6-1-2012

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C. C. Brossy

K. I. Kelson

Colin B. Amos
Western Washington University, colin.amos@wwu.edu

J. N. Baldwin

B. Kozlowicz

See next page for additional authors

Recommended Citation

Brossy, C. C.; Kelson, K. I.; Amos, Colin B.; Baldwin, J. N.; Kozlowicz, B.; Simpson, D.; Ticci, M. G.; Lutz, A. T.; Kozaci, O.; Streig, A.; Turner, R.; and Rose, R., "Map of the late Quaternary active Kern Canyon and Breckenridge faults, southern Sierra Nevada, California" (2012). *Geology Faculty Publications*. 94.
https://cedar.wwu.edu/geology_facpubs/94

Authors

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Map of the late Quaternary active Kern Canyon and Breckenridge faults, southern Sierra Nevada, California

C.C. Brossy[1,*], K.I. Kelson[1], C.B. Amos[2], J.N. Baldwin[1,†], B. Kozlowicz[3], D. Simpson[3], M.G. Ticci[1], A.T. Lutz[1,†], O. Kozaci[1], A. Streig[4], R. Turner[1], and R. Rose[5]
[1]*Fugro Consultants, Inc., 1777 Botelho Drive, Walnut Creek, California 94596, USA*
[2]*Department of Earth and Planetary Sciences, University of California, Berkeley, California 94720, USA*
[3]*URS Corporation, 1333 Broadway, Oakland, California 94104, USA*
[4]*Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403, USA*
[5]*U.S. Army Corps of Engineers, Dam Safety Assurance Program, Sacramento, California 95814, USA*

ABSTRACT

Surface traces of the Quaternary active Kern Canyon and Breckenridge faults were mapped via aerial reconnaissance, analysis of light detection and ranging (LiDAR) elevation data, review and interpretation of aerial photography, field reconnaissance, and detailed field mapping. This effort specifically targeted evidence of late Quaternary surface deformation and, combined with separate paleoseismic investigations, identified and characterized the North Kern Canyon, South Kern Canyon, and Lake Isabella sections of the Kern Canyon fault and the Breckenridge fault. The mapping presented here provides definitive evidence for previously unrecognized Holocene and late Pleistocene east-down displacement along the Kern Canyon and Breckenridge faults. Our results indicate that much of the Kern Canyon fault has undergone Quaternary reactivation to accommodate internal deformation of the otherwise rigid Sierra Nevada block. This deformation reflects ongoing, seismogenic crustal thinning in the southern Sierra Nevada, and highlights the effects of localized tectonic forces operating in this part of the Sierra Nevada.

INTRODUCTION

At a plate tectonics scale, the Sierra Nevada Mountains and the adjacent Central Valley are coupled and together form a quasi-rigid crustal block termed the Sierran microplate (Wright, 1976; Argus and Gordon, 1991). This microplate is bounded by the San Andreas transform system on the west and the eastern California shear zone–Walker Lane belt on the east (Fig. 1). Relative to stable North America, the Sierran microplate moves northwest (Savage et al., 1990; Sauber et al., 1994; Argus and Gordon, 1991, 2001) within a broad zone of deformation between the Pacific plate and North America (Fig. 1). Uplift of this quasi-rigid block on the west resulted in the Sierra Nevada mountain range, and an adjacent linear zone of subsidence on the east resulted in the Central Valley (Unruh, 1991). However, this paired uplift and subsidence relationship becomes more complex in the southern Sierra Nevada and Great Valley where extensive faulting affected the morphology of the range and the adjacent basin (Clark et al., 2005; Maheo et al., 2009).

The southern Sierra Nevada supports the highest elevations in the range, suggesting to some authors that along-strike differences in the present-day morphology reflect localized differences in the tectonic history of the range (Wakabayashi and Sawyer, 2001; Clark et al., 2005; Maheo et al., 2009). For example, although large-scale, plate tectonic forces suggest that the range is undergoing long-term westward tilting and translating as a quasi-rigid block relative to North America, ongoing seismicity indicates that localized forces (superimposed on these more regional stresses) are driving active crustal thinning of the southern Sierra Nevada (Jones and Dollar, 1986; Unruh and Hauksson, 2009). Until recently, this crustal thinning was not recognized as occurring on surface-rupturing faults. Detailed mapping to determine the activity of the Kern Canyon fault system (Fig. 2) reveals that parts of the fault system have been active in the Quaternary as surface-rupturing faults.

This paper describes the surface expression of extensional structures that are actively deforming the southern Sierran microplate (Amos et al., 2010; Nadin and Saleeby, 2010). Specifically, we present map-based evidence of late Quaternary activity on the Kern Canyon and Breckenridge faults, between Harrison Pass on the north and Walker Basin on the south (Fig. 2).

Regional Geologic and Seismotectonic Setting

Analysis of regional seismicity suggests that the state of stress within the crust in the southern Sierra Nevada probably is not uniform (Unruh and Hauksson, 2009). Seismicity occurs across a broad area within the southern Sierra Nevada (Fig. 3). The region is characterized by thinner crust and higher heat flow (Saltus and Lachenbruch, 1991) and hosts discrete clusters of seismicity. For example, the focal mechanisms of a swarm of small earthquakes that occurred in the early 1980s near Durrwood Meadows (Fig. 3) suggest that the range is deforming internally via horizontal extension and normal faulting (Jones and Dollar, 1986; Unruh and Hauksson, 2009). Consequently, the southern Sierra north of Lake Isabella may be influenced by extension in two horizontal directions (i.e., vertical flattening) at the latitude of Durrwood Meadows (~36.5° North latitude, Fig. 3). Unruh and Hauksson (2009) suggest that this flattening deformation in the southern Sierra Nevada may represent thinning of the upper crust in response to local buoyancy forces associated with lateral density variations in the upper mantle (Figs. 1 and 3) (Saleeby et al., 2003; Boyd et al., 2004). In contrast, analysis of regional microseismicity shows that the southern Sierra Nevada, including the area near the southern end of the Breckenridge fault (Rankin Ranch, Figs. 2 and 3), is characterized locally by dextral shearing rather than extension (Brossy et al., 2010; URS/FWLA, 2010).

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*Corresponding author email: c.brossy@fugro.com.
†Present address: Lettis Consultants International, Inc., 1981 N. Broadway, Walnut Creek, California 94596, USA.

Geosphere; June 2012; v. 8; no. 3; p. 581–591; doi:10.1130/GES00663.1; 6 figures; 1 table; 1 plate.

