Late Cenozoic history and styles of deformation along the southern Death Valley fault zone, California

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ABSTRACT

Late Cenozoic deposits in the southern Death Valley region have been offset ~35 km by right-lateral, strike-slip faulting on the southern Death Valley fault zone since Miocene time. Virtually all slip took place prior to ~1 m.y. ago along western traces of the fault zone. During the past 1 m.y., the eastern traces of the fault zone have been active and characterized by oblique slip, with a lateral component of only a few hundred metres. Movement along these eastern traces has formed normal faults and gentle-to-isoclinal folds that have uplifted fan gravel and lacustrine sediments as much as 200 m above the modern alluvial fan surface. Surveying of the longitudinal profile of the Amargosa River, which flows within the eastern traces of the fault zone, suggests that vertical deformation continues today.

The 35 km of right-lateral offset, which is based on matching offset alluvial fan gravel with its source area, refines earlier estimates of 8 to 80 km of movement for the southern Death Valley fault zone, and it is consistent with the geometry of a pull-apart basin model for central Death Valley. Causes for the observed differences in the style and timing of movement of the eastern and western subzones are not well understood. The study area, however, is located a few kilometres north of the intersection of the southern Death Valley and Garlock fault zones. The Garlock fault zone changes its sense of movement from left-lateral strike-slip to east-vergent thrusting against the southern Death Valley fault zone. The resulting compression may have caused the shift in activity and the change in style of deformation along branches of the southern Death Valley fault zone.

INTRODUCTION

The southern Death Valley fault zone is part of a northwest-trending, right-lateral, strike-slip system of faults located in southern Death Valley. Near its southern end, the fault zone intersects the east-trending, left-lateral Garlock fault zone. Both fault zones have been active in late Quaternary time (Davis and Burchfiel, 1973; and this report).

The southern Death Valley fault zone, along with the Northern Death Valley–Furnace Creek fault zone, appears to be related to extension within the southern Basin and Range province (Stewart, 1983). Burchfiel and Stewart (1966) and Wright and others (1974) suggested that movement along these faults produced a "pull-apart basin" in central Death Valley.

The present study was undertaken to determine the amount, age, and style of displacement along a part of the southern Death Valley fault zone just a few kilometres north of its intersection with the Garlock fault zone. The determination of the age and amount of displacement provide information on the relationship of the southern Death Valley fault zone to the formation of the pull-apart basin in central Death Valley and provide constraints on models for the intersection of this fault zone with the Garlock fault zone. In addition, new insights are gained into the varying styles of deformation that may be associated with strike-slip faults.

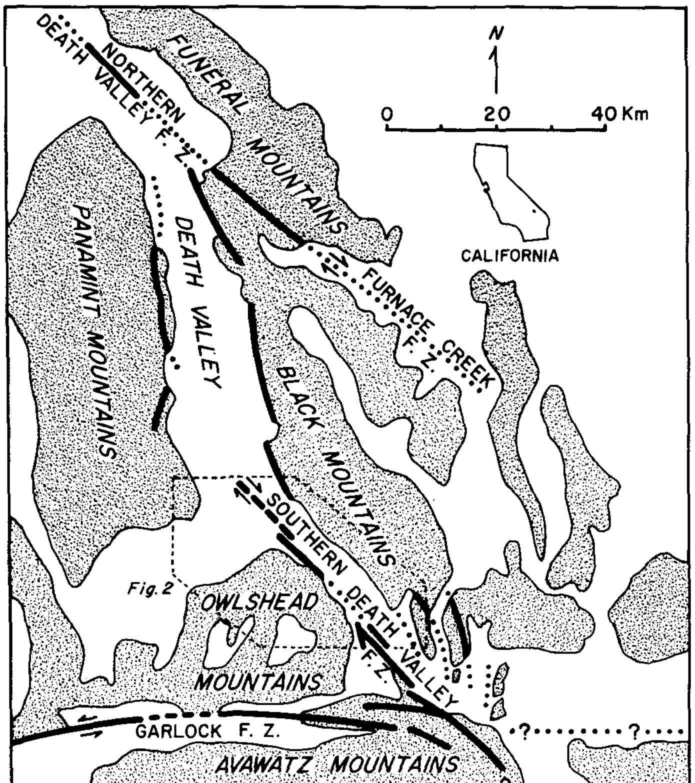

Figure 1. Generalized map of the Death Valley region showing zones of the Death Valley fault system and their relationship to the Garlock fault zone (modified from Wright and Troxel, 1973).

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GENERAL BACKGROUND

The investigation was conducted in southern Death Valley (Fig. 1), where an area of ~200 km^2 was mapped at a scale of 1:24,000 (Butler, 1984a). Previous maps had been published at a scale of 1:250,000 (Noble and Wright, 1954; Jennings and others, 1962). The study area is situated between the Owlshead Mountains and the southern Black Mountains (Fig. 2). The Owlshead Mountains are composed primarily of Cretaceous granitic rocks (Gastil and others, 1967) and Miocene volcanic rocks (Davis and Fleck, 1977; and this report). The southern Black Mountains are composed primarily of Precambrian gneiss and late Precambrian sedimentary rocks (Jennings and others, 1962).

The topography of the field area is characterized mainly by broad alluvial fans that extend into the valley from the Owlshead and Black Mountains (Fig. 2). The fan surfaces are commonly interrupted by small hills formed of older fan gravel and lake sediments uplifted along branches of the southern Death Valley fault zone. The most conspicuous of these hills are the Confidence Hills which rise as much as 200 m above the valley floor at the north end of the mapped area.

