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Evidence for 40–41 km of dextral slip on the southern Death Valley fault: Implications for the Eastern California shear zone and extensional tectonics

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ABSTRACT

Recognition of a pair of pre-Neogene markers together with analysis of published data indicate ~40 km of dextral slip across the southern Death Valley fault zone, California, USA. Stratigraphic overlaps on fault rocks indicate much of the dextral slip predates the late Miocene, placing a significant fraction of the dextral slip in the same time window as regional extension and challenging interpretations that the modern strike-slip system became active post–6–3 Ma. However, these results are consistent with regional evidence that dextral trans-tension began by ca. 12 Ma.

INTRODUCTION

Death Valley (California, USA) is the archetypical pull-apart basin (Burchfiel and Stewart, 1966), yet there is controversy on slip estimates for the bounding strike-slip faults. Discrepancies in strike-slip motion are partially due to complex deformation in a distributed transtensional system that evolved over the last ~12 m.y. (e.g., Serpa and Pavlis, 1996; Snow and Wernicke, 2000; Renik and Christie-Blick, 2013), but scarcity of markers has handicapped resolution of slip.

We present results from detailed mapping in the Noble Hills (Fig. 1) where the southern Death Valley fault system (SDVF) is well exposed and show that these exposures closely match an exposure in the Owlhead Mountains ~40 km to the northwest. We then compare this result to previous estimates and assess the implications of this conclusion.

REGIONAL GEOLOGIC SETTING AND THE SLIP ESTIMATE PROBLEM

The Death Valley region has been a centerpiece for Neogene extensional/trans-tensional tectonic studies in the southern United States Cordillera. Stewart (1967, 1983) and Wernicke et al. (1988) emphasized that there is a rich pre-Neogene record that can be exploited to reconstruct this late Cenozoic history. This record includes stratigraphic markers, Mesozoic contractional structures, and Neogene depos-

its. Both stratigraphic variations and Mesozoic structures trend northeast at nearly right angles to Neogene structures (Fig. 1), potentially providing high-resolution piercing lines to constrain reconstructions (Wernicke et al., 1988).

Stewart (1967) first attempted to reconstruct the Neogene system using stratigraphic markers to infer strike-slip offsets of ~80 km across the Death Valley region. Wright and Troxel (1967) countered this interpretation using stratigraphic details in Death Valley to estimate dextral offset of less than 10 km on SDVF. This low slip estimate stands in marked contrast to relatively robust, large slip estimates for the northern Death Valley fault (NDVF) system. These include Stewart's (1967, 1983) estimate, and that by Snow and Wernicke (1989, 2000), who proposed a displacement of 68 ± 4 km. More recent efforts by Renik and Christie-Blick (2013) emphasized differential slip along the fault but estimated <50 km across what is now Death Valley proper.

The low slip estimate (<10–35 km) for the SDVF has tended to persist in many reconstructions through hypotheses that either transfer slip onto other strike-slip structures (e.g., Wright et al., 1991; Serpa and Pavlis, 1996) and/or onto the extensional complex and transrotational structures (e.g., Wernicke et al., 1988, 1989; Serpa and Pavlis, 1996; Snow and Wernicke, 2000), with different interpretations of timing on the SDVF. This distinction has led