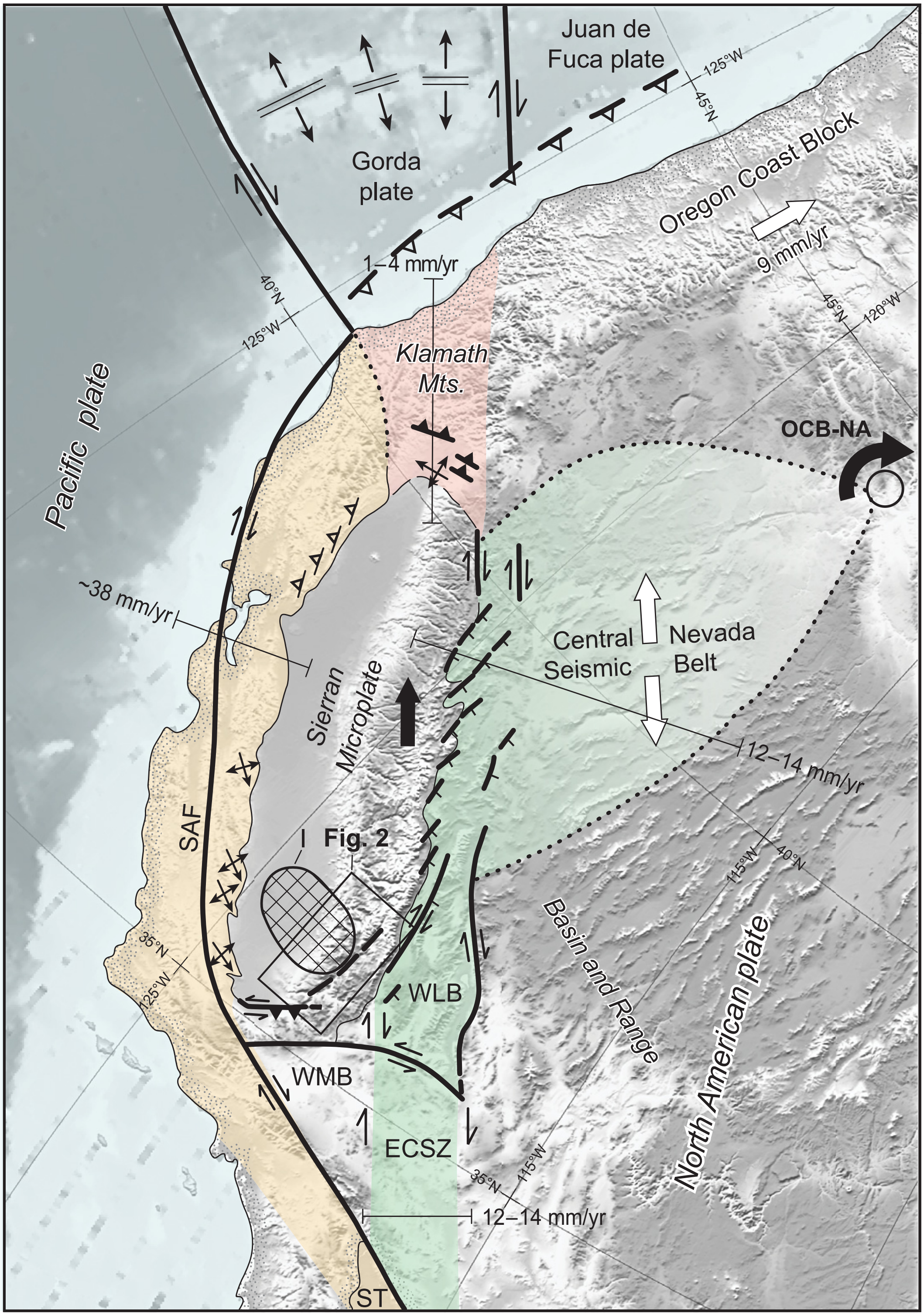

Figure 1. Regional tectonic setting of the Sierran microplate. Oblique Mercator map of the western United States modified from Unruh et al. (2003) using the Euler pole for Sierran–North American motion (Argus and Gordon, 2001) as a basis for projection. In this view, the long axis of the figure is parallel to the motion of the Sierran microplate with respect to stable North America. Pacific–North American plate motion splits into two branches in the northern Salton Trough (ST). Approximately 75% of the total Pacific–North American plate motion (yellow band) is accommodated by slip on the San Andreas fault (SAF) and related structures in western California, and the remaining 25% of the plate motion (green band) is transferred across the western Mojave block by the eastern California shear zone (ECSZ) to the Walker Lane belt (WLB) on the east side of the Sierra Nevada (Savage et al., 1990; Sauber et al., 1994; Argus and Gordon, 1991, 2001). The deformation in the Walker Lane belt spreads eastward into the central Nevada seismic belt and drives northward motion of the Oregon coast block as clockwise rotation around an Euler pole in eastern Oregon and western Idaho (OCB-NA) (Argus and Gordon, 2001). Some Walker Lane belt motion steps west across the northern Sierra crest to the southern Cascadia subduction zone and drives crustal shortening in the northern Sacramento Valley (pink band). WMB—Western Mojave Block; I—Isabella anomaly.

The Kern Canyon Fault System

The north-striking Kern Canyon fault system is a major crustal shear zone oriented nearly parallel with the axis of the southern Sierra Nevada (Fig. 2) that has undergone several periods of deformation since Cretaceous time (Saleeby et al., 2009; Nadin and Saleeby, 2010). It can be subdivided according to the onset and duration of fault activity into: (1) the proto–Kern Canyon fault zone; (2) the Kern Canyon fault zone; and (3) the late Quaternary active Kern Canyon fault.

Proto–Kern Canyon fault zone. The "proto–Kern Canyon fault zone" refers herein to an exhumed, Cretaceous fault zone originally described by Busby-Spera and Saleeby (1990) and Nadin and Saleeby (2001, 2005, 2008). The zone extends from near 36.6° N southward,