STRUCTURAL HISTORY OF THE SOUTHERN DEATH VALLEY FAULT ZONE

Previous Studies

Considerable controversy exists concerning the amount of strike-slip movement in the southern Death Valley region. Estimates range from no more than 8 km (Wright and Troxel, 1967) to 80 km (Stewart, 1967). The displacement proposed by Stewart was based on offset isopach trends of late Precambrian and Paleozoic sedimentary rocks across the northern

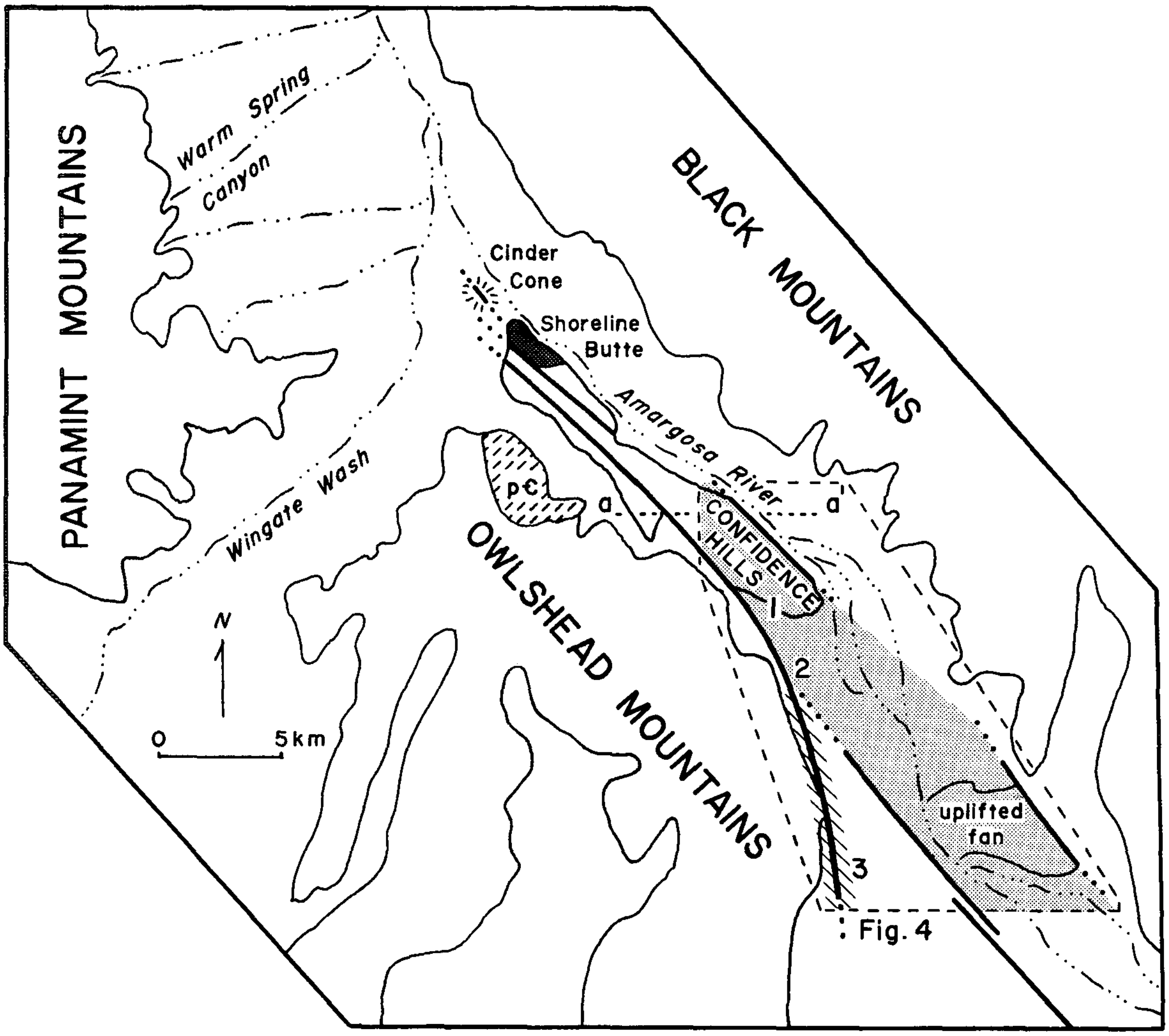

Figure 2. Location map for southern Death Valley, showing the eastern and western subzones of the southern Death Valley fault zone and the position of the field area (Fig. 4) with respect to the Owlshead Mountains, Black Mountains, and Amargosa River. Numbers 1–3 identify locations discussed in the text. The eastern subzone (dot pattern) and the western subzone (diagonal line pattern) are shown only within the study area. Location of Precambrian rocks is shown only within the Owlshead Mountains. Line a–a′ delineates the southern limit for the Precambrian clasts in the Confidence Hills, that were derived from the Owlshead Mountains.

Death Valley fault zone. The inference of smaller displacement by Wright and Troxel was made on the northern part of the southern Death Valley fault zone utilizing the trends of formation contacts and isopach data.

To resolve the controversy, Stewart (1983) suggested that the disagreement arose from the assumptions that the two fault zones were connected and that offsets should be approximately equal for both. He proposed that the two fault zones are related but not connected; movement along the Northern Death Valley–Furnace Creek fault zone began prior to the motion along the southern Death Valley fault zone. Initiation of movement along the southern Death Valley fault zone and continued movement along the Northern Death Valley–Furnace Creek fault zone produced the pull-apart basin in central Death Valley (Fig. 3). Although Stewart's model clarifies the relationship between the two fault zones, questions still remain concerning the amount of offset along the southern Death Valley fault zone. For example, the isopach data of late Precambrian strata that Wright and Troxel (1966, 1967) used to show that the maximum displacement along the southern Death Valley fault zone was no more than 8 km, were recontoured by Hamilton and Myers (1966) to indicate 50 km of right-lateral displacement. This study provides evidence for ~35 km of right-lateral displacement by matching clasts in alluvial fan gravels with their source area.

