Evidence for 65 km of dextral slip across Owens Valley, California, since 83 Ma

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ABSTRACT

The Golden Bear dike in the Sierra Nevada and the Coso dikes in the Coso Range crop out on opposite sides of Owens Valley, California, and strike roughly perpendicular to it. Neither dike reappears along strike across the valley. New data demonstrate that the dike sets are ca. 83 Ma in age, share nearly identical mineralogy and petrography, and intrude similar wall rocks including distinctive 102 Ma leucogranite. Dike bulk-chemical and Sr and Nd isotope compositions are nearly indistinguishable. These data suggest that the dike sets were originally continuous and were offset dextrally by ~65 km. This displacement estimate is consistent with other recent estimates of total slip across Owens Valley. If faulting began during the Pliocene, the average slip rate was significantly faster than the current rate. Alternatively, motion could have been episodic and have begun as early as the Late Cretaceous.

Keywords: Owens Valley, Coso Range, Sierra Nevada, slip rates, geochronology, geochemistry.

INTRODUCTION

The Sierra Nevada block of California is presently moving to the northwest at ~13–14 mm/yr relative to stable North America (Dixon et al., 2000). This motion is taken up in part by dextral transtension across the Owens Valley fault zone, which forms the boundary between the stable Sierra Nevada microplate to the west and the Walker Lane Belt to the east (Fig. 1; Stewart, 1988). The modern predominance of dextral slip across the boundary is indicated by the 1872 Lone Pine earthquake (M_W 7.5+), which produced from 6 to 10 m of dextral slip and ~1 m of east-side-down dip slip (Beanland and Clark, 1994). Geologic (Lee et al., 2001) and geodetic (Dixon et al., 2003) estimates of the long-term horizontal slip rate across the Owens Valley fault zone differ but appear to be converging on ~2–3 mm/yr.

It is generally assumed that dextral displacement across Owens Valley began recently and that total displacement is no more than ~10 km (Lee et al., 2001). However, the timing of dextral slip across Owens Valley has been uncertain, because slip could have occurred in two separate tectonic regimes: oblique plate convergence during the Mesozoic and early Cenozoic, and dextral transtension during the Neogene development of the Walker Lane belt and the Basin and Range province. Furthermore, estimates of total slip across Owens Valley are hampered by the fundamental geologic mismatch across the valley. The Sierra Nevada to the west is dominated by Mesozoic plutonic rocks, whereas the east side of the valley is dominated by late Proterozoic-Paleozoic miogeoclinal rocks (e.g., Bateman, 1992), with few obvious ties to rocks in the Sierras.

Ross (1962) inferred ~5 km of dextral offset on the basis of correlation of the 165 Ma Tinemaha and Santa Rita Flat granodiorite plutons, but rocks of this age and petrography are common on both sides of the valley, and thus the correlation is nonunique (e.g., Bateman, 1992; Coleman et al., 2003; Ernst et al., 2003). Moore and Hopson (1961) observed that the Late Jurassic Independence dike swarm continues across the valley and inferred no more than a few kilometers of offset, but this conclusion was based on only a preliminary understanding of the areal distribution of the swarm.

More recent studies have proposed significantly larger displacement across the eastern margin of the Sierra Nevada (Fig. 1). Stevens et al. (1997) estimated ~65 km of offset by correlating Devonian submarine channels and Permo-Triassic structures in the Inyo Mountains with similar features in the Sierra Nevada. Kistler (1993) and Saleeby and Busby (1993) inferred a similar amount of displacement across a fault zone (that they refer to as intrabatholithic break 3 [IBB3] and eastern intrabatholithic break [EIB], respectively) in the eastern Sierra Nevada on the basis of offset of the initial $^{87}Sr/^{86}Sr$ 0.706 isopleth and metamorphic rocks. Glazner et al. (2003) proposed that the Independence dike swarm was offset at least 65 km and possibly as much as 130 km. Resolving the discrepancy between these estimates of dextral offset at the eastern boundary of the Sierra Nevada microplate is important to understanding Pacific–North American plate motion, partitioning of slip in the Walker Lane belt, energy resources in the Coso and Long Valley geothermal fields, and seismic hazards in the region.

In this paper we offer evidence for the correlation of the Cretaceous Golden Bear and Coso dikes, and their host rocks across the southern end of Owens Valley (Fig. 1; in this paper we define *Owens Valley* broadly to include the southern region between the Sierra Nevada and the Coso Range). The implications of the correlation are threefold. First, these markers are offset right-laterally by 65 km, a much larger offset than previously known in the southern part of the valley. Second, because this estimated offset across southern Owens Valley matches estimates to the north (e.g., Stevens and Stone, 2002), it is likely that the fault zone responsible for offset in the south is the continuation of that which offsets older markers to the north. Finally, because the markers matched across southern

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Owens Valley are much younger than those matched farther north, the new results significantly restrict permissible timing relations.

