Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwestward

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ABSTRACT

In the hypothesis presented here, the Panamint Range is a structural block that was detached during late Cenozoic time from underlying rocks that now form the Black Mountains and was transported tectonically an estimated 80 km to the northwest. Transport occurred along a single low-angle westward-dipping detachment fault, or perhaps along a system of such faults. The estimate of 80 km of transport distance is based on the apparent right-lateral offset of late Precambrian and Paleozoic facies and thickness trends along the Furnace Creek fault zone that bounds the detached block on the northeast. The Death Valley turtleback surfaces are considered to be gigantic mullions related to the detachment surface.

INTRODUCTION

The Death Valley area of California contains a bewildering array of complex geologic structures, including thrust faults, strike-slip faults, low-angle extensional and detachment faults, turtleback surfaces, chaotic megabreccias, horsts and grabens, and tilted blocks, as well as relatively intact mountain blocks (Fig. 1). Many of these features have been related to strike-slip

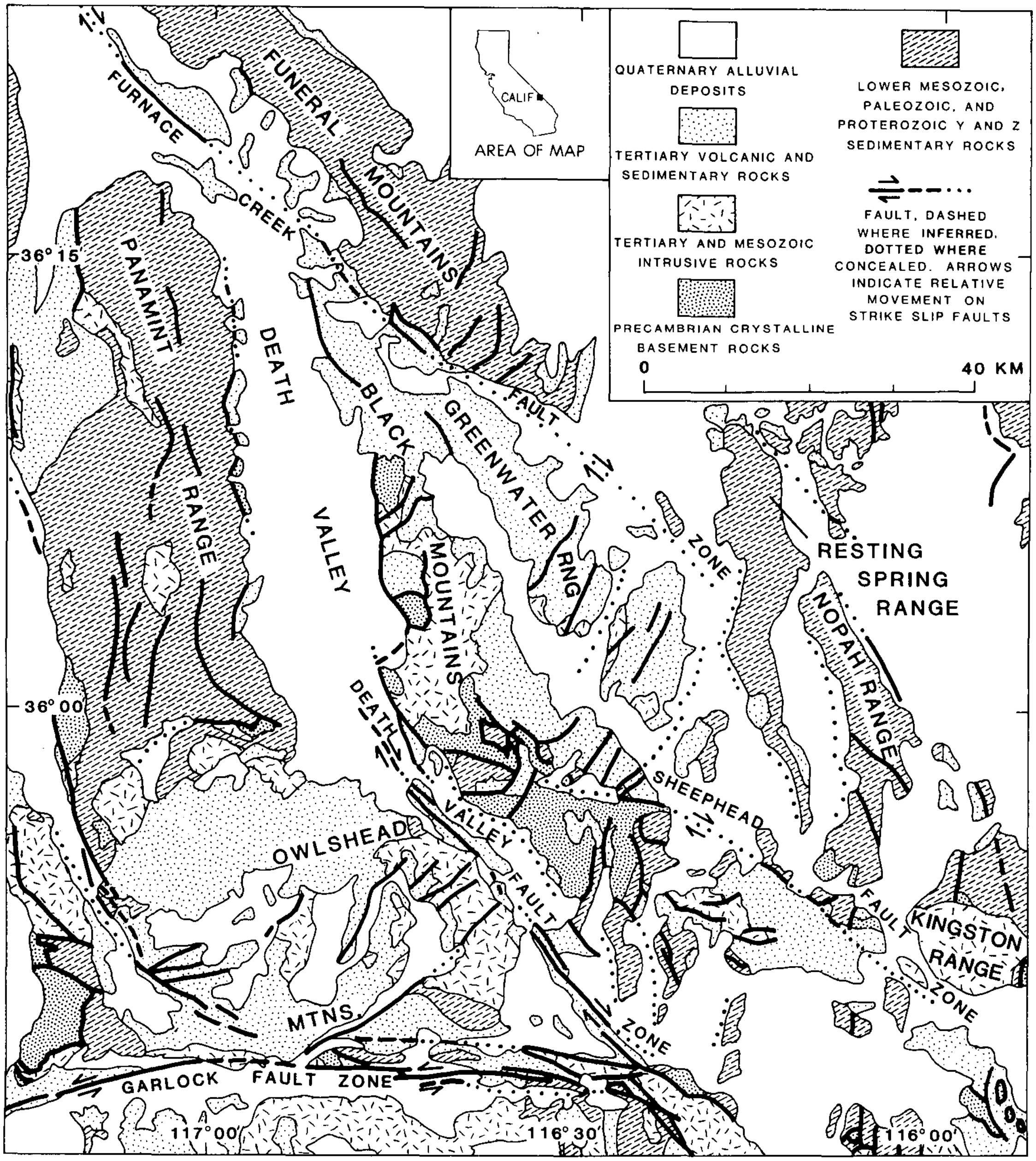

Figure 1. Generalized geologic map of Death Valley area, California. Modified from Wright and Troxel (1973).

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faulting, extensional tectonics, or both. A persistent problem with structural interpretations in the Death Valley area, however, centers around the amount of strike-slip offset on major fault zones. Several geologists (Stewart, 1967; Poole et al., 1967, 1977; Stewart et al., 1968; McKee, 1968; Pelton, 1966; Moore, 1976; Poole and Sandberg, 1977; Miller and Walch, 1977; Oakes, 1977; Cooper et al., 1982) have suggested that right-lateral offset on the Furnace Creek fault zone within and outside the Death Valley area ranges from about 40 to 100 km on the basis of apparent offsets of stratigraphic trends of upper Precambrian and Paleozoic rocks (Fig. 2). Right-lateral offset on the Death Valley fault zone, on the other