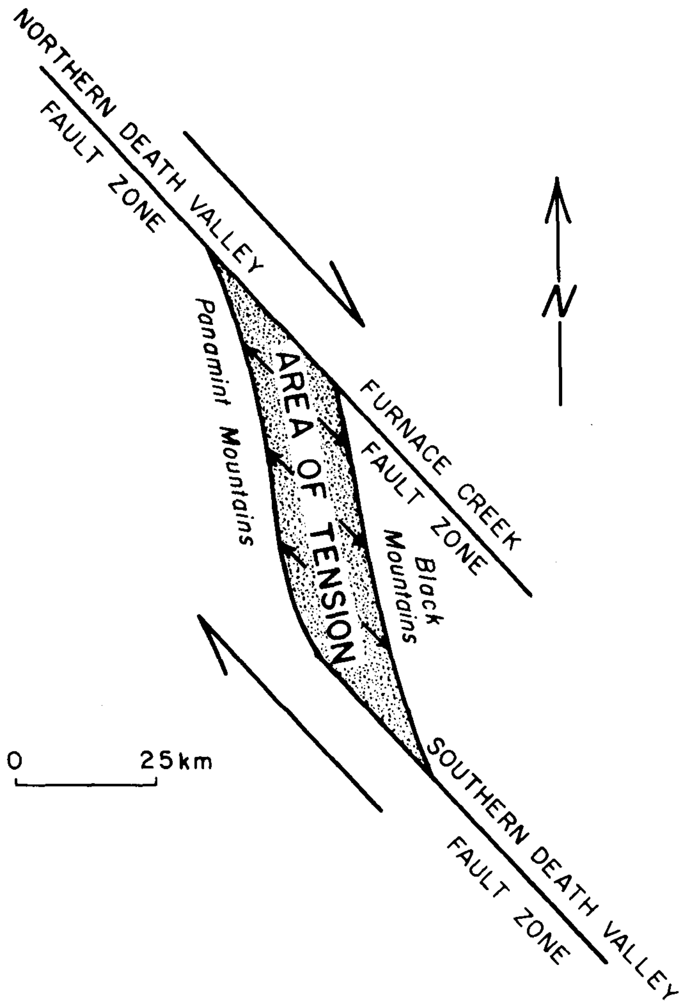

Figure 3. A model for the "pull-apart" basin in central Death Valley (after Burchfiel and Stewart, 1966).

FIGURE 4 EXPLANATION

- Q — Active wash and alluvial fan deposits
- Qf_2 — Old alluvial fan gravels
- Qf_1 — Older alluvial fan gravels
- QTf — Oldest alluvial fan gravels
- QPl — Late Plio- to early Pleistocene lake deposits
- QTls — Late Cenozoic landslide deposits
- Mv — Miocene basalt and andesite
- gr — Cretaceous granitic rocks
- p€ — Undivided Precambrian rocks

SYMBOLS

- Fault trace, dashed where approximate, dotted where concealed
- Axial trace of syncline showing direction of plunge
- Axial trace of anticline showing direction of plunge

Present Study

The southern Death Valley fault zone is herein subdivided into western and eastern subzones for the convenience of discussion (Fig. 2). The western subzone lies along the eastern flank of the Owlshead Mountains (south of point 2, Fig. 4), whereas the eastern subzone is located in the floor of southern Death Valley (Figs. 2 and 4). The two subzones merge near the intersection of the southern Death Valley and Owl Lake fault zones and are coincident to the north (Figs. 2 and 4). North of where the two subzones merge, the southern Death Valley fault zone is considered part of the eastern subzone because the age and style of the most recent deformation is essentially the same as that for the eastern subzone farther south within the mapped area (Fig. 4).

The general trend of the western subzone ranges from due north to N30°W (south of point 2; Fig. 4); the eastern subzone trends approximately N40°W to N50°W (Fig. 2). Although there is some topographic relief along the eastern subzone, fault surfaces in the eastern subzone are not well exposed, as they are located in the floor of the valley. Their straight traces, however, suggest vertical or near-vertical fault planes. At six sites along the western subzone, where there is significant topographic relief (between points 2 and 3, Fig. 4), segments of the fault planes are exposed in deeply incised washes. The strikes vary from N60°W to N15°E, and the dips vary from 35° to 65° to the east or northeast, which implies either that fault planes in the western subzone were not initially vertical or that they have been deformed by motion on the eastern subzone.

