# Intra-arc strike-slip fault exposed at batholithic levels in the southern Sierra Nevada, California

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## ABSTRACT

**The Kern Canyon fault is a major north-trending fault that is continuous for a distance of 140 km in the southern Sierra Nevada, California. Previous geologic mapping and geochronological work along the northern third of the fault indicate that dextral offset occurred sometime after 80 Ma and before 3.5 Ma; this offset was interpreted to be the result of Cenozoic basin-and-range extension. Our new results from the central third of the fault (Kernville–Lake Isabella region) indicate an earlier right-lateral movement history, contemporaneous with emplacement of the largest plutons in the Sierra Nevada. The older structure is termed the proto–Kern Canyon fault zone. The Cenozoic fault trace is a narrow zone of brittle deformation, whereas the Cretaceous fault zone is a broad zone of ductile deformation. U-Pb zircon geochronology on plutonic and metavolcanic rocks involved in the ductile deformation, as well as a pluton that postdates ductile deformation, demonstrate that the proto–Kern Canyon fault zone was active at 85 Ma, and may have begun to move as early as 105 Ma. Longitudinal strike-slip faults are common in modern magmatic arcs where convergence is oblique. The proto–Kern Canyon fault zone may have originated in response to a moderate northward component in subduction of the Farallon plate or perhaps a strong northward component for the Kula plate.**

## INTRODUCTION

Oblique convergence along a subduction margin commonly results in localization of strike-slip deformation in thermally weakened crust of the magmatic arc. Longitudinal strike-slip faults have been reported from many modern magmatic arcs (Allen, 1965; Fitch, 1972; Kaizuka, 1975; Jarrard, 1986). An outstanding example occurs in Sumatra, where oblique convergence is apparently resolved into two components: an arc-normal component, expressed by deformation of the accretionary prism, and an arc-parallel component, expressed by strike-slip displacements along the intra-arc Semangko fault zone (Fitch, 1972; Hayes and Taylor, 1978; Moore and Karig, 1980). Very few longitudinal strike-slip faults have been recognized in ancient magmatic arcs, however, probably because the faults may be obscured by younger intrusive or extrusive events. Additionally, it may be difficult to demonstrate that a fault was active during arc magmatism, particularly if it has been reactivated at a later time.

The Kern Canyon fault (Fig. 1, inset) is a major north-trending right-lateral strike-slip fault 140 km long interpreted to form part of a Cenozoic fault system related to basin-and-range extension (Moore and du Bray, 1978). Field observations along the north and central segments of the fault indicate that it is a narrow zone of brittle deformation less than 100 m wide (Moore and du Bray, 1978; this study). Our new mapping and U-Pb zircon geochronology along the central third of the fault indicate an earlier, mid(?)- to Late Cretaceous dextral movement history, contemporaneous with pluton emplacement, along a broad zone of ductile deformation 0.5–3 km wide, referred to here as the proto–Kern Canyon fault zone.

We show here how stratigraphic, structural, petrological, and geochronological data can be integrated to document the movement history of an ancient intra-arc strike-slip fault, and we relate the proto–Kern Canyon fault zone to Farrallon–North America and Kula–North America plate interactions in Cretaceous time.

## KERN CANYON FAULT

The Kern Canyon fault is expressed as a major topographic feature, controlling much of the course of the only north-south–trending river valley in the Sierra Nevada, thus bisecting the southern part of the range into two prominent crests: the Great Western Divide and the Eastern Crest. The Kern Canyon fault was first recognized by Lawson (1904). Webb (1946) demonstrated that the fault is inactive because it is overlain by unfaulted Tertiary basalt, later dated by Dalrymple (1963) as 3.5 Ma. The northern end of the Kern Canyon fault dies out by branching into several faults across a zone at least 6 km wide (Moore and du Bray, 1978). Mapped offsets in Mesozoic plutonic rocks along the northern third of the fault suggest a progressive southward increase in right-lateral slip from about 6.5 to 13 km of displacement. Reliable slip indicators along the central third of the fault, mapped in this study (Fig. 1) or south of our map area, have not been recognized.