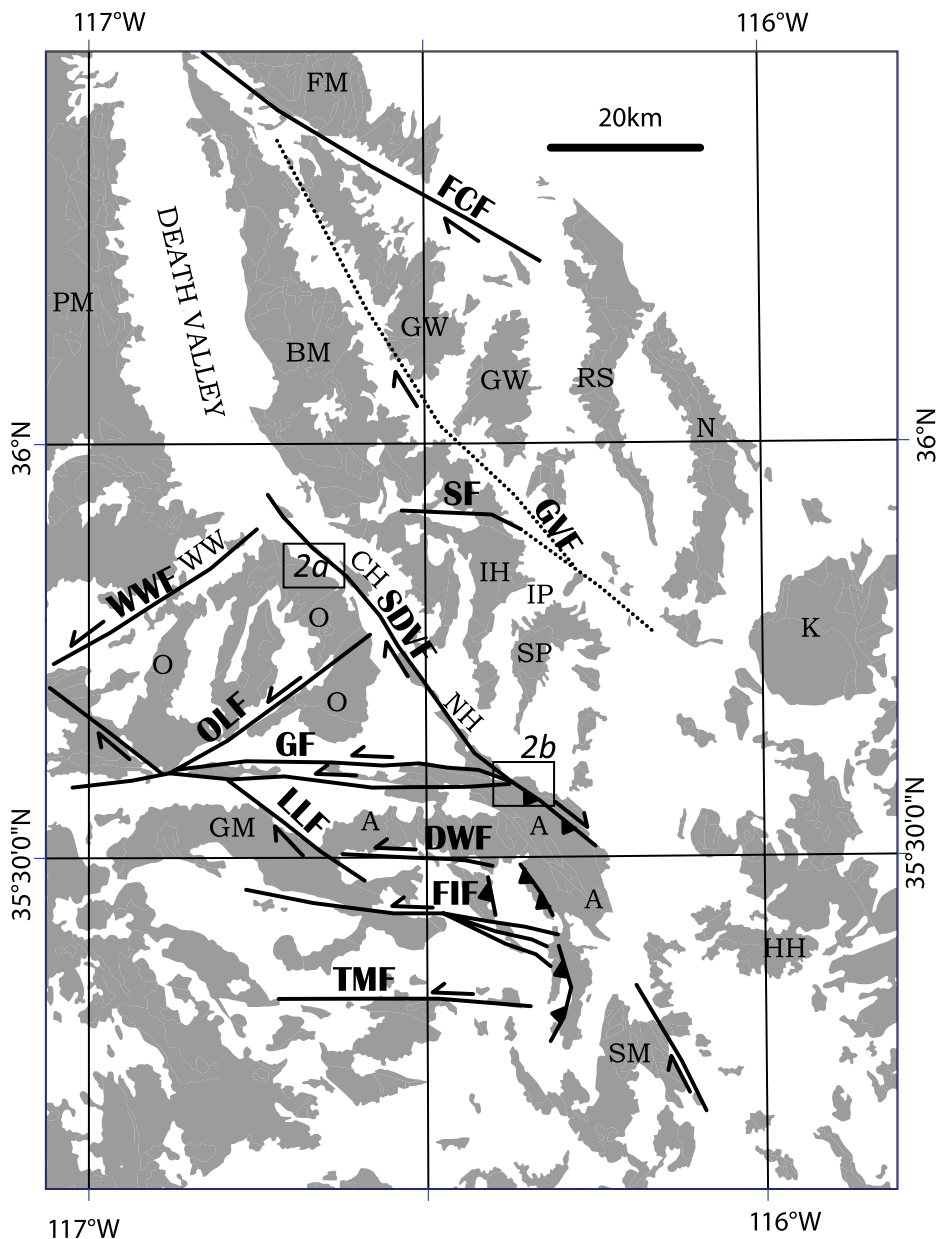
to hypotheses that the Death Valley pull-apart basin is a young (6 Ma to <3 Ma) superposition on an extensional system (e.g., Stewart, 1983; Norton, 2011).

GEOLOGY OF THE SOUTHERN DEATH VALLEY FAULT ZONE IN THE NOBLE HILLS

Recent work by Trullenque et al. (2018) and Klee et al. (2020) using high-resolution digital mapping techniques similar to that of Pavlis et al. (2010) in the vicinity of the SDVF-Garlock intersection, together with previous mapping, provides strong evidence that the low slip estimate for the SDVF is incorrect.

Studies in the Noble Hills have focused on Neogene rocks exposed along the SDVF (Brady, 1984; Brady and Troxel, 1999; Butler et al., 1988; Niles, 2016). Those studies demonstrated that Quaternary deformation of the Noble Hills is dominated by the complex interactions of the sinistral Garlock fault and the dextral SDVF, which produce contractional structures in an area otherwise dominated by extensional tectonics.

In our work, we concentrated on deformation in a structural high within the Noble Hills (Fig. 2B). This effort revealed that this pre-Neogene basement complex was intensely deformed by brittle deformation at low temperatures (Klee et al., 2020). The complex is composed of Proterozoic gneiss and the nonconformably overlying Crystal Springs Formation, and both were intruded by Mesozoic granite. The complex is cut by arrays of faults that range from discrete slip surfaces to broad cataclastic shear zones up to 100 m across. Near-vertical faults are dominant with ubiquitous dextral shear sense indicators, both at the margins of the structural high as well as on faults interior to the structural high. Our studies support the conclusion of Niles