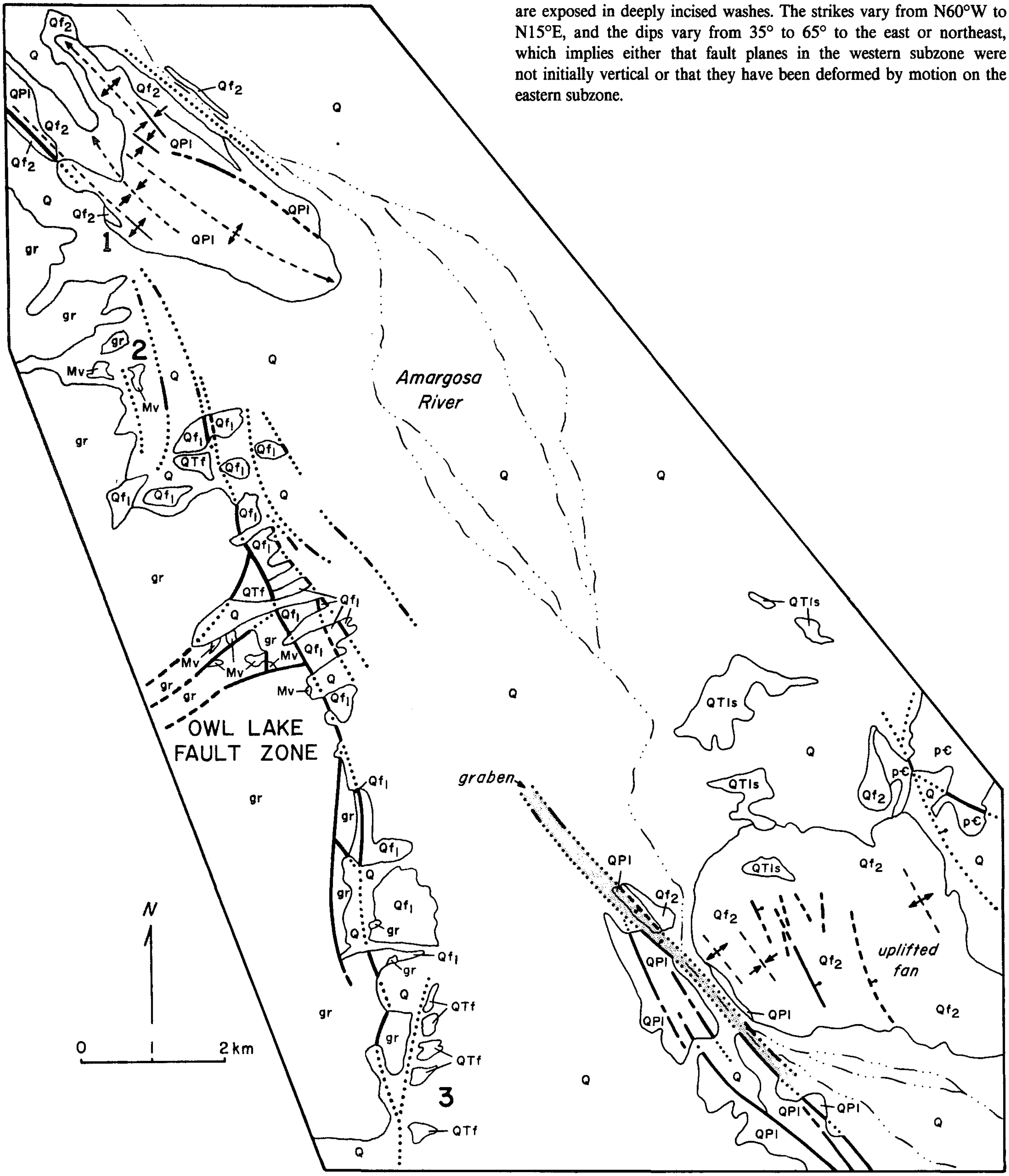

Figure 4. Generalized geologic map of the study area. Graben adjacent to the uplifted alluvial fan identified by dot pattern. Bar and ball symbol shows downthrown side of selected normal faults. Numbers 1-3 correspond to the same reference points as those in Figure 2.

Western Subzone

Evidence for ~35 km of right-lateral displacement along the western subzone of the southern Death Valley fault zone is based on matching remnants of alluvial fan gravel with its source area to the northwest. The fan remnants (QTf, point 3, Fig. 4) contain a mixture of plutonic, metamorphic, volcanic, and sedimentary clasts. Correlation is made on clasts of quartzite of the late Precambrian Crystal Spring Formation, sparse-pebble conglomerate of the late Precambrian Kingston Peak Formation, and Paleozoic carbonate rock containing macrofossils such as crinoids. Of these, only the Crystal Spring Formation occurs in the adjacent Owlshead Mountains. The closest source of the Kingston Peak Formation and of the Paleozoic carbonate rock is Warm Spring Canyon in the southeastern part of the Panamint Mountains (Fig. 2), where the Crystal Spring Formation is also exposed. Reconnaissance mapping south of the field area confirms that the fan remnants found at point 3 (Fig. 4) are the southernmost occurrences of gravel that were probably derived from the southern Panamint Mountains. Because it is uncertain where the fault truncated the ancestral Warm Spring Canyon fan, the distance from the present mouth of Warm Spring Canyon to its southernmost alluvial deposits is an approximation. The distance across the toe of a modern alluvial fan in Death Valley can be as much as 10 km. Because the ancestral Warm Spring Canyon fan could have been truncated near its toe, rather than at its apex, the uncertainty in the offset is on the order of ±5 km. Other fan remnants (QTf) containing the same diagnostic clast types are exposed along the western subzone as far north as point 2 near the southern end of the Confidence Hills (Figs. 2 and 4).

Transport of the gravel from the vicinity of Warm Spring Canyon to its present position along the eastern flank of the Owlshead Mountains solely by sedimentary processes (e.g., fluvial transport or mud flows) is ruled out for the following reasons. First, the deposits near point 3 (Fig. 4) consist of angular, interbedded water-laid and debris-flow deposits, which are characteristic of alluvial fans (Bull, 1977). Second, if this gravel were deposited by a stream flowing south in Death Valley, it would also contain clasts derived from the east side of Death Valley. It does not.

Although the age of the fan described above has not been determined, all of the lateral displacement along the western subzone probably took place between approximately mid-Miocene time and 1 m.y. B.P. The older limit is based on two K-Ar age determinations on volcanic rocks (R. E. Drake, 1982, written commun.) and the assumption that the onset of faulting was approximately coeval with the onset of volcanism. One sample used for radiometric dating was collected adjacent to the southern Death Valley fault zone and yielded an age of 10.66 ± 0.28 m.y. (unit Mv near point 2, Fig. 4). The other was collected adjacent to the Owl Lake fault zone very near its intersection with the southern Death Valley fault zone and yielded an age of 12.66 ± 1.04 m.y. Although the assumption that volcanism and the initiation of faulting are coeval may lead to some error in establishing a maximum age for the initiation of faulting along the western subzone, the Miocene age is consistent with age determinations made by other investigators concerning the onset of Basin and Range extension in this region (Wright, 1976; Wright and Troxel, 1971; Wright and others, 1974, 1984; Stewart, 1983). In addition, a similar relationship between volcanism and faulting was noted by E. I. Smith (1982) for the left-lateral Lake Mead fault zone in the Basin and Range province of southern Nevada, where the initiation of strike-slip movement was coeval with the onset of Miocene volcanism.