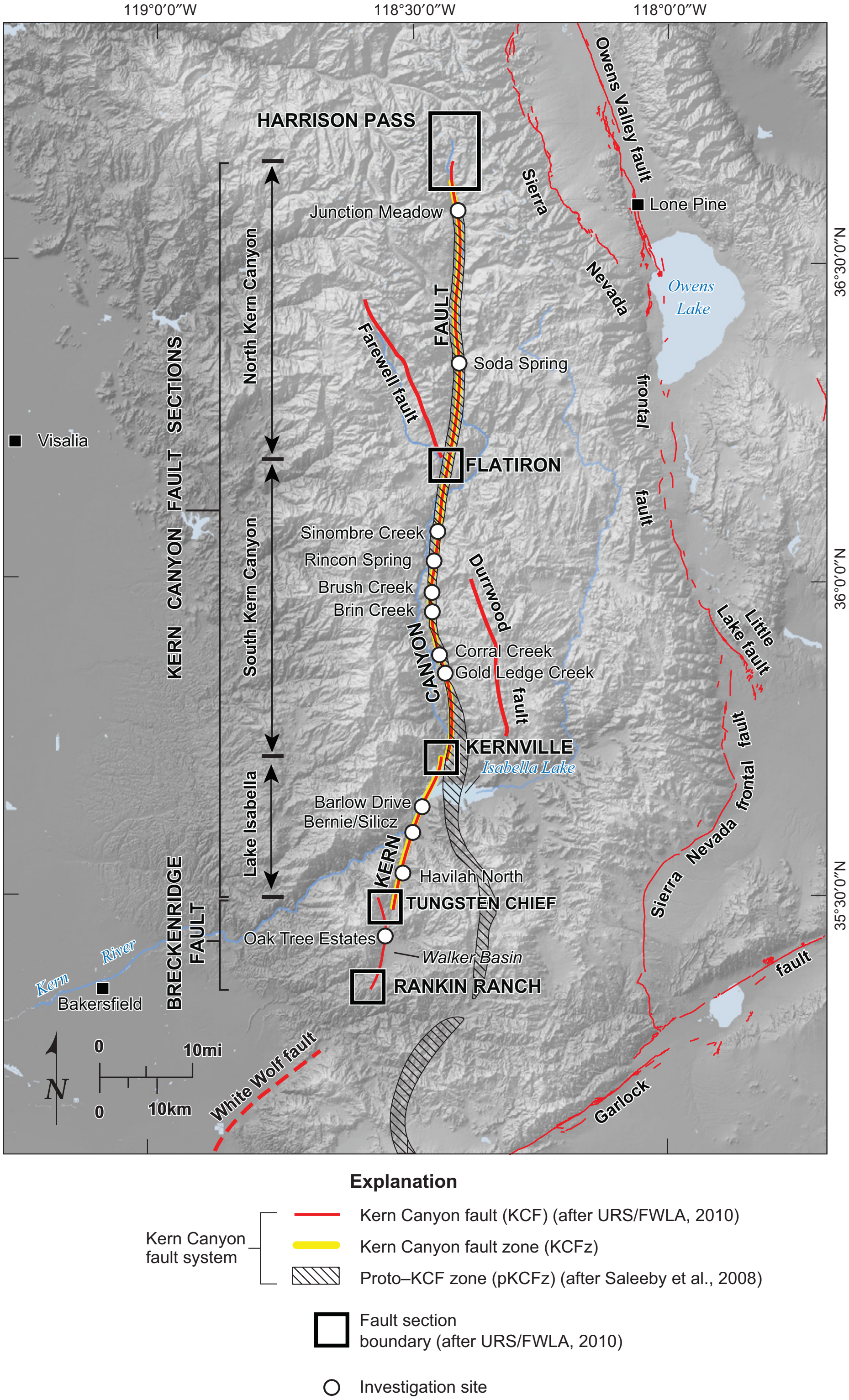

Figure 2. Hillshade topographic map of the southern Sierra Nevada and surrounding region, showing fault sections of the Kern Canyon fault and detailed investigation sites described in Kelson et al. (2010a) and URS/FWLA (2010). Relations between the proto–Kern Canyon fault zone (pKCFz), Kern Canyon fault zone (KCFz), and Kern Canyon fault (KCF) also shown. Proto–Kern Canyon fault zone and Kern Canyon fault zone after Saleeby et al. (2008); Kern Canyon and Breckenridge faults from this study and URS/FWLA (2010); and all others after Jennings (1994 version 2).

along the eastern arm of Isabella Lake, and then south toward the Garlock fault at the southern boundary of the Sierra Nevada (Fig. 2). Where exposed, the proto–Kern Canyon fault zone exhibits extensive mylonitization fabric within a 5-km-wide (3-mi-wide) zone (Nadin and Saleeby, 2005). In places (e.g., the area north of Kernville), this structure coincides with and includes the Kern Canyon fault zone (KCFz, Fig. 2) and/or the late Quaternary active Kern Canyon fault (KCF, Fig. 2).

Kern Canyon fault zone. Herein, the term "Kern Canyon fault zone" refers to the fault as mapped by previous bedrock investigators (Smith, 1964; Matthews and Burnett, 1965; Moore and du Bray, 1978; Ross, 1986) without regard to late Quaternary activity. The roughly north-striking Kern Canyon fault zone is a prominent geologic structure within the southern Sierran microplate that extends for ~135 km from Walker Basin on the south end to near Harrison Pass at the Kings-Kern Divide on the north end (Fig. 2). The Kern Canyon fault zone (Fig. 2) has accommodated multiple episodes of pre-Quaternary crustal deformation, including right-lateral strike slip and east-down normal displacement (Smith 1964; Matthews and Burnett, 1965; Saint-Amand et al., 1975; Moore and du Bray, 1978; Ross, 1986; Busby-Spera and Saleeby, 1990; Nadin and Saleeby, 2001, 2005, 2008, 2010). Nadin and Saleeby (2005) observed that rocks along the northern half of the Kern Canyon fault zone (north of Isabella Lake) show evidence of latest Cretaceous to Paleocene brittle-dextral shearing in a 50-m-wide zone between metamorphic rocks to the west and granite to the east. In the area near Isabella Lake, dextral strike-slip faulting along the Kern Canyon fault zone has displaced bedrock units ~10–12 km (Ross, 1986; Nadin, 2007). At the surface, major shear zones within the Kern Canyon fault zone dip steeply (Ross, 1986; Busby-Spera and Saleeby, 1990; Nadin and Saleeby, 2001, 2005) and have nearly linear traces across rugged topography.

Kern Canyon fault. Both the proto–Kern Canyon fault zone and the Kern Canyon fault zone are distinct from the "Kern Canyon fault," the ~135-km-long, late Quaternary active structure (URS, 2007, 2008; Amos et al., 2010; Kelson et al., 2009a, 2009b; Kozaci et al., 2009). The Kern Canyon fault generally lies within the Kern Canyon fault zone and is traced from a complex intersection with the Breckenridge fault on the south near Walker Basin to a northern termination near the Kings-Kern Divide (Fig. 2) (Dibblee and Chesterman, 1953; Smith, 1964; Matthews and Burnett, 1965; Ross, 1986; Saleeby et al., 2008). Results from regional geologic and seismologic analyses suggest that the active Kern