GOLDEN BEAR AND COSO DIKES

The Golden Bear and Coso dike swarms offer a potential tie across Owens Valley, because each set contains petrographically distinctive porphyry dikes that strike perpendicular to the valley. This study was designed to test this correlation.

The Golden Bear dike crops out north of Mount Whitney for ~15 km, striking northeast near its western end and bending to an easterly strike before disappearing under the sedimentary fill in Owens Valley near Independence (Fig. 1; Moore, 1963, 1981). The dike is typically 10–20 m thick but ranges from 5 to 30 m and is at least 15 m thick where it disappears under the alluvium of Owens Valley. Near the Sierra Nevada crest and along the John Muir Trail, two or three subparallel dikes commonly are present, each ~5–10 m thick.

The Coso dike swarm includes two steeply dipping east-striking dike sets, separated by ~6 km across strike (Fig. 1; Duffield et al., 1980; Whitmarsh, 2002). Major dikes in the Coso swarm are 5–25 m thick and commonly are accompanied by thinner (<2 m) subparallel dikes. The western end of the most continuous dike in the Coso Range is ~20 m thick where it disappears under Mio-Pliocene strata just east of Owens Valley. This dike can be traced discontinuously eastward across the Coso Range, although its outcrop is interrupted by overlapping younger volcanic rocks and alluvium, and no significant lateral offset of the dike across the range is apparent.

Both the Coso and Golden Bear dike sets include very thick (up to 30 m) dikes, yet neither set appears to continue along strike across Owens Valley. The Inyo Mountains east of the Golden Bear dike expose latest Precambrian through early Paleozoic sedimentary rocks intruded by Jurassic and Cretaceous plutons and sparse dikes of the Independence dike swarm, but nothing is petrographically similar to, or as thick as, the Golden Bear dike (Ross, 1965). Similarly, along strike west of the Coso dike swarm, the Sierra Nevada exposes a variety of Mesozoic plutonic rocks but no granite porphyry dikes (Diggles, 1987; Diggles et al., 1987), and reconnaissance of the Sierran range crest west of the Coso dikes has turned up no porphyry dikes (our work and R. Whitmarsh and S. Morgan, 2003, personal commun.).

The Golden Bear dike intrudes Cretaceous plutons and minor Mesozoic metavolcanic and metasedimentary rocks (Moore, 1963, 1981; Chen and Moore, 1982; Saleeby et al., 1990;