Movement along the western subzone of the southern Death Valley fault zone appears to have ceased before deposition of the Qf_2 alluvial-fan

Figure 5. View south across the southern Confidence Hills, showing uplifted lacustrine sediments.

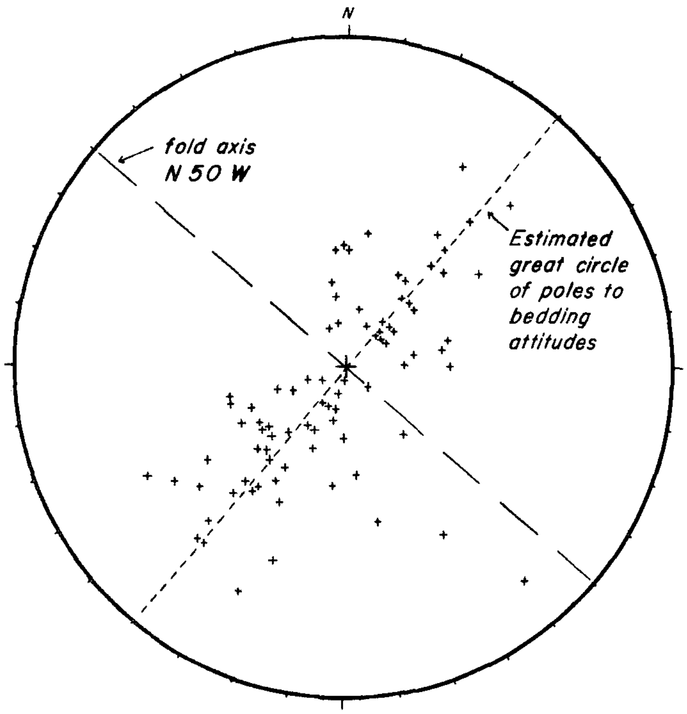

Figure 6. Orientation of poles to bedding in the southern Confidence Hills, plotted on a meridional stereographic lower-hemisphere projection. The indicated fold axis is parallel to traces of the eastern subzone of the southern Death Valley fault zone.

gravel that now lies along the crest of the Confidence Hills (Fig. 4). Because this gravel contains no Precambrian sedimentary detritus south of line a–a′ (Fig. 2), its source must have been rocks lying directly west of its present exposures and therefore directly to the west of the Confidence Hills. A tephra layer just below the fan gravel has a rather imprecise K-Ar age of 0.62 ± 0.52 m.y. (R. E. Drake, 1983, written commun.; located near point 1, Figs. 2 and 4). The ash is magnetically reversed, however, and therefore it must be older than 0.73 m.y. Furthermore, because the time period of 0.90 to 0.97 m.y. was magnetically normal (Mankinen and Dalrymple, 1979), the most probable age for the ash layer is 0.73 to 0.90 m.y. or 0.97 to 1.14 m.y. Little if any lateral displacement could therefore have taken place along the western subzone after ~1 m.y.

Eastern Subzone

The eastern subzone has both lateral and vertical components of movement. Evidence for the movement can be seen in deformed volcanic rocks that have been extruded along the eastern subzone in two areas just north of the field area. The lava flows of Shoreline Butte (Fig. 2), which have a radiometric age of 1.5 m.y., have been uplifted and tilted by movement along the eastern subzone (Wright and Troxel, 1984). About 2 km north of Shoreline Butte, there is a small cinder cone that is cut by two faults with total right-lateral offset on the order of a few hundred metres. The cone has yielded a K-Ar age of 0.69 Ma (Wright and Troxel, 1984). This "split cinder cone" provides clear evidence for the amount and direction of lateral offset along the eastern subzone.

For the purpose of discussion, it is convenient to subdivide the eastern subzone into (1) a northern region adjacent to the Confidence Hills and (2) a southern region adjacent to a large, uplifted alluvial fan (labeled "uplifted fan," Figs. 2 and 4). Both regions of the eastern subzone are characterized by a sequence of lacustrine sediments overlain by alluvial fan gravels. At both locations, the gravel and fan units are folded and faulted, but the lacustrine deposits are locally more deformed than are the overlying fan gravels. This indicates that deformation within the basin started before the encroachment of the alluvial fans. As discussed below, both the northern and southern regions are assumed to have been part of the same lake basin, based primarily on their stratigraphic relationships and on their magnetic polarity stratigraphy.

Confidence Hills. The Confidence Hills, excluding Shoreline Butte, are composed of alluvial fan gravel (Qf_2) which overlies lake sediments (QPl, Fig. 4). The lacustrine deposits are characterized by silt and clay layers and evaporites. The 0.62 ± 0.52–m.y.-old volcanic-ash layer lies just below the base of the gravel. The magnetically reversed ash is clearly not associated with the volcanism at Shoreline Butte or the "split cinder cone." Shoreline Butte is basaltic, whereas the "split cinder cone" is andesite (Wright and Troxel, 1984). In contrast, the ash contains abundant biotite, and the calcium to iron ratios of its glass shards are similar to those of rhyolitic ashes erupted from the Long Valley area near Bishop, California, ~200 km to the northwest of the field area (Izett, 1981; Sarna-Wojcicki and others, 1984).

The Confidence Hills sediments are compressed and folded parallel to the faults of the eastern subzone (Figs. 4 and 5). The movement has uplifted the fan gravel and lacustrine sediments as much as 200 m above the modern alluvial fan surface. The shapes of the folds range from gentle to isoclinal, with vertical or near-vertical axial surfaces. Poles to bedding attitudes (87) measured on traverses across the Confidence Hills, were plotted on a meridional stereographic net (Fig. 6). The fold axis of N50°W determined from this plot is in agreement with the fold axes mapped in the field and is parallel to the general trace of the eastern subzone. Although the field evidence indicates that the major fold axes have been slightly folded and plunge slightly (Fig. 4), most of the bedding attitudes used in Figure 6 were taken from a well-exposed area where the folds were open, cylindrical, and not plunging.