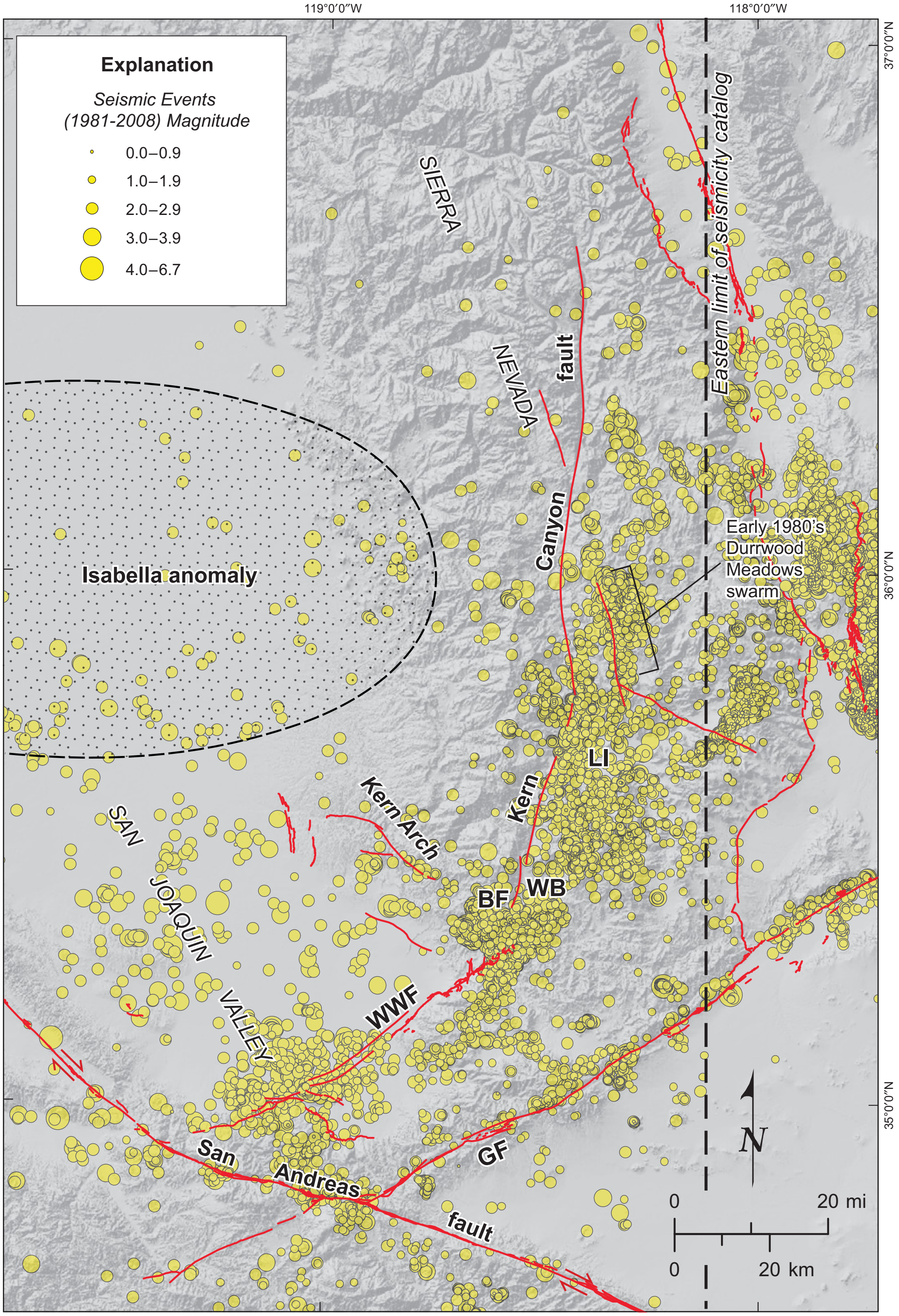

Figure 3. Seismicity in the southern Sierra Nevada and southern San Joaquin Valley. Earthquakes recorded by the Northern and Southern California Seismic Networks. Dashed line indicates eastern limit of seismicity catalog compiled by URS/FWLA (2010); earthquake locations east of the dashed line are from Unruh and Hauksson (2009); Kern Canyon and Breckenridge faults from this study; all others from Jennings (1994 version 2). LI—Lake Isabella; WB—Walker Basin; BF—Breckenridge fault; GF—Garlock fault; WWF—White Wolf fault.

Canyon fault exploits planes of weakness in the Kern Canyon fault zone and/or proto–Kern Canyon fault zone, and probably accommodates generally east-west–directed extension related to deep lithospheric-scale processes (Saleeby et al., 2009; Unruh and Hauksson, 2009).

Previous Work on the Kern Canyon and Breckenridge Faults

Until recently, Quaternary activity of the Kern Canyon fault zone was precluded by the early interpretations of Webb (1946) that a basalt flow, later dated to 3.5 Ma by Dalrymple (1963), overlying the fault zone is not tectonically deformed. However, recent analysis has shown that the fault zone is associated with prominent tectonic geomorphology, including east-facing scarps developed in the basalt flow where it overlies the fault zone (Kelson et al., 2009a; Amos et al., 2010; Nadin and Saleeby, 2010), and our investigations documented evidence of fault displacement elsewhere on the Kern Canyon fault within the past 15 ka (URS, 2006; Kelson et al., 2009a, 2009b; Kozaci et al., 2009). The Breckenridge fault is considered as a possible component of the Kern Canyon fault zone, and hence is included in this mapping effort. This 9- to 11-km-long, north-northeast–striking fault lies ~1–1.5 km west-southwest of the southern termination of the Kern Canyon fault, and borders the western margin of Walker Basin (Dibblee and Chesterman, 1953; Ross, 1986) (Fig. 2).

Previous maps of the Kern Canyon and Breckenridge faults include investigations or compilations by Dibblee and Chesterman (1953), Smith (1964), Matthews and Burnett (1965), Burnett (1976), du Bray and Dellinger (1981), Moore (1981), Moore and Sisson (1985), Ross (1986), Saleeby et al. (2008), and Nadin and Saleeby (2008). The mapping effort described here builds upon these previous works, as well as previous fault characterizations for the U.S. Army Corps of Engineers (USACE) Isabella Project dams (e.g., Page, 2004, 2005; URS, 2006), and is part of a recently completed detailed seismic source characterization (URS/FWLA, 2010) for evaluating seismic hazard at the Isabella Project dams. Herein, we focus on presenting a map of late Quaternary active fault traces at 1:24,000 scale; the detailed fault characterization, including paleoseismic data from individual site investigations and earthquake-rupture scenarios, is too voluminous to adequately present here, but portions of the characterization are summarized elsewhere (Brossy et al., 2010; Kelson et al., 2010b; Lutz et al., 2010, 2011).

GEOLOGIC AND GEOMORPHIC MAPPING METHODS

The Kern Canyon fault and Breckenridge fault were mapped to identify the locations of late Quaternary active fault traces. This mapping was conducted using: (1) stereographic color and black-and-white aerial photos (Table 1); (2) a variety of digital images constructed from high-resolution, LiDAR-derived digital elevation models; and (3) digital orthophotos collected during acquisition of the LiDAR data. LiDAR data collected along the length of the Kern Canyon fault zone and Breckenridge fault covering a total of 643 km^2 (248 mi^2) were collected in four phases: May 2008, July 2008, November 2008, and September 2009. LiDAR-derived renderings of the bare-earth topography and accompanying high-resolution, digital color orthorectified imagery proved highly valuable for evaluating the characteristics of this lengthy fault zone within a largely remote and inaccessible setting. LiDAR data made clear that the late Quaternary depositional record along the Kern Canyon fault is discontinuous, with substantial lengths of the fault present in bedrock terrain. The majority of relevant late Quaternary deposits in the area between Isabella Lake and the Little Kern River, for example, are present mostly along west-flowing drainages at irregular intervals along the South Kern Canyon section of the fault. As a result, a complete tip-to-tail map of the 135-km-long fault shows that only a percentage of this length contains late Quaternary deposits useful for evaluating recent fault activity.

In addition to aerial reconnaissance along the entire Kern Canyon fault zone and Breckenridge fault, ground-based field reconnaissance and detailed site mapping were completed at 12 sites (Fig. 2). Major late Quaternary surficial

TABLE 1. STEREOGRAPHIC AERIAL PHOTOGRAPHS REVIEWED FOR KERN CANYON FAULT STUDY

Date flown	Scale	Type	Photo codes	Source*	Frames	Number of frames	Feature of interest†
21 July 2001	1:15,849	Color infrared	S-KC, 885-125, NPS	NPS	23-30 through 23-36, 24-34 through 24-42, 25-22 through 25-41	36	KCF
22 July 2001	1:15,849	Color infrared	S-KC, 885-125, NPS	NPS	24-21 through 24-33	13	KCF
28 July 1979	1:24,000	True color	BLM, 24, CA-79CC	BLM	2-5N-22 through 2-5N-33, 2-4N-22 through 2-4N-30	21	pKCFz
15 August 1977	1:12,000	True color	USACE	USACE	KE-1-1 through KE1-1-193	193	KCF
22 July 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-5-169	1	Durrwood fault
25 July 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-7-128 through 7-133	6	Farwell fault
25 July 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-7-37 through ELJ-7-42, ELJ-7-135 through ELJ-7-145, ELJ-7-125 through ELJ-7-127, ELJ-7-93 and ELJ-7-94	22	Durrwood fault
1 August 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-9-103 and ELJ-9-104, ELJ-9-95 through ELJ-9-99, ELJ-8-118 through ELJ-8-127, ELJ-8-130 through ELJ-8-135, ELJ-9-73 through ELJ-9-80, ELJ-8-169 and ELJ-8-170, ELJ-9-60 through ELJ-9-68, ELJ-9-27 through ELJ-9-33	49	Farwell fault
2 August 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-9-181 and ELJ-9-182, ELJ-9-187 through ELJ-9-190	6	Durrwood fault
2 August 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-9-223 through ELJ-9-226, ELJ-9-167 though ELJ-9-174	12	Farwell fault
8 August 1962	1:15,840	Black and white	ELJ	USDA-FSA, APFO	ELJ-9-152 through ELJ-9-161, ELJ-10-142 through ELJ-10-144	13	Farwell fault
18 October 1938	1:12,000	Black and white	C-5449	Whittier College	6122 through 6128	7	KCF
20 October 1938	1:17,000	Black and white	C-5449	Whittier College	6245 through 6251	7	KCF

*NPS—National Park Service; BLM—Bureau of Land Management; USACE—U.S. Army Corps of Engineers; USDA-FSA APFO—U.S. Department of Agriculture–Farm Service Agency, Aerial Photography Field Office.

