A new hypothesis for the amount and distribution of dextral displacement along the Fish Lake Valley–northern Death Valley–Furnace Creek fault zone, California-Nevada

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[1] The Fish Lake Valley–northern Death Valley–Furnace Creek fault zone, a ~250 km long, predominantly right-lateral structure in California and Nevada, is a key element in tectonic reconstructions of the Death Valley area, Eastern California Shear Zone and Walker Lane, and central Basin and Range Province. Total displacement on the fault zone is contested, however, with estimates ranging from ~30 to ~63 km or more. Here we present a new synthesis of available constraints. Preextensional thrust faults, folds, and igneous rocks indicate that offset reaches a maximum of ~50 km. Neogene rocks constrain its partitioning over time. Most offset is interpreted as ≤ ~13–10 Ma, accruing at ~3–5 mm/yr in the middle of the fault zone and more slowly toward the tips. The offset markers imply ~68 ± 14 km of translation between the Cottonwood Mountains and Resting Spring–Nopah Range (~60 ± 14 km since ~15 Ma) through a combination of strike slip and crustal extension. This suggests that a previous interpretation of ~104 ± 7 km, based on the middle Miocene Eagle Mountain Formation, is an overestimate by ~50%. Our results also help to mitigate a discrepancy in the ~12–0 Ma strain budget for the Eastern California Shear Zone. Displacement has previously been estimated at ~100 ± 10 km and ~67 ± 6 km for the Basin and Range and Mojave portions of the shear zone, respectively. Our new estimate of ~74 ± 17 km for the Basin and Range is within the uncertainty of the Mojave estimate.

1. Introduction

[2] The Fish Lake Valley–northern Death Valley–Furnace Creek fault zone, a ~250 km long, predominantly right-lateral structure in eastern California and western Nevada, is a key element of research into both (1) displacement budgets for the Eastern California Shear Zone and (2) tectonic reconstructions of the Death Valley area and central Basin and Range Province (Figure 1) [e.g., *Wright and Troxel*, 1967, 1970; *Stewart*, 1967, 1983, 1992; *Stewart et al.*, 1968, 1970; *Wernicke et al.*, 1988a, 1988b; *Snow and Wernicke*, 1989, 2000; *Dokka and Travis*, 1990a, 1990b; *Snow*, 1992a; *Stevens et al.*, 1991, 1992; *Serpa and Pavlis*, 1996; *Reheis and Sawyer*, 1997; *Bennett et al.*, 2003; *McQuarrie and Wernicke*, 2005; *Frankel, Brantley, et al.*, 2007; *Frankel, Dolan, et al.*, 2007]. Each line of research is of general significance (the former to the distributed accommodation of plate boundary motion, and the latter to mechanisms of crustal extension), but important uncertainties are still to be resolved in both cases. Dextral displacement across the Eastern California Shear Zone is thought to be ~28% of San Andreas transform fault system, averaged since 12 Ma [*McQuarrie and Wernicke*, 2005]. Displacement estimated for the portion of the shear zone in the western Basin and Range (~100 ± 10 km), however, is ~150% of the value for the Mojave portion (~67 ± 6 km; Figure 1) [*McQuarrie and Wernicke*, 2005; *Lease et al.*, 2009]. Palinspastic reconstructions of the Death Valley area have been influential in the development of the low-angle normal fault and rolling hinge models of extension. The restored positions of critical markers are nonetheless disputed, and the manner in which crustal extension has been accommodated is unresolved [cf., e.g., *Hamilton*, 1988; *Wernicke et al.*, 1988a; *Snow and Wernicke*, 2000; *Topping*, 2003; *Miller and Pavlis*, 2005].

[3] Total displacement on the Fish Lake Valley–northern Death Valley–Furnace Creek fault zone is contested, with recent estimates ranging from as little as ~30 km [*Çemen and Baucke*, 2005] to ~63 km or more [e.g., *Snow and Wernicke*, 2000]. There has been disagreement over the correlation of piercing points as well as the original configuration of correlated markers, e.g., local sinuosity in the regional trends of isopachs and facies boundaries [e.g., *Prave and*

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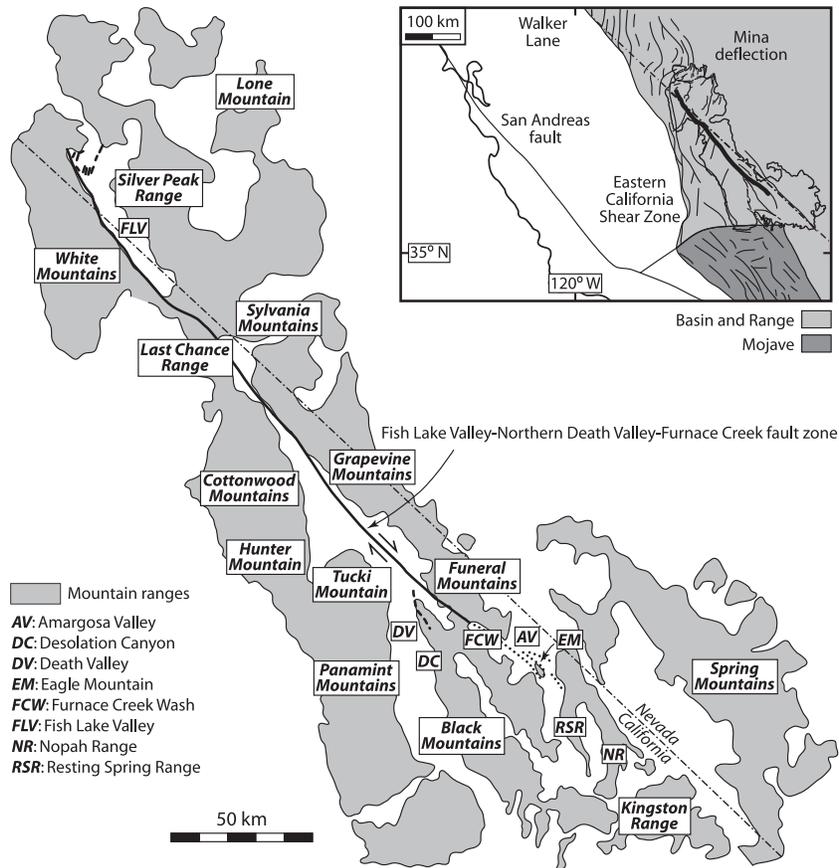
Figure 1. Location of the Fish Lake Valley–northern Death Valley–Furnace Creek fault zone. Fault zone and local ranges and valleys; location shown by outline in regional map. Bold, dashed line near southern tip of fault zone represents a strand that developed relatively late in the history of the fault zone, as a link to a predominantly normal fault system along the Black Mountain front (Figure 2). Adapted from *Snow* [1992a], *Reheis and Sawyer* [1997], *Wright and Troxel* [1999], *Snow and Wernicke* [2000], *Oldow et al.* [2001], *Miller and Pavlis* [2005], *Faulds and Henry* [2008], *Oldow et al.* [2008], and *Lease et al.* [2009]. Inset shows fault zone (bold) in context of Basin and Range and Mojave Provinces (shaded), and of faults of the Eastern California Shear Zone, Mina deflection, and Walker Lane (differentiated by the change in structural grain).

Wright, 1986a, 1986b; *Stewart*, 1986]. Comprehensive syntheses have been published [e.g., *Snow and Wernicke*, 1989, 2000; *Serpa and Pavlis*, 1996], but several recent observations along the Death Valley portion of the fault zone cast doubt on elements of those reconstructions [e.g., *Miller and Friedman*, 1999; *Turner and Miller*, 1999; *Czajkowski and Miller*, 2001; *Czajkowski*, 2002; *Niemi*, 2002; *Miller*, 2003; *Çemen and Baucke*, 2005; *Golding Luckow et al.*, 2005; *Miller and Pavlis*, 2005; *Renik et al.*, 2008]. Few interpretations have integrated piercing points from the entire length of the fault zone, from northern Fish Lake Valley, through Death Valley and Furnace Creek Wash, to the central Amargosa Valley in the vicinity of Eagle Mountain (FLV, DV, FCW, AV, EM in Figure 1). This is important for distinguishing spatial variations in offset from temporal variations [e.g., *Christie-Blick and Biddle*, 1985, p. 22], both of which are documented in this example.

[4] Here we present such a synthesis. For ease of reference, we use the name "Furnace Creek fault zone" for the entirety of the structure over all of its history, including both active and inactive segments. We propose a new hypothesis for the distribution of dextral displacement along strike and over time. Our synthesis has implications for the long-term displacement budget of the Eastern California Shear Zone and for the magnitude of extension across Death Valley.

2. Geologic Setting

[5] Rocks and structures exposed in ranges surrounding the Furnace Creek fault zone reflect a protracted geological history. The oldest rocks constitute a 1.7 Ga crystalline basement [*Wasserburg et al.*, 1959; *Silver et al.*, 1962; *Wright et al.*, 1981; *DeWitt et al.*, 1984], most extensively exposed in the Black Mountains (Figure 1). Mesoproterozoic to Paleozoic siliciclastic and carbonate rocks record episodic rifting and passive margin development, and the onset of convergent plate boundary tectonics [e.g., *Stewart*, 1972; *Christie-Blick and Levy*, 1989; *Levy and Christie-Blick*, 1991; *Burchfiel et al.*, 1992; *Wright and Prave*, 1993]. In late Paleozoic-Mesozoic time, and possibly into the Paleogene, these rocks were deformed by folding and thrust faulting and, in

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western ranges, intruded by arc-related plutonic rocks [*Burchfiel et al.*, 1992, and references therein; *Miller*, 2003]. Today, some of the contractile structures are not visible directly because they have been reactivated or cut out by normal faults. Their existence can be inferred nonetheless from bedding attitudes and older-over-younger relations [e.g., *Snow and Wernicke*, 1989; *Snow*, 1990, 1992a; *Çemen and Wright*, 1990].

[6] There is evidence in the area for extensional disruption of the orogen as early as late Cretaceous-Paleogene time [e.g., *Hodges and Walker*, 1990; *Saylor*, 1991; *Applegate et al.*, 1992; *Hoisch and Simpson*, 1993; *Applegate and Hodges*, 1995], but Basin and Range extension and strike-slip deformation in this portion of the Eastern California Shear Zone are predominantly Miocene and younger [e.g., *Snow and Lux*, 1999; *Snow and Wernicke*, 2000; *McQuarrie and Wernicke*, 2005]. Sufficient extension has occurred at least locally to exhume high-grade metamorphic rocks in four prominent extensional complexes: in the Silver Peak–Lone Mountain area, in the northern Funeral Mountains, at Tucki Mountain in the northern Panamint Mountains, and in the western Black Mountains (Figures 1 and 2). Broadly

synextensional sedimentary and volcanic rocks have accumulated in valleys along the fault zone, and also at selected localities within what are now adjacent ranges.

[7] Given that the Furnace Creek fault zone contributes to plate boundary dextral shear and is coordinated with Basin and Range normal faults, it is generally assumed that much, or all, of the displacement occurred since mid-Miocene time. Most of the available piercing points from which substantial offset is inferred are pre-Cenozoic, however. Thus, the time of onset of strike-slip deformation is not well constrained. The Fish Lake Valley–northern Death Valley portion remains active today, and is linked southward to the active dextral-normal central and southern Death Valley fault zones (Figure 2); motion has ceased on the Furnace Creek Wash–Amargosa Valley section (FCW and AV in Figure 1).

3. Magnitude and Distribution of Dextral Displacement

[8] Dextral displacement is inferred here to reach a maximum of ~50 km in the north central portion of the fault zone, and
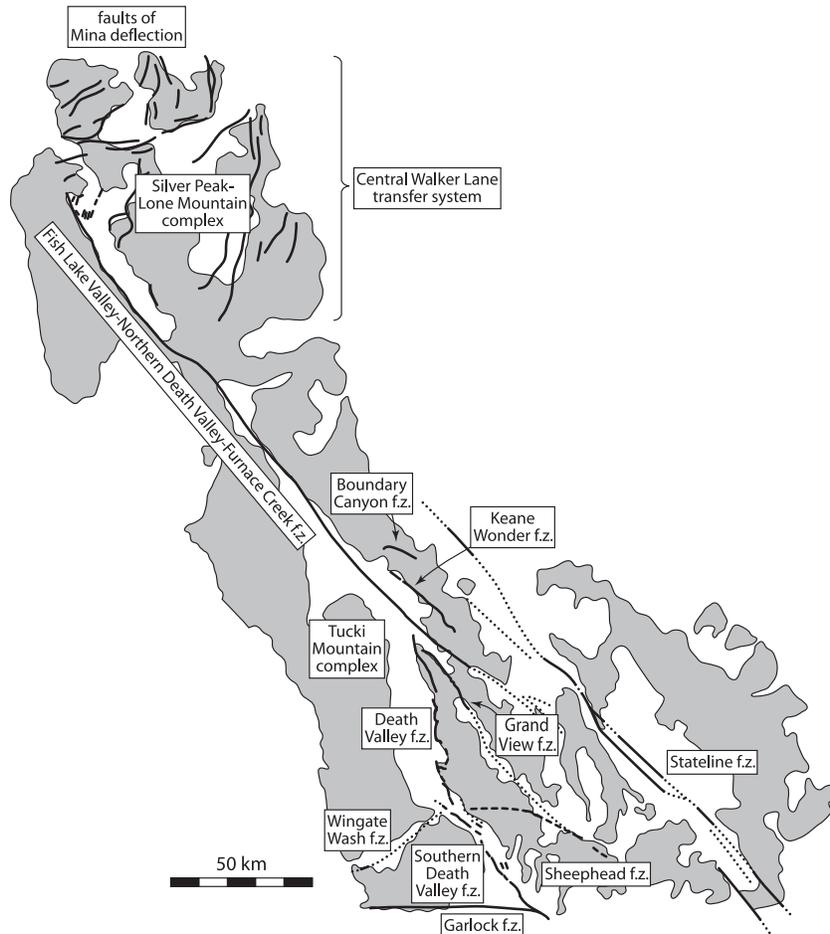

Figure 2. Selected normal and strike-slip faults in the vicinity of the Furnace Creek fault zone, including structures related to the Basin and Range, Eastern California Shear Zone, and Walker Lane. Motion sense of individual faults is discussed in text. The Walker Lane, Mina deflection, Garlock, and Southern Death Valley faults continue outside area of figure. Adapted from *Wright et al.* [1991], *Snow* [1992a], *Reheis and Sawyer* [1997], *Wright and Troxel* [1999], *Snow and Wernicke* [2000], *Golding Luckow et al.* [2005], *Miller and Pavlis* [2005], *Guest et al.* [2007], and *Oldow et al.* [2008].

to decrease toward the tips. Preextensional faults, folds and igneous rocks (Figure 3) provide the best constraint on total displacement for specific segments of the fault, though with uncertainty both in the correlation of markers and in determining offset once correlation has been established. From northwest to southeast, these include the Slate Canyon–Dry Creek thrust fault (SC, DC in Figure 3), the quartz monzonite of Beer Creek (QM in Figure 3), the Grapevine–Last Chance thrust fault (G, LC in Figure 3), the White Top–Marble Canyon box fold (WT, MC, DB in Figure 3), the Schwaub Peak–Panamint thrust fault (SP, P-s, P-d in Figure 3), and the Clery–Western Black Mountains thrust fault (C, WBM in Figure 3). Miocene and younger igneous and sedimentary rocks constrain the partitioning of displacement over time (offsets in Figure 4).

