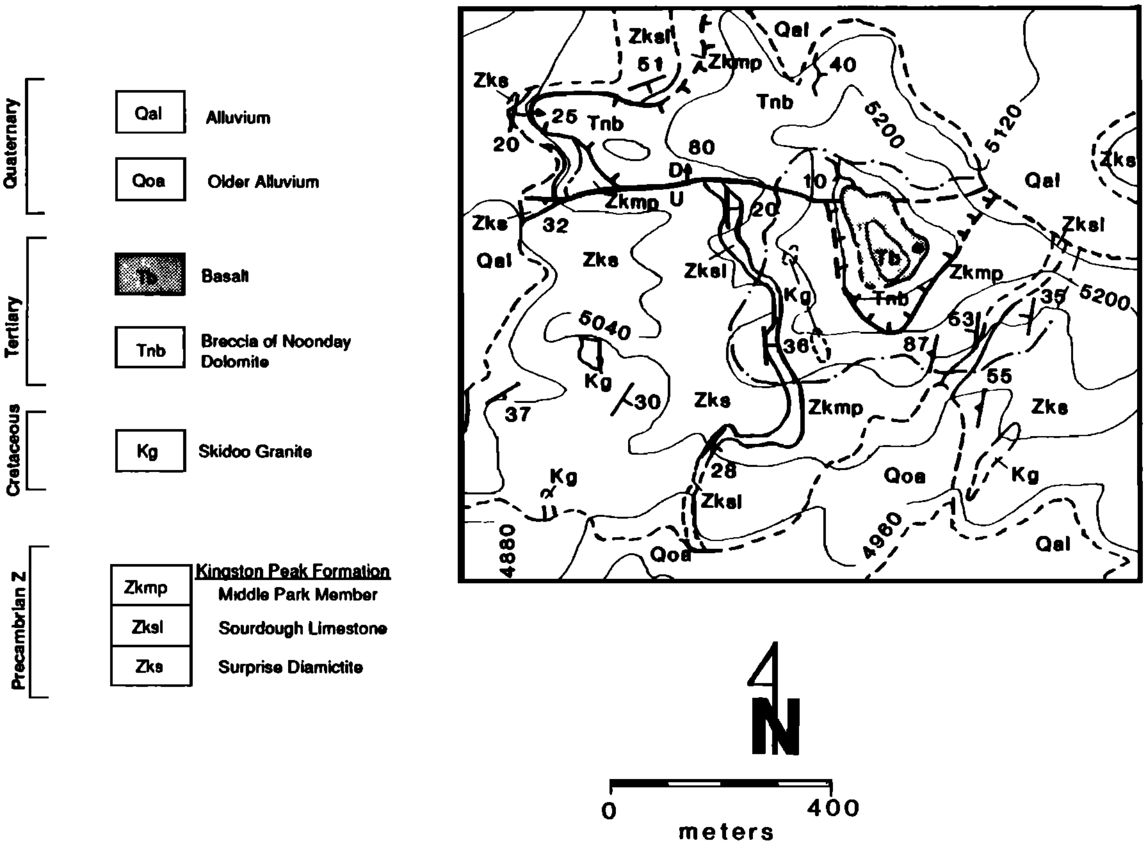


Fig. 5. Detailed geologic map of White Sage Flat area, SW Harrisburg Flats (see Plate 1 for location). Topography (in feet) is represented by thin solid lines. The filled circle indicates the collection location for geochronology samples (Table 1).

Age Constraints

Despite the occurrence of several volcanic horizons within the Nova Formation, very few geochronologic data are available for the sequence. Reconnaissance K-Ar ages reported by Hall [1971], Larsen [1979], Sternlof [1988] and W. Hildreth [unpublished data] for lower Nova volcanic rocks range from 5.3 ± 0.8 Ma to 4.0 ± 0.4 Ma (2s). Schweig [1984] argued convincingly that portions of the fanglomerate sequence in the northern Argus Range (Figure 1) that he believed to be correlative with what we call the lower Nova Formation may have been deposited before 6.1 Ma.