Most of the faulting that deformed the strata in the Confidence Hills occurred after the volcanism that produced Shoreline Butte, because similar deformation affects both Shoreline Butte and the Confidence Hills (Wright and Troxel, 1984). As indicated above, the clast content of the gravel in the Confidence Hills suggests that during the deformation there was *no significant* lateral offset along the fault zone between the Owlshead Mountains and the Confidence Hills.

Another line of evidence that suggests that little or no lateral offset has occurred across the eastern subzone is the pattern of streams that drain the northeastern Owlshead Mountains. Antecedent streams flow across the central Confidence Hills and enter the Amargosa River (Fig. 7). As the easternmost trace of the subzone is approximately coincident with the Amargosa River (Fig. 4), the drainage pattern of the antecedent tributaries should record lateral slip on any fault west of the Amargosa River. In fact, the streams are deflected no more than a few hundred metres where they cross the faults. At the southern end of the Confidence Hills, however, the streams draining the Owlshead Mountains are deflected southward and do not cross the Confidence Hills (Fig. 7). It could be that their drainage basins were too small to provide sufficient water, and/or the rate of uplift of the Confidence Hills was too rapid for these streams to downcut and maintain their channels.

Uplifted Alluvial Fan. Within the eastern subzone in the southeastern part of the field area (Figs. 2 and 4), a large fan adjacent to the Amargosa River has been uplifted and isolated from its source area to the east. The fan is deformed by northwest-trending horsts and grabens having vertical displacements of less than 5 m, and by gentle folds (Fig. 4). The fold axes are generally parallel to the trend of the eastern subzone (Fig. 4). Pebble counts on either side of the fault between the fan and its source are identical, suggesting that the lateral offset is negligible. In addition, bedrock of both Precambrian gneiss and the Crystal Spring Formation crop out on

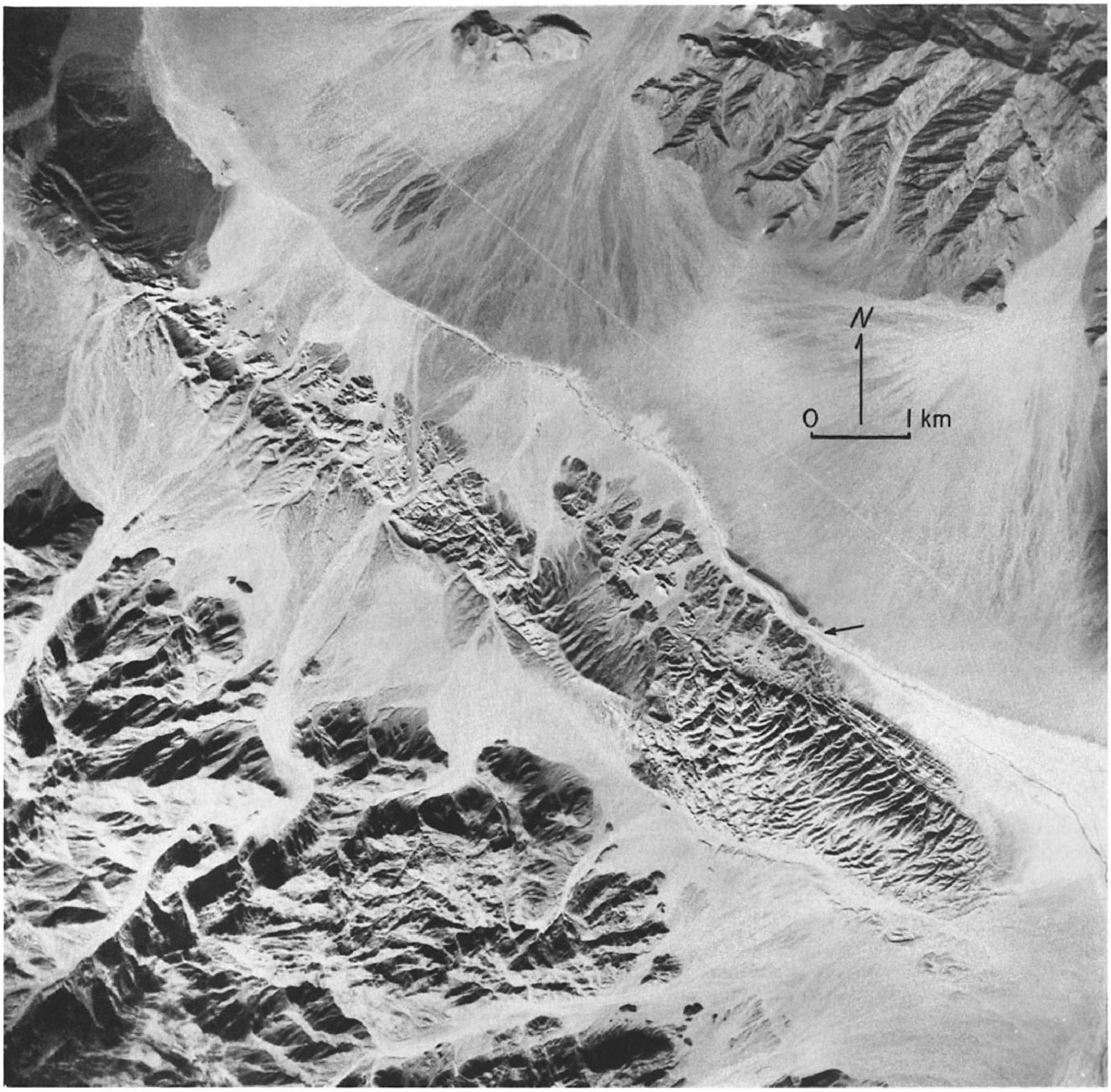

Figure 7. Aerial photograph of the southern Confidence Hills. Arrow points to the place where the Amargosa River follows a branch of the eastern subzone of the southern Death Valley fault zone. Note antecedent streams crossing perpendicular to the trend of the Confidence Hills in the area shown in the left half of the photograph, whereas in the lower right, the streams flow around the southern end of the Confidence Hills. The northeast part of the Owlshead Mountains is shown in the lower left corner of the photograph. Photograph from the National Oceanic and Atmospheric Administration.

both sides of the fault and do not appear to be offset laterally (Fig. 4). Furthermore, Tertiary landslide blocks (QTls, Fig. 4) that are partially buried by the faulted fan appear to have been derived from a source directly to the northeast.