3.1. Slate Canyon–Dry Creek Thrust Fault

[9] The Slate Canyon thrust in the Silver Peak Range (SC in Figure 3; see also Figure 1) correlates across Fish Lake Valley with a thrust fault in the Dry Creek area of the White Mountains (DC in Figure 3; see also Figure 1); the distance between the traces, as measured along the Furnace Creek fault zone, implies ~20 km of dextral displacement (Figure 5) [*Reheis and McKee*, 1991; *Reheis and Sawyer*, 1997]. The thrust faults are interpreted to correlate because both place Cambrian over Ordovician rocks and verge generally south or southwestward [*Buckley*, 1971; *Krauskopf*, 1971; *Crowder et al.*, 1972; *Robinson and Crowder*, 1973; *Stewart et al.*, 1974]. In the footwall of each fault, granitic rocks intrude the same Lower Ordovician siliciclastic unit [*Buckley*, 1971]. Some workers have correlated the Slate Canyon and Dry Creek faults with the
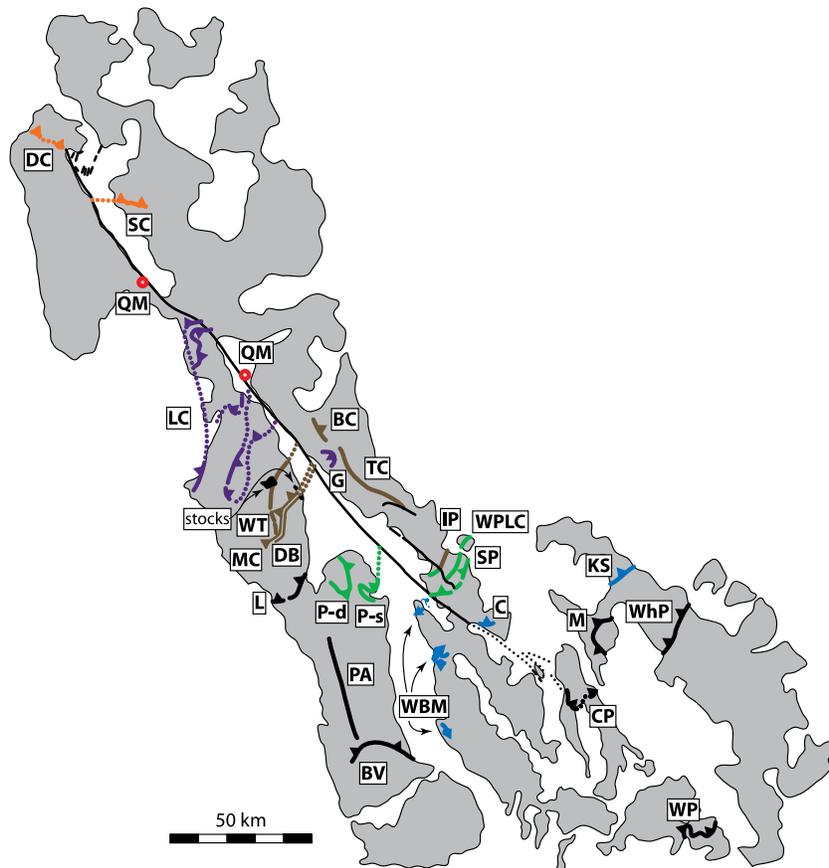

Figure 3. Markers inferred to predate faulting and therefore record total displacement, with additional features pertinent to the interpretation of the markers. Black and colored lines represent folds and thrusts, with the latter distinguished by upper plate teeth. Colors emphasize inferred structural correlations. Circles show tie points in quartz monzonite of Beer Creek. Abbreviations: BC, Bonnie Claire thrust; BV, Butte Valley thrust; C, Clery thrust; CP, Chicago Pass thrust; DB, Dry Bone syncline; DC, Dry Creek thrust; G, Grapevine thrust; IP, Indian Pass syncline; KS, Kwichup Spring thrust; L, Lemoigne thrust; LC, Last Chance thrust system; M, Montgomery thrust; MC, Marble Canyon thrust; PA, Panamint anticline; P-d, Panamint thrust (deep exposure); P-s, Panamint thrust (shallow exposure); QM, quartz monzonite; SC, Slate Canyon thrust; SP, Schwaub Peak thrust; TC, Titus Canyon anticline; WBM, Western Black Mountains thrust system; WP, Winters Pass thrust; WhP, Wheeler Pass thrust; WPLC, Winters Peak/Lees Camp anticline; WT, White Top fold pair. Adapted from *Krauskopf* [1971], *Crowder et al.* [1972], *Robinson and Crowder* [1973], *Stewart et al.* [1974], *Snow and Wernicke* [1989, 2000], *Snow* [1992a], *Reheis and Sawyer* [1997], *Wright and Troxel* [1999], *Niemi* [2002], *Miller and Pavlis* [2005], and *Oldow et al.* [2008].

Alluvial fan 2 offset:
~0.18 ± 0.02 km
since ~0.07 ± 0.01 Ma

Sedimentary contact offset:
~0.55 ± 0.03 km
since ~0.13 +0.06/-0.03 Ma

Alluvial fan 1 offset:
~5.9 +1.1/-1.4 km
since ~0.62 +0.08/-0.02 Ma

Granitic stock offset:
~32 km since ~7.6 ± 0.3 Ma

Basaltic gravel offset:
~8 km since ~3.3 Ma,
~4.05 km since ~1.2 Ma

Alluvial fan 3 offset:
~0.3 ± 0.01 km
since ~0.07 ± 0.02 Ma

Furnace Creek Formation offset:
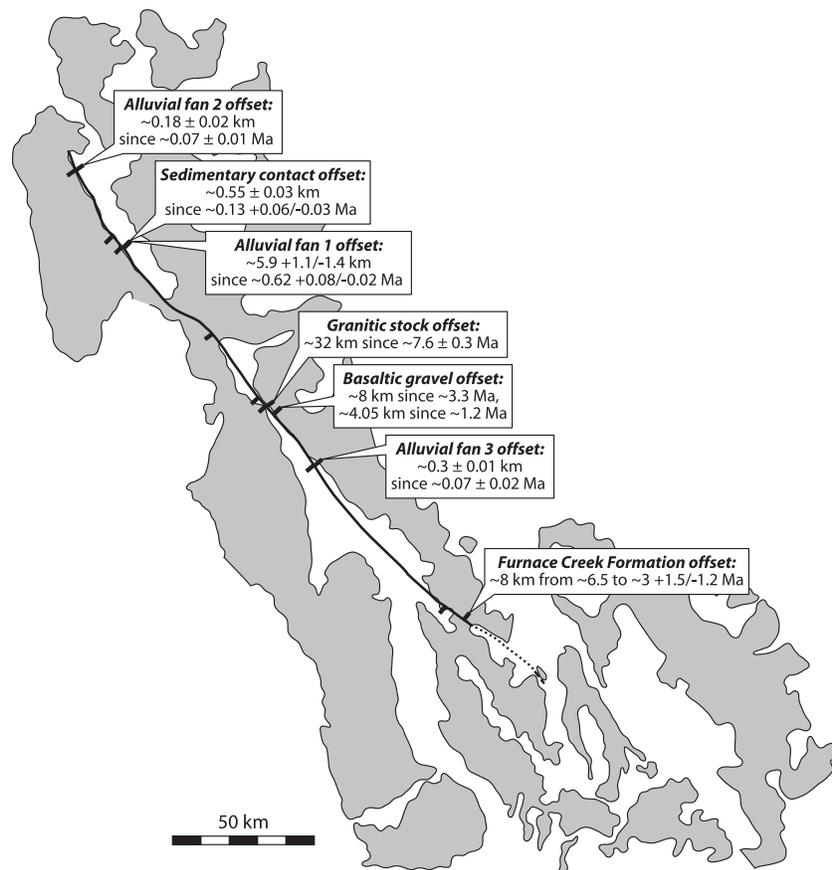~8 km from ~6.5 to ~3 +1.5/-1.2 Ma

50 km

Figure 4. Offsets of selected Neogene markers. Adapted from *Oakes* [1977, 1987], *McKee* [1985], *Reheis and Sawyer* [1997], *Blair and Raynolds* [1999], *Klinger* [2001], and *Frankel, Brantley, et al.* [2007, 2007].

Roberts Mountains thrust [e.g., *Oldow*, 1984; *Stockli et al.*, 2003], whereas others have interpreted the Roberts Mountains thrust to lie farther north, past the termination of the Furnace Creek fault zone [e.g., *Buckley*, 1971]. As much as ~5.9 +1.1/−1.4 km of the total dextral displacement in the vicinity of the Slate Canyon and Dry Creek thrusts is inferred to have accrued since just ~0.62 +0.08/−0.02 Ma, based on the offset and age of alluvial fan sediments in central Fish Lake Valley (FLV in Figure 1; alluvial fan 1 in Figure 4 and Table 1) [*Reheis and Sawyer*, 1997].

3.2. Quartz Monzonite of Beer Creek

[10] Correlation of the Middle Jurassic quartz monzonite of Beer Creek (QM in Figure 3) between the Sylvania and White Mountains (Figure 1) implies ~40–50 km of dextral displacement, and most likely ~50 km (Figure 5) [*McKee*, 1968; *Reheis and McKee*, 1991; *Reheis and Sawyer*, 1997]. Uncertainty in offset results from each exposure being a partial representation of a three-dimensional body, rather than a linear feature intersecting the fault zone at a single point. Although this marker has been regarded as "the best estimate of total motion on the Furnace Creek fault" [*Niemi*, 2002, p. 200], correlation of the exposures could be further tested by "fingerprinting" each of them with modern geochemical techniques. Along this same part of the fault zone, *Reheis* [1993] initially interpreted a ~40 km offset of a distinctive, ~6 Ma sandstone to imply that most or all of the quartz monzonite displacement accumulated after

Miocene time. Subsequently, she concluded that this was unlikely because the implied slip rate would have nearly equaled the total displacement rate for the Basin and Range at that latitude, leaving no way to account for the contributions of other faults in the region [*Reheis and Sawyer*, 1997]. So either the initial correlation was incorrect, or the sandstone was originally distributed in such a way that its total offset since ~6 Ma is less than ~40 km.

3.3. Grapevine–Last Chance Thrust Fault

[11] The Grapevine thrust in the Grapevine Mountains (G in Figure 3; see also Figure 1) is widely considered to correlate with the Last Chance thrust system in the Last Chance Range and Cottonwood Mountains (LC in Figure 3; see also Figure 1) [e.g., *Stewart et al.*, 1966; *Wernicke et al.*, 1988a; *Snow and Wernicke*, 1989, 2000; *Snow*, 1990, 1992a; *Niemi*, 2002]. Both structures verge eastward and have stratigraphic throws estimated at ~5–6 km [*Reynolds*, 1969; *Snow*, 1990, 1992a; *Snow and Wernicke*, 2000; *Niemi*, 2002].

[12] Their offset along the Furnace Creek fault zone, however, is poorly quantified. *Snow and Wernicke* [2000] inferred that a ramp in the system had been displaced ≥ 63 km between the Cottonwood and Grapevine Mountains. *Niemi* [2002, 2012] showed that the Grapevine ramp actually reflects the cutoff of an antecedent anticline, and does not match the ramp in the Cottonwood Mountains.