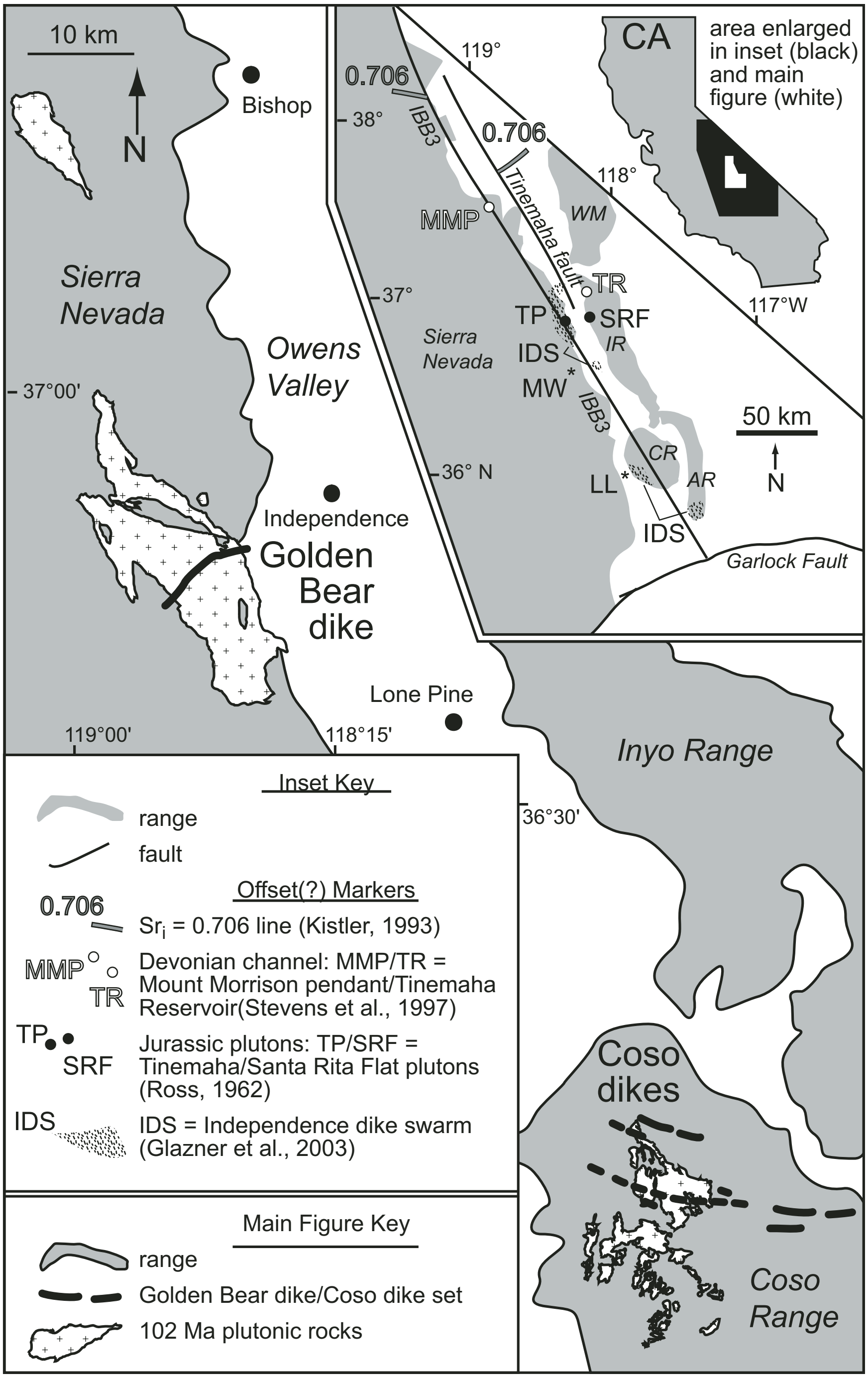

Figure 1. Locations of the Golden Bear and Coso dikes, adjacent to Owens Valley. Main figure shows the Golden Bear and Coso dikes striking into the valley, where they intrude 102 Ma plutons. Both the dikes and the plutons provide distinctive markers that can be matched across the valley and are consistent with 65 km of dextral displacement since 84 Ma. Inset shows other markers across Owens Valley that earlier workers suggested indicate from 0 to 65 km of dextral offset across the valley. Also shown are the traces of the Tinemaha fault (Stevens et al., 1997; Stevens and Stone, 2002) and intrabatholithic break 3 (IBB3; Kistler, 1993), which are hypothesized to accommodate offset of these markers. Note that the section of IBB3 between 38°N and 36.5°N is correlative with the eastern intrabatholithic break (EIB) of Saleeby and Busby (1993). Not all known locations of Independence dikes are indicated. Instead, patterned areas show only the densest parts of the dike swarm as defined by Glazner et al. (2003). AR—Argus Range; CR—Coso Range; IR—Inyo Range; WM—White Mountains; other abbreviations are described in the key.

Kylander-Clark, 2003). Cretaceous wall rocks are dominated by coarse-grained leucogranite of the Bullfrog and Independence plutons and associated granodiorite plutons (the 102 Ma Dragon pluton and an unnamed pluton). The Coso dike set intrudes Sierra-like Mesozoic plutons that include the leucogranite of Cactus Flat, which is commingled with mafic granodiorite on the western side of the Coso Range (Whitmarsh, 2002). Other rocks in the area include Mesozoic metasedimentary and metavolcanic rocks.

The Golden Bear and Coso dikes are both K-feldspar quartz monzonite porphyries with a color index <5. The center of a dike typically contains 25–30 vol% K-feldspar phenocrysts that range from 2 to 4 cm in length with an aspect ratio of 2:1. Plagioclase (approximately An_{35}, 25–30 vol%) forms subhedral, subequant grains typically 1–4 mm in diameter. Quartz (~15 vol%) typically forms distinctive equant, euhedral, and bipyramidal crystals 2–5 mm in diameter. Mafic minerals include 1–3 mm crystals of biotite and rare hornblende. The distinctive petrographic character shared by the Golden Bear and Coso dikes has not been found in any other dikes in the region.

U-PB GEOCHRONOLOGY

To test the correlation of the Golden Bear and Coso dikes and their host rocks, two samples each from the Golden Bear and Coso dikes and samples from the Independence and Cactus Flat plutons were collected for U-Pb zircon geochronology (Table DR1).[1] Although three of the four units had been dated previously, some of the dates lacked the precision needed for testing the correlation. The Independence pluton yielded a low-precision U-Pb age of 112 Ma (Chen and Moore, 1982), but mapping in the area shows it to be coeval with the 102 Ma Dragon pluton (Saleeby et al., 1990). The leucogranite of Cactus Flat yielded an Rb-Sr whole-rock date of 102 Ma (Kistler 1993), suggesting that it and the Independence pluton could be the same age. Whitmarsh (2002) reported a U-Pb age of 88.3 Ma for the Coso dike; however, this data set was later reinterpreted to indicate an age of 84 ± 1 Ma (J.D. Walker, 2003, personal commun.).