hand, has been estimated as less than 8 km on the basis of apparent continuity of Precambrian stratigraphic trends across the southern Death Valley area (Wright and Troxel, 1967, 1970; Davis, 1977). The difference in apparent offset on the Furnace Creek and Death Valley fault zones has been difficult to explain in the past because the two fault systems were considered to be connected, and if this were so, the amount of offset on one should be approximately the same as on the other. I suggest here a hypothesis that seems to reconcile the two seemingly opposed views of strike-slip offset and at the same time offers an explanation for some diverse structural features observed in the Death Valley area.

HYPOTHESIS

I propose that Precambrian through Mesozoic rocks of the Panamint Range once lay adjacent to the Resting Spring and Nopah Ranges (Fig. 3), were detached from underlying Precambrian rocks of the Black Mountains, and were transported to the northwest along a single low-angle detachment fault, or perhaps a system of such faults. The amount of northwest transport, about 80 km, is based on the apparent offset of sedimentary trends along the Furnace Creek fault zone that bounds the detachment block on the northeast. Turtleback surfaces and chaotic breccia are related to shearing and brecciation near the detachment surface between the Panamint block and the underlying rocks of the Black Mountains block.

In the reconstruction (Fig. 3), the Black Mountains block is also shown as moving northwest, although the original position of the Black Mountains block and of the Greenwater Range to the east cannot be precisely fixed in the hypothesis presented here. The reconstruction follows from the idea that the main part of the Panamint Range block once lay over the main outcrops of Precambrian crystalline rocks in the Black Mountains and requires sizable extension in the area of the Greenwater Range between the Black Mountains and the Resting Spring Range. Other reconstructions are possible, however, and the Black Mountains block may have originally had a more westerly position relative to the original position of the Panamint Range.