[13] Younger markers constrain displacement in the Grapevine–Last Chance portion of the fault zone, although
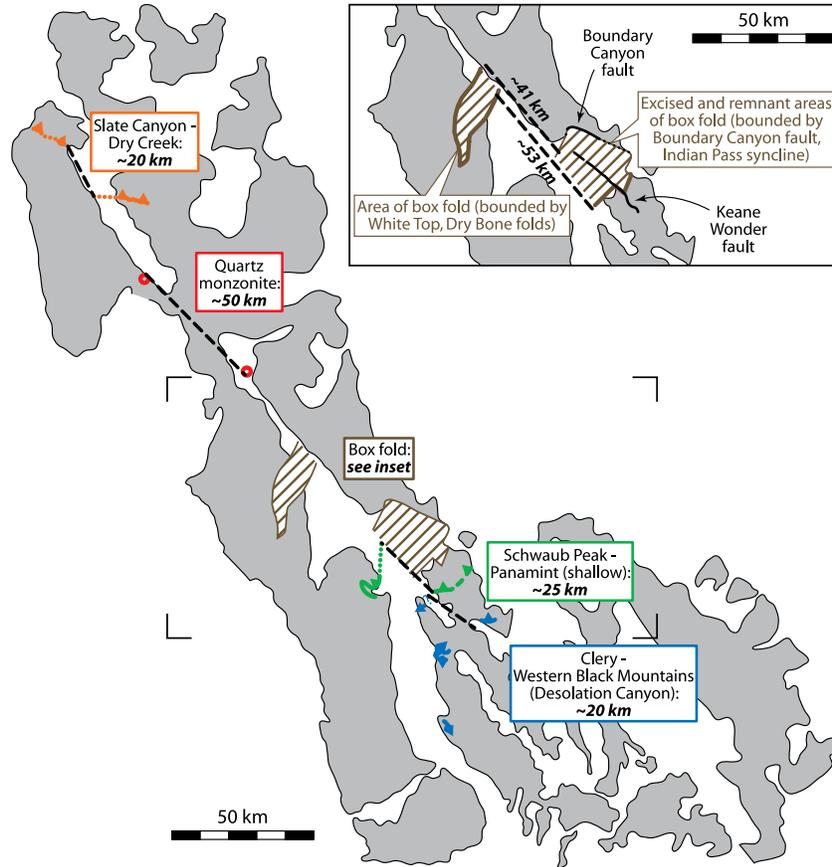
Figure 5. Location of total offset estimates. Dashed tie lines represent total offset. Inset (top right, same scale as main figure) shows details of how box fold offset was calculated. Brown-and-white-striped areas show span of box fold in Cottonwood Mountains (defined between White Top and Dry Bone fold axes) and in Funeral Mountains (defined between Boundary Canyon fault, which excised at least part of the structure, and Indian Pass syncline axis). Black dashed lines represent maximum and minimum displacement estimates. Maximum estimate of ~53 km is distance between southern limits of box fold in each mountain range. (Note additional offset along Keane Wonder fault.) Minimum estimate of ~41 km is distance between northern limit of box fold in Cottonwood Mountains and northernmost possible limit of excised fold in Funeral Mountains.

they provide only minimum estimates of total offset. Correlation of granitic stocks suggests ~32 km of dextral displacement since ~7.6 ± 0.3 Ma (Figure 4) [*Oakes*, 1987], an interpretation that could be further tested by geochemical comparison of the stocks. Extrapolating the average slip rate implied by this marker (32 km per 7.6 ± 0.3 Myr) back to 10–13 Ma (when faulting likely began; section 4.2) implies a total offset of ~49 ± 8 km, which is compatible with other nearby estimates, such as from the quartz monzonite. The final ~8 km has been interpreted to have accrued since ~3.3 Ma (a maximum age estimate), and the last ~4.05 km since ~1.2 Ma (a minimum age estimate), based on the progressive offset of basaltic alluvial fan gravel from its source (Figure 4) [*Klinger and Sarna-Wojcicki*, 2001].

3.4. Box Fold

[14] A pair of west and east vergent structures in the Cottonwood Mountains is inferred to correlate with comparable structures in the Grapevine–Funeral Mountains block (Figure 1). The structures in the Cottonwoods are the west vergent White Top fold pair and the east vergent Marble

Canyon thrust and Dry Bone footwall syncline (WT, MC, DB in Figure 3). Taken together (Figure 6A), they define a faulted box fold with 3.5 ± 1.1 km of vertical structural relief on the fold pair and 3.0 ± 0.3 km of stratigraphic throw on the thrust [*Snow and Wernicke*, 1989, 2000; *Snow*, 1990, 1992a]. The structures are inferred to be no younger than late Permian to Middle Triassic, based on crosscutting relationships with stocks of that age (Figure 3) [*Snow et al.*, 1991].

[15] East of Death Valley, the box fold includes several structures dispersed by subsequent faulting. The west vergent structure manifests in the northern Grapevine Mountains as the imbricate Bonnie Claire thrust system (BC in Figure 3) [*Niemi*, 2002] and in the central and southern Grapevines as an upright to recumbent fold pair: the Titus Canyon anticline and associated synclines (TC in Figure 3) [*Reynolds*, 1969; *Snow and Wernicke*, 1989; *Niemi*, 2002]. This correlation assumes that the Grapevine Mountains structures have rotated counterclockwise [*Snow and Prave*, 1994; *Snow and Wernicke*, 2000]. The thrust fault's stratigraphic throw and the structural relief of the fold pair are both ≥ ~2.4–2.5 km [*Reynolds*, 1969; *Snow*

Table 1. Timing of Offsets and Implied Average Displacement Rates[a]

Constraint	Offset (km)			Start Date[b] (Ma)			Displacement Rate[c] (mm/yr)			Notes
	Max	Pref	Min	Max	Pref	Min	Max	Pref	Min	
Slate Canyon–Dry Creek Thrust (1,2)	20	20	15	13	11	10	2.0	1.8	1.2	Start dates follow section 4.2.
Quartz monzonite (1,2,3)	50	50	40	13	11	10	5.0	4.5	3.1	Start dates follow section 4.2.
Box fold	53	47	41	16	11.5	9	5.9	4.1	2.6	Range of possible offset shown in Figure 5. Start dates follow section 4.2.
Schwaub Peak–Panamint thrust	33	25	17	18.5	13	11	3.0	1.9	0.9	Max, min, offsets from uncertainty in projections of thrusts to fault zone. Start dates follow section 4.2: max from en echelon folds (4), pref from onset of significant extension in northern Black Mountains, min from Eagle Mountain Formation (5).
Clery–Western Black Mountains thrust	30 (6)	20	10	18.5	13	11	4.6	2.0	0.6	Max, min offsets from uncertainty in projection of thrusts to fault zone. Cessation of faulting in this area ≤4.5 and >1.8 Ma (7,8); our preferred estimate is ~3 Ma (section 3.6).
Sandstone (9)		40			6			6.7		
Granitic stocks (10, 11, 12)		32		7.9	7.6	7.3	4.4	4.2	4.1	
Furnace Creek Formation (7)		8			6.5		4.0	2.3	1.7	Cessation of faulting in this area ≤4.5 and >1.8 Ma (7,8); our preferred estimate is ~3 Ma (section 3.6).
Alluvial fan 1 (2)	7	5.9	4.5	0.7	0.62	0.6	11.7	9.5	6.4	
Basaltic gravel (13, 14)		8			3.3			1.9		Displacement rate calculated for 3.3–1.2 Ma.
		4.05			1.2			3.4		Displacement rate calculated for 1.2–0 Ma.
Alluvial fan 2 (15)	0.2	0.18	0.16	0.08	0.07	0.06	2.9	2.5	2.1	Max, pref, min displacement rates from (15).
Sedimentary contact (2)	0.58	0.55	0.52	0.19	0.13	0.1	5.75	4.4	2.7	
Alluvial fan 3 (16)	0.31	0.3	0.29	0.09	0.07	0.05	6.1	4.5	3.1	Max, pref, min displacement rates from (16).

[a]References used for estimates of offset and start dates, where not indicated otherwise in notes. Note that additional, younger markers have been identified along the fault zone; see *Reheis and Sawyer* [1997] and *Frankel, Brantley, et al.* [2007, 2007] for summaries. Numbers in parentheses are data sources as follows: 1, *Reheis and McKee* [1991]; 2, *Reheis and Sawyer* [1997]; 3, *McKee* [1968]; 4, *Çemen et al.* [1999]; 5, *Niemi et al.* [2001]; 6, *Çemen and Baucke* [2005]; 7, *Blair and Raynolds* [1999]; 8, *Knott et al.* [2005]; 9, *Reheis* [1993]; 10, *Oakes* [1977]; 11, *McKee* [1985]; 12, *Oakes* [1987]; 13, *Klinger* [2001]; 14, *Klinger and Sarna-Wojcicki* [2001]; 15, *Frankel, Dolan, et al.* [2007]; 16, *Frankel, Brantley, et al.* [2007].

[b]Start date reflects time when indicated offset began to accrue. For pre-Neogene markers, this is the start of Neogene faulting. For other markers, it is the age of the marker.

[c]Max, pref, min displacement rate obtained by dividing max, pref, min displacement by min, pref, max duration, respectively. Duration equal to interval between start date and 0 Ma unless otherwise noted.

and Wernicke, 1989; *Niemi*, 2002]. The age of these structures is not tightly constrained. Crosscutting relationships indicate that deformation started between Mississippian or Pennsylvanian and Oligocene time, and possibly continued into Miocene time [*Niemi*, 2002]. The east vergent counterpart to the structures, which is not exposed in the Grapevine Mountains, would originally have lain still farther to the east. At the southern end of the range, the west vergent fold pair decreases significantly in amplitude and becomes relatively upright in the vicinity of the underlying Boundary Canyon detachment (Figure 2), a normal fault inferred to have separated the Grapevine and Funeral Mountains in Neogene time [e.g., *Reynolds et al.*, 1986; *Troxel and Wright*, 1989; *Hoisch and Simpson*, 1993; *Wright and Troxel*, 1993; *Applegate and Hodges*, 1993, 1995].

[16] We hypothesize that any southward continuation of the fold pair, as well as much or all of its east vergent counterpart, was excised during exhumation of high-grade metamorphic rocks in the northern Funeral Mountains (with an along-strike continuation of the fold pair potentially still present under cover in the Amargosa Valley). A missing, excised thrust fault in that area has been previously interpreted on the basis of (1) thermobarometric evidence for overburden exceeding the stack of preserved thrusts and (2) comparisons of suites of contractile structures across the Furnace Creek fault zone [*Hodges and Walker*, 1990; *Czajkowski*, 2002; cf. *Hoisch and Simpson*, 1993]. *Applegate and Hodges* [1995] suggested that the high-grade rocks originated not

in the footwall of an additional fault between the Grapevine and Schwaub Peak thrusts (G, SP in Figure 3), but beneath the basal décollement of the fold and thrust belt. The missing overburden totals ~12–18 km [*Applegate and Hodges*, 1995], more than the throw of individual thrust faults in the region. In the hypothesis of *Applegate and Hodges* [1995], lateral extrusion of a crustal wedge at depth would have permitted excision of the décollement and exhumation of high-grade material without requiring upper crustal normal faulting [cf. *Hodges and Walker*, 1990; *Mattinson et al.*, 2007]. This deep-seated mechanism was intended to rationalize Late Cretaceous mineral cooling ages with the absence of an extensional basin of that age.

[17] We agree that an original, subdécollement location for the high-grade rocks can account for the paleopressures, but infer, in addition to that explanation, another thrust fault between the Grapevine and Schwaub Peak thrusts. Such a fault is consistent with a paleodepth estimate of ~22 km for strata in the Indian Pass area (IP in Figure 3) [*Hoisch and Simpson*, 1993], rocks that were not derived from below the basal décollement. Although such a fault would need to have been at least partially excised by upper crustal normal faulting and erosion, just a few kilometers of uplift and downcutting would most likely suffice to excise the thrust, and that could have been accomplished during Miocene activity on the Boundary Canyon detachment. Additional, earlier normal faulting cannot be ruled out because the associated basin may have been sufficiently localized not
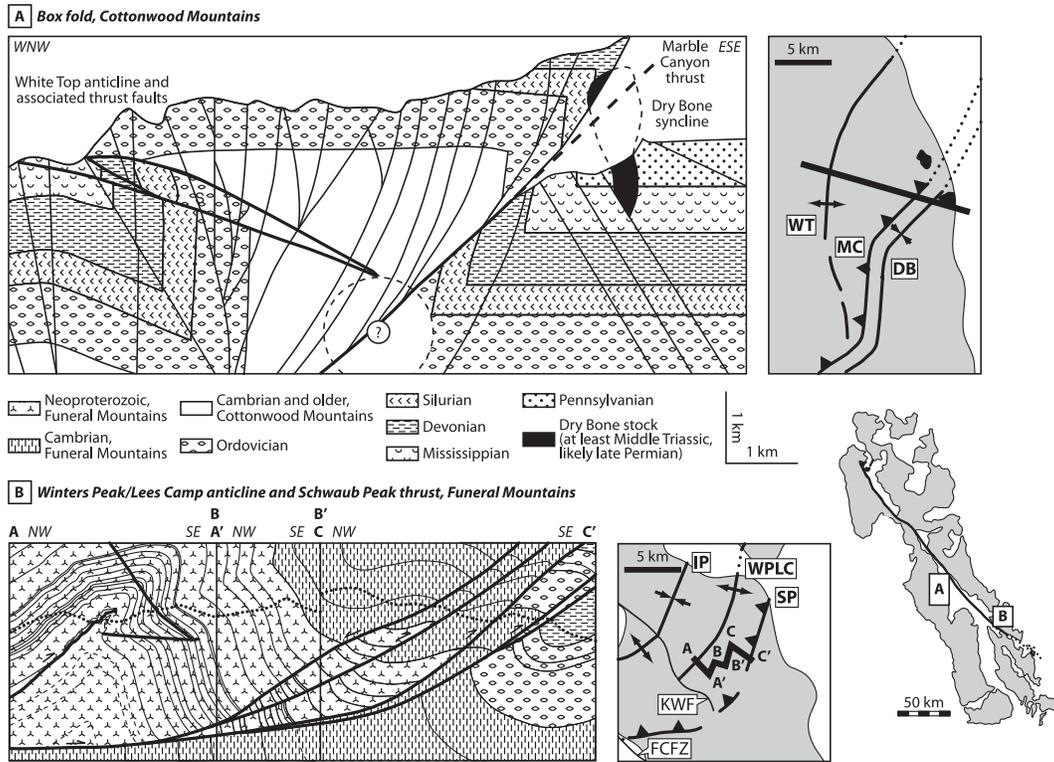
Figure 6. Cross sections of structures in Cottonwood and Funeral Mountains. Line locations shown in maps to right of each section. (A) Cross section of box fold in Cottonwood Mountains, with displacement along normal faults restored. Box fold is defined by west vergent structures shown at left (White Top fold and associated thrust faults) and east vergent structures shown at right (Marble Canyon thrust and Dry Bone syncline). Interaction between west and east vergent structures at depth is uncertain (circled area with question mark). (B) Cross section of Winters Peak/Lees Camp anticline and Schwaub Peak thrust in Funeral Mountains. Dotted line shows present-day topography. Geology above topography and at depth is projected from outside the plane of section. The Winters Peak/Lees Camp and Schwaub Peak structures verge southeastward, very nearly parallel to each other, with only minor overprinting on the anticline showing northwest vergence. Note that a westward tilt correction would produce a west vergent fold carried by an east directed thrust fault. Abbreviations: DB, Dry Bone syncline; FCFZ, Furnace Creek fault zone; IP, Indian Pass syncline; KWF, Keane Wonder fault; MC, Marble Canyon thrust; SP, Schwaub Peak thrust; WPLC, Winters Peak/Lees Camp anticline; WT, White Top fold pair. Adapted from *Snow* [1990] and *Czajkowski* [2002].

to have survived subsequent erosion. We consider the hypothesized thrust fault excised in this manner to provide a potential correlate for the portion of the box fold equivalent to the Marble Canyon thrust.

