Chapter 6

Assessment of Neogene and Quaternary activity along the Kern Canyon fault, southern Sierra Nevada, California

Abstract

Geomorphic and geophysical evidence suggests that the Kern Canyon fault, the longest fault in the southern Sierra Nevada, is an active structure, and has been reactivated at discrete times over the past ca. 100 m.y. in response to changing lithospheric stresses. In addition to pronounced seismic activity in the area, the region exhibits high-relief fault scarps, geomorphic anomalies, and granitic basement in fault contact with a Quaternary debris flow deposit. Constant-elevation (U-Th)/He age determinations in apatite also suggest ~600 m of west-side-up motion along the fault post-40 Ma. The Sierra Nevada and adjoining Great Valley are generally considered to move as a stable block with respect to North America, but seismic anomalies in the southern part of the batholith suggest this is an oversimplified model. Due to the complexity of late Cenozoic motion and faulting patterns through the Basin and Range province and westward of it, it has proven difficult to ascribe motion in the southern Sierra Nevada to any particular faults. We present evidence here that the Kern Canyon fault has been reactivated at least twice since Miocene time. While this activity may relate to Basin and Range extension and/or stress imparted via San Andreas and/or Garlock Fault motion, we propose instead that an imbricate system of eastward-migrating normal faults, among which is the Kern Canyon fault, is developing in response to mantle lithosphere removal beneath the southern Sierra Nevada. In either scenario, activity along

the fault indicates that, at least along its southern 150 km, the Sierra Nevada is not as stable as it is modeled to be. Reactivation of the Kern Canyon fault at several discrete times over the past ca. 100 m.y. suggests that deformation readily localizes along pre-existing crustal weaknesses.

Introduction

There has been a lack of clear evidence that structures internal to the Sierra Nevada batholith (SNB) accommodated deformation after 50 Ma. But these structures seem likely given the immediate proximity of large-scale faults and active tectonic systems (e.g., the San Andreas and Garlock faults, and the Basin and Range (B&R) province [Fig. 1; Niemi, 2003; Jones and Dollar, 1986]), and clear evidence for relief increase within the batholith since 32 Ma (Clark et al., 2005). The presence of north-south-striking faults with normal offset within the SNB and the timing of motion along these structures are of particular interest in light of the recently proposed idea that convective removal of the lithosphere underlying the batholith began in Pliocene time (e.g., Jones et al., 2004; Saleeby and Foster, 2004). Furthermore, regions abutting the SNB (Indian Wells Valley to the east and the San Joaquin Valley to the west, Fig. 1) have complex extensional histories in Neogene and locally in latest Paleogene time (Nugent, 1942; Tennyson, 1989; Loomis and Burbank, 1988; Goodman and Malin, 1992; Monastero et al., 1997), suggesting the likelihood of extensional structures within the batholith itself.

The Kern Canyon fault (KCF), the longest and most prominent structure in the axial region of the SNB (Figs. 1 and 2), figures prominently in assessment of extensional systems in the Cenozoic era. This 130 km long lineament likely underwent discrete periods of deformation throughout its ca. 100 Myr history. It was first reported by Lawson (1904), first mapped and described by Webb (1936), and later ascribed various amounts of right-lateral offset: 6.5–15 km (Moore and du Bray, 1978) and 16 km (Ross, 1986) based on offset pluton margins. Recent motion along the KCF was dismissed in large part because a basalt flow dated at 3.5 Ma (Dalrymple, 1963) was reported to cap the fault near its northern extent (Webb, 1936). However, our field investigations of the basalt reveal that it is deformed, with pervasive fracture sets and small-scale shear planes that coincide with the trace of the fault. Other features clearly indicate that the KCF has been active in Quaternary time. Fault scarps with sharp relief, ponding of sediments east of the fault, and continued seismic activity in the area suggest the fault is active, albeit moderately, with west-side-up normal motion. The Sierra Nevada is considered to be a stable, non-deforming block coupled neither to the Pacific plate to the west nor to the North American plate to the east (Fig. 1; Argus and Gordon, 1991; Dixon et al., 1995, 2000; Henry and Perkins, 2001; Bennett et al., 1999, 2003; Sella et al., 2002). Yet structures internal to the block suggest that this scenario is oversimplified, and plate kinematic models that account for stability in the batholith should be modified in light of recent tectonic activity. We focus here on the evidence for recent movement along the KCF, and its implications for regional deformation expressed within the Sierra Nevada microplate.