The most important constraints on the minimum age of the Emigrant subsystem are the map relations illustrated in Figure 5. At this locality in the southwestern Harrisburg Flats area, a small, flat-lying exposure of olivine basalt lies in flow contact on one of the westernmost extensional riders of the Emigrant subsystem. The basalt covers the trace of an ENE-striking, high-angle fault that cuts the low-angle fault at the base of the rider and therefore must postdate its emplacement. Harding [1987] demonstrated that the sequence of faulting in the Emigrant duplex progressed from east to west, in the direction of fault movement. As one of the westernmost riders in the duplex, the fault block capped by the basalt should be one of the youngest, and we can reasonably infer that the bulk (if not all) of the movement on the Emigrant subsystem occurred before eruption of the basalt. Whole rock K-Ar data for two samples from this flow (Table 1) yield ages of 3.6 ± 0.3 Ma and 3.8 ± 0.3 Ma (2s). Combined with existing ages for volcanic units within the lower Nova, we interpret these data as indicative of a 6.1 to 3.6 Ma approximate age range for movement on the Emigrant subsystem and deposition of the lower and middle Nova Formation.

We infer, as did Hall [1971], that the active depocenter for the basin shifted westward after 3.6 Ma to the hanging wall of the Towne Pass fault. The youngest age of movement on the Towne Pass fault is not constrained well. Several small lacustrine limestone deposits that may mark Plio-Pleistocene sag ponds occur along the fault trace (Plate 1). In the

TABLE 1. K-Ar Data

Sample	$^{40}Ar^{rad}$,mol/gm	$^{40}Ar^{rad}/^{40}Ar^{tot}$	K_2O,wt%	Age
1	7.0842×10^{-12}	0.13269	1.344	3.6±0.3 Ma
2	7.3636×10^{-12}	0.14465	1.345	3.8±0.3 Ma

Sample is a fresh, porphritic quartz-olivine basalt. Sample location is shown on Figure 5 by solid circle symbol, approximate location is UTM 11SML04842204018220. Sample preparation and analysis by J. Stock at the U.S. Geological Survey laboratories, Menlo Park, California. Potash analyses by flame photometry; Ar analyses were performed by isotope dilution procedures [Dalrymple and Lanphere, 1969] with a standard 60° sector, 15.2 cm radius, Nier-type mass spectrometer. Precision of the data is the estimated analytical uncertainty at 2s. Decay constants are $\lambda_\varepsilon + \lambda_{\varepsilon'} = 5.81 \times 10^{-11}$ yr^{-1} and $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; atomic abundance of $^{40}K = 1.167 \times 10^{-4}$.

Towne Pass area, slightly degraded scarps along the fault trace also indicate relatively recent movement.

THE PANAMINT BASIN

Panamint Valley developed as a consequence of right-lateral movement on the Hunter Mountain fault zone on the north and unnamed structures separating the Slate Range and Panamint Mountains on the south (Figure 1; Burchfiel et al.[1987]). We refer to this Pliocene – Recent depocenter as the Panamint Basin.

Stratigraphy and Basin Characteristics

The oldest exposed units of the Panamint Basin sequence are lacustrine deposits described by Hall [1971]. These include white to tan claystones, siltstones, sandstones, and limestones up to 65-m thick. The lacustrine deposits occur in isolated outcrops at a variety of elevations up to 645 m, roughly 200 m above the valley floor. Most outcrops have been tilted slightly by young faults related to the latest stages of valley development [Smith, 1976].

The lacustrine deposits are overlain by poorly consolidated to unconsolidated alluvial fan and playa deposits, with minor sand lenses and landslide breccias. The fanglomerates were derived both by erosion of denuded bedrock and by reworking of the Nova Formation conglomerates [Hall, 1971].

The depth of alluvial fill in the central part of northern Panamint Valley is constrained by a core hole that struck bedrock beneath the sediments at a depth of 118 m [Smith and Pratt, 1957]. MIT 1985 Field Geophysics Course and Biehler [1987] presented gravity, seismic refraction, resistivity, and magnetotelluric data indicating between 100 and 200 m of fill throughout much of northern Panamint Valley.

Structural Evolution

Burchfiel et al. [1987] suggested that Panamint Valley and Saline Valley to the north are paired pull-apart basins on opposite sides of the predominantly strike-slip, NW-trending Hunter Mountain fault zone (Figure 1). The principal growth fault for the Panamint Basin is the NNW-trending, west-dipping Panamint Valley fault zone [Noble, 1926] which occurs at the western foot of the Panamint Mountains (Figure 2).