[18] Although correlating a portion of the box fold with a fault that is now missing may seem speculative, we caution against assuming that all map traces of the original fold-and-thrust belt are preserved in some form – particularly where exhumation has been extreme, as in the case of the northern Funeral Mountains metamorphic core complex. Given the inherent uncertainties in correlating preextensional structures, it seems judicious not to invoke missing thrust structures arbitrarily, but to allow for them – as hypotheses – where clues are available. In the case of the box fold, those clues include: (1) the observation that its Grapevine Mountains expression appears to be truncated by the Boundary Canyon fault, (2) the thermobarometric evidence for additional overburden, (3) the presence of a syncline at the southern end of the core complex near Indian Pass (IP in Figure 3, Figure 5) [*Troxel and Wright*, 1989; *Çemen and Wright*, 1990;

Wright and Troxel, 1993], which implies that the east vergent portion of the box fold was not entirely excised, and (4) the unlikelihood that other Funeral Mountains thrust faults correlate with the box fold (discussed below).

[19] The inference that the box fold originally continued through the northern Funeral Mountains implies dextral offset of ~47 ± 6 km along the Furnace Creek fault zone (Figure 5). A minimum offset of ~41 km is required by the distance between the fold in the Cottonwood Mountains and the Boundary Canyon fault (Figure 5 inset). This minimum estimate represents the possibility that the Grapevine Mountains expression of the box fold not only decreases in amplitude in the southernmost portion of that range, but dies out altogether under Cenozoic cover in the area of the Boundary Canyon fault. A maximum estimate is the distance between Indian Pass syncline and its potential equivalent in the Cottonwood Mountains, the Dry Bone syncline adjacent to the Marble Canyon thrust (DB, MC in Figure 3, Figure 5). The distance between the Indian Pass and Dry Bone synclines is ~53 km, accounting for ~5 km

of dextral displacement on the Keane Wonder fault (Figure 5 inset) [*Çemen and Wright*, 1990]. Although the Indian Pass fold appears to be fairly open, it is possible that the exposure represents only the lower limb and part of the trough of a larger, tighter structure, and that the axis of the latter, at the same stratigraphic level, is located farther to the northwest. Note also that normal faulting within the range has spread out the fold in map view, exaggerating its openness. In any case, our interpretation does not depend critically on this syncline, because correlations between structures southeast of the Cottonwood Mountains box fold do not permit it to restore much past the Indian Pass area.

[20] Our estimate of ~47 ± 6 km is less than estimates from previous reconstructions using the White Top and Marble Canyon structures: ~68 ± 4 km [*Snow and Wernicke*, 1989, 2000; *Snow*, 1990, 1992a] and ~80 km [*Stevens et al.*, 1992]. Only the extreme upper limit on our estimate approaches 64 km. The still larger estimate of ~80 km involves correlating the box fold with the east vergent Clery thrust (C in Figure 3) and an unnamed, west vergent anticline nearby. These structures are not a good match. The unnamed anticline dies out abruptly along strike [*Snow and Wernicke*, 1993], and there is no particular structural similarity to suggest correlation of the Marble Canyon and Clery thrusts. As acknowledged by *Stevens et al.* [1992, p. 1069], the thrust correlation was a "by-product" of reconstructing Mississippian facies belts.

[21] The ~68 ± 4 km estimate was based on the identification of the west and east vergent Funeral Mountains structures as the Winters Peak/Lees Camp anticline and the Schwaub Peak thrust, respectively (WPLC and SP in Figures 3 and 6). The distance is the length of a displacement vector between the box fold in the Cottonwood and Funeral Mountains (projected into Death Valley), corrected for offsets along normal and strike-slip faults at the edge of each range. The uncertainty of 4 km accounts for errors in the orientation of the contractile structures, as well as a possible upper limit on displacement set by a Cottonwood Mountains intrusion (stock indicated by the eastern arrow in Figure 3 and shown in more detail in Figure 6) that has no correlate in the Funeral Mountains.

[22] Because the regional fold-and-thrust belt generally verges eastward, the west vergent portion of the box fold correlation was presented as the "unique" key to a set of three contractile-structure matches between the Cottonwood and Funeral Mountains [*Snow and Wernicke*, 1989]. The other two correlations involve the Marble Canyon and Schwaub Peak thrusts (the east vergent portion of the box fold), and the Lemoigne and Clery thrusts farther south (sections 3.5 and 3.6 and Figure 3). As expressed in the original paper, the set of correlations is "based largely on recognition of the backfold as a regionally persistent, unique structural marker" [*Snow and Wernicke*, 1989, p. 1359]. This distinctive structure is hypothesized to have originated as part of a broad anticlinorium mechanically localized between the Paleozoic shelf-slope transition and an imbricate thrust stack in older, clastic strata [*Snow and Wernicke*, 1989].

[23] Our correlation scheme is consistent with this "uniqueness" argument. We accept the west vergent correlation between the Cottonwood and Grapevine Mountains (White Top and Titus Canyon fold pairs) and reinterpret only its location in the footwall of the Boundary Canyon fault:

excision from the northern Funeral Mountains is still consistent with the anticlinorium explanation. Interpreting the footwall expression of the box fold as the Winters Peak/Lees Camp anticline and the Schwaub Peak thrust does not account for the missing overburden discussed above. Moreover, later work casts doubt on the correlation [*Czajkowski*, 2002].

1. The Winters Peak/Lees Camp anticline verges southeast rather than west (Figure 6B) [*Wright and Troxel*, 1993; *Czajkowski and Miller*, 2001; *Czajkowski*, 2002]. (*Stevens et al.* [1992] also argued that the White Top and Winters Peak/Lees Camp folds have different orientations.) Previous interpretation of west vergence may have been guided by a minor northwest vergent overprint (Figure 6B) [*Czajkowski and Miller*, 2001; *Czajkowski*, 2002] or by a westward tilt correction for the Funeral Mountains range block. Regardless, the fold is nearly parallel to the Schwaub Peak thrust (Figure 6B), in contrast to the geometry of the White Top and Marble Canyon structures in the Cottonwood Mountains, which strongly diverge upward (Figure 6A). *Czajkowski* [2002] interpreted the Winters Peak/Lees Camp anticline not as part of a box fold but as a detachment fold that developed with the Schwaub Peak thrust. She proposed that the anticline formed by buckling above the Schwaub Peak thrust. Support for this interpretation includes isoclinally folded, relatively weak marble in the core of the fold, with the overlying section including alternating strata of higher and lower competency that exhibit flexural slip and flexural flow.

2. The northwest vergent overprint on the Winters Peak/Lees Camp anticline dies out upward [*Czajkowski*, 2002]. This poses a problem both for correlation to the White Top fold pair, which represents a higher structural level and also amplifies upward [*Czajkowski*, 2002], and for correlation to the Titus Canyon fold pair, which deforms a higher part of the stratigraphic section than the Winters Peak/Lees Camp anticline.

3. The Winters Peak/Lees Camp anticline and Schwaub Peak thrust are inferred to be Cretaceous [*Czajkowski and Miller*, 2001; *Czajkowski*, 2002]. The ~92 Ma timing of peak paleopressure in the northern Funeral Mountains requires imposition of a Cretaceous load [*Mattinson et al.*, 2007], beyond the original sedimentary overburden and Permian-Triassic thrust sheets. *Applegate and Hodges* [1995, their Figure 7] inferred the additional load to come from the combined thickness of the Schwaub Peak and lower thrust plates. (Note that, at the time of their publication, the loading was not yet constrained as Cretaceous.) The work of Applegate and Hodges and Mattinson et al. together suggests that Schwaub Peak thrust (and its associated Winters Peak/Lees Camp fold) were involved in the ~92 Ma event. This means that these structures postdate the Cottonwood Mountains box fold substantially.

[24] The existence of these Funeral Mountains structures supports our estimate of box fold offset. Because the Grapevine Mountains show no expression of the Winters Peak/Lees Camp or Schwaub Peak (or Clery) structures, the Boundary Canyon detachment could not have moved the Grapevine terrane farther than from a paleoposition
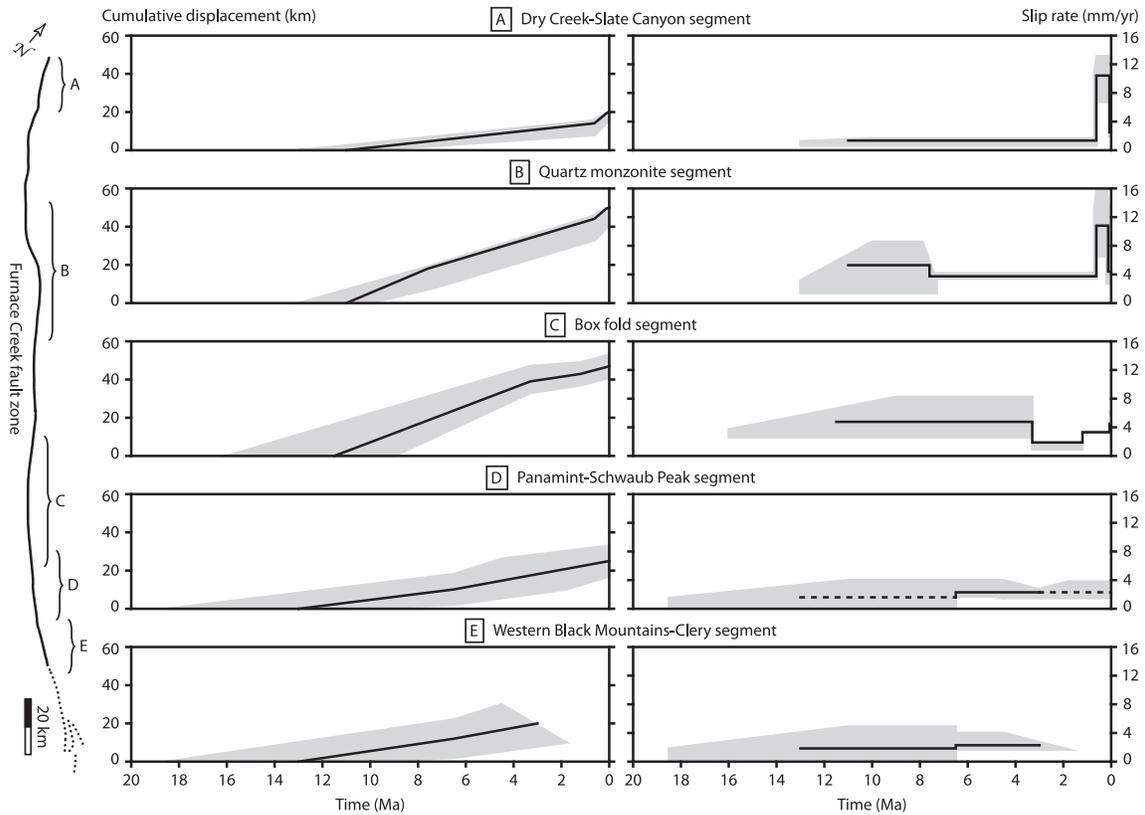
Figure 7. Displacement and displacement rate over time and along strike (values listed in Tables 2a and 2b). Black curves are based on best estimates of offset for individual markers. Gray shading accounts for uncertainty in both timing and magnitude of those offsets. (If only the timing or the magnitude were uncertain, then the slip rate plots would show rectangular error envelopes; it is the combined uncertainty that produces more trapezoidal envelopes. See Table 2b for details.) Only the youngest interval for the Schwaub Peak–Panamint thrust segment is not directly constrained. The Furnace Creek Formation records ~8 km of displacement between ~6.5 and ~3 +1.5/−1.2 Ma (section 3.6). Motion on the fault zone is inferred to have ceased thereafter in the Furnace Creek Wash area, where the Furnace Creek Formation is located, but not in the Schwaub Peak–Panamint thrust segment of the fault zone. So post-~3 Ma motion on that segment is not quantified but is required for the cumulative displacement and slip rate plots. As a rough estimate, we applied the ~6.5–3 Ma slip rate to post-~3 Ma activity, calculating ~6.86 km of displacement for ~3–0 Ma, and implying ~10.14 km for ~13–6.5 Ma. The slip rate plot shows dashed lines for these time intervals.

above the north central Funeral Mountains. The "uniqueness" argument does not cover the east vergent portion of the box fold: "there is nothing geometrically distinctive about a series of east directed thrusts, and there would be a good chance of finding another palinspastically permissible correlation" [*Snow and Wernicke*, 1989, p. 1357].

3.5. Schwaub Peak–Panamint Thrust Fault

[25] We correlate the Schwaub Peak thrust and associated folds with the Panamint thrust in the Panamint Mountains (SP, P in Figure 3). This correlation implies ~25 ± 8 km of displacement (Figure 5). Although our reconstruction also permits the Lemoigne thrust in the Cottonwood Mountains (L in Figure 3) to correlate with the Panamint and Schwaub Peak thrusts, a simpler interpretation is that the Lemoigne instead dies out along strike before reaching the Furnace Creek fault zone. The rest of this section addresses, first, the Schwaub Peak–Panamint correlation, and second, interpretations of the Lemoigne thrust.