We divide the central segment of the Kern Canyon fault into a north-northwest–south-southeast–trending north branch and a northeast-southwest–trending south branch (Fig. 1). The south branch is similar to the segment of the fault north of our mapped area, described by Moore and du Bray (1978), in two important ways: (1) it is largely within granitic rocks, and (2) deformation is restricted to a narrow zone that is entirely brittle in character (i.e., a crush zone). The north branch of the fault in our map area, in contrast, separates metamorphic roof-pendant rocks from granitic rocks, and ductile deformation features occur along a broad zone in both rock types. These ductile deformation features are crosscut by the youngest granites and are overprinted by a narrow crush zone along the north branch of the fault. The belt of ductilely deformed rocks, referred to as the proto–Kern Canyon fault zone, trends north-northwest–south-southeast along its length and thus diverges from the south branch of the Kern Canyon fault (Fig. 1).

## PROTO–KERN CANYON FAULT ZONE

The proto–Kern Canyon fault zone is a north-northwest–trending, steeply dipping mylonite-phyllonite belt that has dextral shear indicators that involve three major rock types (Fig. 1): (1) greenschist to sillimanite grade metasedimentary rocks of early Mesozoic protolith age, referred to as the Kings sequence (Saleeby et al., 1978; Saleeby and Busby-Spera, 1986); (2) metavolcanic and subvolcanic rocks, and lesser interstratified metasedimentary rocks, that yield mid-Cretaceous U-Pb zircon ages (Busby-Spera, 1983; Saleeby, unpub. data); and (3) pre-83 Ma, Upper Cretaceous granitic rocks. Stratigraphic, structural, and geochronological data from these rocks, both within and outside the proto–Kern Canyon fault zone, provide constraints on the nature and timing of intra-arc strike-slip movements in the southern Sierra Nevada.

Figure 2. Proto–Kern Canyon fault zone is defined by phyllonitic to mylonitic textures in metasedimentary pendant rocks, and mylonitic textures in granitic rocks as young as 85 ±1 Ma. Kern Canyon fault is narrow crush zone.

formed ($D_1$) metasedimentary rocks of the Kings sequence. A nondeformed, moderately east-dipping, homoclinal section of quartzite-clast metasedimentary breccia and interstratified metacalcareous mudstone lies at the base of the mid-Cretaceous section. The metasedimentary breccia has angular to subangular quartzite clasts and a ($D_1$?) cleavage internal to the clasts, as well as lesser vein quartz clasts, both derived from the Kings sequence. The coarseness and angularity of the clasts and the restricted clast types suggest accumulation near the base of a fault scarp. The clasts are commonly supported in a grit-mudstone matrix and show no preferred orientation, stratification, or grading, thus suggesting deposition from debris flows. Some breccias, however, are normally graded and stratified, which suggests deposition from turbidites in a lacustrine or marine basin.

The quartzite-clast breccias are overlain by intermediate lithic lapilli tuffs and silicic ignimbrite sheets several hundred metres thick, dated as 102 Ma. The ignimbrites become progressively more cleaved and flattened upsection as the proto–Kern Canyon fault zone is approached to the northeast (Fig. 1), until they form mylonites with ribbon quartz along the fault zone ($D_3$ event).

The quartzite-clast breccias and interstratified metacalcareous mudstones form the host rocks for well-developed peperites along the margins of rhyolitic intrusions dated at 105 Ma. Peperites are formed by mixing of magma and wet sediment and are useful for demonstrating contemporaneity of volcanism and sedimentation (Kokelaar, 1982).

The mid-Cretaceous sequence in Erskine Canyon, in summary, consists of fault-talus breccias and interstratified turbidites, ponded ignimbrites, and penecontemporaneous hypabyssal intrusions. This sequence may represent the fill of a volcano-tectonic depression that formed along the proto–Kern Canyon fault zone during its early movement history.

## Mylonitic Granites

Ductilely deformed granites, which occur as discontinuous remnants intruded by nondeformed granites, have been recognized along the north branch of the Kern Canyon fault and south of Kernville, where the proto–Kern Canyon fault zone diverges from the Kern Canyon fault (Fig. 1). The mylonitic granite body south of Kernville intruded the mid-Cretaceous Kernville mafic intrusion along its southwest margin, but its contact relations with the undifferentiated Upper Cretaceous granitoids (Fig. 1) are not very well exposed. Structures within the larger mylonitic granite body along the north branch of the Kern Canyon fault, and its contact relations with a nonmylonitized granite, are very well exposed and indicate that dextral slip occurred during emplacement of the Late Cretaceous batholith.