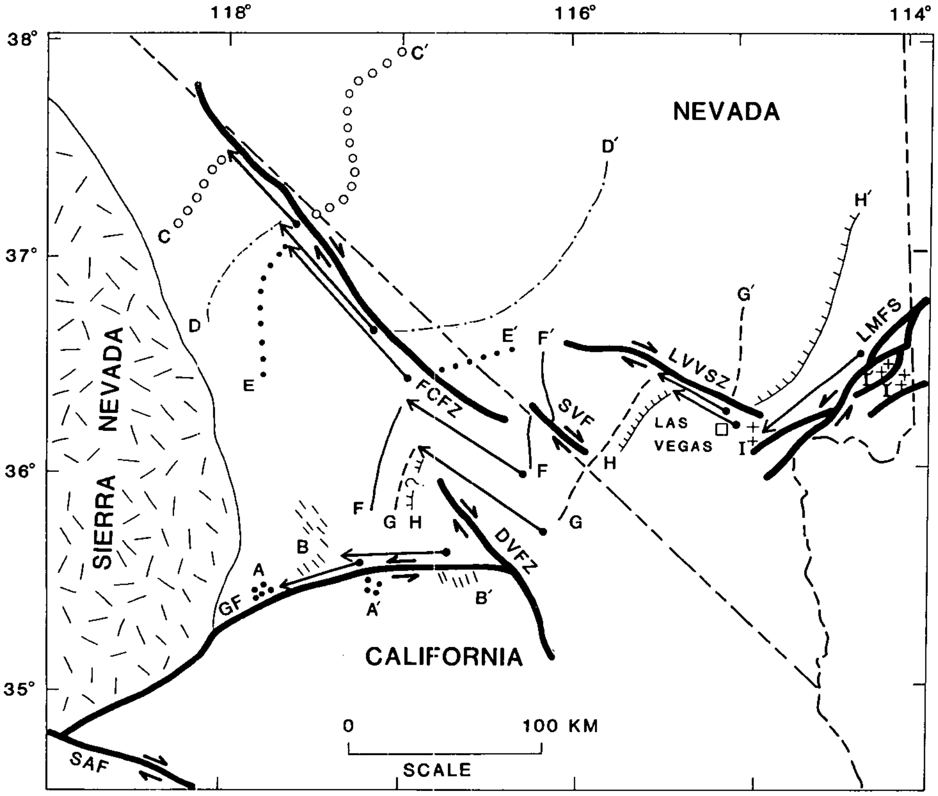

Figure 2. Major strike-slip faults in eastern California and southern Nevada, showing offset geologic trends. Dot indicates inferred original position of geologic feature relative to its position on opposite side of major strike-slip fault or detachment fault; arrow indicates direction and amount of offset. A–A', Paleozoic metasedimentary rocks (Smith and Ketner, 1970); B–B', Mesozoic dike swarms (Smith, 1962); C–C', facies boundary of Lower Cambrian Harkless Formation and Zabriskie Quartzite (Stewart, 1967); D–D', western limit of Lower Mississippian limestone unit (F. G. Poole, *in* Stewart et al., 1968); E–E', 100-m isopach for Upper Ordovician (Caradocian and Ashgillian) rocks (Miller and Walch, 1977, Fig. 14); F–F', 150-m isopach of Lower Cambrian Zabriskie Quartzite (slightly modified from Stewart, 1970, Fig. 25); G–G', 600-m isopach of Proterozoic Z Stirling Quartzite (Stewart et al., 1970); H–H', southwestern limit of Upper Mississippian (late Chester) shale unit (modifed from F. G. Poole, *in* Stewart et al., 1968); I–I', Mesozoic and Tertiary strata (Bohannon, 1979). Strike-slip faults or shear zones: SAF = San Andreas fault; GF = Garlock fault; FCFZ = Furnace Creek fault zone; DVFZ = Death Valley fault zone; SVF = Stewart Valley fault; LVVSZ = Las Vegas Valley shear zone; LMFS = Lake Mead fault system.

EVIDENCE AND DISCUSSION

Tectonic Denudation of the Black Mountains

A 10-km-thick section of Precambrian and Paleozoic strata (Hunt and Mabey, 1966; Wright et al., 1974b) is exposed in the Panamint Range, Funeral Mountains, Resting Spring Range, and Nopah Range but is largely absent in the Black Mountains (Fig. 1). The absence of this section in the Black Mountains requires either erosion on a gigantic scale or tectonic denudation. Erosion of a 10-km-thick sequence from the Black Mountains seems unlikely because appropriately thick sequences of sedimentary debris that would have been derived from such erosion have not been found. In addition, the preservation of this thick sequence in the Panamint Range and the adjacent Funeral Mountains, Resting Spring Range, and Nopah Range and its absence in directly adjoining areas are difficult to explain by erosion alone. The most likely explanation appears to be that the sedimentary sequence has been removed tectonically and now forms the Panamint Range block.