3.5.1. Correlation of the Schwaub Peak and Panamint Thrusts

[26] The correlation of the Schwaub Peak and Panamint thrusts was suggested but not developed by *Czajkowski* [2002] on the basis of mid-Cretaceous or younger ages inferred for both structures [*Hodges et al.*, 1990; *Wernicke et al.*, 1993; *Snow and Wernicke*, 2000; *Czajkowski and Miller*, 2001; *Czajkowski*, 2002]. The Schwaub Peak thrust and the Panamint thrust at its shallower level exposure (P-s in Figure 3) are each associated with hangingwall anticlines, hangingwall ramps, and overturned footwall synclines [*Wernicke et al.*, 1988b; *Troxel and Wright*, 1989; *Hodges et al.*, 1989; *Snow and Wernicke*, 1989; *Snow*, 1992a; *Wright and Troxel*, 1993; *Snow and Wernicke*, 2000; *Czajkowski*, 2002]. Their stratigraphic throws are 3.8 ± 0.2 km and ~5 km, respectively [*Hodges et al.*, 1989; *Snow and Wernicke*, 1989; *Wright and Troxel*, 1993]. An alternative interpretation, in which the Schwaub Peak correlates with a thrust in the northern Cottonwood Mountains [*Stevens et al.*, 1992], is not viable because of differences in the timing of

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thrusting (references above), original thrust fault geometry, and proximity to metamorphosed strata [*Snow and Wernicke*, 1993]. We follow *Snow and Wernicke* [2000, and references therein] in regarding the latter, the Cottonwood Mountains thrust, as part of the Last Chance system.

[27] The Schwaub Peak–Panamint correlation differs from a prior interpretation of the Panamint thrust, which holds that its exposures at shallow and deep levels represent the updip and downdip continuations, respectively, of the Chicago Pass thrust system in the Resting Spring and Nopah ranges (CP in Figure 3; RSR, NR in Figure 1). Whereas the deeper-level exposure of the Panamint thrust is in highly metamorphosed rock, the deeper-level exposure of the Chicago Pass thrust is not, posing a challenge to the correlation (M. B. Miller, personal communication, 2009). In addition, the Chicago Pass system has potential correlates along strike: the Winters Pass, Wheeler Pass, and possibly Montgomery thrusts (WP, WhP, M in Figure 3) [*Wernicke et al.*, 1988a, 1988b, 1993; *Snow and Wernicke*, 2000]. If correlative, these map view counterparts imply that no additional match is required. We infer that the updip and downdip continuations of the Chicago Pass thrust were simply eroded away and/or down-faulted and buried.

3.5.2. Interpretations of the Lemoigne Thrust

[28] Although it is conceivable that the Lemoigne thrust (L in Figure 3) correlates with the Panamint–Schwaub Peak thrust, a more parsimonious interpretation is that it dies out along strike before reaching the Furnace Creek fault zone, which lies ~35 km northeast of the thrust's nearest exposure. Of all the contractile structures in the Cottonwood Mountains, the Lemoigne thrust crops out farthest from the latter fault zone.

[29] A Lemoigne–Panamint correlation was proposed by *Serpa and Pavlis* [1996] and is consistent with several observations. *Serpa and Pavlis* [1996] noted the similarity in both upper and lower plate rocks, despite the slightly lower 3.0 ± 0.3 km of throw for the Lemoigne thrust [*Snow and Wernicke*, 1989]. The correlation is also consistent with the presence of hangingwall ramps and footwall synclines in both structures [*Snow and Wernicke*, 1989; *Snow*, 1992a; *Wernicke et al.*, 1993; *Snow and Wernicke*, 2000]. The two thrust faults are separated by the normal fault system of the Tucki Mountain complex (Figure 1). More specifically, the Lemoigne footwall structurally overlies the Panamint hangingwall. Thus, correlation requires heave on the normal fault system to be approximately the map view separation between the thrust fault traces, where each emplaces Cambrian over Permian strata [*Snow and Wernicke*, 2000]. That amounts to perhaps ~16 km (L to P-s in Figure 3), depending on vertical axis rotation and the original configuration of exposed thrust sections.

[30] Either option for the Lemoigne thrust is consistent with available evidence for the paleoposition of the Cottonwood Mountains relative to the Panamint Mountains, but there is no independent support for a restoration of the Cottonwood Mountains so far to the southeast that the two thrusts merge. Palinspastic reconstruction of younger features suggests that the Lemoigne thrust originally projected toward and possibly overlapped the northern Panamint Mountains [*Andrew and Walker*, 2009]. Substantial overlap has been inferred from correlation of the White Top and Panamint

anticlines (PA in Figure 3) [*Wernicke et al.*, 1988a, and references therein], but there is significant evidence against this proposed match. Whereas the White Top fold is no younger than late Permian to Middle Triassic [*Snow et al.*, 1991], the Panamint anticline is younger, having been most recently interpreted variously as Jurassic, Cretaceous, and Miocene [*Labotka and Albee*, 1988, and references therein; *Snow and Wernicke*, 1989; *Hodges et al.*, 1990]. Also casting doubt on the correlation are the observations that the White Top fold pair terminates southward within the Cottonwood Mountains [*Snow*, 1990, 1992a; *Snow and Wernicke*, 2000] and that there is no equivalent to the rest of the box fold, including the Marble Canyon thrust, within the Panamint Mountains.

[31] The age of the Lemoigne thrust is not sufficiently well constrained to test its correlation with the Panamint thrust, which is of mid-Cretaceous age or younger. The Lemoigne thrust has been represented as crosscut by the Jurassic Hunter Mountain batholith (Figure 1) [e.g., *Burchfiel et al.*, 1970; *Snow et al.*, 1991; *Snow*, 1992a]; however, map relations are ambiguous in detail [*Hall and Stephens*, 1962; *Hall*, 1971; *Stevens and Stone*, 2005]. A fold interpreted as intrusion-related deforms the thrust [*Dunne*, 1986, citing B. C. Burchfiel, personal communication, 1985], and the batholith folds, intrudes, and metamorphoses hangingwall strata [*Hall and Stephens*, 1962; *Hall*, 1971; *Dunne*, 1986; *Snow and Wernicke*, 1989]. Yet the batholith does not clearly crosscut the fault itself. Similarly, mapped thrust traces locally crosscut the batholith or follow its edge [*Hall and Stephens*, 1962; *Hall*, 1971]. Nonetheless, the batholith is not significantly offset or otherwise deformed by the fault. Although the Lemoigne thrust has been correlated with a Permian fold southwest of the range [*Snow*, 1992a; *Snow and Wernicke*, 2000], that correlation does not establish the Lemoigne age any more than a Panamint thrust correlation does.

[32] A third, more speculative interpretation exists for the Lemoigne-Panamint relationship. If the shallow and deep exposures of the Panamint thrust are not actually the same structure (requiring revision to reconstructions of normal faulting in the northern Panamint Mountains [e.g., *Wernicke et al.*, 1993]), only the deeper fault need be mid-Cretaceous or younger. That fault could then still correlate with the Schwaub Peak thrust, while the shallower level fault could correlate with both the Lemoigne thrust and a structurally lower thrust east of Death Valley such as the Clery.

3.6. Clery–Western Black Mountains Thrust System

[33] We correlate the Clery thrust (C in Figure 3) with one or more of the thrust traces identified in the western Black Mountains (WBM in Figure 3), following *Çemen and Baucke* [2005]. These authors observed that the same Cambrian and Ordovician units are juxtaposed across the Clery thrust and a thrust near Desolation Canyon in the Black Mountains (DC in Figure 1), and hypothesized that the Desolation Canyon thrust relates in some way to thrust faults exposed at deeper structural levels elsewhere in the same range (Figure 3) [*Otton*, 1976; *Holm*, 1992; *Miller and Friedman*, 1999; *Turner and Miller*, 1999;

Miller, 2003; *Miller and Pavlis*, 2005]. The relationship between the various Black Mountains thrust faults remains uncertain, however. *Çemen and Baucke* [2005] inferred dextral offset of 30 ± 5 km. Although their exact rationale for this number was not given, it seems to be a maximum estimate of the distance between the Clery and Desolation Canyon structures (Figure 3). We tentatively infer a displacement of ~20 ± 10 km (Figure 5), depending on the strike of the latter fault and accounting for the possibility that the Clery correlates more directly with one of the other traces of the Black Mountains thrust system.

[34] An alternative hypothesis is that the Clery thrust is a frontal splay of the Schwaub Peak thrust, and therefore was originally linked to the Panamint system. *Serpa and Pavlis* [1996] proposed a Clery-Panamint-Lemoigne correlation on the basis of similar upper and lower plate strata, building on the prior Clery-Lemoigne correlation of *Wernicke et al.* [1988a, 1988b], *Snow and Wernicke* [1989], and *Snow* [1992a]. If the Panamint–Schwaub Peak system gains a frontal splay eastward in the form of the Clery thrust, a lateral ramp would be implied in approximately the position of the Furnace Creek fault zone. The ramp would provide a preexisting weakness, potentially helping to explain the location of the fault zone. We view this hypothesis as less likely because it does not account for the Black Mountains thrust faults.

[35] Both hypotheses permit, but do not require, the view that upper Oligocene to Miocene deposits, now found in the Funeral, Panamint, and Cottonwood Mountains, accumulated in the same basin and drainage system [*Wernicke et al.*, 1993; *Snow and Lux*, 1999; *Snow and Wernicke*, 2000; cf. *Çemen et al.*, 1999]. The tightest paleogeographic constraint arises from the inference that remnants of the same ~15 Ma alluvial fan deposits are present near the Clery and Panamint thrusts, implying an original distance of ≤ 10–20 km between those structures [*Snow and Lux*, 1999; *Niemi et al.*, 2001; cf. *Çemen et al.*, 1999]. In both our interpretations of the Clery thrust, its original distance from the Panamint–Schwaub Peak thrust is ≤ ~19 km, which is its present-day distance from the Schwaub Peak thrust.

[36] The final 8 km of displacement on this segment of the Furnace Creek fault zone occurred between 6.5 Ma and perhaps ~3 Ma, as documented by synkinematic Furnace Creek Formation sediments (Figure 4) [*Blair and Raynolds*, 1999]. The deposits were originally inferred to be 6.5–4.5 Ma [*Blair and Raynolds*, 1999], but more recent interpretations suggest the youngest are <3.5 Ma, perhaps ~3 Ma, with fault-related deformation in Furnace Creek Wash ceasing by > ~1.8 Ma [*Knott et al.*, 2005]. Part of the difference between these estimates may relate to activity on different fault strands at different times.

3.7. Mesoproterozoic-Paleozoic Stratigraphic Markers

[37] Although several Mesoproterozoic-Paleozoic stratigraphic markers are of historical significance in suggesting dextral displacement consistent with our estimates, e.g., the ≤ ~45–50 km offset of a Cambrian facies boundary, located between the ~50 km quartz monzonite offset and the ~20 km Slate Canyon–Dry Creek offset [*Stewart*,

1967, 1992], as well as the offset of Cambrian isopachs in the vicinity of the Panamint and Schwaub Peak thrusts [*Prave and Wright*, 1986a], we regard constraints from such markers as imprecise, for several reasons.

1. Pre-Mesozoic rocks have been substantially deformed by crustal shortening as well as extension and strike slip, including dextral faults other than the Furnace Creek structure. It is therefore difficult to isolate the Furnace Creek component of total displacement, especially because it is not the only dextral fault in the area [e.g., *Fridrich*, 1999, and references therein; *Guest et al.*, 2007].
2. Control points for stratigraphic markers are sparse, particularly in the Grapevine, Funeral, and Black Mountains [see, e.g., *Stevens et al.*, 1991, 1992; *Snow*, 1992b; *Snow and Wernicke*, 2000, Figure 5].
3. The regional trend of isopachs and facies boundaries is oriented at a smaller angle to the Furnace Creek fault zone than the traces of contractile structures [e.g., *Snow and Wernicke*, 2000, Figure 5]. The stratigraphically based offsets are therefore inherently less well constrained than the structural ones. This effect may be underappreciated because crustal shortening reduced the southeast-northwest distance between stratigraphic control points, increasing the apparent angle between stratigraphic contours and the Furnace Creek fault zone.
4. In contrast to relatively simple regional patterns, isopachs and facies transitions are likely to have been originally sinuous or irregular in detail, and their exact configuration has been debated [cf., e.g., *Prave and Wright*, 1986a, 1986b; *Stewart*, 1986]. Thus, even if the markers can be correlated, their realignment remains poorly constrained.

4. Timing of Faulting

4.1. Pre-Neogene Activity

[38] We speculate that any pre-Neogene motion on the fault zone was Late Cretaceous or perhaps Paleogene in age. This is consistent with similarity in offsets between the mid-Cretaceous Schwaub Peak–Panamint thrust and older Paleozoic-Mesozoic markers. Late Cretaceous–Paleogene dextral displacement has been identified along various structures, from ranges immediately west of Fish Lake Valley and Death Valley to the Sierra Nevada [e.g., *Kylander-Clark et al.*, 2005, and references therein; *Bartley et al.*, 2007, and references therein].

[39] If it occurred at all, Late Cretaceous dextral transfer faulting seems most explicable between what are now the northern Panamint and Funeral Mountains, although we infer that any such displacement would have been limited. Northwest directed extension of that age has been inferred along shear zones in the northern Funeral Mountains (Figure 1) [*Applegate et al.*, 1992; *Applegate and Hodges*, 1995] and was potentially linked to transport along the early extensional complex at Tucki Mountain (Figures 1 and 2) [*Applegate et al.*, 1992; *Andrew and Walker*, 2009]. Realignment of the box fold and the Schwaub Peak–Panamint thrust implies a left step between these complexes, permissive of dextral transfer faulting, although they need not have been bounded by strike-slip faults at all. Transfer faulting would have displaced the box fold and not the quartz monzonite. Those markers have respective offsets of ~47 ± 6 km and

~50 km, and the difference between these values limits the horizontal component of the transfer-related displacement. In addition, the late Miocene granitic stocks (section 3.3) indicate an average post-~7.6 Ma displacement rate of ~4.2 mm/yr. At that rate, the full ~47–50 km offset could be achieved if faulting initiated at ~11–12 Ma, consistent with previous interpretations for that part of the fault zone [e.g., *Reheis and Sawyer*, 1997; *Oldow et al.*, 2008].