Geographic Abbreviations: A=Avawatz Mountains, BM=Black Mountains, FM=Funeral Mountains, HH=Halloran Hills, GM=Granite Mountains, GW=Greenwater Range, IH=Ibex Hills, IP=Ibex Pass, K=Kingston Range, N=Nopah Range, O=Owlshead Mountains, PM=Panamint Mountains, RS=Resting Spring Range, SM=Soda Mountains; SP=Saddle Peak Hills; WW=Wingate Wash. Fault Abbreviations: DWF=Drinkwater Lake; FCF=Furnace Creek; FIF=Ft. Irwin; GF=Garlock; GVF=Grandview; LLF=Leach Lake; OLF=Owl Lake; SF=Sheephead; SDVF=Southern Death Valley; TMF=Tiefort Mountain Fault; WWF=Wingate Wash. Figure is drawn from GIS files for the California Geologic map: maps.conservation.ca.gov/cgs/gmc.

Figure 1. Regional map of the Death Valley–northeast Mojave Desert region, California, USA. Major Pliocene–Pleistocene strike-slip and thrust faults are shown but normal faults are omitted for clarity. GIS—geographic information system.

(2016), who noted that the Neogene section is depositional on granite at the northern tip of the basement high (Fig. S1 in the Supplemental Material¹), but the margins are strike-slip faults that overprint the unconformity. These observa-

¹Supplemental Material. Supplemental figure of the Noble Hills. Please visit <https://doi.org/10.1130/GEOL.S.14120396> to access the supplemental material, and contact editing@geosociety.org with any questions.

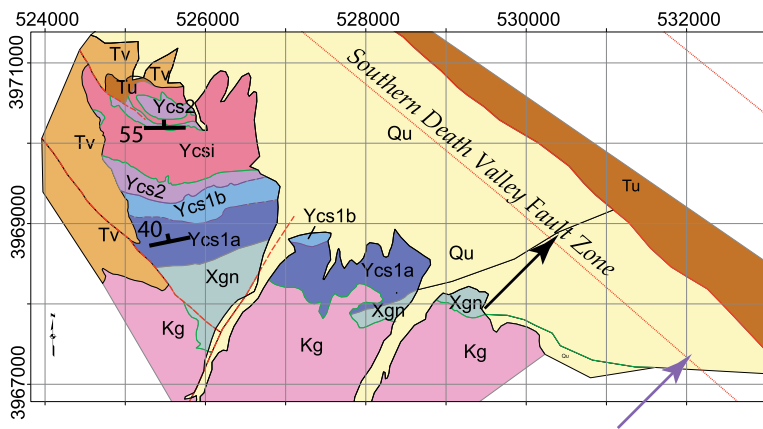
tions indicate that significant faulting postdates the Neogene nonconformity, but that significant motion had also occurred well before deposition of the Neogene cover. The overlapping rocks have not been directly dated, but Niles (2016) showed that they were no younger than ca. 3.5 Ma. Based on lithology and stratigraphic position, Brady and Troxel (1999) correlated the unit with the Owlhole Spring Formation dated at 6–8 Ma, an estimate we accept here.

At map scale (Fig. 2B), we observed that to the southeast, the distinctive cataclastic granites of the bedrock high can be traced into a broad fault zone well inboard of the Avawatz Mountains front. This cataclastic zone is clearly part of the SDVF but merges with cataclastic rocks (fr in Fig. 2B) developed along the eastern trace of the Garlock/Mule Springs fault (Brady, 1984). This geometry shows that the SDVF sensu stricto lies east of this intersection, and, therefore, rocks to the east of the line labeled Fault A in Figure 2B have been transported by most, or all, of the dextral motion on the SDVF. This fault block contains north-facing units that are truncated against the fault, including, from southeast to northwest: exposure of coarse-grained Mesozoic granite; Proterozoic basement; and the Crystal Springs Formation with its characteristic Mesoproterozoic mafic intrusions. The Crystal Springs Formation strikes ENE and dips uniformly through this section at moderate to steep angles of 50°–90°. Across the fault to the west (Fig. 3), the Avawatz Mountains contain very different rocks, including Triassic diorite, minor younger granites, and roof pendants of Proterozoic to Mesozoic rocks engulfed in diorite (Brady, 1984; Spencer, 1990; Pavlis et al., 1998).