†KCF—Kern Canyon fault; pKCFz—proto–Kern Canyon fault zone.

geologic units were delineated at these sites to evaluate the suitability of deposits that are preserved undeformed across and also cut by the faults as potentially datable markers. These markers were used to reconstruct the sense and rate of fault displacement during later portions of the fault characterization study, the results of which are summarized elsewhere (Kelson et al., 2009a, 2009b, 2010a, 2010b; Kozaci et al., 2009; Amos et al., 2010; Brossy et al., 2010; Lutz et al., 2010, 2011; URS/FWLA, 2010).

RESULTS

Our detailed mapping of the Kern Canyon fault played a critical role in the identification of three distinct sections of the fault (the North Kern Canyon, South Kern Canyon, and Lake Isabella sections), as well as the geographic extent of the Breckenridge fault (Fig. 2) (Kelson et al., 2010a; URS/FWLA, 2010). Mapping along the Kern Canyon and Breckenridge faults indicates that the faults accommodate predominantly east-down normal slip, with no consistent evidence for lateral or oblique slip. Plate 1[1] (Sheets 1 through 8) shows the surface traces of the Kern Canyon and Breckenridge faults with attributes modeled after the U.S. Geological Survey (USGS) National Quaternary Fault and Fold Database, as well as the major late Quaternary surficial deposits used to constrain the age and location of faulting. Below we summarize major tectonic-related geomorphic features along the sections of the fault.

Tectonic Geomorphology of the Kern Canyon and Breckenridge Faults

North Kern Canyon Section

The north Kern Canyon section runs from the Kings-Kern Divide on the north, southward to the Flatiron (Fig. 2). Along this section, the Kern Canyon fault lies along the margin of, or within, the U-shaped gorge of the upper Kern Canyon. The canyon starts as a steep hanging valley headwall below a broad, denuded bedrock upland plateau near the Kings-Kern Divide (Plate 1, Sheet 1 [see footnote 1]). North of Kern Canyon, the upland plateau is a glacially denuded terrain of exposed bedrock that lacks widespread Quaternary surficial deposits to evaluate postglacial faulting (Plate 1, Sheet 1 [see footnote 1]). South of the plateau, the walls of Kern Canyon are generally mantled with active talus cones, and latest Holocene fluvial deposits cover the valley floor. Field reconnaissance revealed that late Pleistocene glacial deposits along the walls of the canyon have been modified by hillslope or fluvial processes, and are largely unsuitable for recording recent tectonic deformation. In addition, the clearly younger postglacial deposits along the floor of the upper Kern Canyon do not exhibit prominent tectonic geomorphology and probably postdate the most recent surface rupture on the Kern Canyon fault. Bedrock notches near Red Spur Ridge on the west wall of Kern Canyon correspond to the position of an older fault zone mapped by Burnett (1976) and Moore (1981), and are inferred to coincide with the active trace of the Kern Canyon fault (Plate 1, Sheets 1 and 2 [see footnote 1]). The discontinuous character of surficial deposits in this northernmost section of Kern Canyon (north of Red Spur Ridge) precludes conclusive evaluation of late Quaternary activity, and the age of the most recent rupture along this part of the fault is unknown (Plate 1, Sheets 1 and 2 [see footnote 1]).

Farther south, we observed strong geomorphic evidence for latest Pleistocene activity on the Kern Canyon fault at Soda Spring in the form of faulted glacial deposits (Amos et al., 2010). Specifically, at Soda Spring (Fig. 1; Plate 1, Sheet 3 [see footnote 1]), the Kern Canyon fault displaces a Tioga-age terminal moraine in the form of several east-facing fault scarps. Amos et al. (2010) report a ^{10}Be cosmogenic exposure age of 18.1 ± 0.5 ka for the moraine and interpret a minimum of 2.8 $+0.6/-0.5$ m of normal fault slip associated with the Kern Canyon fault since deposition of this moraine deposit. This large amount of slip is likely the result of several earthquakes, one or more of which probably occurred prior to 15 ka, and therefore we interpret that this section of the Kern Canyon fault has experienced surface rupture within the past 15,000 yr (Plate 1, Sheets 1–4 [see footnote 1]).

The Kern Canyon fault traverses rugged and mountainous terrain between Soda Spring and the Flatiron, striking roughly north-south as a steeply dipping, linear fault zone with minor westerly and easterly deviations (Plate 1, Sheets 3–6 [see footnote 1]). South of Soda Spring, the Kern River was dammed in 1868 by an earthquake-triggered landslide (Clayton, 1873; Townley and Allen, 1939), forming Little Kern Lake. Toppozada et al. (1981) concluded the seismicity that triggered the landslide was "a swarm of small earthquakes" located somewhere near the headwaters of the Kern River and Lone Pine.

Farther south, a complex area of surface faulting occurs at the Flatiron (Plate 1, Sheet 4 [see footnote 1]) where a basalt flow dated at 3.5 Ma (Dalrymple, 1963) overlies and is offset by the fault zone. Here, at least three east-facing scarps with at least 15 m (50 ft) total of east-down displacement (URS, 2007) and extensive shearing of the basalt in the near-vertical cliffs flanking the western edge of the Flatiron exist (Nadin and Saleeby, 2010). Many other fault-related lineaments deform the basalt of the Flatiron (Plate 1, Sheet 4 [see footnote 1]). Other than the thin, discontinuous veneer of late Quaternary deposits in Kern Canyon, the Flatiron basalt is the only location where the fault zone intersects deposits that record post-Tertiary deformation along the Kern Canyon fault. The high degree of fault complexity here is attributed to the intersection of the Kern Canyon fault with the Farewell fault and several volcanic vents (Kelson et al., 2010b), as well as the rheological properties of the well-jointed basalt that manifest faulting differently than nearby previously sheared granitic and metamorphic rocks within the proto–Kern Canyon fault zone.

South Kern Canyon Section

Along the South Kern Canyon section, from the Flatiron to Kernville, the Kern Canyon fault forms an east-facing bedrock escarpment that impounds late Quaternary alluvium in a discontinuous series of small, perched, triangular-shaped basins (Plate 1, Sheets 4–6 [see footnote 1]). High bedrock scarps are typically present where resistant metamorphic rock (on the west) and less resistant and grussified granitic rock (on the east) erode differentially to form a distinct topographic escarpment or alignment of linear tributary valleys. These features are prominent north of Kernville in an area referred to as "Rincon" on standard USGS topographic maps (Plate 1, Sheets 4 and 5 [see footnote 1]; Fig. 4). Along the Rincon, the Kern Canyon fault is very linear and narrow, defined by a nearly continuous series of fault-related geomorphic features, such as side-hill benches, fault-line valleys, saddles, east-facing topographic scarps, right- and left-deflected drainages, springs, and vegetation- and groundwater barrier–derived tonal lineaments traversing late Quaternary deposits and bedrock.