Relations between mylonitized and nonmylonitized granites and the Kern Canyon fault are well displayed at the north end of the granite mylonite body (Fig. 2). Here, a nonmylonitized potassium feldspar–megacrystic granite cross-cuts deformational fabrics of the mylonitized granite at high angles, in very sharp contact. Small screens of the granite mylonite are engulfed in the nonmylonitized granite, and dikes emanating from the nonmylonitized granite intrude the granite mylonite along planes of schistosity. The nonmylonitized granite completely cuts out the granite mylonite at its northernmost end and becomes involved in a 10-m-wide crush zone, probably produced by Cenozoic movements along the Kern Canyon fault.

Kinematic indicators in the granite mylonite are abundant and consistently indicate dextral shear. Relations between S and C fabrics ("schistosite" or foliation and "cisaillement" or shear; Berthe et al., 1979) show only dextral shear. Both surfaces dip vertically or very steeply to the east, and the S surfaces strike 14°–30° more westerly than C surfaces, which strike approximately north-south. The S surfaces are quartz and feldspar ribbon aggregates, and the C surfaces are thin layers of reduced grain size. Feldspar grains up to 2 cm in length are broken and displaced within the more ductile matrix, indicating dextral shear (similar to Fig. 9 of Simpson and Schmid, 1983), and dikes intruded at high angles to the S-C fabric are also broken and displaced in a dextral sense. At other localities, dikes are asymmetrically folded in a dextral sense. Asymmetrical feldspar augen with fine-grained "tails" are common in thin section. Biotite mica "fish" with the (001) cleavage tilted back against the sense of shear (terminology of Lister and Snoke, 1984) are dextral in sense. Finally, penetrative biotite mineral lineations plunge less than 20° to the north along the cleavage plane, which suggests subhorizontal slip and a minor component of uplift on the east side relative to the west side of the proto–Kern Canyon fault zone.

The granite mylonite body shows a progressive increase in intensity of deformation with proximity to the Kern Canyon fault, suggesting that the Cenozoic fault trace coincides with the locus of maximum slip along the proto–Kern Canyon fault zone in this area. This increase in the intensity of deformation is expressed by a decrease in grain size of porphyroclasts, accompanied by increased recrystallization of quartz and feldspar into ribboned aggregates. The spacing of C surfaces becomes closer and the angle between C and S surfaces becomes lower with proximity to the Kern Canyon fault. Magmatic biotite books do not survive within 200 m of the Kern Canyon fault, due largely to comminution along C surfaces.

With distance from the Kern Canyon fault, strain in the granite mylonite body becomes more heterogeneous. Severe grain-size reduction and subparallel S-C fabrics are restricted to thin shear zones, millimetres thick, that are spaced centimetres to decimetres apart. Between these thin shear zones, the C surfaces are at a 15°–25° angle to S surfaces, and the feldspars appear to have undergone relatively little grain-size reduction, although quartz is ribboned. Pegmatite dikes, schlieren bands up to 0.5 m thick, and small mafic inclusions are preserved. Pegmatite dikes intruded at high angles to the foliation are discontinuous due to folding (within 0.5 km of the Kern Canyon fault) or breakage and displacement (farther from the fault), whereas those parallel to the foliation are continuous for tens of metres. The angle between S and C surfaces is higher in the pegmatites (30°–40°) than in the granite.

## TIMING, EXTENT, AND AMOUNT OF INTRA-ARC WRENCHING

We have obtained very tight age constraints on the timing of at least some of the strike-slip movement along the proto–Kern Canyon fault zone. U-Pb zircon data from both the mylonitized granite and the nonmylonitized granite of Figure 2 show that mylonitization occurred between 85 and 83 Ma (Fig. 3; Table 1).

Figure 3 is a concordia plot of zircon data from the mylonitized and nonmylonitized granites. The data points are internally concordant to slightly discordant, with upward dispersion from lower intercepts. This pattern is typical of southern Sierra Cretaceous granitoids that were emplaced in the Kings sequence (Saleeby et al., 1987; Saleeby, 1987, 1989) and is a result of the entrainment of Early Proterozoic detrital zircon, which is abundant in the metaclastic wall rocks. The nearness to concordia and the linearity of the data points result in precise lower intercept ages and make the likelihood of disturbance components in the discordance pattern highly unlikely. The upper intercept ages are very rough approximations of the overall isotopic character of the entrained zircon, although detrital zircon analyses from Kings sequence rocks commonly yield results within the range of the