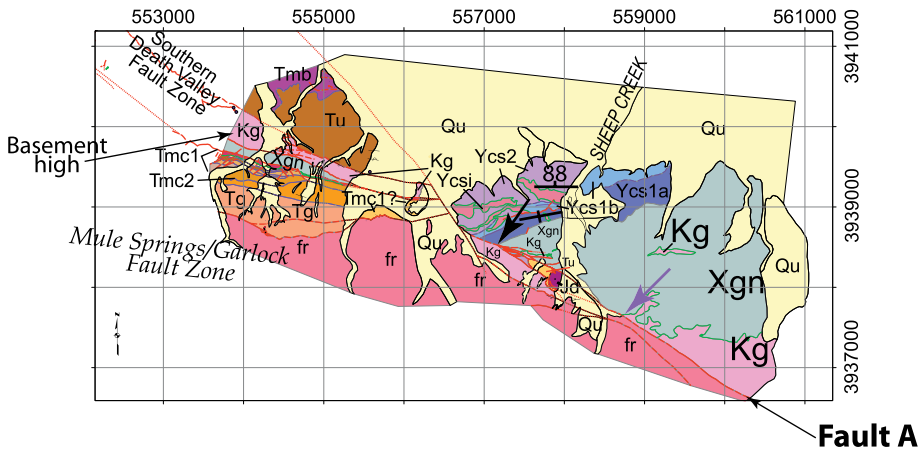
This fault block at the Avawatz Mountains front is significant because it is similar to an exposure at the northeast tip of the Owlshead Mountains, just west of the SDVF (Figs. 1 and 2A). The match between these two exposures is striking (see arrows for reference in Fig. 2): (1) the basic orientation and facing of the basement–Crystal Springs assemblage match across the fault, and (2) the positions of the granite intrusions into basement also match closely. In the Owlshead locality, the orientation of the rocks is demonstrably pre-ca. 14 Ma, as signified by a nearly flat-lying unconformity (Fig. 2A). Although only Quaternary deposits provide an equivalent constraint at the Avawatz Mountains front (Fig. 2B), it is likely the bedding has not been rotated significantly because bedding is nearly perpendicular to likely rotation axes from young contraction. Using the offset positions of either the basement-cover contact (base of the Crystal Springs Formation) or the granite-basement contact (arrows in Figs. 2A and 2B) indicates a net dextral offset of 40.5 km (straight-line distance) to 41.5 km (along-fault distance).

Further support for this offset marker pair is provided by the geology of the Noble Hills bedrock high. Because of structural position, these rocks must be a slice picked up somewhere along the fault trace, with less net slip than the total fault slip. Lithologically, however, the slice is closely akin to the offset markers: Crystal Springs Formation, basement, and granite, albeit with a much higher percentage of granite. Examination of the geology along the SDVF trace (Fig. 3A) suggests the slice was