Data from the western sample of the Golden Bear dike yield fractions that cluster near concordia between 83 and 84 Ma (Fig. 2A) and yield a weighted mean $^{206}Pb/^{238}U$ age of 83.4 ± 0.4 Ma with a mean square of weighted deviates (MSWD) of 1.14. Results from the eastern sample of the Golden Bear dike are more scattered, but five of the seven fractions fall on concordia between ca. 83.5 and 81 Ma (Fig. 2B). The other two fractions (z6a and b) yield dates older than Whitney intrusive suite plutons intruded by the dike and thus clearly contain an inherited component. Because this sample came from the same dike as the western sample, we interpret the data to reflect an age of 83.4 Ma and varying amounts of inheritance and Pb loss.

Both samples of the Coso dikes resemble the eastern Golden Bear sample in yielding fractions that cluster between 82 and 86 Ma, and other fractions that scatter toward older Mesozoic ages, including some that are older than plutons intruded by the dikes (Fig. 2C and D). In view of Whitmarsh's (2002) date of ca. 84 Ma from another Coso dike sample, we interpret the Coso dike results also to be consistent with an age of 83.4 Ma with varying amounts of inheritance and Pb loss.

Three of the six zircon fractions from the Independence pluton yielded U-Pb ages that cluster between 102 and 103 Ma (Fig. 2E) with a $^{206}Pb/^{238}U$ weighted mean age of 102.5 ± 0.2 Ma (MSWD = 0.45). The other three fractions analyzed from this sample yield significantly younger, discordant ages that are interpreted to reflect Pb loss ± inheritance.

U-Pb zircon data from all five fractions from the leucogranite of Cactus Flat cluster near concordia between 100.5 and 102.5 Ma (Fig. 2F). Linear regression of the data yields an upper intercept of 101.6 ± 0.8 Ma (MSWD = 1.9), which we accept as the best estimate of the age of this sample.

GEOCHEMISTRY

Correlative dikes and wall rock should have comparable major element, trace element, and isotopic compositions. Therefore, multiple samples from the Golden Bear and Coso dike sets, and a single sample each from the Independence pluton and the leucogranite of Cactus Flat, were collected for geochemical and isotopic analyses (Table DR2 [see footnote 1]). At several locations, samples were collected from the center and margin of a single dike to look for variation caused by crystal fractionation or contamination. Whole-rock major and trace element data were obtained by X-ray fluorescence spectrometry (XRF; major and trace element data) and inductively coupled plasma–mass spectrometry (ICP-MS; additional trace element data) performed at Washington State University. Isotopic analyses were performed at the University of North Carolina. Analytical methods are described in the footnote to Table DR2 (see footnote 1).

The Golden Bear and Coso dike swarms have strongly similar major oxide concentrations. Only Na_2O concentrations do not significantly overlap between the two dike sets (Fig. 3; Table DR2 [see footnote 1]). Trace element concentrations are also broadly similar between the dike sets, with several notable exceptions. Concentrations of Ba, Rb, Th, and U vary widely with little or no overlap between the two dike sets. Tantalum concentrations also do not overlap. Whereas light rare-earth-element (LREE) patterns of the dikes all are similar, the Coso dike set (La/Yb ~91) shows marked depletion of heavy REE (HREE) patterns in comparison with the Golden Bear dikes (La/Yb ~53). Significantly, core-to-margin differences at a given location in the Golden Bear dike commonly span most or all of the observed range of major, trace, and REE concentrations. The Independence and Cactus Flat leucogranites are broadly similar in major and trace element concentrations (Table DR2 [see footnote 1]), but because only a single sample of each was analyzed, no quantitative comparison was made.

The initial Sr (Sr_i) and Nd ($\varepsilon_{Nd}[t]$) isotope ratios of the Golden Bear and Coso dike sets do not quite overlap, but the ratios vary regularly in space (Table DR2 [see footnote 1]). The least radiogenic Sr_i was found in the westernmost Golden Bear sample (0.70694; Fig. 4), and Sr_i becomes generally more radiogenic to the east (as high as 0.70836 in a Coso dike sample). Margin samples are consistently less radiogenic than samples from dike centers (e.g., 0.70694, margin; 0.70721, center). Although there are fewer Nd analyses, initial $\varepsilon_{Nd}(t)$ data mirror the Sr patterns (Table DR2 [see footnote 1]). For example, Golden Bear samples from the west are as high as $\varepsilon_{Nd}(t) = -5.97$, and Coso dikes range as low as $\varepsilon_{Nd}(t) = -8.74$. Likewise, the one margin/center pair analyzed from the Coso dikes shows a shift toward less radiogenic Nd at the margin ($\varepsilon_{Nd}[t] = -6.70$ at the margin, and $\varepsilon_{Nd}[t] = -7.78$ at the center). The Independence pluton and leucogranite of Cactus Flat have distinctly lower Sr_i relative to the dikes but resemble each other (0.70572 and 0.70597, respectively; Fig. 4).