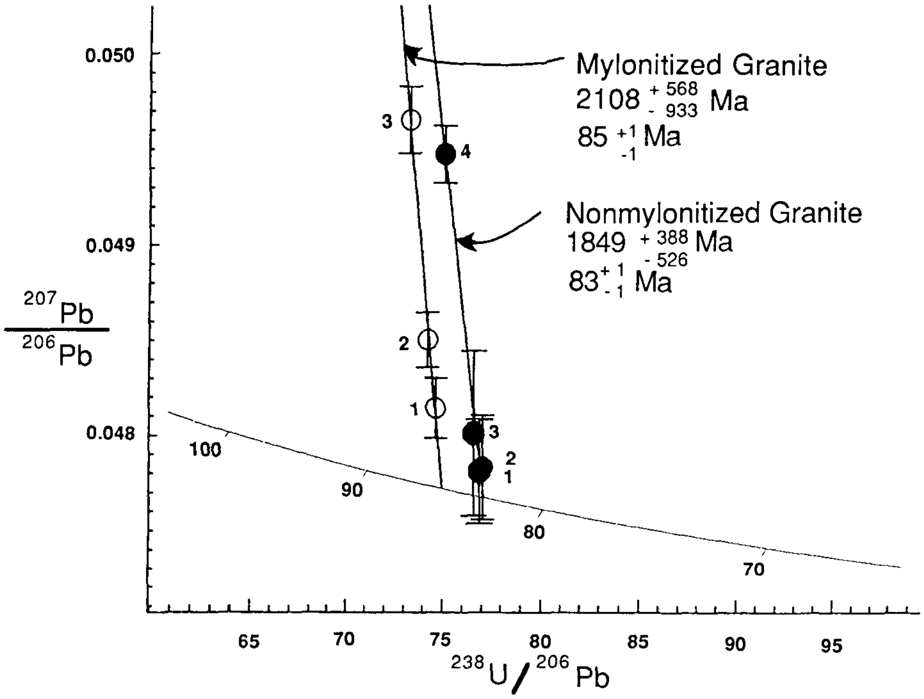

**Figure 3. Concordia diagram (Tera and Wasserburg, 1972) of U-Pb zircon data from granite mylonitized along proto-Kern Canyon fault zone (three fractions—open circles) and granite that postdates movement along proto-Kern Canyon fault zone (four fractions—solid circles). This diagram plots ratio of radiogenic Pb isotopes against $^{238}U/^{206}Pb$ parent/daughter ratio.**

TABLE 1. ZIRCON ISOTOPIC AGE DATA

| Sample | Fraction† (µm) | Amount Analyzed (mg) | Concentration (ppm) | | Atomic ratios | | | | Isotopic ages§ (Ma) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $^{238}U$ | $^{206}Pb^*$ | $^{206}Pb/^{204}Pb$ | $^{206}Pb^*/^{238}U$ | $^{207}Pb^*/^{235}U$ | $^{207}Pb^*/^{206}Pb^*$ | $^{206}Pb^*/^{238}U$ | $^{207}Pb^*/^{235}U$ | $^{207}Pb^*/^{206}Pb^*$ |
| 1 | 1/20 | | | | | | | | | | |
| | 1. <45 | 4.3 | 713 | 8.0 | 10248 | 0.01298 (0.00010) | 0.08555 | 0.04783 (0.00028) | 83 | 83 | 90±15 |
| | 2. 45-62 | 5.7 | 679 | 7.6 | 10731 | 0.01301 (0.00011) | 0.08571 | 0.04781 (0.00027) | 83 | 84 | 89±14 |
| | 3. 62-80 | 4.1 | 451 | 5.1 | 1844 | 0.01306 (0.00011) | 0.08639 | 0.04801 (0.00044) | 84 | 84 | 99±21 |
| | 4. 80-120 | 6.7 | 522 | 6.0 | 4420 | 0.01332 (0.00011) | 0.09081 | 0.04947 (0.00015) | 85 | 88 | 169±8 |
| 2 | 2/20 | | | | | | | | | | |
| | 1. <45 | 5.1 | 872 | 10.1 | 751 | 0.01340 (0.00010) | 0.08887 | 0.04814 (0.00016) | 86 | 86 | 106±8 |
| | 2. 45-62 | 5.3 | 786 | 9.2 | 724 | 0.01347 (0.00010) | 0.09007 | 0.04850 (0.00015) | 86 | 88 | 123±8 |
| | 3. 62-80 | 2.1 | 253 | 3.0 | 607 | 0.01364 (0.00011) | 0.09332 | 0.04965 (0.00017) | 87 | 91 | 178±9 |

+Separation process.