A Northeast Owlshead Mountains



B Northeast Avawatz Mountains



C Restoration of Avawatz block relative to Owlshead Mountains

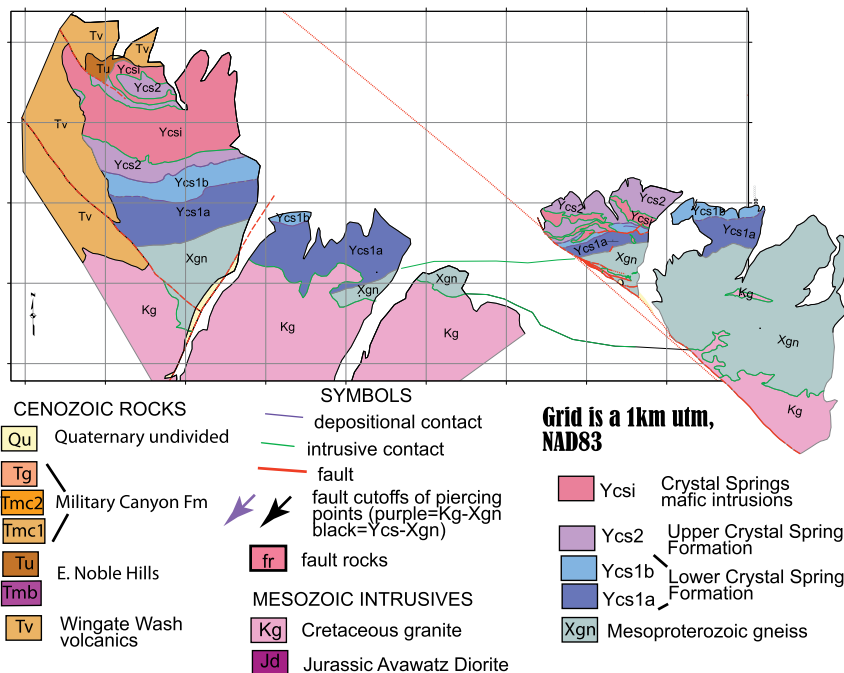


Figure 2. Geologic maps of the area of offset markers proposed in this study (California, USA): (A) geologic map modified from Pavlis et al. (2012) with some additions in the southeast corner; (B) geologic map from this study; (C) map showing proposed restoration of slip on the southern Death Valley fault (SDVF). UTM—Universal Transverse Mercator; NAD83—North American Datum 1983.

derived from along the Owlshead Mountains front, but close to Crystal Springs Formation exposures, because roof pendants farther south are all high-grade marbles (m in Fig. 3A). Similarly, it cannot be locally derived basement from the Avawatz Mountains because all rocks west of the SDVF and south of the Garlock fault are dominated by mafic granitoids (e.g., Spencer, 1990; Brady, 1984; Pavlis et al., 1998).

DISCUSSION

Additional Evidence for ~40 km of Offset

Brady (1984) and Brady and Troxel (1999) showed that conglomerates west of the SDVF (THH in Fig. 3A) had clasts with no known source directly to the east, across the fault. Rather, the clasts had close affinity with rocks now exposed to the south and east in the Halloran Hills (Figs. 1 and 3). This marker is blunt, but restoration of 40 km of the slip on the SDVF would place these Neogene sediments directly southwest of their interpreted source (Fig. 3C). Similarly, Butler et al. (1988) tied Neogene gravels in the Noble Hills to an Owlshead Mountain source (labeled G in Fig. 3), leading to an estimate of ~35 km of offset on the fault. Bennie W. Troxel (deceased) later questioned the conclusion based on field details (unpublished field observations by B. Troxel and T. Pavlis), and Caskey et al. (2010) and Niles (2016) questioned other details. Nonetheless, Butler et al.'s (1988) conclusion is fully consistent with our slip estimate here.

Farther north, Serpa and Pavlis (1996) used the northern limit of Mesozoic plutonism as a marker for reconstruction, which, together with a similar marker, indicated that the northern limit of subjacent granitoids is consistent with 30–40 km of slip (Fig. 3). Similarly, Luckow et al. (2005) and Canalda (2009) suggested that middle Miocene volcanics in Wingate Wash (Fig. 1) were dextrally offset from volcanic rocks near Ixex Pass (Fig. 1). This correlation is a coarse marker because the volcanics cover large areas on either side of the SDVF, but if the northern limit of known exposures is mapped (Fig. 3A), the resultant offset is also ~40 km. Note, that an outlier of these volcanics lies well north of our line in the Amargosa Chaos (blue asterisk in Fig. 3), and this issue is considered further below.

Finally, Stewart (1967) mapped multiple stratigraphic trends that indicate ~80 km of dextral displacement across the southern Death Valley region (Fig. 3). We note here that the main evidence for the low slip interpretation on the SDVF is the analysis of the Neoproterozoic section by Wright and Troxel (1967). Their work showed multiple stratigraphic pinch-outs extending WSW from the Kingston Range to the Ixex Hills (Fig. 1) and then northwestward through the Amargosa Chaos to the Panamint Mountains (Fig. 3A). Note, however, that the