Roughly 8-10 km of right-slip movement and 0-2 km of down-to-the-south dip-slip movement on the Hunter Mountain fault zone can be established by matching a unique linear element that occurs on both sides of the structure: the intersection of a high-angle intrusive contact and an overlapping Cenozoic basalt. Because the Hunter Mountain fault zone served as a transfer structure [Gibbs, 1984] between the Panamint and Saline basins, Burchfiel et al. [1987] concluded that the calculated net slip on the Hunter Mountain fault zone matched the cumulative slip on faults of the Panamint Valley fault zone. Palinspastic reconstruction of the area based on the derived slip vector completely restores correlative volcanic flows that occur on either side of the valley but do not underlie the alluvial fill [MIT 1985 Field Geophysics Course and Biehler, 1987], indicating that the Panamint Valley fault zone dips less that 15° beneath the valley [Burchfiel et al., 1987; Sternlof, 1988].

Exposed scarps along the Panamint Valley fault zone have low to moderate dips (15° -42° W). Along with the geological and geophysical evidence for a very shallow dip of the detachment beneath the valley these surface dip measurements strongly suggest that the fault zone is listric. This interpretation is supported by the observation that volcanic flows on the Darwin Plateau "roll over" toward the valley, as they should if transported in the hanging wall of a strongly listric normal fault [Hamblin, 1965]. Detailed studies of the most recent fault scarps within the Panamint Valley fault zone indicate that Holocene movements were characterized by both dip-slip and right-slip components [Hopper, 1947; Smith, 1976]. Minor strike-slip movement of this kind is a common characteristic of pull-apart basins in which the bounding normal and transfer faults strike obliquely to each other [Walker et al., 1986].

Age Constraints

The opening of Panamint Valley transected the Nova Basin, such that Nova Formation lithologies are exposed in the ranges on either side of the valley

[Schweig, 1984]. Thus initiation of the valley must postdate the 6.1–3.6 Ma age of the lower and middle Nova Formation. This conclusion is consistent with the 5.0 Ma age obtained by Sternlof [1988] for the youngest basalt flow which was clearly offset by movement on the Panamint Valley and Hunter Mountain fault systems. Scarps of the Panamint Valley system are developed on upper Nova Formation subcrop, suggesting a post-3.6 Ma age of initiation. If Saline Valley and Panamint Valley developed simultaneously, as argued by Burchfiel et al. [1987], then the maximum age of initiation of Saline Valley (3.0 Ma; Burchfiel [1969], Ross [1967, 1968], and Sternlof [1988]) corresponds to the maximum age of Panamint Valley. An abundance of Recent fault scarps along the Hunter Mountain and Panamint Valley fault zones, as well as within the valley, attest to the continuing evolution of the basin [Smith, 1976].

THE WILDROSE CANYON AREA

The Emigrant fault zone, the Towne Pass fault, and the Panamint Valley fault zone converge near the mouth of Wildrose Canyon (Plate 1 and Figure 6). These structures have been partially exhumed by erosion, providing direct evidence of their three-dimensional geometry. We have mapped most of the area at a scale of 1:10,000, and our results are shown in simplified form as the tectonic map in Plate 1.

The western limits of this area display structures characteristic of much of the eastern boundary of the Panamint Basin. The individual range-bounding faults (representing the Panamint Valley fault zone) are rectilinear to slightly curvilinear in map view, have dips ranging from nearly 80°W to less than 30°W, and juxtapose Quaternary alluvium and upper Precambrian metasedimentary rocks. Individual faults have traces which vary in length from less than 1 km to roughly 4 km. Contiguous faults overlap substantially, and some segments clearly veer away from the range front and into the range as they terminate.

North of the mouth of Wildrose Canyon the range-bounding fault scarps are somewhat degraded because the footwalls predominantly consist of poorly consolidated Nova fanglomerates. At the southern end of the area the footwall is made up of crystalline rocks, and the steep, western front of the range appears to represent a virtually unmodified, exhumed surface of the Panamint Valley fault zone. Here the lower portions of the range front are quite planar. Linear regression analysis of eight topographic profiles and several direct measurements of the surface yield an estimated dip of 34° ± 5° (2s uncertainty).