DISCUSSION

Correlation of Golden Bear and Coso Dikes

The Golden Bear and Coso dike sets are petrographically indistinguishable, and their abundant K-feldspar megacrysts and euhedral bipyramidal

[1]GSA Data Repository item 2005103, locations and U/Pb zircon, major and trace element and isotopic data for dikes and wall rocks, is available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

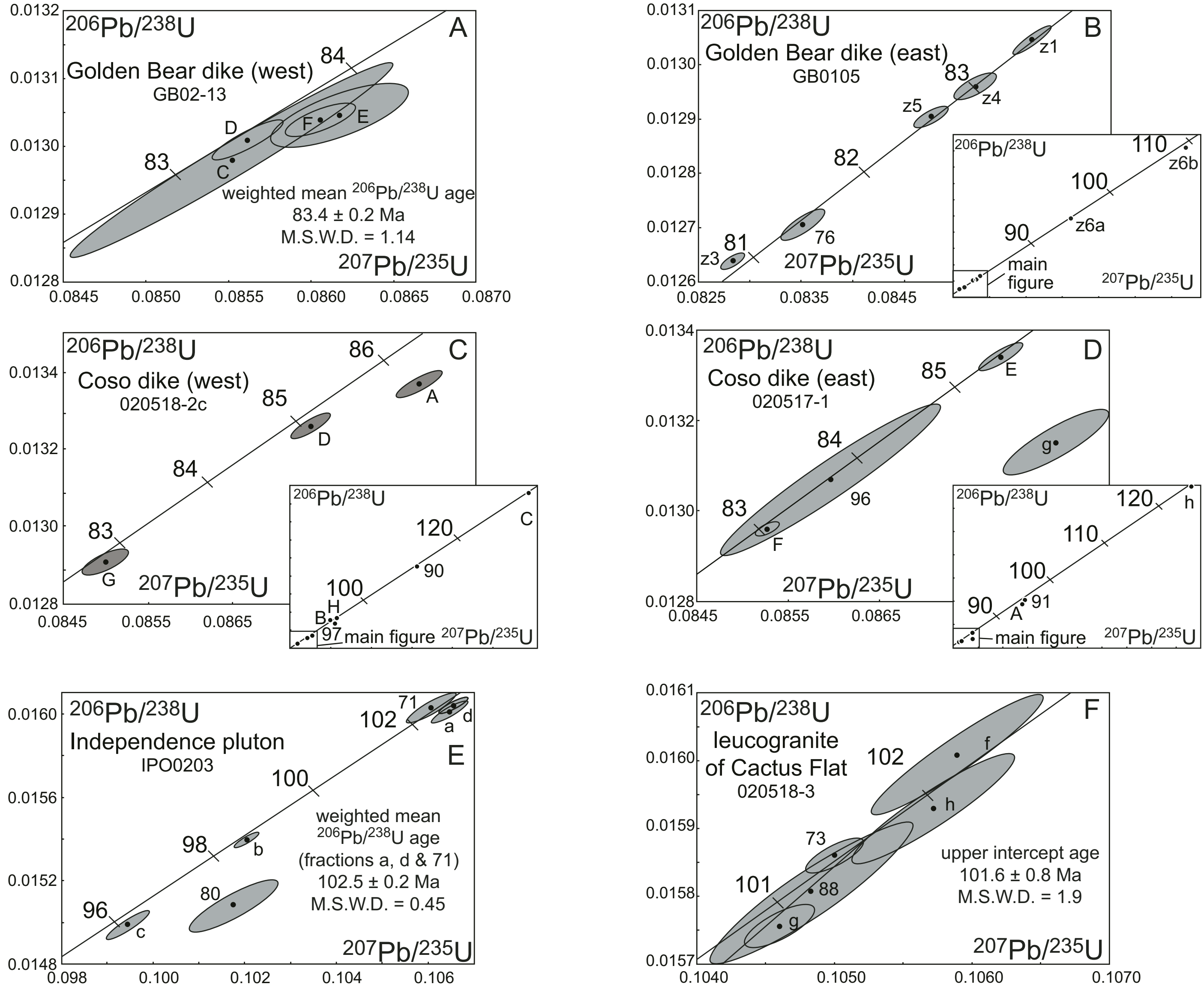

Figure 2. Zircon U-Pb geochronologic data for the Golden Bear and Coso dikes and their wall rocks. All samples are characterized by inheritance and/or Pb-loss patterns. We accept the weighted mean $^{206}Pb/^{238}U$ for the westernmost Golden Bear sample as the age of the dike and interpret the Coso dike data to be consistent with that age and therefore are likely correlative. The two leucogranite wall rock samples have ages that overlap within uncertainty, and we propose that they, too, are correlative.

quartz phenocrysts clearly distinguish the dikes from other dikes in the region, which include mafic, intermediate, and felsic dikes of the 148 Ma Independence dike swarm (Moore and Hopson, 1961; Chen and Moore, 1979), and aplite dikes of various ages. The only petrographically similar rocks in this part of the Mesozoic arc occur in plutons such as the Whitney Granodiorite (83.5 Ma; Saleeby et al., 1990) and the Papoose Flat pluton (83 Ma; Miller, 1996).