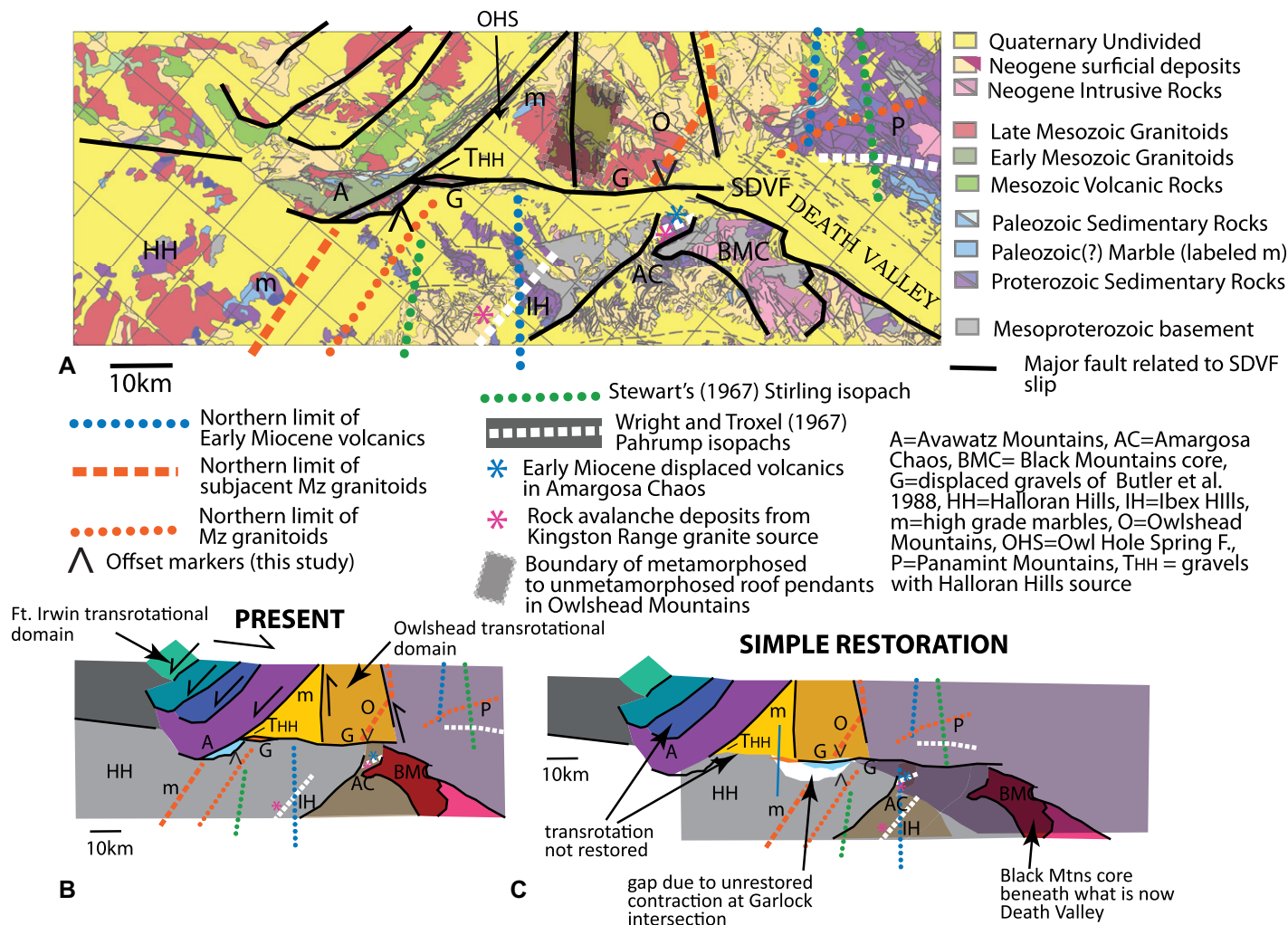


Figure 3. (A) Geologic map along the southern Death Valley fault (SDVF; California, USA) with offset markers discussed in *rhw* text (from geographic information system files in Workman et al. [2002] merged with California geologic map: maps.conservation.ca.gov/cgs/gmc/). Figure is rotated with motion along the SDVF vertical. Mz—Mesozoic. (B) Simplified fault blocks from A. (C) Rigid body restoration of 40 km of slip on the SDVF transferred to the Black Mountains frontal fault in simple pull-apart assumption. See text for details.

Amargosa Chaos and its Neogene cover (Amargosa Chaos basin of Topping, 1993) are detached and displaced to the northwest along a low-angle normal fault system (Amargosa fault). Thus, these displaced rocks are not a meaningful marker constraining strike-slip motion on the SDVF because they were carried along a separate fault system. Indeed, if the Amargosa Chaos rocks are excluded from the Wright and Troxel (1967) map (Fig. 3), these markers are similar to the northern limit of the Neogene volcanic rocks. This observation also explains the seeming outlier of Neogene volcanics at the base of the Amargosa Chaos basin (blue asterisk in Fig. 3) because they were displaced along with underlying rocks.