4.2. Neogene Activity

[40] Most Neogene motion along the full length of the fault zone is interpreted to be ~13–10 Ma and younger. In Fish Lake Valley, activity is inferred to have begun at ~13–10 Ma. The earliest indication is from the extension apparently coordinated with the Furnace Creek fault zone in the Silver Peak–Lone Mountain complex (Figure 2) [*Oldow et al.*, 2008, and references therein], where synkinematic deposits are as old as ~15–13 Ma, and ~13 or ~12 Ma in their western reaches [*Stewart and Diamond*, 1990; *Diamond and Ingersoll*, 2002; *Oldow et al.*, 2008]. Zircon fission track ages from the footwall are ~11 Ma [*Oldow et al.*, 1994]. The shift from a tectonically quiescent to active landscape around and west of the fault zone has been estimated as ~10 Ma, potentially 11.9–8.2 Ma, based on the ages of an erosional surface and fault-related deposits [*Reheis and Sawyer*, 1997]. It is possible, however, that the landscape relates more to vertical than to lateral tectonism. *Stockli et al.* [2003] suggested that strike-slip faulting in Fish Lake Valley began at ~6 Ma, but this does not account for the ~13 ± 5 km difference in offset between the Jurassic quartz monzonite and the late Miocene granitic stocks. Such a young inception date was considered unlikely by *Reheis and Sawyer* [1997] because the implied average slip rate would have nearly equaled the total displacement rate for the Basin and Range at that latitude, leaving no way to account for the contributions of other faults in the region.

[41] Along northern to central Death Valley, the inception of Furnace Creek activity is inferred to have been coeval with the onset of Neogene extension in the northern Funeral Mountains at ~12–11 Ma. The $^{40}Ar/^{39}Ar$ cooling ages indicate rapid (extensional) exhumation at that time [*Applegate and Hodges*, 1993; *Applegate*, 1994]. A pre-12 Ma, potentially ~16 Ma, unconformity has been interpreted as the earliest evidence of extension [*Applegate*, 1994; *Saylor and Hodges*, 1994], but hanging wall strata have also been interpreted to date the onset at ~9 Ma [*Reynolds et al.*, 1986].

[42] The inception of dextral motion from central Death Valley to the Amargosa Valley has been debated. We interpret it to be approximately early Miocene, with an intensification of activity in late middle Miocene time. The oldest reported evidence of strike slip is ~19–18 Ma for interpreted en echelon folds and an associated reverse fault in the southeastern Funeral Mountains [*Çemen et al.*, 1999]. Inverted stratigraphy observed in clasts in synkinematic deposits in the same area, alternatively interpreted as ~16–17 Ma [*Çemen et al.*, 1999] and ~15 Ma [*Snow and Lux*, 1999], has been viewed as consistent with some lateral migration as well as uplift of the source area [*Çemen et al.*, 1999]. If those deposits correlate with an ~15 Ma alluvial fan remnant near Tucki Mountain, minimal displacement could have accrued before that time (section 3.6) [*Snow and Lux*, 1999; cf. *Çemen et al.*, 1999]. Development of a basin along Furnace Creek

Wash at ~14 Ma [e.g., *Çemen et al.*, 1985, 1999; *Wright et al.*, 1999; *Miller and Prave*, 2002] indicates tectonism and possibly activity on the Furnace Creek fault zone itself, consistent with the interpretation of *Fridrich and Thompson* [2011]. In the northern Black Mountains, evidence indicates prolonged motion on midcrustal, ductile extensional shear zones that began between 16 and 12 Ma [*Holm et al.*, 1992; *Holm and Dokka*, 1993; *Miller*, 1999; *Miller and Pavlis*, 2005, and references therein]. This is consistent with differential tilting of Cambrian and middle Miocene strata at Eagle Mountain from 13.4–11.6 Ma, and especially after 11.6 Ma (EM in Figure 1) [*Niemi et al.*, 2001; *Renik et al.*, 2008]. *Norton* [2011] proposed that strike-slip tectonism in Death Valley postdates extension and did not start until ~3 Ma, but this is inconsistent with (1) the difference in offsets between pre-Pliocene and Plio-Pleistocene markers along the Furnace Creek fault zone, (2) the observation that the Miocene and younger Furnace Creek basin is bounded by the Furnace Creek fault zone and shows pre-3 Ma, strike-slip deformation [e.g., *Blair and Raynolds*, 1999; *Wright et al.*, 1999; *Miller and Prave*, 2002], and (3) the pre-Pliocene development of the Eastern California Shear Zone and Walker Lane [e.g., *McQuarrie and Wernicke*, 2005; *Oldow et al.*, 2008], including strike-slip structures in the central Death Valley region such as the Stateline fault system [*Guest et al.*, 2007; *Fridrich and Thompson*, 2011] and the Sheephead fault zone [*Renik*, 2010].

5. Displacement Rates

[43] Average displacement rates over both the full history of the fault zone and shorter time intervals are generally between 3 and 5 mm/yr in the middle section of the fault zone, and they drop off toward its tips (Tables 1, 2b and Figure 7). We assume minimal pre-Neogene movement. We also assume relatively uniform development of the fault zone (to the extent shown by the smooth curves in Figure 7), given the absence of more Miocene and Pliocene markers. The long-term average rate (~13–10 to 0 Ma) is as great as ~4.1–4.5 mm/yr, one of the highest, if not the single highest, Neogene average displacement rates among the dextral faults of the Eastern California Shear Zone [*Reheis and Sawyer*, 1997; *Brady and Troxel*, 1999; *Bartley et al.*, 2007; *Guest et al.*, 2007, and references therein; *Andrew and Walker*, 2009; *Renik*, 2010]. That rate, as well as rates over most shorter time spans, is comparable to geodetically calculated rates, which vary from ~3 to ~8 mm/yr [*Frankel et al.*, 2008, and references therein]. Our best-estimate rates (black curves in Figure 7) are closer to the low end of geodetic rates before the Pleistocene, but they are higher than geodetic rates during that epoch along the northern and central portion of the fault zone. It is possible to construct smoother slip rate curves within our error envelopes, but the Pleistocene acceleration may also be real. *Reheis and Sawyer* [1997] noted a synchronous increase in vertical motion along the northern part of the fault zone as well as other structures in the region. Referring to the work of *dePolo* [1989] and *Gillespie* [1991], Reheis and Sawyer suggested a connection to the eruption of the Bishop ash at around the same time.

[44] The other notable change in displacement rate over time is at ~3 Ma (Figure 7), when motion appears to have ceased in the Furnace Creek Wash–Amargosa Valley area.

Table 2a. Values Used for Cumulative Displacement Plots in Figure 8[a]

Contraints Used	Preferred		Top of Error Envelope		Base of Error Envelope	
	Date (Ma)	Cumulative Offset (km)	Date (Ma)	Cumulative Offset (km)	Date (Ma)	Cumulative Offset (km)
Slate Canyon–Dry Creek thrust, alluvial fan 1, alluvial fan 2	11	0	13	0	10	0
	0.62	14.1	0.7	15.5	0.6	8
	0.071	19.822	0.079	19.842	0.063	14.802
	0	20	0	20	0	15
Quartz monzonite, granitic stocks, alluvial fan 1, sedimentary contact	11	0	13	0	10	0
	7.6	18	7.9	18	7.3	8
	0.62	44.1	0.7	45.5	0.6	33
	0.125	49.45	0.19	49.48	0.1	39.425
	0	50	0	50	0	40
Box fold, basaltic gravel, alluvial fan 3	11.5	0	16	0	9	0
	3.3	39	3.3	47	3.3	33
	1.2	42.95	1.2	48.95	1.2	36.95
	0.066	46.703	0.092	52.712	0.05	40.694
	0	47	0	53	0	17
Schwaub Peak–Panamint thrust, Furnace Creek Formation	13	0	18.5	0	11	0
	6.5	10.14	6.5	18.14	6.5	2.14
	3	18.14	4.5	26.14	1.8	10.14
	0	25	0	33	0	41
Clery–Western Black Mountains thrust, Furnace Creek Formation	13	0	18.5	0	11	0
	6.5	12	6.5	22	6.5	2
	3	20	4.5	30	1.8	10

[a]Dates and cumulative offsets derived from individual marker ages and offsets (Table 1).

We regard this development as incompletely understood, but the fault zone is inferred to have merged with the central Death Valley fault (Figure 2) at this time, through northward growth of the latter [*Knott et al.*, 2005]. Available data (Tables 2a and 2b) lack sufficient resolution to confirm or deny a change in plate boundary motion at ~8 Ma [*Atwater and Stock*, 1998; *Oldow et al.*, 2008] or ~6 Ma [e.g., *Doubrovine and Tarduno*, 2008], except perhaps along segment B, where the data potentially suggest that the slip rate decreased in late Miocene time.

[45] Were the Furnace Creek fault zone to have evolved according to the classical pattern for a single fault not initially linked to other structures, it should have lengthened over time, with the maximum slip and slip rates located in the central portion of the fault. The overall pattern of offset matches expectations. The timing constraints, however, do not. Much of the fault zone became active at close to the same time in the late middle Miocene, and the southeastern end of the fault, between Furnace Creek Wash and the Amargosa Valley become inactive while displacement continued elsewhere.

6. Relationship to Associated Extension

[46] The observed behavior is consistent with dextral displacement along the Furnace Creek fault zone having accrued in coordination with northwest-southeast extension in the western part of the Basin and Range Province (Figure 1). Neither strike slip nor extension is a simple byproduct of the other: extension has not been restricted to bends in the fault zone or to stepovers at its tips, and dextral slip represents more than the transfer of extension between juxtaposed blocks. The Furnace Creek fault zone is one of several regional-scale dextral faults with approximately the same orientation [e.g., *Reheis and Sawyer*, 1997]. Variations in its displacement are taken up not only by normal faults, but by other strike-slip and oblique-slip faults, for example, in the vicinity of the Mina Deflection (Figure 1), and by the central Death Valley, the Grand View and Stateline fault systems (Figure 2), and small faults west of Fish Lake Valley [*Reheis and Sawyer*, 1997; *Guest et al.*, 2007; *Oldow et al.*, 2008; *Fridrich and Thompson*, 2011]. The Furnace Creek fault zone is not just a lateral ramp in the normal fault systems of central Death Valley, but a structure of equivalent importance in regional strain accommodation. Dextral offset is greatest between the north central Funeral Mountains and the White Mountains, where the box fold and quartz monzonite are located (Figure 8). The maximum extension *differential* across the fault zone is interpreted between the southern Funeral Mountains range block and the highly extended terrane of the Black Mountains, central Death Valley, and Tucki Mountain (Figure 8). Farther to the northwest, extension on the Boundary Canyon fault system reduces the differential. *Mancktelow and Pavlis* [1994] showed that evidence in the Black Mountains for both northeast directed shortening and clockwise, vertical axis rotation is best explained by distributed dextral shear. *Mancktelow and Pavlis* [1994, p. 679] explained that "the extension cannot be viewed as a two-dimensional process where the strike-slip systems served solely as displacement transfer features."

[47] Strike slip and extension are thus best viewed as coordinated but only partially related phenomena, with displacement transferred back and forth in an environment of regionally distributed transtension [*Mancktelow and Pavlis*, 1994; *Serpa and Pavlis*, 1996]. For example, just as the Furnace Creek fault zone has transferred strain to extensional complexes at its tips, so have those complexes passed strain to other strike-slip faults on their far sides. The reduction in dextral slip toward the Amargosa Valley (AV in Figure 1) was associated with extension from the Resting Spring Range to the central Death Valley area. In the southern part of this extended terrane, strain was passed to the dextral Sheephead and Southern Death Valley fault zones and to

Table 2b. Values Used for Slip Rate Plots in Figure 8[a]

Constraints Used	Preferred			Slip Rates Using Maximum and Minimum Increments of Time and Displacement[b]				
	Time Interval (Ma)	Slip Rate (mm/yr)	Cumulative Offset at Interval Start, End (km)	Time Interval (Ma)	Slip Rate (mm/yr)	Cumulative Offset at Interval Start, End (km)	Slip Rate (mm/yr)	Cumulative Offset at Interval Start, End (km)
Slate Canyon–Dry Creek thrust, alluvial fan 1, alluvial fan 2	11–0.62	1.36	0, 14.1	13–0.6	0.65	0, 8	1.25	0, 15.5
	0.62–0.071	10.42	14.1, 19.822	0.6–0.079	13.13	8, 14.842	8.26	15.5, 19.802
	0.071–0	2.51	19.822, 20	0.079–0	2.00	14.842, 15	2.51	19.802, 20
				10–0.7	0.86	0, 8	1.67	0, 15.5
				0.7–0.063	10.74	8, 14.842	6.75	15.5, 19.802
				0.063–0	2.51	14.842, 15	3.14	19.802, 20
Quartz monzonite, granitic stocks, alluvial fan 1, sedimentary contact	11–7.6	5.29	0, 18	13–7.3	1.40	0, 8	3.16	0, 18
	7.6–0.62	3.74	18, 44.1	7.3–0.7	4.17	8, 35.5	3.79	18, 43
	0.62–0.125	10.81	44.1, 49.45	0.7–0.1	6.54	35.5, 39.425	10.80	43, 49.8
	0.125–0	4.40	49.45, 50	0.1–0	5.75	39.425, 40	5.20	49.8, 50
				10–7.9	3.81	0, 8	8.57	0, 18
				7.9–0.6	3.77	8, 35.5	3.42	18, 43
				0.6–0.19	9.57	35.5, 39.425	15.80	43, 49.8
				0.19–0	3.03	39.425, 40	2.74	49.8, 50
Box fold, basaltic gravel, alluvial fan 3	11.5–3.3	4.76	0, 39	16–3.3	2.60	0, 33	3.70	0, 47
	3.3–1.2	1.88	39, 42.95	3.3–1.2	1.88	33, 36.95	0.93	47, 48.95
	1.2–0.066	3.31	42.95, 46.703	1.2–0.05	3.26	36.95, 40.694	3.27	48.95, 52.712
	0.066–0	4.50	46.703, 47	0.05–0	6.12	40.694, 41	5.76	52.712, 53
				9–3.3	5.79	0, 33	8.25	0, 47
				3.3–1.2	1.88	33, 36.95	0.93	47, 48.95
				1.2–0.092	3.38	36.95, 40.694	3.40	48.95, 52.712
				0.092–0	3.33	40.693, 41	3.13	52.712, 53
Schwaub Peak–Panamint thrust, Furnace Creek Formation	13–6.5	1.56	0, 10.14	18.5–6.5	0.18	0, 2.14	1.51	0, 18.14
	6.5–3	2.29	10.14, 18.14	6.5–4.5	4.00	2.14, 10.14	4.00	18.14, 26.14
	3–0	2.29	18.14, 25	4.5–0	1.52	10.14, 17	1.52	26.14, 33
				11–6.5	0.48	0, 2.14	4.03	0, 18.14
				6.5–1.8	1.70	2.14, 10.14	1.70	18.14, 26.14
				1.8–0	3.81	10.14, 17	3.81	26.14, 33
Clery–Western Black Mountains thrust, Furnace Creek Formation	13–6.5	1.85	0, 12	18.5–6.5	0.17	0, 2	1.83	0, 22
	6.5–3	2.29	12, 20	6.5–4.5	4.00	2, 10	4.00	22, 30
				11–6.5	0.44	0, 2	4.89	0, 22
				6.5–1.8	1.70	2, 10	1.70	22, 30

[a]Dates and cumulative offsets derived from individual marker ages and offsets (Table 1). Along each segment of the fault zone, slip rates are calculated for the time intervals defined by the age differences between two markers. Uncertainty in slip rate for each of those intervals depends on four variables: the age and offset of the older marker, and the age and offset of the younger marker. Therefore, to produce the error envelopes in Figure 8b, four different slip rate histories were calculated, using maximum and minimum increments of time and displacement.
[b]Based on maximum and minimum marker ages and offsets.

the sinistral Garlock and Wingate Wash faults (Figure 2) [*Renik*, 2010; *Golding Luckow et al.*, 2005]. An additional pathway for strain transfer was hypothesized by *Guest et al.* [2007], in the form of a stepover to the dextral Stateline fault (Figure 2).