Some of the zircon U-Pb data from the Golden Bear and Coso dikes are complicated by inheritance and Pb loss. However, Whitmarsh's (2002) data and our results all are consistent with our best-determined age of 83.4 ± 0.2 Ma (Fig. 2A), which came from the western Golden Bear dike.

Geochemical evidence concerning correlation of the Golden Bear and Coso dikes is somewhat more complicated than petrographic and geochronologic evidence. The major oxide concentrations of the two dike sets are remarkably similar, but trace element data vary significantly, particularly for Ba, Rb, Th, U, Ta, and HREE (Fig. 3). However, because margin-to-core variations at a given location span the ranges of the elements that vary most (e.g., Th and U), we interpret this variation to result from internal differentiation of the dikes and/or wall-rock contamination. The fact that isotopic compositions of dike margins lie between the compositions of dike cores and wall rocks also suggests wall-rock contamination (Fig. 4). Although the ranges of isotopic values of the two dike sets overlap little, the dikes show a consistent pattern of increasing initial $^{87}Sr/^{86}Sr$ and decreasing ε_{Nd} from west to east, mirroring the pattern seen in the batholith as a whole (Kistler and Peterman, 1973).

The geochemical similarity and unique age of the wall rocks also support correlation of

	Avg.	Golden Bear Max.	Golden Bear Min.	Coso dikes Max.	Coso dikes Min.
SiO_2	68.53	69.88	68.03	69.32	66.18
TiO_2	0.40	0.45	0.36	0.50	0.35
Al_2O_3	16.41	16.77	15.72	17.00	16.25
FeO	2.22	2.62	2.03	2.60	1.78
MgO	0.68	0.71	0.59	0.85	0.60
CaO	2.46	2.93	2.45	2.92	1.77
K_2O	3.82	3.96	3.59	4.08	3.82
Na_2O	4.61	4.52	4.30	5.07	4.50
Pb	14	15	12	19	8.0
Ba	1510	1450	843	2600	1510
Rb	110	140	110	100	91
Th	9.6	20	8	7	5
U	2.2	4.1	1.7	1.8	1.1
Nb	8.8	10	8.4	8.7	7.3
Ta	0.61	0.74	0.72	0.52	0.45
Sr	697	659	591	926	577
Zr	198	207	153	229	189
Hf	5.0	5.2	4.3	5.6	4.9
Ga	21	22	20	22	21
Y	8	9	7	8	6
V	39	42	33	49	33
La	38.3	39.5	31.0	42.6	38.8
Nd	24.9	25.7	19.5	28.7	24.4
Sm	4.08	4.41	3.28	4.78	3.84
Gd	2.52	2.96	2.18	2.97	2.14
Yb	0.56	0.75	0.57	0.54	0.40

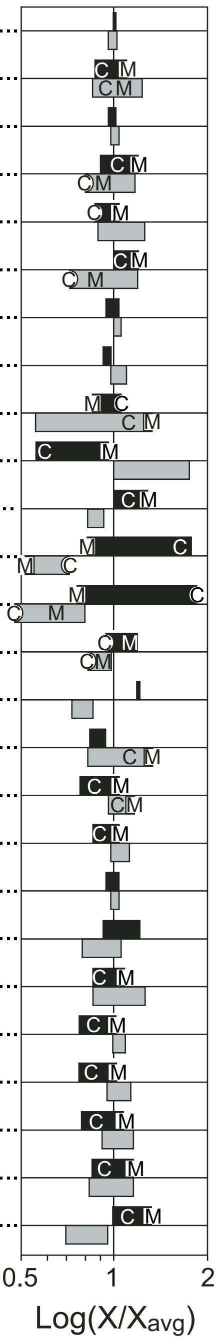

Figure 3. Summary of geochemical data for the Golden Bear and Coso dikes. Major oxides listed as weight percentages, and all other elements as parts per million. Not all analyzed elements are shown: a complete list of analyses and data for individual samples are in Table DR2 (see footnote 1). Listed average is the average of all dike analyses. Plotted ranges are calculated by normalizing maximum and minimum values for Golden Bear and Coso dikes to average of all dikes. C and M indicate analyses of core and margin samples collected from a single dike within 10 m of each other and are shown only if there was a measurable difference between the two samples. For many elements, a significant amount of the total variation observed occurs between adjacent core and margin samples, suggesting that the variation may result from internal differentiation of the dikes and/or wall rock contamination. For most elements there is a significant overlap in the range of oxide and elemental concentrations between the two dike sets. See text for complete discussion.