Stratigraphic Reconstruction

The reconstruction shown in Figure 3 juxtaposes rocks of similar character in the Funeral Mountains and Resting Spring, Nopah, and Panamint Ranges and reconciles different interpretations concerning right-lateral offset in the Death Valley area. As mentioned above, right-lateral offset on the Furnace Creek fault zone has been estimated as about 40 to 100 km, whereas offset on the Death Valley fault zone is estimated as less than 8 km. In Figure 3, the thickness of the Lower Cambrian Zabriskie Quartzite is shown as an example of the reconstruction of stratigraphic data. The Zabriskie is widespread in eastern California and western Nevada (Stewart, 1970) and exhibits general south to southwest thickness and facies trends similar to trends in other Paleozoic units in California and Nevada. These trends appear to be offset across the Furnace Creek fault zone. The reconstruction shown in Figure 3 juxtaposes similar thicknesses of the Zabriskie and shows a continuation of south to southwest regional trends. Reconstruction of other upper Precambrian to Mesozoic units, although not shown here, would be similar to that for the Zabriskie.

Motion in the southern Death Valley area, according to the hypothesis presented here, is largely extensional, and little if any right-lateral offset is required along the Death Valley fault zone. In the southern Death Valley area, following the reconstruction shown in Figure 3, stratigraphic units are extended and spread out to the northwest. For example, such extension may account for the present general northwest trend of the platform facies of the Noonday Dolomite (Wright and Troxel, 1970; Wright, et al., 1974b), and other Precambrian sedimentary units, although the original trend may have been more nearly northeast (Fig. 3).