The uphill-facing scarps along the South Kern Canyon section have significantly impeded west-flowing drainages and locally have ponded alluvium on the east side of the fault zone. The areas directly west of these scarps typically include discontinuous remnants of uplifted alluvial deposits, paleochannels, and bedrock pediments that are incised by steep, west-flowing bedrock channels that drop abruptly to the Kern

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[1] Plate 1. PDF file of map of the late Quaternary active Kern Canyon and Breckenridge faults, southern Sierra Nevada, California: KCF—Kern Canyon fault; LiDAR—light detection and ranging. Map is 1:24,000 scale when printed on 21 in. × 36 in. sheets. 8 sheets. To view and/or print at full-size, please visit http://dx.doi.org/10.1130/GES00663.S1 or the full-text article on www.gsapubs.org.

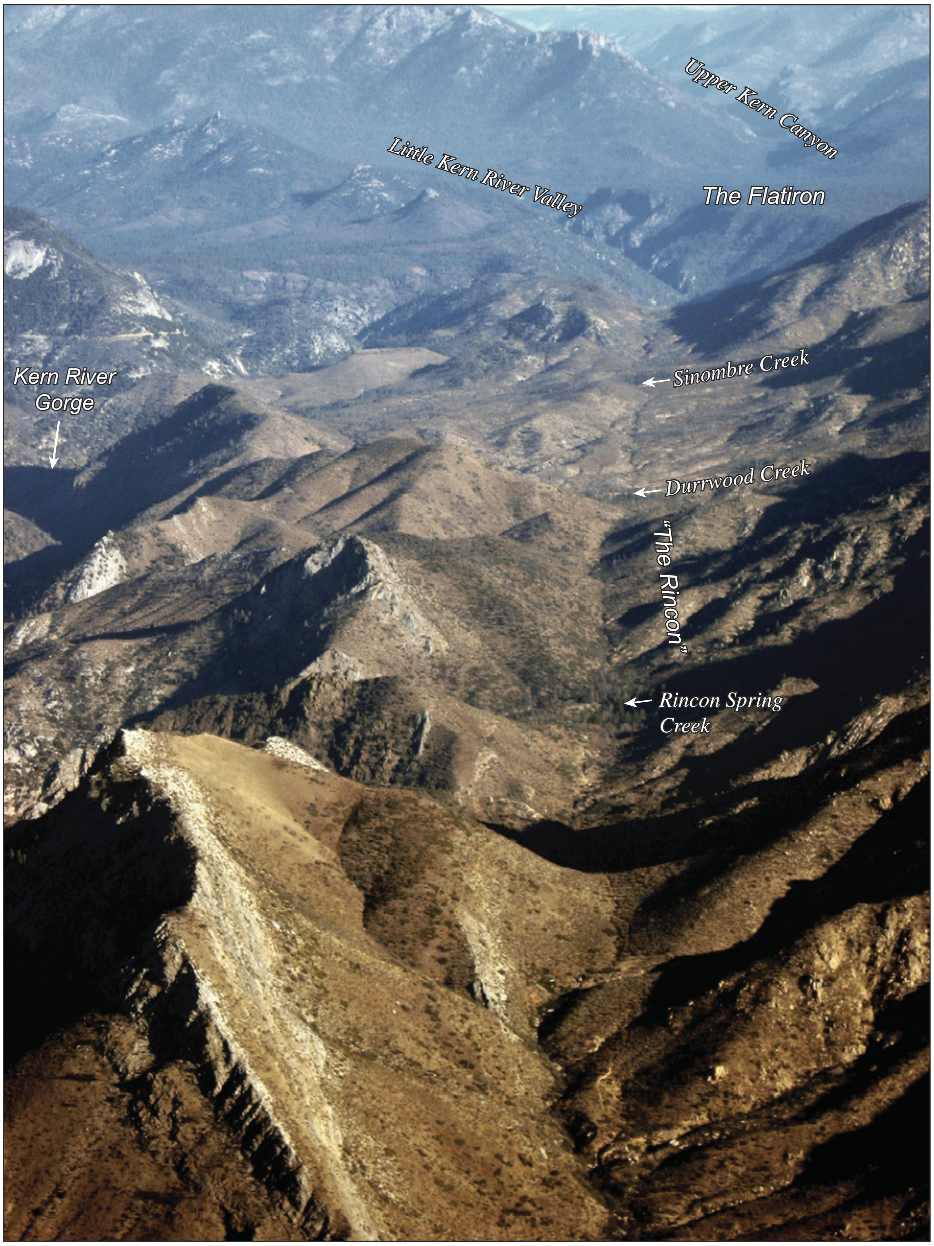

Figure 4. Oblique aerial photograph looking north along the south Kern section of the Kern Canyon fault. The prominent alignment of linear bedrock notches, saddles, and sidehill benches that creates the Rincon is apparent. Note that the Kern Canyon fault runs along the Rincon, not the Kern River gorge, along this section of the fault.

River (e.g., Brush Creek, Brin Canyon, and Packsaddle Canyon, Plate 1, Sheet 5 [see footnote 1]). Larger drainage valleys that intersect the Kern Canyon fault are commonly associated with a series of alluvial deposits that are progressively inset such that relatively younger deposits are lower in elevation and closer to the active channel (e.g., Corral Creek, Plate 1, Sheet 6 [see footnote 1]). Localized decrease of stream gradients directly east of the Kern Canyon fault escarpment along the Rincon has produced aggradation and multiple alluvial surfaces that generally bury deposits or surfaces that are correlative to uplifted equivalents to the west of the fault. Active and abandoned drainages have a pattern of fault-parallel deflection where westerly flow is impeded by the east-facing fault scarp. For example, at Brin Canyon the Kern Canyon fault displaces a pediment surface in an east-down sense, creating an uphill-facing, 4-m-high scarp that ponded alluvium and produced an apparent dextral stream deflection (Plate 1, Sheet 5 [see footnote 1]; Fig. 5). Other abandoned former drainage outlets occur as wind and water gaps along the fault, some of which were reoccupied by deflected drainages.

Paleoseismic data from the Rincon Spring and Brush Creek sites demonstrate Holocene rupture on this fault section. At Rincon Spring, trenches excavated across an east-facing scarp developed in coarse-grained debris flow deposits exposed faulted latest Pleistocene (ca. 50–11 ka) and early to mid-Holocene deposits as well as unfaulted late Holocene deposits (Kelson et al., 2010a; URS/FWLA, 2010; Lutz et al., 2011). At Brush Creek, trenching exposed a well-developed bedrock shear zone and faulted late Pleistocene and Holocene alluvium (Kelson et al., 2010a; URS/FWLA, 2010). Trench exposures indicate normal, east-down displacement of Holocene sediments and clearly demonstrate multiple surface ruptures within the past 15,000 yr along the South Kern Canyon section of the Kern Canyon fault.