*Radiogenic-nonradiogenic correction and calculation of uncertainties (in parentheses).

§Decay constants as in Saleeby et al. (1990).

cited values. From the zircon data of Figure 3 and Table 1, the mylonitized granite is thought to have crystallized at 85 ±1 Ma and the nonmylonitized granite at 83 ±1 Ma.

Movement along the proto–Kern Canyon fault zone thus appears to have ceased prior to the intrusion of the nonmylonitized granite (Fig. 2) at 83 Ma. This pluton is the same age as the potassium feldspar-megacrystic granite of Mount Whitney and its granodioritic rim, the Paradise pluton (Saleeby et al., 1990), which together represent one of the largest composite plutons in the Sierra Nevada (Moore and du Bray, 1978). This composite pluton lies along the northernmost end of the Kern Canyon fault crush zone and shows no evidence of ductile deformation (Moore and du Bray, 1978); however, a granite pluton to the west of the northernmost Kern Canyon fault, dated at 97 ±2 Ma by the U-Pb zircon method (Busby-Spera, 1983), shows evidence for syncrystallization ductile deformation along a major right-lateral strike-slip fault related to the Kern Canyon fault (Moore and Sisson, 1985). A belt of granite mylonites with dextral shear indicators also extends at least 30 km southward from the area of Figure 1 (Saleeby et al., 1987; C. A. Gazis and J. B. Saleeby, in prep.); thus, the proto–Kern Canyon fault zone was at least 130 km long.

The amount of displacement along the proto–Kern Canyon fault zone is not yet known because we have not located any reliable piercing points in the area we have mapped (Fig. 1). Shallowly north plunging lineations in granite mylonites along the proto–Kern Canyon fault zone suggest that the component of dip slip is less than one-fourth of the component of strike slip; thus, the 10 km vertical separation suggested by geologic relations may require at least 40 km of strike-slip separation. Alternatively, a much higher component of dip slip may have occurred along the proto–Kern Canyon fault zone between 100 and 85 Ma, although there are no kinematic indicators of this type of slip. Ongoing field and geochronological work is expected to reveal more details about the movement history of the proto–Kern Canyon fault zone.

## CONCLUSIONS

The Kern Canyon fault is a Cenozoic crush zone 140 km long; dextral offset is up to 13 km and probably developed in response to the extension of the Great Basin (Moore and du Bray, 1978). We have presented evidence for an earlier, intrabatholithic dextral movement history along a fault zone in part coincident and in part divergent from the Cenozoic fault, termed the proto–Kern Canyon fault zone. This fault zone is a broad zone of ductile deformation that was clearly active at 85 Ma, and probably began to move as early as 105 Ma. It was thus active during emplacement of the largest plutons in the Sierra Nevada, and it may have been a longer fault, with greater dextral slip, than the Cenozoic fault.

Engebretson et al. (1985) used ocean-plate data to suggest that subduction of oceanic crust below the western United States had a moderate component of northward movement between about 110 and 85 Ma, and a very strong component of northward movement by around 85 Ma. Our continental margin data from the southern Sierra Nevada support the interpretation that convergence was right-oblique from 105 to 85 Ma.

## REFERENCES CITED

Allen, C., 1965, Transcurrent faults in continental areas: Royal Society of London Philosophical Transactions, ser. A, v. 258, p. 82–89.

Berthe, D., Choukroune, P., and Jegouzo, P., 1979, Orthogneiss, mylonite and non-coaxial deformation of granites: The example of the South Armorican shear zone: Journal of Structural Geology, v. 1, p. 31–42.

Busby-Spera, C.J., 1983, Paleogeographic reconstruction of a submarine volcanic center: Geochronology, volcanology, and sedimentology of the Mineral King roof pendant, Sierra Nevada, California [Ph.D. thesis]: Princeton, New Jersey, Princeton University, 290 p.

Dalrymple, G.B., 1963, Potassium-argon dates of some Cenozoic volcanic rocks in the Sierra Nevada, California: Geological Society of America Bulletin, v. 74, p. 379–390.