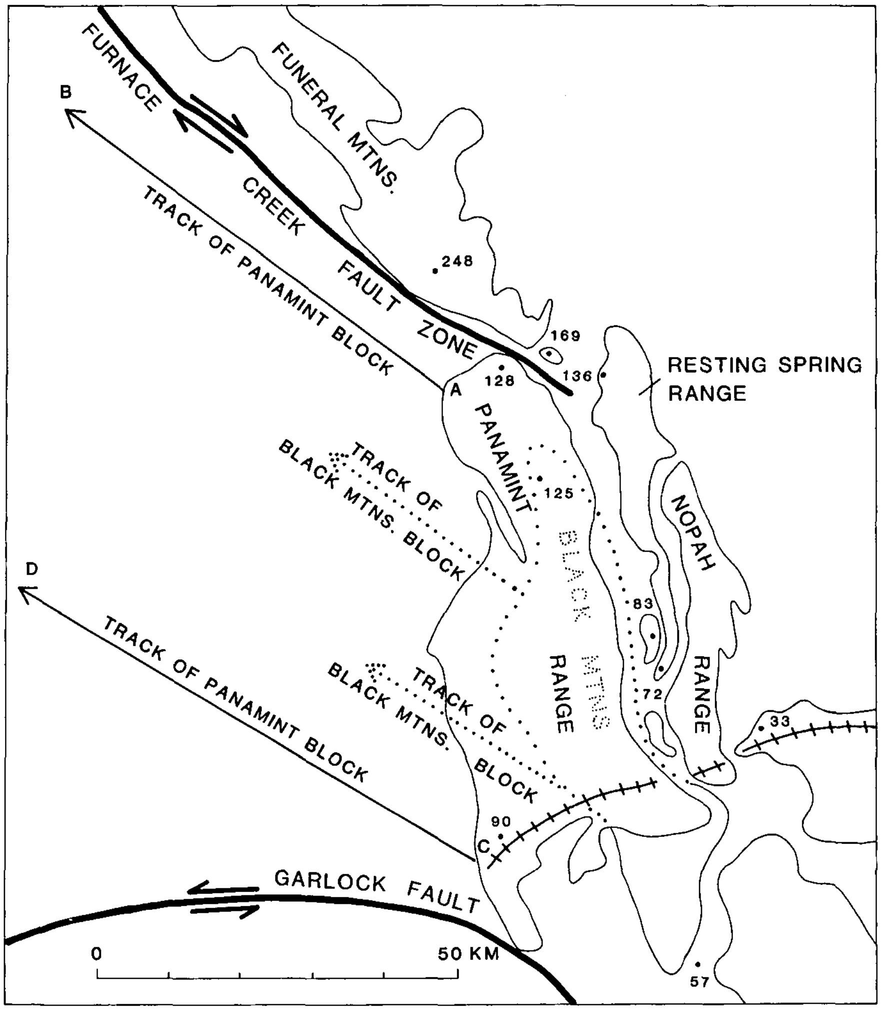

Figure 3. Reconstruction of Death Valley area prior to detachment faulting. Dotted pattern indicates prefaulting position of Black Mountains block below Panamint Range block. Numbers indicate thickness of Zabriskie Quartzite in metres. Cross-hatched line indicates trend of platform facies of Noonday Dolomite prior to detachment faulting. B and D indicate present positions of areas that were at A and C, respectively, prior to detachment faulting.

Abrupt Southeastern End of Furnace Creek Fault Zone

The Furnace Creek fault zone is part of a well-defined feature that extends for 200 km in eastern California (Fig. 2), yet it abruptly ends west of the Resting Spring Range (Fig. 1). In the reconstruction, strike-slip offset is needed to accommodate motion between the Panamint Range and Black Mountains blocks relative to the Funeral Mountains but dies out to the southeast where relative motion between the Resting Spring Range, Nopah Range, and Funeral Mountains is small.

Low-angle Detachment Faulting and the Amargosa Fault

In the hypothesis presented here, the Panamint Range block moved northwestward along a single detachment fault or a system of parallel low-angle detachment faults. The northwest movement of the Black Mountains block (Fig. 3), if it occurred, apparently was on a separate and structurally lower detachment fault. In part, at least, the detachment fault on which the Panamint Range block moved northwest is postulated as being the Amargosa thrust of Noble (1941), here called the Amargosa fault because it is considered to be a low-angle normal fault rather than a thrust fault.

Noble (1941) applied the name "Amargosa thrust" to a widespread flat fault of middle or later Tertiary age extending throughout a large area near and east of southern Death Valley. He indicated that the upper allochthonous plate moved westward and applied the name "Amargosa chaos" to a complex mosaic of blocks and slices of upper Precambrian, Paleozoic, and Tertiary rocks lying on the fault surface. Hunt and Mabey (1966) proposed that the "Amargosa thrust" extended into the Panamint Range. They noted that this "thrust" was curious because younger rocks were moved over older ones and concluded that the "thrust" is really a normal fault (Hunt and Mabey, 1966, p. A99). They also recognized the westward movement of the Panamint Range structural block on the fault and the exposure of autochthonous rocks in the Black Mountains (Hunt and Mabey, 1966, Fig. 108). Thus, Hunt and Mabey first recognized many of the structural elements used here in developing the hypothesis that the Panamint Range was detached from the Black Mountains and transported northwestward.

Wright and Troxel (1969, 1973) also recognized that many of the features related by Nobel (1941) to thrusting are actually caused by normal faulting. They proposed that the Amargosa chaos is a product of drag on the underside of blocks rotated along master listric (downward-flattening) normal faults. They recognized a system of westward-dipping low-angle faults in the southern Death Valley area that they interpreted as indicating 30% to 50% extension of the original width of the southern Death Valley area. Perhaps the most dramatic difference between Wright and Troxel's ideas and those of Noble (1941) and Hunt and Mabey (1966) is their interpretation that a single widespread low-angle fault comparable to Noble's "Amargosa thrust" does *not* exist in the southern Death Valley area.

The hypothesis presented here fits with the concept of Noble (1941) and Hunt and Mabey (1966) that a major low-angle detachment fault (the so-called Amargosa thrust) extends throughout a large part of the Death Valley area. The Panamint Range block moved northwestward on this surface. This hypothesis is not necessarily incompatible with the multiple low-angle faults recognized by Wright and Troxel (1969, 1973), because such faults could merge downward into a single master detachment fault in a manner similar to the "domino style" of faulting proposed by Wernicke (1981) for rooted low-angle normal faults (Fig. 4).