In the vicinity of Tuber Canyon (Plate 1), the footwall of the Panamint Valley fault zone consists of variegated fault gouge and brecciated structural horses of upper Precambrian strata, both characteristic of the Emigrant fault zone. These relationships support other lines of evidence (discussed above), suggesting a post-Emigrant age for the Panamint Valley fault zone.

Approximately 1.7 km north of Tuber Canyon the Panamint Valley structure strikes directly into a large hill of upper Nova Formation fanglomerates, and is truncated by a NE striking, NW dipping fault that places upper Nova lithologies on Emigrant fault zone rocks (Plate 1). Northeast of the hill of fanglomerates, for a distance of ~1 km, this structure acts as the range-bounding fault. Along this segment the relief at the range front is more subdued than it is near Tuber Canyon (Figure 6) even though the footwall lithologies are similar; linear regression analysis of nine topographic profiles along this segment yielded an estimated fault dip of 20° ± 5° (2s), while one direct measurement of the surface indicated a somewhat steeper dip of 28°. A few hundred meters south of the mouth of Wildrose Canyon, this low-angle structure climbs into the Panamint Range. It is replaced as the range-bounding fault by a poorly exposed, NW striking fault which dips 78°SW and juxtaposes Quaternary alluvium and upper Nova Formation lithologies. Unfortunately, the intersection between this fault and the more shallowly dipping structure is unexposed.

We have mapped the northward continuation of the more shallowly dipping fault for ~2.5 km into the range. Throughout this distance the structure dips shallowly (< 27°) westward. At 2.5 km the surface clearly bifurcates. One strand maintains a shallow dip (< 20°) but strikes off to the northeast and corresponds to the roof fault of the Emigrant fault zone in the Harrisburg Flats area (Figure 2). The other strand maintains its northerly strike but increases its dip and corresponds to the Towne Pass fault. We stress that there is a completely smooth transition between the three structures; there is no indication here that the low-angle fault approaching from the south cuts the Towne Pass fault, or that the Towne Pass fault cuts the Emigrant roof fault.

INTERPRETATION

Field relationships in the Wildrose Canyon area imply that the Towne Pass fault is a hanging wall splay off the Emigrant detachment. In this interpretation the low-angle surface south of the merger between the two faults is a segment of the Emigrant roof fault that remained active (as a segment of the Towne Pass fault) after the rest of the Emigrant subsystem had ceased activity.

The field evidence also suggests that this same low-angle segment acted as a portion of the growth fault for modern Panamint Valley. We infer that the Nova and Panamint basins did not develop independently and that Panamint Valley is the most recent phase in a continuum. Just as the principal depocenter for the Nova Basin stepped westward