As is the case in the Confidence Hills, the faulted alluvial fan overlies a sequence of lacustrine strata, and in places the contact is gradational and thus conformable. Like the Confidence Hills, the gravel and fan units are folded and faulted, but the lacustrine deposits are locally more deformed than is the overlying fan gravel. The lacustrine deposits exposed in the Confidence Hills and beneath the uplifted alluvial fan are very similar in lithology, and because of their proximity and lack of topographic relief between them, were probably part of the same lake basin. If they were part of the same lake basin, then it is possible to constrain the age of the deformation that uplifted the alluvial fan. This hypothesis is substantiated

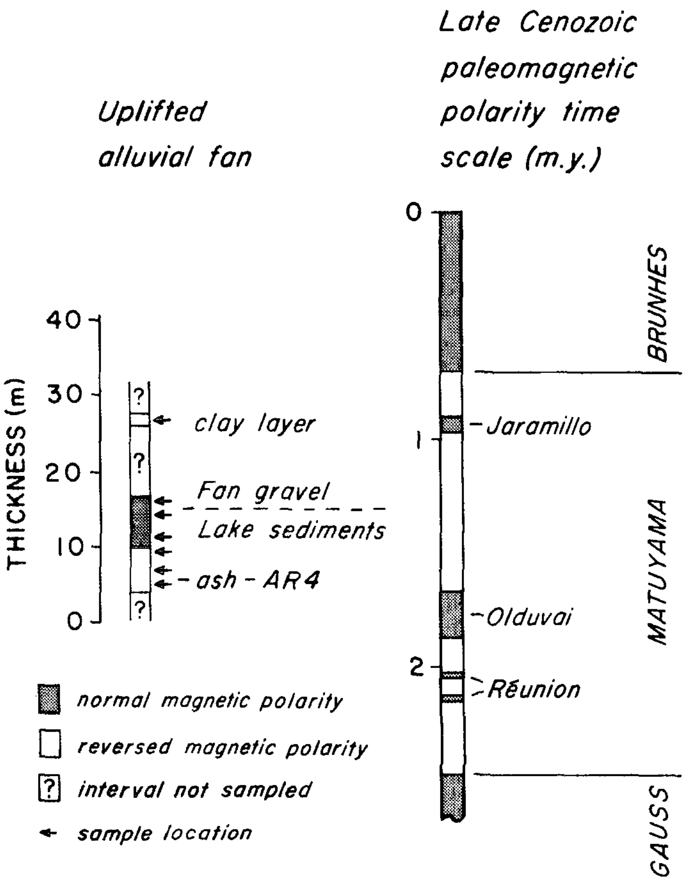

Figure 8. Results of paleomagnetic sampling in the vicinity of the uplifted alluvial fan, compared to the late Cenozoic magnetic polarity time scale (from Mankinen and Dalrymple, 1979). Three samples were collected and analyzed at each horizon.

in part by paleomagnetic measurements made in the lacustrine deposits that lie just below the uplifted fan gravel.

Samples for the paleomagnetic measurements were collected from the upper part of the lacustrine deposits exposed along the east bank of the Amargosa River and along a tributary wash just east of the graben (Fig. 4). A total of 21 samples were collected from 7 horizons. The samples were systematically measured with stepwise alternating-field demagnetization to peak fields of 40 mT. All of the samples showed unambiguous polarities. In stratigraphic sequence, the polarities changed from reversed to normal and back to reversed (Fig. 8). The lower reversed sequence contains an ash layer (AR-4, in Fig. 8) that appears similar to the 1.27-m.y.-old Mesa Falls ash (Izett, 1981), based on its magnetic polarity, and calcium to iron ratios in its glass shards, as determined on an electron microprobe. The Mesa Falls ash, however, has not been previously identified in the Death Valley region (A. M. Sarna-Wojcicki, 1986, personal commun.). The presence of the reversed/normal/reversed pattern indicates that the lake sediments are at least 900,000 yr old, because that is the age of the youngest polarity sequence that could exhibit such a pattern (Mankinen and Dalrymple, 1979). The normal part of the sequence would be the Jaramillo event, which lasted from 970,000 to 900,000 yr ago.

The next oldest normal event within the Matuyama reversed polarity epoch is the Olduvai event, which lasted from 1.87 to 1.67 Ma. It is less likely that this is the event recorded in these sediments for the following reasons. The Shoreline Butte basalt at the north end of the Confidence Hills is 1.5 m.y. old (Wright and Troxel, 1984) and has horizontal shorelines preserved on its flows (Hooke, 1972). The tephra layer at the top of the lacustrine sequence in the Confidence Hills was deposited after ~1.14 Ma. Therefore, one or more large lakes existed in southern Death Valley at some time during the past 1.5 m.y. If the magnetically normal part of the reversed/normal/reversed paleomagnetic sequence represents the Jaramillo event (0.97 to 0.90 Ma), then deposition of alluvial fan gravels was occurring at approximately the same time in both the region of the Confidence Hills and the uplifted alluvial fan. In addition, there are no shorelines cut into the uplifted fan, nor are there any lacustrine deposits on top of the uplifted fan gravel. If the uplifted alluvial fan had been deposited during the Jaramillo event (1.87 to 1.76 Ma), a much more complicated explanation is required to allow for preservation of the fan surface. It seems likely that the lake sediments of the Confidence Hills and adjacent to the uplifted alluvial fan were deposited within a basin that was eventually inundated with alluvial fan debris, with deposition of fan material beginning during the normal polarity period between 0.97 and 0.90 Ma. If the age estimate for the uplifted fan gravel in the southeastern part of the field area is correct, the deformation of the uplifted alluvial fan took place within the past 970,000 yr.