As envisioned here, the detachment surface includes the "Amargosa thrust" mapped by Hunt and Mabey (1966) low on the east side of the Panamint Range where latest upper Proterozoic sedimentary rocks in the upper plate are in fault contact with middle and upper Proterozoic crystalline basement rocks in the lower plate. On the west side of the Panamint Range, lower and middle Proterozoic crystalline basement rocks lie unconformably below upper Proterozoic and Cambrian sedimentary rocks, unbroken by major detachment faults (Albee et al., 1981). These relations suggest that the detachment fault along which the Panamint Range moved northwestward dips beneath the range and cuts downward through lower and middle Proterozoic crystalline basement rocks. This fault may be the upper part of a crustal scale fault, similar to the type described by Wernicke (1981), that cuts downward to the northwest and is rooted deep in the crust or in the upper mantle.

Turtleback Surfaces

Turtleback surfaces are little-eroded domical fault surfaces that were first recognized and described in the Death Valley area (Currey, 1938). Three such surfaces along the west side of the Black Mountains structural block extend elongated for 5 to 8 km in the northwest direction, are 2 to 5 km wide, and have a relief of about 800 to 1,500 m. Wright et al. (1974a) considered the turtleback surfaces to be colossal fault mullions. The surfaces contain striations, slickensides, and extension fractures with orientations compatible with northwest extension. This extension is consistent with the movement direction of the Panamint Range block proposed here. The turtleback surfaces are here considered to represent a part of the detachment fault upon which the Panamint Range moved northwestward.

TIME OF MOVEMENT

Latest movement on detachment faults in the Death Valley area has clearly occurred in late Cenozoic time because upper Tertiary volcanic rocks are incorporated in the Amargosa chaos above the Amargosa fault in the southern Death Valley area (Noble, 1941). These volcanic rocks are believed to be correlative with 6- to 8-m.y.-old (Fleck, 1970) rocks in the Black Mountains assigned to the Artist Drive Formation and the partly equivalent "older volcanics" of Drewes (1963). In part, however, detachment faulting may be contemporaneous with late Cenozoic volcanism and sedimentation. Wright et al. (1974a), for example, have suggested that the turtleback surfaces were developed in part contemporaneously with deposition of the upper Cenozoic rocks in the Black Mountains. In addition, upper Cenozoic sedimentary rocks, locally more than 3,000 m thick (Drewes, 1963) in the Black Mountains, are interpreted here to have been deposited in basins resulting from the void produced when the Panamint Range block moved out of the Black Mountains area. Wright and Troxel (1971), furthermore, suggested that the depositional basin of the volcanic rocks in the Black Mountains and the adjacent Greenwater Range was tectonically controlled in an extensional area between the Furnace Creek fault zone and the Sheephead fault zone (Fig. 1). In the Black Mountains, the main tectonic denudation conceivably occurred before, or perhaps in part during, depositon of the Artist Drive Formation and the "older volcanics" of Drewes (1963). These rocks are considered by Drewes (1963) to have been deposited locally on Precambrian crystalline basement rocks, although the contact of the volcanic rocks with adjacent rocks is now largely a fault, and the normally intervening thick Precambrian and Paleozoic sedimentary sequence occurs as only local thin remnants. These relations permit the interpretation that the Precambrian and Paleozoic sequence was largely removed, presumably by the tectonic denudation proposed here, from the Black Mountains before deposition of the Artist Drive Formation or the "older volcanics" of Drewes (1963).

REGIONAL RELATIONS

The detachment and northwest movement of the Panamint Range block as described above is considered to occur on a northwest-dipping low-angle fault that may be rooted deep in the crust or extend through the crust—a rooted normal fault (Wernicke, 1981). If so, the region west of the Panamint Range also moved westward at the same time as the Panamint block. This interpretation explains the sizable right-lateral offset (Fig. 1) along the Furnace Creek fault zone outside, as well as within, the Death Valley area. In such a scheme, the Garlock fault, which has been described by Davis and Burchfiel (1973) as an intracontinental transform that accommodates greater extension to the north than to the south, can be viewed as the southern boundary of the region of relatively great extension. If the movement on the Garlock and Furnace Creek faults has been synchronous, then the triangular area (Fig. 2) between them must have undergone a major component of lateral extension at right angles to the dominant extension in order to fill in the space between the two diverging faults as the intervening area moved northwestward. The fragmentation of the Death Valley area into major 5- to 25-km wide basin-