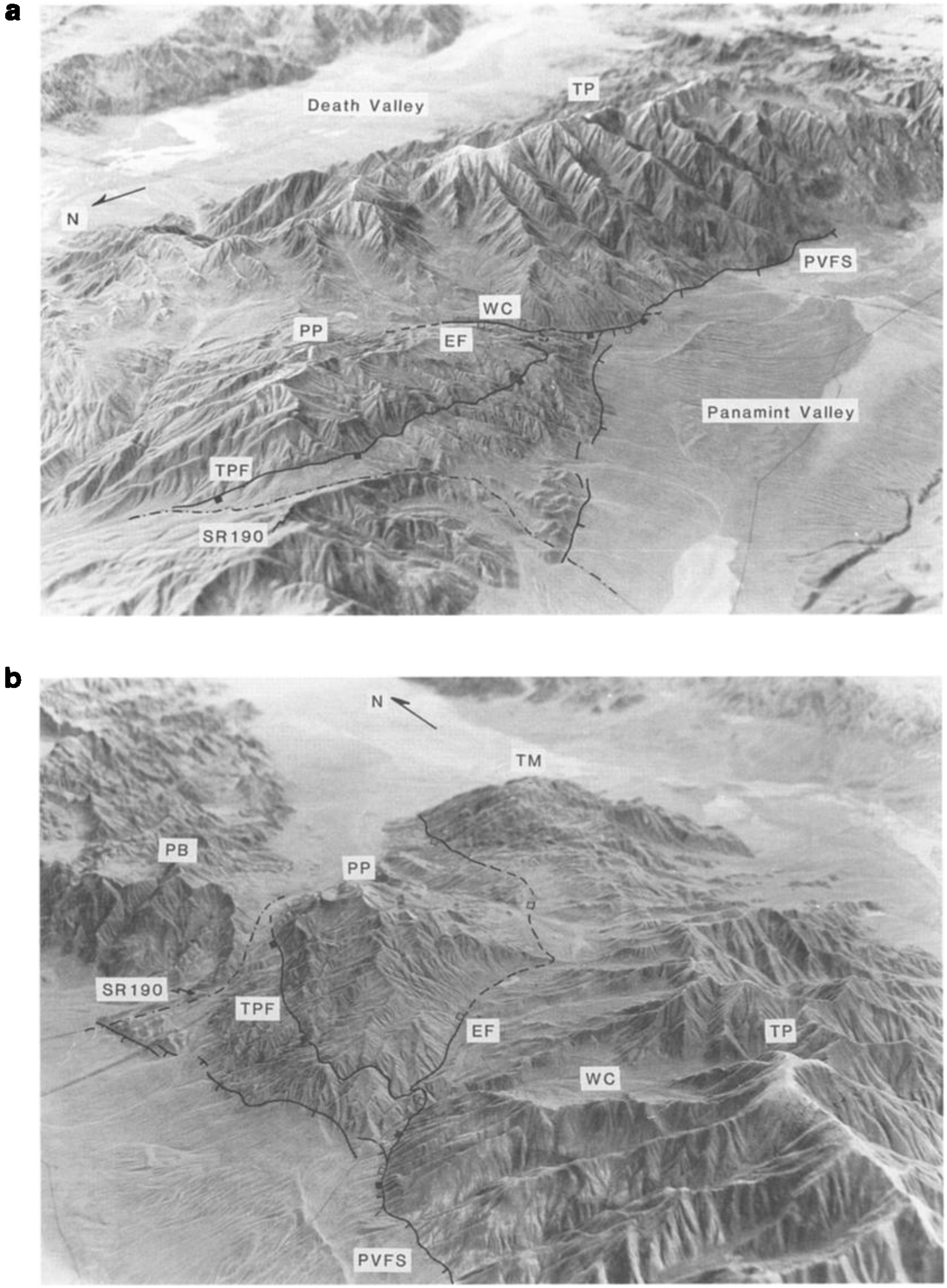


Fig. 6. Oblique photographs of a topographic model of the Death Valley National Monument at the Furnace Creek Visitors Center, which provides the vantage of aerial photography at a fraction of the cost. (a): Southeastward view from above Hunter Mountain. The Nova basin sensu stricto is the diamond-shaped area exposed between the Emigrant fault, the Panamint Valley fault zone, and State Route 190. Panamint Valley lies in the lower right corner of the photograph. Merger of the Emigrant, Towne Pass, and Panamint Valley faults is well-displayed in this photograph. (b): View looking NNE, taken from above Surprise Canyon. Note the topographic expression of the Nova basin's growth faults, and the inflection of the Emigrant fault's trace at fault junctions. EF, Emigrant fault; PB, Panamint Butte; PP, Pinto Peak; PVFS, Panamint Valley fault system; TM, Tucki Mountain; TP, Telescope Peak; TPF, Towne Pass fault; and WC, Wildrose Canyon.