the Golden Bear and Coso dike sets. Adjacent to Owens Valley, both dike sets intrude 102 Ma leucogranite (Figs. 1 and 2E and F). Although common farther to the west, plutons with 102 Ma U-Pb zircon dates are known in the eastern Sierra only in the vicinity of the Golden Bear dike (Stern et al., 1981; Chen and Moore, 1982; Saleeby et al., 1990; Coleman and Glazner, 1997), and the leucogranite of Cactus Flat is the only 102 Ma pluton known on the east side of Owens Valley (Chen and Moore, 1982; McKee and Conrad, 1996; Coleman et al., 2003).

The intrusion of 83 Ma granodiorite porphyry dikes into 102 Ma leucogranite plutons is a unique association that compellingly argues for correlation of the Golden Bear and Coso dike sets. The chemical and isotopic data do not demand correlation of the dikes, but they are consistent with it. Consequently, we conclude that the Golden Bear and Coso dike sets were once continuous and have been offset by right-lateral motion across Owens Valley.

Cumulative Offset

Correlation of the Golden Bear and Coso dikes requires significant right-lateral displacement since 83 Ma. The displacement magnitude is relatively insensitive to the precise location of the fault(s) that accommodated it, because the Golden Bear and Coso dikes dip steeply and strike at high angles to the valley. Restoring the easternmost Golden Bear outcrops to a position adjacent to the westernmost Coso dike outcrops yields ~65 km of right slip (Fig. 1). Aligning the Golden Bear dike with the northernmost mapped exposures of the Coso dikes reduces the estimate to ~60 km. These estimates (60–65 km) resemble at least three other recent estimates of offset across the valley (Kistler, 1993; Stevens et al., 1997; Glazner et al., 2003), but they are significantly less than the possible ~130 km offset indicated by the 148 Ma Independence dike swarm (Glazner et al., 2003).

Locus of Slip

Previous work determined the approximate location of the fault zones responsible for dextral offset in the northern end of Owens Valley, but offers little information about where that fault zone tracked to the south (Fig. 1 inset). It is possible that the Tinemaha fault (Stevens et al., 1997) is correlative with the fault that offsets the Golden Bear and Coso dikes; however, the trace of the Tinemaha fault is queried by Stevens and Stone (2002) south of Tinemaha Reservoir. The northern section of Kistler's (1993) IBB3 accomplishes offset of the $^{87}Sr/^{86}Sr$ 0.706 isopleth attributed to the Tinemaha fault by Stevens et al. (1997). The southward continuation of IBB3, however, departs from the hypothesized location of the Tinemaha fault and instead tracks through the high Sierra, where it is likely coincident with Saleeby and Busby's (1993) EIB fault. Both the IBB3 and the EIB are too far west to accomplish offset of the Golden Bear dike. Farther south, Kistler (1993) postulated that his IBB3 fault cuts through the Coso Range, where he interpreted it to be cut by the 102 Ma leucogranite of Cactus Flat. Therefore, if the IBB3 fault does continue south, motion across it must predate dike intrusion and cannot correlate with the fault that offsets the dikes.

Consequently, offset of the Golden Bear and Coso dikes must have occurred across a previously unrecognized fault segment. Our work places the southern continuation of this fault zone between the Sierra Nevada and the White-Inyo-Coso ranges (Fig. 1). Although mostly buried by alluvium, a major strand of the fault system apparently can be located within 10 m at Little Lake on the west side of the Coso Range, where Jurassic plutonic rocks with abundant Independence dikes are juxtaposed against a distinctive Jurassic gneiss that lacks such dikes (Bartley et al., 2003). These authors describe a series of NNW-striking phyllonitic shear zones with dextral reverse oblique shear-sense indicators, and a broad zone of brecciation and cataclasis across which they were unable to determine kinematics. Because (1) the Coso dike and Independence dike swarm east of Little Lake appear to be continuous with little or no lateral offset, and (2) no evidence exists for significant dextral shearing immediately west of this area, we tentatively conclude that most of the 65 km slip is focused through the Little Lake area.