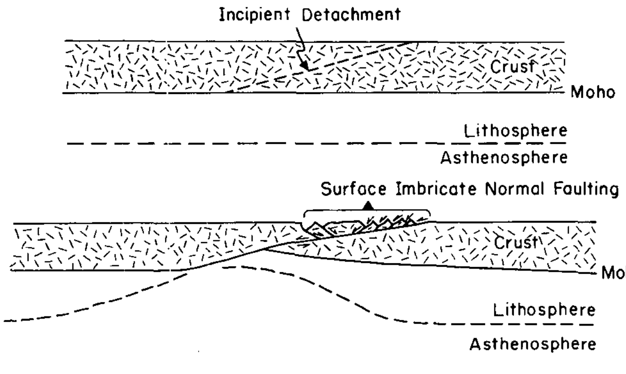

Figure 4. Model of rooted low-angle normal fault from Wernicke (1981).

range blocks, including the deep graben or half-graben of Death Valley itself, is considered to be younger than the detachment faulting, because the detachment surfaces (including the Amargosa fault) are cut by high-angle faults that bound the major blocks (Drewes, 1963; Hunt and Mabey, 1966, p. 100). A late phase of right-lateral movement is also possible to account for the development of the right-lateral Death Valley fault zone and the graben or half-graben of Death Valley that may be a "pull apart" structure resulting from right-lateral displacement (Burchfiel and Stewart, 1966).

REFERENCES CITED

Albee, A. L., Labotka, T. C., Lanphere, M. A., and McDowell, S. D., 1981, Geologic map of the Telescope Peak quadrangle, California: U.S. Geological Survey Geologic Quadrangle Map GQ-1532, scale 1:62,500.

Bohannon, R. G., 1979, Strike-slip faults of the Lake Mead region of southern Nevada, *in* Armentrout, J. M., Cole, M. R., and TerBest, Harry, Jr., eds., Cenozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 3, p. 129–139.

Burchfiel, B. C., and Stewart, J. H., 1966, "Pull-apart" origin of the central segment of the Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439–442.

Cooper, J. D., Miller, R. H., and Sundberg, F. A., 1982, Environmental stratigraphy of the lower part of the Nopah Formation (Upper Cambrian), southwestern Great Basin, *in* Cooper, J. D., Troxel, B. W., and Wright, L. A., eds., Geology of selected areas in the San Bernardino Mountains, western Mojave Desert, and southern Great Basin, California, Field trip number 9: Geological Society of America, Cordilleran Section Guidebook, p. 97–114.

Currey, H. D., 1938, "Turtleback" fault surfaces in Death Valley, California [abs.]: Geological Society of America Bulletin, v. 49, p. 1875.

Davis, G. A., 1977, Limitations on displacement and southeastward extent of the Death Valley fault zone, California, *in* Short contributions to California geology: California Division of Mines and Geology Special Report 129, p. 27–33.

Davis, G. A., and Burchfiel, B. C., 1973, Garlock fault: An intracontinental transform structure, southern California: Geological Society of America Bulletin, v. 84, p. 1407–1422.

Drewes, Harald, 1963, Geology of the Funeral Peak quadrangle, California, on the east flank of Death Valley: U.S. Geological Survey Professional Paper 413, 78 p.

Fleck, R. J., 1970, Age and tectonic significance of volcanic rocks, Death Valley area, California: Geological Society of America Bulletin, v. 81, p. 2807–2816.

Hunt, C. B., and Mabey, D. R., 1966, Stratigraphy and structure, Death Valley, California: U.S. Geological Survey Professional Paper 494-A, 162 p.

McKee, E. H., 1968, Age and rate of movement of the northern part of the Death Valley–Furnace Creek fault zone, California: Geological Society of America Bulletin, v. 29, p. 509–512.

Miller, R. H., and Walch, C. A., 1977, Depositional environments of Upper Ordovician through Lower Devonian rocks in the southern Great Basin, *in* Stewart, J. H., Stevens, C. H., and Fritsche, A. E., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 165–180.

Moore, J. N., 1976, Depositional environments of the lower Cambrian Poleta Formation and its stratigraphic equivalents, California and Nevada: Brigham Young University, Geologic Studies, v. 23, pt. 2, p. 23–28.