Lake Isabella Section

The Lake Isabella section of the Kern Canyon fault (Fig. 1) continues from Kernville southwestward along Isabella Lake, through the Hot Spring and Havilah valleys, to just north of Walker Basin (Plate 1, Sheets 6–8 [see footnote 1]). There are structural and geomorphic complexities associated with a west step in the active Kern Canyon fault near Kernville (Plate 1, Sheet 6 [see footnote 1]). We identify evidence of multiple fault traces, including an eastern trace mapped by Ross (1986), who, based on bedrock relationships, inferred that a fault trace is concealed under recent alluvium near the northern arm of Isabella Lake. The western map trace is associated with the Big Blue fault of Prout (1940), which aligns with a prominent series of saddles and linear valleys, bedrock scarps, notches, and vegetation and tonal lineaments that separate a low bedrock ridge from Isabella Lake to the east (Plate 1, Sheet 6 [see footnote 1]). Our field observations along the proto–Kern Canyon fault zone south and east of Lake Isabella, where the Kern Canyon fault is outside the proto–Kern Canyon fault zone, indicate an absence of geomorphic evidence of late Quaternary displacement along the proto–Kern Canyon fault zone.

The Big Blue fault strikes south toward the town of Wofford Heights, where it runs along the margin of a prominent linear bedrock ridge against which a large alluvial fan is impounded (Plate 1, Sheet 6 [see footnote 1]). East of the linear bedrock ridge along the western shore of Isabella Lake, we map faulting of a gravel deposit containing highly weathered granitic and metamorphic boulders. The steeply dipping

Figure 5. Oblique aerial photograph of the location where the Kern Canyon fault crosses Brin Creek. View is to the west-northwest. Photograph shows fault-deflected stream channel and uplifted alluvial surface on the west side of fault.

shears and faults in this area strike north to north-northwest, and are similar to fault orientations documented in bedrock south of Wofford Heights by Ross (1986). The eastern trace of Ross (1986) and the western trace (the Big Blue fault of Prout, 1940) likely merge beneath Isabella Lake south of Wofford Heights and continue southward as a single fault trace along the eastern side of Engineers Point and beneath the right abutment of the Isabella Auxiliary Dam.

In the vicinity of the Auxiliary Dam, the Kern Canyon fault is defined by a linear bedrock ridge composed predominantly of granodiorite, with discontinuous tonal and vegetation lineaments preserved in late Quaternary alluvium and colluvium and aligned calcareous mineral springs (Plate 1, Sheet 7 [see footnote 1]). Near the town of Lake Isabella, these features are continuous along the western side of Hot Spring Valley, a southward continuation of the low-relief area presently occupied by Isabella Lake. On the western side of the Kern Canyon fault in Hot Spring Valley there is strong evidence for uplift and abandonment of alluvial deposits and stream channels (Fig. 6). These wind gaps and terrace deposits indicate a complex history of interaction between long-term fault uplift and west-flowing stream channels, such as the present and ancestral Erskine and Bodfish creeks and possibly the South Fork of the Kern River (Plate 1, Sheet 7 [see footnote 1]).

In addition to the prominent geomorphic signature of the Kern Canyon fault across young Holocene deposits in Hot Spring Valley, paleoseismic evidence from three sites along this reach of the fault demonstrate Holocene activity. For example, trenches adjacent to the Auxiliary Dam (i.e., “the Barlow site”) exposed faulted and warped colluvium and suggest two to three Holocene to possibly late Pleistocene surface ruptures occurred (Lutz et al., 2010, 2011). About 4 km southwest of the Auxiliary Dam (e.g., “the Bernie-Silicz Avenue site”), multiple trenches exposed faulted and warped, well-bedded alluvium and provided evidence for two or three Holocene surface ruptures (Kozaci et al., 2009; Lutz et al., 2010, 2011). Collectively, the geomorphic and paleoseismic evidence shows that the Lake Isabella section has experienced multiple surface ruptures within the past 15,000 yr (Plate 1, Sheets 6 and 7 [see footnote 1]).

At the southern end of Hot Spring Valley (near the town of Bodfish), the Kern Canyon fault traverses steep rugged terrain, aligns with a narrow saddle and a series of subtle side-hill benches, and continues south into the Clear Creek drainage (Plate 1, Sheet 7 [see footnote 1]). North of where it crosses Clear Creek, east-facing bedrock scarps, wind and water gaps, springs, and ponded alluvium are associated with the Kern Canyon fault (Plate 1, Sheet 7 [see footnote 1]). Trenches in colluvium deposited along the Kern Canyon fault north of Clear Creek provide evidence of at least two Holocene and one late Pleistocene surface ruptures (Lutz et al., 2010; Lutz et al., 2011). South of Clear Creek, the distinct geomorphic expression along the Lake Isabella fault section (Plate 1, Sheets 7 and 8 [see footnote 1]) decreases, and the Kern Canyon fault branches into multiple fault traces with poor geomorphic expression in the Havilah Canyon (Plate 1, Sheet 8 [see footnote 1]). This area contains aligned saddles, linear drainages, and east-facing faceted bedrock spurs along the fault trace, although a sparsity of surficial deposits precludes confidence in constraining the fault’s location and activity at the southern end of this fault section. Due to the lack of clear

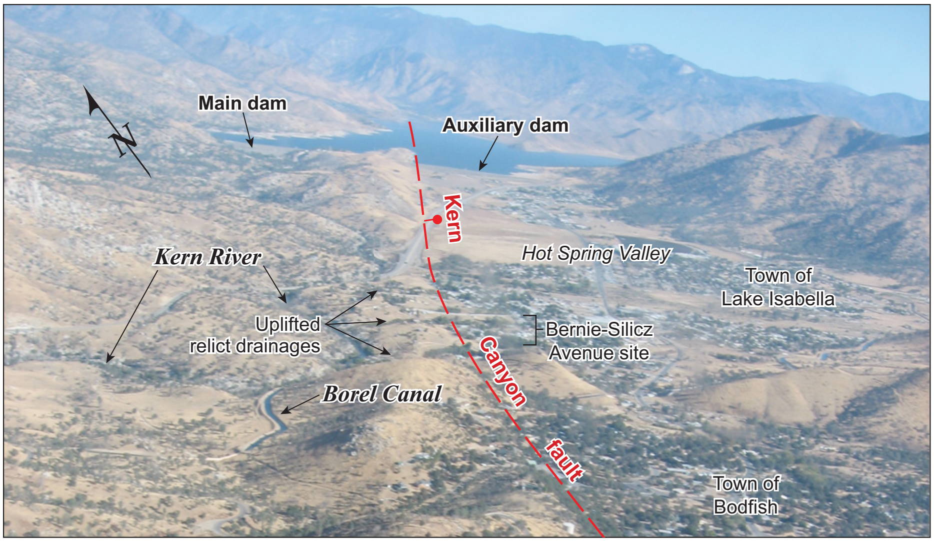

Figure 6. Oblique aerial photograph looking northeast across the southern Hot Spring Valley. Photograph shows several uplifted relict drainages (wind gaps) located on the upthrown side (west side) of the Kern Canyon fault near the Bernie-Silicz Avenue paleoseismic site.

Holocene-age geomorphic evidence, we interpret that the fault has been active since the latest Pleistocene, and we assign an age of activity of <130,000 yr for the southernmost reach of the south Lake Isabella section of the Kern Canyon fault (Plate 1, Sheets 7 and 8 [see footnote 1]).