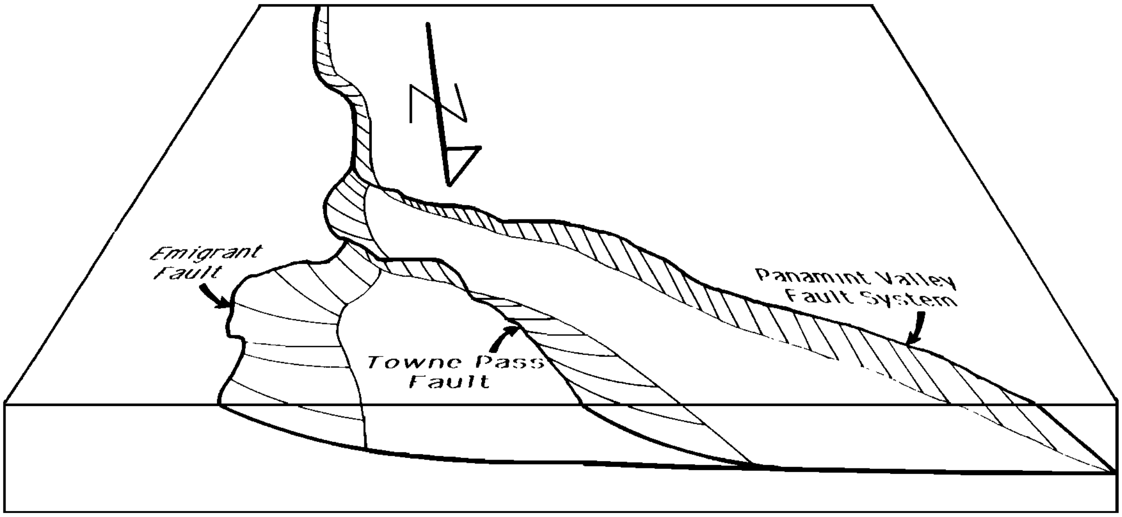


Figure 7. Interpretive perspective diagram of the relationships between the Emigrant, Towne Pass, and Panamint Valley faults. View is toward the south. The heaviest lines indicate the surface trace of the fault, while the thinnest lines indicate the dip of the fault surface. The front, vertical surface is equivalent to the cross section in Plate 1. Note that faults join at inflections of the fault trace and that all three faults have the same trace south of Tuber Canyon (here lying at the same latitude as the northern tip of the North arrow). The Towne Pass and Panamint Valley faults sole into the Emigrant fault at depth, indicating that while the active depocenters of the basins migrated westward with time, deformation at depth was occurring along the same surface.

beyond the Towne Pass fault in Late Pliocene time, it shifted still further westward (to Panamint Valley) in latest Pliocene to Pleistocene time (Figure 7). In many ways, Panamint Valley is simply the most recent subbasin within the developing Nova Basin. Seen from a perspective millions of years in the future, the Nova Basin and Panamint Valley would appear to be part of a single, complex extensional basin.

IMPLICATIONS

Fault relationships on the western flank of the Panamint Mountains illustrate the dangers involved in presuming that large-scale extension in the Basin and Range is divorced from the development of modern Basin and Range topography. Many workers [e.g., Davis and Burchfiel, 1975; Wernicke et al., 1982; and Wernicke et al., 1988] present compelling evidence that large-magnitude extension occurred north of the Garlock fault in Neogene time. The Panamint Mountains fit all of the stock definitions of a "metamorphic core complex" [e.g., Davis and Coney, 1979; Armstrong, 1986; Davis and Lister, 1988], yet one of the structures responsible for its unroofing (the Emigrant detachment) clearly moved as recently as Pliocene time [Hodges et al., 1989]. Development of the Panamint Valley fault zone, in every sense a Basin and Range "range-bounding fault," seems to have been part of the same process of core complex evolution.

We do not mean to imply here that high-angle, range-bounding faults do not occur in the Basin and Range; dozens of studies have documented the existence of a wide variety of geometries, from low-angle to high-angle and from planar to markedly listric [e.g., Anderson et al., 1983]. However, field relationships in the Wildrose Canyon area and elsewhere in the southwestern United States [e.g., Dickinson et al., 1987] illustrate the existence and importance of young, low-angle, range-bounding faults in the Basin and Range.

CONCLUSIONS

The Nova and Panamint basins have similar structural and sedimentological histories; both developed as a consequence of westward movement on low-angle detachments. The Nova Basin records unroofing of the Panamint metamorphic core complex in late Miocene(?) – Pliocene time by displacement along the Emigrant detachment and related faults. The Panamint basin was formed in late Pliocene – Recent time during simultaneous evolution of the high-angle Hunter Mountain fault zone and low-angle Panamint Valley detachment. Because of the lack of evidence for a significant time break between deposition in the two basins, and because some growth fault segments seem to have been common to both basins, we conclude that Panamint Valley is simply the most recent stage in the evolution of the Panamint metamorphic core complex. In this area there is no indication that the development of "classic" Basin and Range topography is a different process than tectonic denudation by movement on low-angle detachments.

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