Timing of Offset

Significant dextral offset of Cretaceous dikes across southern Owens Valley places new limits on the timing of the offset and clarifies the correlations of different proposed fault segments in Owens Valley and the eastern Sierra Nevada. Stevens et al. (1997) and Stevens and Stone (2002) proposed ~65 km of dextral slip across northern Owens Valley in the Middle to Late Triassic but did not exclude a younger age for the offset. The 65 km offset between the Cretaceous Golden Bear and Coso dikes (Kylander-Clark, 2003), and a comparable estimate of offset of the Jurassic Independence dikes across Owens Valley (Glazner et al., 2003), led Stevens et al. (2003) to concede that the 65 km offset across the northern end of the valley was likely correlative and therefore younger than 83 Ma. Kistler (1993) proposed ~90 km of offset of the $^{87}Sr/^{86}Sr$ 0.706 isopleth across the IBB3 prior to the Early Cretaceous, because the fault is interpreted to be cut by Late Cretaceous plutons along its length. Because offset of the Golden Bear and Coso dikes is incompatible with both the location and the age of the IBB3, we conclude that the IBB3 is unrelated to the Tinemaha fault (Stevens and Stone, 2002) and probably correlates with shear zones exposed in the high Sierra that preserve complicated pre–92 Ma deformational histories (e.g., Mahan et al., 2003). If so, then slip across the Tinemaha fault after 83 Ma may also explain the offset of the Sr isopleth.

At current estimates of long-term slip rate across Owens Valley of 2–3 mm/yr, 65 km of offset could accumulate in ~20–30 m.y. This is compatible with the late Cenozoic right-oblique subduction setting of California (Atwater and Stock, 1998), and slip could have commenced when the San Andreas system started to form in the late Oligocene. Indeed, there is evidence that dextral slip began in the Mojave Desert in the early Miocene (Glazner et al., 2002). If dextral slip instead commenced in the Pliocene (Lee et al., 2001; Monastero et al., 2002; Stockli et al., 2003), and if all of the Golden Bear–Coso offset accumulated since then, then the slip rate must have been >20 mm/yr, which is more than half of the total Pacific–North American plate motion.

Accommodating all of the slip in the late Cenozoic presents problems, however, because such rapid offset would certainly affect the Garlock fault, which shows little evidence for disruption by north- to northwest-striking faults. Indeed, many dextral faults in the Mojave Desert die out before reaching the Garlock fault, and it is not clear how ongoing dextral slip south of the Garlock is transmitted to the north (e.g., Oskin and Iriondo, 2004). If much of the slip is pre-Miocene (and thus predates initiation of the Garlock fault; Monastero et al., 1997), then this problem is solved. In support of this possibility, Tobisch et al. (1995) showed that favorable conditions for dextral shear existed in the eastern Sierra since ca. 90 Ma. Tikoff and de Saint Blanquat (1997) and Sharp et al. (2000) reported evidence of Late Cretaceous dextral shear in the Sierra until ca. 80 Ma, and Bartley et al. (2003) proposed that Laramide-age dextral slip across the eastern margin of the Sierra Nevada rooted into the southern Sierra and accommodated extensional unroofing of high-pressure rocks exposed there. Thus, a complex history of dextral offset east of the main Sierra escarpment, beginning just after 83 Ma and persisting through the 1872 Lone Pine earthquake, seems likely.

CONCLUSIONS

The Golden Bear and Coso dike sets are coeval K-feldspar quartz monzonite porphyry dike sets that cut wall rocks of similar types and ages. Each set crops out for many kilometers along strike without apparent interruption but ends abruptly at Owens Valley. Major element, trace element, and isotopic geochemistry of the dikes either are closely similar or vary in systematic ways that are compatible with correlation of the dikes. Correlation implies 60–65 km of right-lateral offset across Owens Valley since 83.4 Ma.

If the entire 65 km of offset across Owens Valley occurred during the late Neogene, then the average slip rate must have been faster than current estimates of the present-day long-term average. Alternatively, much of the slip could have occurred in the Late Cretaceous–early Paleogene, when the plate-tectonic setting also favored dextral shearing.

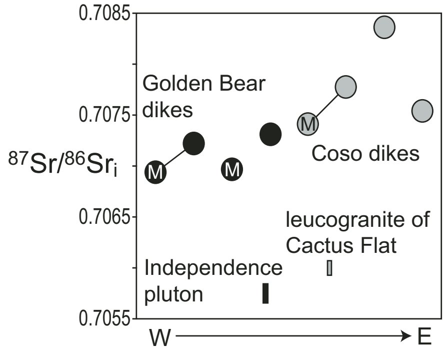

Figure 4. Sr isotopic data for the Golden Bear and Coso dike sets and their wall rocks. Samples are arranged from west to east with no distance scale along the horizontal axis. M indicates samples collected at the dike margin, and samples connected with a solid line indicate margin/center samples collected adjacent to each other. There is a general progression of increasing $^{87}Sr/^{86}Sr_i$ from west to east. Margin samples are consistently shifted away from center samples and toward the isotopic composition of adjacent wall rocks.

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