Geologic setting

The KCF is a fault zone in which metasedimentary and granitic rocks are highly fractured, sheared, and mineralogically altered over the width of several hundred meters. For almost half of its length, the brittle KCF overprints a ductile shear zone, termed the Proto-Kern Canyon fault (PKCF) (Fig. 2; Busby-Spera and Saleeby, 1990). The PKCF is a ~130 km-long, primarily dextral strike-slip fault exposed along an oblique crustal section that traverses almost 25 km of batholithic emplacement depths from its northern to its southern end (Pickett and Saleeby, 1993; Chapter 3). The KCF and PKCF coincide for ~60 km along their northern segments, but south of latitude 35˚44′, at Lake Isabella, the faults bifurcate (Fig. 2). The PKCF follows a southeastward trajectory and eventually roots into lower crust tectonites of the Rand thrust system (Chapter 3), while the KCF follows a southwesterly route, possibly connecting with the Breckenridge and White Wolf (WWF) faults (Figs. 1 and 2; Ross, 1986). At its northern extent, the apparent trace of the PKCF dies out at ~36˚07′ N with structural complications not to be addressed in this thesis, while the KCF has been mapped up to latitude 36˚40′ N, where it likely branches into several smaller faults (Moore and du Bray, 1978).

At least three stages of deformation are recorded in the KCF damage zone, and are particularly well expressed at Lake Isabella. Early ductile shear is preserved in a zone of S-C mylonites and phyllonites; a later, dominant phase of brittle faulting led to through-going cataclasis; and finally, late-stage minor faulting resulted in thin, hematitic gouge zones. In several locations along the KCF, synkinematic tourmaline and other boron-rich hydrothermal minerals indicate moderately high-temperature (300˚-400˚C) fluids permeated the fault during movement (Moore et al., 1983). Pluton emplacement depths along the length of the KCF, estimated using the Al-in-hbl geobarometer (Ague and Brimhall, 1988; Chapter 3), range from ~6 to ~25 km. This oblique crustal section records the varied history of the (P)KCF system over the past ~100 Myrs.

The relationship of progressive stages of deformation between PKCF and KCF motion where they coincide north of Lake Isabella (Fig. 2), characterized by early ductile shear overprinted first by major brittle faulting and later by minor faulting, is typical of the entire northern segment of the KCF. South of Lake Isabella, where the faults bifurcate, the early phase ductile deformation along the southern segment of the KCF is less pronounced, and brittle overprint along the PKCF is likewise much less intense. It has proven difficult to tease out the chronology of PKCF versus KCF motion. The oldest activity clearly recorded along the PKCF is ca. 95 Ma, and this is most clearly expressed along its medial zone near the latitude of Lake Isabella (Fig. 2), where the two structures diverge.

Kinematic History of the Kern Canyon Fault System

Cretaceous Movement

Timing of brittle deformation along the KCF spans a possible 70 m.y. range. The PKCF, which is overprinted by the KCF and is likely its earlier, ductile expression, was active primarily as a dextral strike-slip fault from ca. 95 Ma–75 Ma (Busby-Spera and Saleeby, 1990; Saleeby et al., 2006). Tectonic denudation and erosive downcutting through the batholith likely brought rocks previously deforming in the ductile regime into the brittle regime progressively with fault motion through time (Chapter 3). Early KCF history indicates it was also primarily a dextral strike-slip fault (Moore and du Bray, 1978; Ross, 1986; Busby-Spera and Saleeby, 1990; Chester, 2001). Despite their similar styles of motion and the smooth transition in timing of motion from ductile to brittle regimes, we consider it also likely that major KCF activity is distinctly younger than that of the PKCF. While the KCF localized along a pre-existing weakness along its northern half, the lack of coincidence between the PKCF and the KCF along their southern segments suggests that during its post-Cretaceous history, the KCF responded to different forces than those exerted during PKCF motion.

Ross (1986) estimated timing of offset along the KCF at 80-90 Ma based on dating of a deformed body of granodiorite by the Rb/Sr (Kistler and Peterman, 1973) and K/Ar (Bergquist and Nitkiewicz, 1982) techniques. These ages coincide with fading motion along the ductile phase PKCF (Busby-Spera and Saleeby, 1990; Saleeby et al., 2006, in review), after which time deformation along at least the middle section, in the vicinity of Lake Isabella, took place along the brittle KCF. A possible (re)activation of the KCF at 50-55 Ma is suggested by K/Ar biotite data (Jenkins, 1961; Evernden and Kistler, 1970) from a cataclastic zone in the pervasively mylonitized granite of Cannell Creek. Recent analyses of (U-Th)/He in apatite collected along constant elevation transects indicates post-40 Ma activity along the KCF (Maheo, personal communication). Two horizontal transects between Walker Basin and Lake Isabella indicate ~600 m of west-side-up offset along the KCF and a parallel structure to the west.