Figure 3C shows a simple restoration of 40 km of slip on both the SDVF and the Amargosa fault system. This restores the northern limit of early Miocene volcanics and the Pahrupp Group pinch-outs of Wright and Troxel (1967) to their equivalent positions in the Ibex

Hills (Fig. 3C), and pre-extensional markers other than Stewart's restore to within 1–5 km—a close correlation given the crude positions for some of these markers. The offset gravels recognized by Butler et al. (1988) over-restore in this reconstruction (G in Fig. 3), which is expected for a syntectonic deposit. A feature that is not taken into account in Figure 3C is the well-documented transrotation south of the Garlock fault (e.g., Schermer et al., 1996). Slip estimates that constrain the transrotation vary (e.g., Schermer et al., 1996; Pavlis et al., 1998) but predict rotations less than the paleomagnetic data. Nonetheless, contraction at the ends of the transrotational blocks is well documented (Fig. 1), including the faults at the eastern Avawatz Mountains front, which accounts for gaps in our reconstruction (Fig. 3C). Similarly, rock avalanche deposits in the Amargosa Chaos basin (pink asterisk in Fig. 3C) do not restore close to their Kingston Range source, indicating extensional and/or strike-slip faults to the east have displaced

these markers as well as Stewart's markers. Additional work is needed to fully integrate our slip estimate with these known issues.

Broad-Scale Implications for Transtensional Systems

Our findings have implications for transtensional mechanics as well as the plate-tectonic evolution of southwestern North America. The Death Valley area is one of the best-documented transtensional systems on Earth, yet uncertainties in how slip is distributed among strike-slip versus extensional structures remain, complicating understanding of the driving process(es) for extension. Geodetic studies (e.g., Lifton et al., 2013) demonstrate that Death Valley now lies in the core of a distributed dextral system, the Eastern California shear zone/Walker lane belt (ECSZ/WL), which takes up more than 10% of Pacific–North American plate motion. To the south, this motion is taken up primarily by transrotational panels, but north of the Garlock fault,

the westerly motion of the Sierra Nevada relative to the Mojave produces a broad, transtensional system (e.g., Dokka and Travis, 1990).

Ages of synextensional strata (e.g., Holm et al., 1994) show that modern Death Valley is relatively young (ca. 6 Ma), but slip histories of other faults allow a range of interpretations pre-6 Ma. Studies of the NDVF/Furnace Creek fault show that the fault system initiated during middle Miocene extension (e.g., Renik and Christie-Blick, 2013), but this link has been elusive for the SDVF. Our ~40 km slip estimate for the SDVF is consistent with the estimate by Renik and Christie-Blick (2013) of <50 km for strike-slip motion at the northern margin of the basin (Renik and Christie-Blick, 2013), and our timing constraints suggest both fault systems moved throughout the main extensional event. This result, together with other recent work (e.g., Renik and Christie-Blick, 2013; Pavlis et al., 2014), suggests a new family of reconstructions is needed that account for these new observations. When completed, reconstructions could be used in an integrated geodynamic model to evaluate the mechanics of interactions among pull-apart basins, regional extension, and transrotation.

Any geodynamic analysis of the region needs to consider that our result suggests that strike-slip motion was prominent throughout the regional extension, implying the system was plate driven, with gravitational effects being secondary. This conclusion is consistent with evidence that strike-slip motion was prominent to the north in the Walker Lane from 14 to 12 Ma onward (e.g., Oldow et al., 2008; Busby, 2013) and driven by plate motion (Lee et al., 2020). This suggests the ECSZ/WL represents a long-lived plate-boundary process linked to the evolving transform margin. Serpa and Pavlis (1996) emphasized this plate-driven hypothesis with interpretations that transrotation played a major role during the extension, and synextensional folds in the system were produced by distributed dextral shear. Our observations here suggest distributed shear models of this type need to be reconsidered for the entire span of the extension from ca. 12 Ma to present.

CONCLUSIONS

New studies in southern Death Valley suggest that the net dextral slip on the SDVF is 40–41 km. Previous estimates of <10 km used markers that are themselves displaced by detachment faults, indicating those markers are minimum slip estimates. Evidence showing that 8–6 Ma Neogene sediments onlap SDVF cataclases suggests that much of the dextral slip occurred during the main extension from 12 to 6 Ma. This challenges interpretations that the Death Valley pull-apart is a post-6 Ma structural feature, but it is consistent with regional evidence that dextral transtension in the ECSZ/WL belt began in the middle Miocene.

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