[48] In Fish Lake Valley, the northwestward decrease in dextral displacement was accompanied by a shuttling of strain east-northeastward, to the "central Walker Lane displacement transfer system" (Figure 2) [*Reheis and Sawyer*, 1997; *Oldow et al.*, 2008, p. 274]. The configuration of the transfer system changed over time. From ~12 to ~3 Ma, dextral displacement was absorbed by northwest directed extension in the Silver Peak–Lone Mountain extensional complex (Figure 2) [*Oldow*, 1992; *Oldow et al.*, 1994, 2008, 2009]. After ~3 Ma, dextral displacement was transferred to east-northeast striking, sinistral-normal oblique faults in the same general area, which form part of the Mina deflection (Figures 1 and 2) [*Oldow*, 1992; *Oldow et al.*, 1994, 2008, and references therein]. Some of the extension accrued in Fish Lake Valley itself, starting at ~6–4 Ma [*Reheis and Sawyer*, 1997]. On the other side of the transfer system, the strain was accommodated by the northwest oriented,
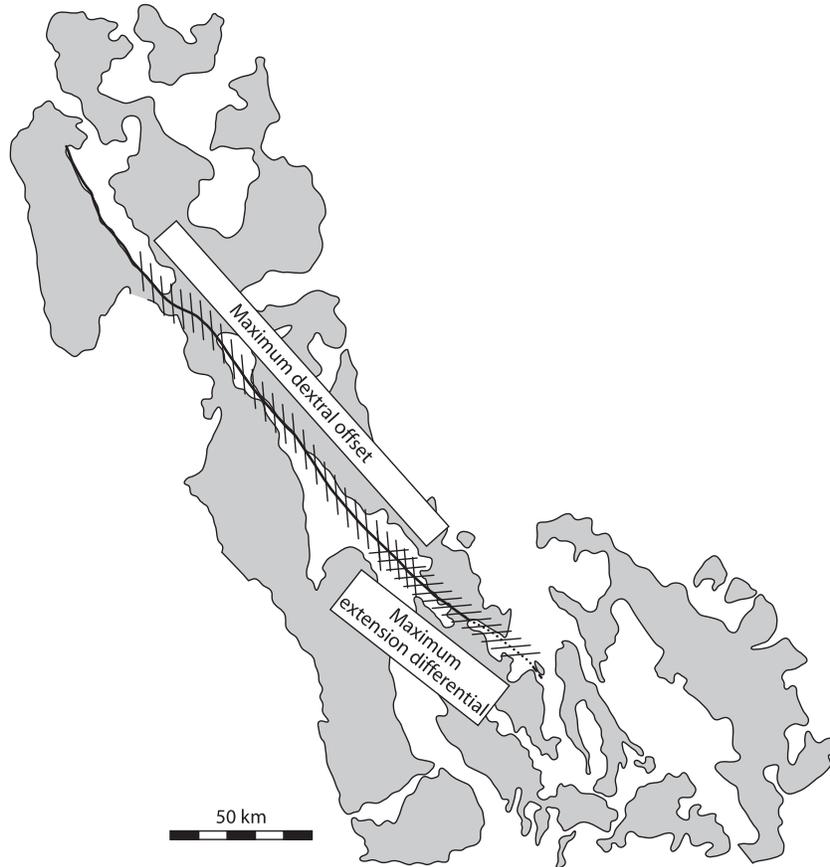
Figure 8. Zones of maximum extension differential (approximate) and maximum dextral offset (as constrained by available markers). See text for details. The two zones overlap only partially, indicating that the Furnace Creek fault zone is not just a lateral ramp in the normal fault systems.

predominantly dextral Walker Lane (Figure 1) [*Oldow et al.*, 2008, and references therein].

7. Implications for Displacement Between the Cottonwood Mountains and Resting Spring–Nopah Range

7.1. Magnitude and Direction

[49] We interpret tectonic transport of ~68 ± 14 km oriented ~ N58° ± 6°W between the Cottonwood Mountains and the Resting Spring and Nopah ranges, with displacement since ~15 Ma totaling ~60 ± 14 km oriented ~N57° ± 6°W. These figures sum displacements between the Cottonwood and Panamint Mountains and between the Panamint Mountains and Resting Spring–Nopah Range block.

[50] Our Cottonwood-Panamint estimate, ~8.4–16 km in the direction ~N65°W, is based on Neogene markers and contractile structures [*Andrew and Walker*, 2009]. Volcanic and sedimentary deposits indicate 8.4 km of displacement, oriented N65°W, since ~15 Ma [*Andrew and Walker*, 2009]. Earlier displacement is limited by (1) the mismatch between the Panamint and White Top anticlines (section 3.5) and (2) the lack of an alternative Cottonwood Mountains correlate to the Panamint anticline, as well as the lack of an alternative Panamint Mountains correlate to the White Top anticline. Thus, total displacement between the ranges

is less than the separation of the anticlines, 22 ± 3 km directed N45°W [e.g., *Wernicke et al.*, 1988a, and references therein; *McQuarrie and Wernicke*, 2005]. By the same reasoning, a stricter limit of ~16 km total displacement is set by noncorrelation of the Lemoigne and Panamint thrusts (section 3.5).

[51] Our estimate between the Panamint Mountains and Resting Spring–Nopah Range block, ~52 ± 14 km oriented N56° ± 7°W, implies that the area widened by a stretch of ~2.5 ± 0.5. The area of interest and the azimuth of displacement are shown by the double-headed arrow in Figure 9A. The azimuth reflects kinematic indicators in the northern Black Mountains [*Miller*, 1991] and the approximate average strike of the Furnace Creek fault zone in this area. The widening of the area between the Panamint Mountains and Resting Spring–Nopah Range block can be viewed as the map view widening of two thrust plates. The Chicago Pass thrust plate (purple in Figure 9B) is exposed discontinuously between the Nopah Range and the Western Black Mountains thrust (CP, WBM in Figure 3). (Note that the Nopah Range and Resting Spring Range actually expose a thrust stack. Local complexities notwithstanding, we follow *Snow and Wernicke* [2000] in interpreting the major structure as the Chicago Pass thrust system.) Outcrops of the Western Black Mountains thrust plate (red in Figure 9B) are, in turn, bounded to the west by the Panamint thrust (P-s in Figure 3). Thus, to estimate the displacement between
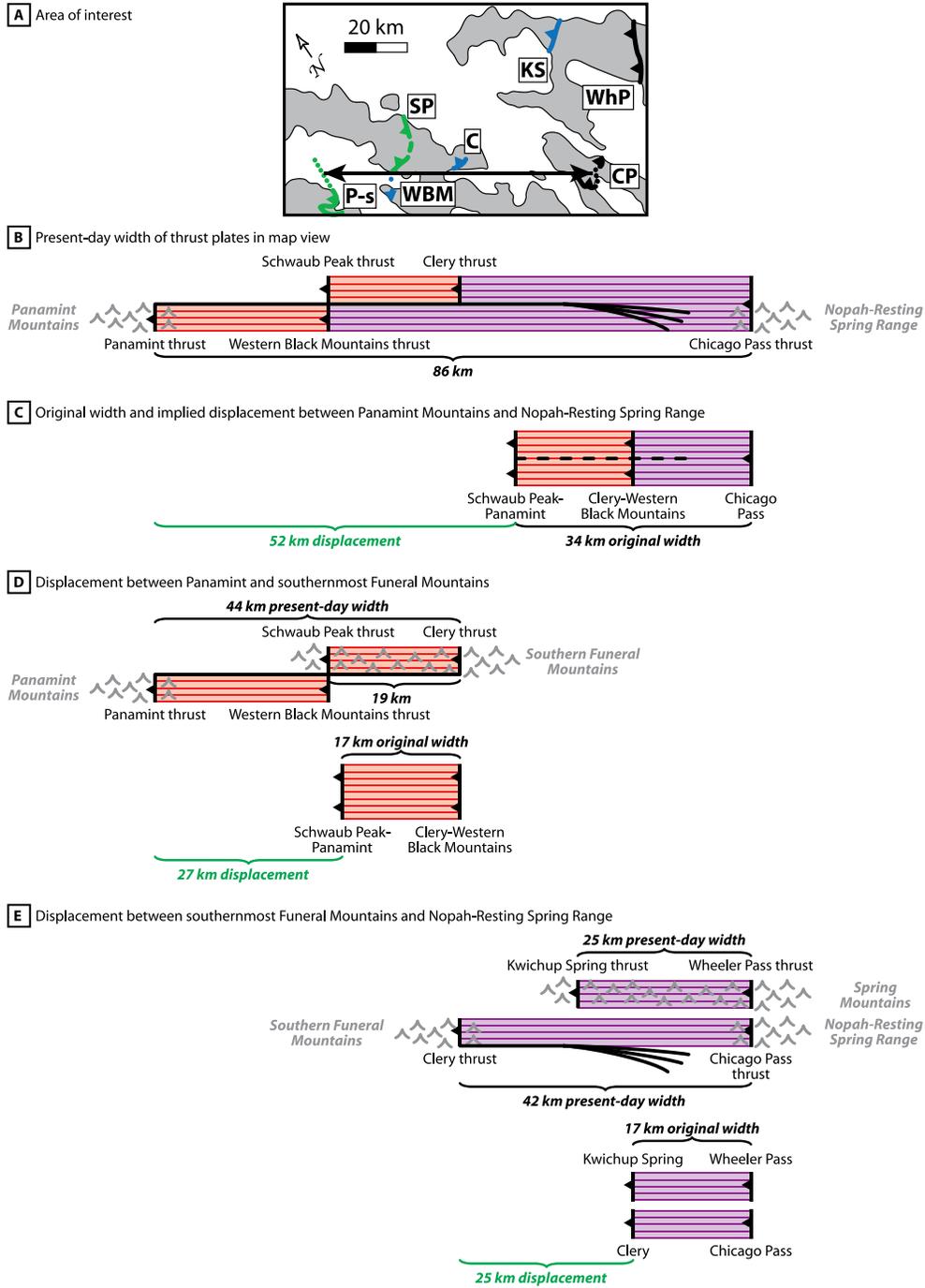
16

Figure 9. Distances used in calculating displacement between range blocks. (A) Area of displacement calculation. Double-headed arrow shows azimuth of widening (N56°W) between endpoints in Panamint and Nopah–Resting Spring blocks (ranges labeled in Figure 1). Thrust fault abbreviations follow Figure 3. (B) Thrust plates in area of interest, on either side of Furnace Creek fault zone. Chicago Pass plate shown in purple. Western Black Mountains and Clery plates (correlative) shown in red. (C) Displacement between Panamint Mountains and Nopah–Resting Spring Range is ~52 km, equal to the present-day width of the thrust plates (86 km) minus their original width (~34 km). (D and E) Details of calculation. See text for additional information.

the Panamint Mountains and the Resting Spring–Nopah Range block, we calculated the original widths of the two thrust plates (Figure 9C), and subtracted this from the present-day width in map view. This approach is justified because each thrust plate is exposed across its full width within a single range block along strike to the northeast.

[52] The along-strike equivalent to the Western Black Mountains thrust plate is the Clery thrust plate in southern Funeral Mountains (Figures 1 and 9D), bounded by the

Clery and Schwaub Peak thrusts (C, SP in Figure 3). This thrust plate is now ~19 km wide (Figure 9D). Restoration of minor normal faulting within the Funeral Mountains indicates that the thrust plate has widened by a stretch of ~1.15 ± 0.05 [*Prave and Wright*, 1986a], implying an original width of ~17 km. The Western Black Mountains thrust plate has now both widened and moved northwestward from its original continuity with the Clery thrust plate, so that the total displacement between the Panamint and southern Funeral Mountains is ~27 km (Figure 9D).