Noble, L. F., 1941, Structural features of the Virgin Spring area, Death Valley, California: Geological Society of America Bulletin, v. 52, p. 941–1000.

Oakes, E. H., 1977, Geology of the northern Grapevine Mountains, northern Death Valley, California: Laramie, University of Wyoming, 107 p.

Pelton, P. J., 1966, Mississippian rocks of the southwestern Great Basin, Nevada and California [Ph.D. thesis]: Houston, Texas, Rice University, 99 p.

Poole, F. G., and Sandberg, C. A., 1977, Mississippian paleogeography and tectonics of the western United States, *in* Stewart, J. H., Stevens, C. H., and Fritsche, A. E., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 67–85.

Poole, F. G., Baars, D. L., Drewes, Harald, Hayes, P. T., Ketner, K. B., McKee, E. D., Teichert, Curt, and Williams, J. S., 1967, Devonian of the southwestern United States, *in* Oswald, D. H., ed., International Symposium on the Devonian System, Volume 1: Calgary, Alberta Society of Petroleum Geologists, p. 879–912.

Poole, F. G., Sandberg, C. A., and Boucot, A. J., 1977, Silurian and Devonian paleogeography of the western United States, *in* Stewart, J. H., Stevens, C. H., and Fritsche, A. E., eds., Paleozoic paleogeography of the western United States: Society of Economic paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 39–65.

Smith, G. I., 1962, Large lateral displacement on Garlock fault, California, as measured from offset dike swarms: American Association of Petroleum Geologists Bulletin, v. 46, p. 85–104.

Smith, G. I., and Ketner, K. B., 1970, Lateral displacement on the Garlock fault, southeastern California, suggested by offset sections of similar metasedimentary rocks: U.S. Geological Survey Professional Paper 700-D, p. D1–D9.

Stewart, J. H., 1967, Possible large right-lateral displacement along fault and shear zones in the Death Valley–Las Vegas area, California and Nevada: Geological Society of America Bulletin, v. 78, p. 131–142.

——1970, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U.S. Geological Survey Professional paper 620, 206 p.

Stewart, J. H., Albers, J. P., and Poole, F. G., 1968, Summary of regional evidence for right-lateral displacement in the western Great Basin: Geological Society of America Bulletin, v. 79, p. 1407–1413.

——1970, Reply *to* Discussion *on* Summary of regional evidence for right-lateral displacement in western Great Basin: Geological Society of America Bulletin, v. 81, p. 2175–2180.

Wernicke, Brian, 1981, Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645–648.

Wright, L. A., and Troxel, B. W., 1967, Limitations on right-lateral, strike-slip displacement, Death Valley and Furnace Creek fault zones, California: Geological Society of America Bulletin, v. 78, p. 933–949.

——1969, Chaos structure and basin and range normal faults: Evidence for a genetic relationship: Geological Society of America Abstracts with Programs Pt. 7, p. 242.

——1970, Discussion *on* Summary of regional evidence for right-lateral displacement in the western Great Basin: Geological Society of America Bulletin, v. 81, p. 2167–2174.

——1971, Evidence for tectonic control of volcanism, Death Valley: Geological Society of America Abstracts with Programs, v. 3, p. 221.

——1973, Shallow-fault interpretation of basin and range structure, *in* DeJong, K. A., and Scholten, Robert, eds., Gravity and tectonics: New York, John Wiley & Sons, p. 397–407.

Wright, L. A., Otton, J. K., and Troxel, B. W., 1974a, Turtleback surfaces of Death Valley viewed as phenomena of extensional tectonics: Geology, v. 2, p. 53–54.

Wright, L. A., Troxel, B. W., Williams, E. G., Roberts, M. T., and Diehl, P. E., 1974b, Precambrian sedimentary environments of the Death Valley region, eastern California, *in* Death Valley region, California and Nevada, Field trip no. 1: Geological Society of America, Cordilleran Section Guidebook, p. 27–35.

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Reviewer's comment

An imaginative hypothesis to explain widely disparate interpretations in a well-known region.

M. L. Zoback

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