The southwestern edge of the faulted fan is truncated by a graben through which flows the Amargosa River (Fig. 4). Fluvial terrace gravels of three ages are preserved on either side of the graben. Most of the outcrops are too small to show on the generalized field map, and so they are included as part of the active wash and alluvial fan deposits (Q in Fig. 4). A detailed discussion of these terrace deposits is given in Butler (1984a, 1984b). The intermediate and oldest terraces are offset by the faults that formed the graben. All three terrace gravels are well cemented with calcium carbonate and unconformably overlie tightly folded lacustrine deposits. The gravel of intermediate age is most extensive and is as much as 3 m thick. Remnants of this unit crop out on either side of the fault that forms the western boundary of the graben. Movement along the fault fractured the cemented terrace gravel into large blocks (as much as several metres in longest dimension). The maximum measured vertical offset is approximately 12 m. There is no evidence for a lateral component of displacement.

An even younger phase of deformation has occurred immediately upstream (southeast) of the graben. Doming of the flood plain of the Amargosa River has steepened the channel gradient to approximately twice that measured within and downstream of the graben. In response, the river has incised its channel through the uplifted area. Upstream and downstream of the dome, the modern channel of the Amargosa River averages 1 to 1.5 m in depth, but within the area of doming, the channel depth reaches 4.6 m.

The uplift is probably related to localized shortening generally oriented perpendicular to the faults, which seems to be characteristic of the eastern subzone of the southern Death Valley fault zone. In addition to evidence cited for bulk shortening to the north in the Confidence Hills, significant shortening has been documented for the southern Death Valley fault zone along the front of the Avawatz Mountains (Troxel, 1970; Brady, 1984, 1986; Brady and Verosub, 1984; Troxel and Butler, unpub. map and report).

SUMMARY AND CONCLUSIONS

The Death Valley region is located in the southwestern part of the Basin and Range province of southeastern California and southern Nevada—a region characterized by mid-Tertiary to Holocene extension. Cenozoic strike-slip faults have been recognized in the Basin and Range province for many years, but their relationship to the tectonic features of the province is still being debated (Wright, 1976; Wernicke and others, 1982; Stewart, 1983). In the 1960s, several investigators began to focus on the relationship of the strike-slip faults to the formation of structural elements within the Basin and Range province (Wise, 1963; Burchfiel and Stewart, 1966; Hill and Troxel, 1966). During that time, Death Valley was described as a pull-apart basin by Burchfiel and Stewart (1966, Fig. 3). Our documentation of ~35 km of right-lateral displacement along the southern Death valley fault zone complements earlier evidence for right-lateral displacements on the Northern Death Valley–Furnace Creek fault zone. Right-lateral offsets sufficient to form the basin thus have now been documented on both bounding fault zones.

Like many strike-slip faults, the southern Death Valley fault zone is characterized by *en echelon* traces. In this study, these traces have been divided into two subzones, which appear to have significant differences. In terms of orientation, fault branches of the western subzone are arcuate and commonly dip 35° to 65° to the east or northeast, whereas in the eastern subzone, the branches strike slightly more westerly, and their almost straight-line surface traces suggest a near-vertical dip. In terms of type and timing of movement, fault branches in the older western subzone have much more lateral offset, and the faulted units are less folded than in the younger eastern subzone.

We believe that a possible explanation for the differences observed along the two subzones of the southern Death Valley fault zone may be related to interactions between the southern Death Valley fault zone and the Garlock fault zone. The two fault systems intersect a few kilometres south of the study area. The Garlock fault zone clearly shows left-lateral slip along its length, but the nature of its eastern termination is contested (Davis and Burchfiel, 1973; Plescia and Henyey, 1982; Brady and Verosub, 1984; Brady, 1986; Troxel and Butler, unpub. map and report). Davis and Burchfiel (1973) and Plescia and Henyey (1982) argued that the Garlock fault continues east of its intersection with the southern Death Valley fault zone, although they indicated that the Garlock fault zone is offset ~8 km by the southern Death Valley fault zone. Troxel and Butler (unpub. map and report), Brady (1986), and Brady and Verosub (1984) argued that the main branch of the Garlock fault flattens southward beneath the Avawatz Mountains as an east-vergent reverse fault, and the older branches of the southern Death Valley fault zone terminate against the Garlock fault. This eastward "ramping" has occurred since Miocene time, and thus the Garlock fault zone has been active during the same time period that the southern Death Valley fault zone has been active. The latter model is preferred primarily because evidence presented in this study documents ~35 km of right-lateral slip along the southern Death Valley fault zone. Such motion is not compatible with an eastern extension of the Garlock fault, which permits only minor displacement on the southern Death Valley fault zone.

The east-directed thrusting of the Avawatz Mountains is probably responsible for the shift in the most recent activity along the southern Death Valley fault zone from its western to its eastern branches. Indeed, this shift has been traced along the southern Death Valley fault zone to the area south of the study area and north of the Avawatz Mountains (Troxel, 1970). As the Avawatz Mountains were being thrust to the east along a branch of the Garlock fault zone, therefore, branches of the southern Death Valley fault zone were deflected or bent to the east. This interaction would explain the difference in age and styles of deformation of the two subzones of the southern Death Valley fault zone.

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