[53] The along-strike equivalent to the Chicago Pass thrust plate is the Wheeler Pass thrust plate in the Spring Mountains (Figures 1 and 9E). This is based on correlation between the Chicago Pass and Wheeler Pass thrusts (CP, WhP in Figure 9A) [*Snow and Wernicke*, 2000], and between the Clery and Kwichup Spring thrusts (C, KS in Figure 9A) [*Snow and Wernicke*, 2000]. Tilt correcting the essentially unextended Spring Mountains implies a width of ~17 km for the Wheeler Pass thrust plate [*Snow and Wernicke*, 2000]. Restoring the now ~42 km wide Chicago Pass plate to the same, ~17 km width produces a displacement estimate of ~25 km (Figure 9E). So the total displacement between the Panamint Mountains and the Resting Spring–Nopah Range block is the sum of ~27 km (Figure 9D) and ~25 km (Figure 9E), or ~52 km (Figure 9C).

[54] We estimate an uncertainty in magnitude of ± ~14 km and in orientation of ± ~7°, on the basis of several considerations. Limited outcrop and low dips complicate the attempt to measure thrust plate widths between the Panamint, Black, and Resting Spring–Nopah range blocks today. The original widths are likely to have varied by an uncertain amount both along strike and down dip. The amount and direction of displacement probably varied somewhat even within the study area. There is evidence for vertical axis rotation in the Black Mountains [*Holm et al.*, 1993; *Petronis et al.*, 2002], but the effect on the kinematic indicators is unclear because the dimensions of rotated blocks are difficult to assess.

[55] The ~52 ± 14 km of total displacement between the Panamint Mountains and Resting Spring–Nopah Range block sets an upper limit on the magnitude of extension between them. It is probably an overestimate, however. Part of the separation between the ranges has arisen because the Resting Spring and Nopah ranges are located past the tip of a major strike-slip fault and the Panamint Mountains block was translated along that fault. The extension between the ranges could equal the full displacement between them only if offset on the Furnace Creek fault represented no more than an extension differential, which does not appear to be the case (section 6).

[56] At the other extreme, if the Furnace Creek fault zone were purely an expression of plate boundary dextral shear superimposed on an extending region, extension would be the full displacement between the ranges (~52 ± 14 km) minus the strike-slip transport of the Panamint Mountains (~25 ± 8 km): ~27 ± 22 km. Even this is not the absolute minimum, because a poorly quantified component of strike slip between the Panamint Mountains and Resting Spring–Nopah Range block is accommodated by the Grand View fault, by oblique faults in the Furnace Creek horsetail splay, and by other unnamed faults [*Burchfiel et al.*, 1983; *Wright and Troxel*, 1999].

7.2. Partitioning of Displacement Between the Death Valley–Furnace Creek Wash and Amargosa Valley Areas

[57] The displacement of ~52 km between the Panamint Mountains and Resting Spring–Nopah Range block is partitioned rather evenly between the Death Valley–Furnace Creek Wash area and the Amargosa Valley, at ~27 km and ~25 km, respectively. The Death Valley–Furnace Creek Wash area is spanned almost exactly by the Clery and Western Black Mountains thrust plates (Figure 9D), now ~44 km but originally ~17 km, implying ~27 km of displacement. This leaves ~25 km of displacement to be accommodated across the Amargosa Valley.

[58] The estimate of ~27 km in the Death Valley–Furnace Creek Wash area is supported by other evidence for the paleoposition of the Panamint Mountains either adjacent to the Black Mountains or minimally overlapping them. (1) Essentially unmetamorphosed Proterozoic-Paleozoic strata are exposed intermittently in the north, central, and southern Black Mountains, and although the preserved record is fragmentary and brittlely deformed, it is in many places demonstrably autochthonous [e.g., *Wright and Troxel*, 1984; *Prave and Wright*, 1986a, 1986b; *Topping*, 1993; *Miller and Prave*, 2002; *Miller and Pavlis*, 2005], (2) the Black Mountains show no roots of Mesozoic plutonic rocks found in the Panamint and Cottonwood Mountains [e.g., *Miller and Prave*, 2002; *Miller and Pavlis*, 2005], and (3) Pre-Cenozoic cooling ages from midcrustal rocks exposed along the central Black Mountains front [*Holm et al.*, 1992; *Meurer*, 1992; T. L. Pavlis as cited by *Holm et al.*, 1994] indicate minimal overburden at the onset of Miocene extension, although the hypothesis that the rock is allochthonous is a potential alternative [*Holm and Wernicke*, 1990; *Holm et al.*, 1992; *Holm and Dokka*, 1993; cf. *Meurer*, 1992; T. L. Pavlis as cited by *Holm et al.*, 1994; *Renik*, 2010].

7.3. Comparison With Previous Interpretations

[59] Our displacement estimates of ~52 ± 14 km between the Resting Spring–Nopah Range block and Panamint Mountains and ~27 km in the Death Valley–Furnace Creek Wash area are compatible with some previous reconstructions [e.g., *Labotka and Albee*, 1988] (and lower estimates of *McKenna and Hodges* [1990], *Wright et al.* [1991], *Serpa and Pavlis* [1996], *Wright and Troxel* [1999], *Miller* [2002], and *Miller and Pavlis* [2005]) but are substantially less than indicated in others [e.g., *Stewart*, 1983, 1986; *Wernicke et al.*, 1988a; *Topping*, 1993; *Snow and Wernicke*, 2000; *Niemi et al.*, 2001; *McQuarrie and Wernicke*, 2005; *Fridrich and Thompson*, 2011; *Norton*, 2011]. The latter were based on three general lines of evidence: (1) correlation of pre-Cenozoic structural and stratigraphic markers, particularly the Panamint and Chicago Pass thrusts; (2) interpretation of the scarcity of Mesoproterozoic-Paleozoic sedimentary cover in the Black Mountains to indicate preextensional burial beneath the Panamints; and (3) reconstruction of Neogene depositional systems. The pre-Cenozoic markers, both structural and stratigraphic, are discussed in section 3, with the exception of correlations between the Butte Valley thrust (BV in Figure 3) and the Winters Pass thrust [*Snow and Wernicke*, 2000] or the Chicago Pass thrust [*Serpa and Pavlis*, 1996]. Because the Butte Valley

thrust is substantially south of the Furnace Creek fault zone, however, greater displacement at that latitude could potentially be accommodated by vertical axis rotations and/or the Miocene-Pliocene Sheephead fault zone (Figure 2) [*Renik*, 2010]. Right-lateral displacement along the Sheephead fault zone, which totals as much as ~18.5 ± 8.5 km [*Renik*, 2010], could help to account for a displacement differential between the southern Death Valley area (where the Butte Valley thrust is located) and the central and northern Death Valley areas (where the Furnace Creek fault zone is located). Another possible solution – the most parsimonious explanation – is for the Butte Valley and correlate(s) to have originated in a configuration such as a relay, implying they were kinematically related but not immediately adjacent.

[60] Our reconstruction permits substantial tectonic denudation of the Black Mountains without requiring complete restoration of the Panamint terrane atop them. We view the paucity of pre-Cenozoic outcrop to reflect a combination of faulting, erosion, and burial by abundant Cenozoic sedimentary and volcanic rocks. Various indicators suggest substantial preextensional erosion [*Prave and Wright*, 1986a, 1986b]. Miocene strata lie in depositional contact with Cambrian strata at Eagle Mountain (EM in Figure 1) [*Renik et al.*, 2008] and the southern Panamint Mountains (Figure 1) [*Golding Luckow et al.*, 2005], and with Neoproterozoic strata in the Black Mountains near the Sheephead fault zone (Figures 1 and 2) [*Renik*, 2010]. Pre-Cenozoic cooling ages from several broadly denuded areas in the southeastern Black Mountains [*Holm et al.*, 1992; *Holm and Dokka*, 1993] suggest that a scarcity of sedimentary rock does not require predominantly extensional exhumation.

[61] Miocene strata in the southern Black Mountains and Amargosa Valley suggest greater displacement than we interpret, but they are reconcilable with our results. Inferred alluvial fan and rock avalanche deposits there, thought to have been sourced in the Panamint Mountains and Kingston Range (Figure 1), have been used to reconstruct a distance of 15–20 km between the ranges until 7.8 Ma and a displacement of 75 km thereafter [*Topping*, 1993] (summarized more generally by *Fridrich and Thompson* [2011]). However, the inferred source areas are not necessarily unique, and one alternative potential source is the southern Black Mountains (Figure 1) [e.g., *Snow and Wernicke*, 2000]. Some of the discrepancy may relate to vertical axis rotation and/or displacement along the Sheephead fault zone, as described above.

[62] A reevaluation of the ~15–11 Ma Eagle Mountain Formation, which is exposed in Furnace Creek Wash, at Eagle Mountain, and on the east flank of the Resting Spring Range, substantially reduces the significance of these rocks for palinspastic reconstruction [*Renik et al.*, 2008]. Clasts from the Hunter Mountain batholith in the Cottonwood Mountains (Figure 1) that were originally interpreted to have accumulated at an alluvial fan, and imply that the Cottonwood Mountains were no more than 10–20 km from the Resting Spring Range until after ~11 Ma [*Niemi et al.*, 2001], are now interpreted to have been transported and deposited in a river system [*Renik et al.*, 2008]. Taken together, structural and stratigraphic evidence suggests that the terrane immediately south of the southeastern Furnace Creek fault zone widened by a stretch of ~2.5, rather than a stretch as high as ~4–5 [*Snow and Wernicke*, 2000; *Niemi et al.*, 2001; *McQuarrie and Wernicke*, 2005].

7.4. Implications for the Eastern California Shear Zone

[63] Our new estimates of displacement along the Furnace Creek fault zone and between the Panamint Mountains and Resting Spring–Nopah Range block offer a way to mitigate the ~33 ± 16 km discrepancy in the ~12–0 Ma strain budget of the Eastern California Shear Zone. The inconsistency has been hypothesized to derive in part from underestimation of displacement in the Mojave, because the inferred displacement there does not include diffusely distributed deformation [*McQuarrie and Wernicke*, 2005]. We suggest instead that the previously inferred displacement in the western Basin and Range was too high by ~26 ± 17 km (Table 3). The Basin and Range estimate of ~100 ± 10 km oriented N25°W [*McQuarrie and Wernicke*, 2005] was based upon offsets across central and northern Death Valley. A direct input to the calculation of cumulative displacement in that reconstruction is the Eagle Mountain Formation [*McQuarrie and Wernicke*, 2005, Figure 4 and Table 2]. It is interpreted to indicate displacement of 104 ± 7 km in the direction N67°W, implying a N25°W component of 77 ± 5 km (Table 3), between the Cottonwood Mountains and eastern Resting Spring Range. We estimate a N 25°W displacement component of ~51 ± 12 km between the Cottonwood Mountains and Resting Spring–Nopah Range block. (Only a very small fraction of this displacement is likely to have occurred before 12 Ma, given the timing of motion on the Furnace Creek fault zone; see section 4.) This implies a reduction in the previously calculated value of ~26 ± 17 km. Replacing 77 ± 5 km with ~51 ± 12 km in the summed Eastern California Shear Zone displacement in the western Basin and Range yields a new estimate of ~74 ± 17 km (instead of ~100 ± 10 km). This is within error of the estimate in the Mojave, 67 ± 6 km [*Lease et al.*, 2009]. Resolving the discrepancy between

Table 3. Estimates of Displacement Between Cottonwood Mountains and Resting Spring–Nopah Range

Ranges	Marker	Total Displacement (km)	Azimuth	Difference in Azimuth From N25°W (deg)	Resolved Displacement Toward 335°[a] (km)
Cottonwood, Panamint	Volcanic and sedimentary deposits [*Andrew and Walker*, 2009]	8.4	N65°W	40	6
Panamint, Resting Spring–Nopah	Thrust plates (this paper, Figure 8)	52 ± 14	N56° ± 7°W	31 ± 7	45 ± 12
Cottonwood, Resting Spring–Nopah	Above markers				51 ± 12
Cottonwood, Resting Spring	Eagle Mountain Formation [*Niemi et al.*, 2001]	104 ± 7	N67°W	42	77 ± 5

[a]Resolved displacement calculated as (total displacement) × cos(difference in azimuth).

the two regions is critical to the concept of the Eastern California Shear Zone. *Dokka and Travis* [1990a, p. 333], who coined the term, explained that the "inference of a regional zone of right shear that includes the Death Valley region and the south central and eastern part of the Mojave Desert Block is based on the observation that both areas display similar amounts of late Cenozoic right slip."

8. Conclusions

[64] A review of markers along the Furnace Creek fault zone leads to a new hypothesis for the distribution of dextral displacement along strike and over time (Figure 7). The first-order pattern involves an increase of total offset from the fault tips to a maximum of ~50 km in northern Death Valley and southern Fish Lake Valley, and accruing at rates of between 3 and 5 mm/yr, mainly since late middle Miocene time. Full displacement is best constrained by five pre-Cenozoic markers: the Slate Canyon–Dry Creek thrust, the quartz monzonite of Beer Creek, the White Top–Marble Canyon box fold, the Schwaub Peak–Panamint thrust, and the Clery–Western Black Mountains thrust. The estimates of magnitude and timing of strike slip, the interpretations of various markers, and the inferences about the relationship between strike slip and extension in the region presented in this paper have implications for palinspastic reconstruction in the Death Valley region and displacement budgets in the Eastern California Shear Zone:

1. We estimate ~68 ± 14 km of displacement, oriented N ~58 ± 6°W, between the Cottonwood Mountains and the Resting Spring–Nopah Range, with displacement since ~15 Ma totaling ~60 ± 14 km oriented N ~57 ± 6°W. This includes transport of ~8.4–16 km directed ~N65°W between the Cottonwood and Panamint Mountains and ~52 ± 14 km oriented N56° ± 7°W between the Panamint Mountains and the Resting Spring–Nopah Range block. The latter is relatively evenly partitioned between the Death Valley–Furnace Creek Wash area and the Amargosa Valley area. Our results suggest that the previous interpretation of ~104 ± 7 km for displacement between the Cottonwood Mountains and Resting Spring–Nopah Range block is an overestimate by a factor of ~50%.
2. Post-12 Ma displacement oriented N25°W in the Eastern California Shear Zone north of the Garlock fault appears to be lower than previously thought, at ~74 ± 17 km, and within error of the estimate in the Mojave, 67 ± 6 km.

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