Elan, R., 1985, High-grade contact metamorphism at the Lake Isabella north shore roof pendant, southern Sierra Nevada, California [M.S. thesis]: Los Angeles, University of Southern California, 202 p.

Engebretson, D.C., Cox, A., and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific basin: Geological Society of America Special Paper 206, 59 p.

Fitch, T.J., 1972, Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the western Pacific: Journal of Geophysical Research, v. 77, p. 4432–4460.

Hayes, D.E., and Taylor, B., 1978, Tectonics, *in* Hayes, D.E., compiler, A geophysical atlas of the east and southeast Asian seas: Geological Society of America Map and Chart Series MC-25.

Jarrard, R.D., 1986, Terrane motion by strike-slip faulting of forearc slivers: Geology, v. 14, p. 780–783.

Kaizuka, S., 1975, A tectonic model for the morphology of arc-trench systems, especially for en-echelon ridges and mid-arc faults: Japanese Journal of Geology and Geography, v. 45, p. 9–28.

Kokelaar, B.P., 1982, Fluidization of wet sediments during the emplacement and cooling of various igneous bodies: Journal of Geology, v. 90, p. 717–724.

Lawson, A.C., 1904, Geomorphogeny of the upper Kern basin: University of California Department of Geological Sciences Bulletin, v. 3, p. 291–386.

Lister, G.S., and Snoke, A.W., 1984, S-C mylonites: Journal of Structural Geology, v. 6, p. 617–638.

Moore, G.F., and Karig, D.E., 1980, Structural geology of Nias Island, Indonesia: Implications for subduction-zone tectonics: American Journal of Science, v. 280, p. 193–223.

Moore, J.G., and du Bray, E., 1978, Mapped offset on the right-lateral Kern Canyon fault, southern Sierra Nevada, California: Geology, v. 6, p. 205–208.

Moore, J.G., and Sisson, T.W., 1985, Geologic map of the Kern Peak quadrangle, Tulare County, California: U.S. Geological Survey Geologic Quadrangle Map GQ-1584.

Saleeby, J.B., 1987, Discordance patterns in Pb/U zircon ages of the Sierra Nevada and Klamath Mountains: Eos (Transactions, American Geophysical Union), v. 68, p. 1514–1515.

——1989, Progress in tectonic and petrogenetic studies in an exposed cross section of young (100 Ma) continental crust, southern Sierra Nevada, California, *in* Salisbury, M.H., ed., Exposed cross sections of the continental crust: Dordrecht, Netherlands, D. Reide, NATO Advanced Studies Institute.

Saleeby, J.B., and Busby-Spera, C.J., 1986, Field-trip guide to the metamorphic framework rocks of the Lake Isabella area, southern Sierra Nevada, California, *in* Dunne, G.C., ed., Mesozoic and Cenozoic structural evolution of selected areas, east-central California: (Geological Society of America Cordilleran Section meeting guidebook): Los Angeles, California State University, p. 81–94.

Saleeby, J.B., Goodin, S.E., Sharp, W.D., and Busby, C.J., 1978, Early Mesozoic paleotectonic-paleogeographic reconstruction of the southern Sierra Nevada region, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 2, p. 311–336.

Saleeby, J.B., Sams, D.B., and Kistler, R.W., 1987, U/Pb zircon, strontium, and oxygen isotopic and geochronological study of the southernmost Sierra Nevada batholith, California: Journal of Geophysical Research, v. 92, p. 10,443–10,446.

Saleeby, J.B., Kistler, R.W., Longiaru, S., Moore, J.G., and Nokleberg, W.J., 1990, Middle Cretaceous metavolcanic rocks in the Kings Canyon area, central Sierra Nevada, California, *in* Anderson, J.L., ed., Cordilleran magmatism: Geological Society of America Memoir 174.

Simpson, C., and Schmid, S.M., 1983, An evaluation of criteria to deduce the sense of movement in sheared rocks: Geological Society of America Bulletin, v. 94, p. 1281–1288.

Tera, F., and Wasserburg, G.J., 1972, U/Pb systematics in lunar basalts: Earth and Planetary Science Letters, v. 17, p. 65–78.

Webb, R.W., 1946, Geomorphology of the middle Kern River basin, southern Sierra Nevada, California: Geological Society of America Bulletin, v. 57, p. 355–382.

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