Breckenridge Fault

Walker Basin is a triangular-shaped alluvial basin bounded on the west by the Breckenridge fault and the Greenhorn Mountains bedrock escarpment (Lawson, 1906; Dibblee and Chesterman, 1953; Webb, 1955; Ross, 1986; Nadin and Saleeby, 2008) (Plate 1, Sheet 8 [see footnote 1]). Late Quaternary alluvial and fluvial deposits comprise the floor of Walker Basin and abut the steep, east-facing bedrock escarpment along the Breckenridge fault. Alluvial fans on the western side of the valley emerge directly at the mountain front, and fan deposits generally are not present on both sides of the fault. One exception is at the Oak Tree Estates site along the north-central part of the Breckenridge fault, where east-facing fault scarps are developed on several late Pleistocene alluvial fan surfaces (Brossy et al., 2010). Farther south, distinct tectonically related geomorphic features are not present south of Rankin Ranch at the southern end of Walker Basin, suggesting that the late Quaternary Breckenridge fault does not extend south beyond Rankin Ranch (Plate 1, Sheet 8 [see footnote 1]).

DISCUSSION

Our mapping along the length of the Kern Canyon and Breckenridge faults supports previous studies suggesting that the southern Sierra Nevada is undergoing internal deformation and thus may be distinct from the Sierra Nevada to the north (Wakabayashi and Sawyer, 2001; Clark et al., 2005; Maheo et al., 2009; Saleeby et al., 2009; Nadin and Saleeby, 2010). Specifically, the presence of the Kern Canyon fault as an active normal fault supports that the southern Sierra Nevada is currently compartmentalized south of ~36.6°N latitude into several blocks that have different uplift histories (Maheo et al., 2009). This compartmentalization of the southern Sierra has occurred intermittently, in particular, when the proto–Kern Canyon fault zone was active in the Cretaceous and the Kern Canyon fault zone was active in the Miocene (Nadin and Saleeby, 2008; Saleeby et al., 2009). The late Quaternary normal faulting on the Kern Canyon fault and Breckenridge fault represents only the latest chapter in the long history of the Kern Canyon fault system (e.g., Nadin and Saleeby, 2010).

The overall morphology of the Sierra Nevada hints at its compartmentalization. For example, average and peak elevations in the Sierra Nevada range steadily increase southward to Mount Whitney, then abruptly decrease (Clark et al. 2005), and at ~36.5°N (the latitude of the Kings-Kern Divide and about the northern end of the Kern Canyon fault), the range-crest of the Sierra Nevada is separated into two high-elevation ridges: the Great Western Divide and the high peaks along the eastern crest of the Sierra Nevada. These ridges are separated by the deep gorge of Kern Canyon and by the Kern River, the only major south-flowing river within the Sierra Nevada block, which also happens to generally coincide with the location of the Kern Canyon fault. Furthermore, thermochronology work shows that north of Kernville, the proto–Kern Canyon fault zone (and the coincident Kern Canyon fault of this study) divide a relict (80–32 Ma; Clark et al., 2005) landscape into an untilted eastern portion (i.e., the Kern Plateau) and a western portion having an ~9° west tilt (i.e., the Greenhorn-Breckenridge horst of Maheo et al., 2009) that was uplifted in the Pliocene to Pleistocene.

The presence of Kern Canyon fault as an active normal fault within the southern Sierra Nevada has consequences for understanding the pattern of deformation through time within the Sierra Nevada block as well as the adjacent Walker Lane and Basin and Range. For example, Unruh and Hauksson (2009) proposed that seismogenic extension in the southern Sierra Nevada is related to the thinning of upper crust above lithosphere that is flowing toward the Isabella anomaly, rather than westward propagating Basin and Range extension encroaching into the Sierra Nevada (e.g., Jones and Dollar, 1986; Saltus and Lachenbruch, 1992). They favor this explanation for the vertical crustal flattening because it is consistent with NE-SW stretching along the northeastern margin of the Isabella anomaly and the proposed westward propagation of dextral shear and strike-slip faulting from the Walker Lane (see Unruh and Hauksson Figs. 10 and 12B). Unruh and Hauksson (2009) call upon the late Neogene tectonic history of the Indian Wells Valley where a period of extensional deformation was overprinted by strike-slip faulting (Monastero et al., 2002) as a possible analogue to the active seismogenic extension in the southern Sierra Nevada. In contrast, Nadin and Saleeby (2010) have a slightly different interpretation of deformation in the southern Sierra Nevada batholith. While they concur that Basin and Range extension is not propagating westward, they instead argue that normal faulting has migrated eastward since the Pliocene. They do not call upon any contribution from dextral shear or strike-slip faulting of the Walker Lane to explain the active extension, arguing that modern seismicity segregates the normal faulting on the Kern Canyon fault from dextral strike-slip faulting occurring to the east. Nadin and Saleeby (2010) conclude that the recent, west-side-up, vertical motion on the Kern Canyon fault is mostly likely caused only by local horizontal extension along the eastern margin of the Isabella anomaly due to the removal of mantle lithosphere. Additional seismotectonic analysis of the region may be required in order to fully arrive at a consensus on the causes of the late Quaternary extension in the southern Sierra Nevada.

The presence of the Kern Canyon fault in an area previously thought to lack late Quaternary faults has implications for local and regional seismic hazards. The Kern Canyon fault passes under one of the dams that create Isabella Lake, a 500,000+ acre-ft reservoir that is located 35 miles upstream of Bakersfield (population ~300,000). Work is currently under way to mitigate the fault rupture hazard at the dam site. The Kern Canyon fault runs through or very close to several towns (Kernville, Lake Isabella, Wofford Heights, and Bodfish), as well as a distributed rural population located in mountainous terrain, that are at risk from strong shaking and surface rupture hazards. In addition, the presence of such an active tectonic structure of great length (135 km) in the region revises probabilistic ground motion values in the southern part of the Central Valley and has implications for seismically sensitive facilities across the region such as power generation, water supply, and transportation infrastructure.

CONCLUSION

Detailed geologic and geomorphic mapping along the entire length of the ~135-km-long Kern Canyon fault zone and the collinear, 11-km-long Breckenridge fault identified late Quaternary traces of both faults. The detailed map of the Kern Canyon and Breckenridge fault traces shows that late Quaternary faulting is typically concentrated along one or more, near-vertical to steeply east-dipping, north- to north-northeast–trending faults that exhibit east-down movement with no apparent lateral component of slip. The faults exhibit east-facing scarps along almost every individual strand, consistent with paleoseismic trench exposures that demonstrate east-down normal displacement along east-dipping fault strands (Amos et al., 2010; Kelson et al., 2010a; Lutz et al., 2010, 2011). This mapping supports interpretations that the Sierran microplate is not a rigid block with a consistent history throughout. Specifically, the southern Sierra Nevada is undergoing internal extensional deformation via lengthy normal faults and is distinct from the Sierra Nevada to the north.

ACKNOWLEDGMENTS

Many thanks go to all those involved in the Kern Canyon fault characterization study and especially the landowners who granted access. We also acknowledge the USACE personnel who realized the value of collecting LiDAR data for this study. Comments by Bill Bryant, Cathy Busby, Jeff Unruh, and an anonymous reviewer improved the form and content of this manuscript.

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Manuscript Received 21 January 2011
Revised Manuscript Received 8 December 2011
Manuscript Accepted 12 December 2011