Miocene Reactivation

The possible early Cenozoic movement history of the KCF is poorly constrained. However, geomorphic evidence and stratigraphic relations in the adjacent southern San Joaquin Valley (SJV) (Figs. 1 and 2) clearly indicate remobilization of the KCF in mid-Cenozoic time that is likely related to Late Oligocene to early Miocene extension recorded in the eastern SJV (Bartow, 1991; Goodman and Malin, 1992; Reid, 2006). The modern channel through which the lower Kern River (south of Lake Isabella) exits the western slope of the Sierra Nevada was a relatively minor creek in Miocene time. At that time, the Kern River followed the Kern Canyon–Breckenridge fault valley and exited the Sierra Nevada through modern-day lower Walker Creek (Figs. 2 and 3a; MacPherson, 1977). Evidence for this Kern River paleo-drainage lies in the voluminous Bena submarine fan deposits in the Maricopa sub-basin of the SJV. Remnants of the Bena channel, through which these large sediment loads were carried, can be clearly discerned in digital elevation models (Fig. 2). The load of the Plio-Pleistocene to Holocene Walker Creek, by comparison, is much less. Indeed, the Walker basin drainage area is quite small in comparison with the drainage area that feeds the Kern River.

Bena fan sediments carried by the Kern River spread freely northwestward across much of the Maricopa sub-basin in the southern SJV (Fig. 3a). However, data from industry and CALCRUST seismic studies, as well as industry boreholes and surface mapping around the southeast edge of the SJV, indicate that these sediments did not extend southward. They were trapped by the WWF, which acted as a major bounding structure along the southern edge of the sub-basin in Miocene time (Fig. 3a; Goodman and Malin, 1988). This southeast-side-up normal displacement pattern of the WWF in

Neogene time was accompanied by an unknown quantity and sense of strike-slip displacement, such that the WWF acted as a transfer structure that partitioned the southernmost SJV into the two differentially extending sub-basins, the Maricopa to the northwest and the Tejon embayment (Fig. 3a) to the south.

Both the Maricopa sub-basin and the Tejon embayment are cut by northwest-striking faults whose geometry links them to other lineaments within the southern SNB (Fig. 3a). In the Maricopa basin, stratigraphic relations along the northeast-side-down Edison fault (Figs. 2 and 3a) suggest that its normal displacement history began as early as latest Oligocene time (Dibblee and Warne, 1988). Furthermore, the upper Bena fan, which, as mentioned before, was built through much of Miocene time by the ancestral Kern River, partly buried the Edison fault and partly breached across the fault and ponded against the WWF to the south (Fig. 3a). Surface relations of the Edison fault (Dibblee and Warne, 1988) and sub-surface data on Tejon embayment basin floor normal faults pose a consistent fault geometry that appears to be continuous with northwest-striking, high-angle faults and fracture-controlled lineaments that cut the southern SNB. (U-Th)/He apatite ages record middle to late Cenozoic normal displacements on some of these lineaments (Fig. 3b; Maheo, personal communication). Textural and structural relations between these faults and fracture systems, coaxial ductile fabrics developed under biotite-grade conditions, and regional Ar/Ar and K/Ar data (Ross, 1989a, 1989b; Saleeby et al., in review) suggest that these systems are inherited from the initial unroofing structures of the southern SNB. Many of these structures strike at high angles to, and are bounded by, the WWF-Breckenridge-KCF system as well as the PKCF (Fig. 3a).

In latest Miocene time (ca. 10 Ma), west-side-up normal displacement along the Breckenridge-KCF system, and probable east-side-up normal faulting along the Kern River fault (i.e., uplift of the Greenhorn Mountains horst, Figs. 2 and 3c) resulted in the capture of the Kern River by the current lower course creek drainage, and the termination of Bena fan growth from the Walker Creek exit (Fig. 3b). Discharge of the full Kern load from its new lower course resulted in the building out of the Uppermost Miocene Stevens submarine fan in the SJV in a position that is now ~30 km northwest of the abandoned Bena fan, across the future trace of the Bakersfield arch. Intermontane sediment ponding related to the river capture event also resulted in the alluviation of South Fork Valley and Walker Basin (Fig. 2).

Quaternary Reactivation

Through a study of aerial photos, Ross (1986) identified a series of breaks in slope and well-aligned topographic notches, some of which he identified as scarps, from Havilah to Lake Isabella. He enlisted the help of R. E. Wallace, who wrote to Ross that the scarp features were so subdued that major recent movement seemed unlikely, and geomorphology (i.e., lack of obvious stream offsets) indicates that any strike-slip motion was pre-Quaternary. However, seismic activity near Kernville, including a series of earthquakes in 1868 (Barosh, 1969; Ross, 1986) and the 1983-84 Durrwood Meadows earthquake swarm (Figs. 3c and 4; Jones and Dollar, 1986), suggests that the KCF is active. The Durrwood Meadows swarm was determined to be concentrated on a north-south-striking plane 10 km east of the KCF (Jones and Dollar, 1986).

The apatite (U-Th)/He transects indicating post-40 Ma activity along the KCF delineate separate strands of faulting. Two east-west oriented, horizontal transects across

Walker Basin and across Lake Isabella indicate ~600 m of west-side-up offset along the KCF and a parallel structure to the west (Maheo, personal communication). Analysis of high-resolution digital elevation models suggests that the parallel lineament, ~10 km west of the KCF, runs through Split Mountain (Fig. 3b). These parallel, west-side-up steps suggest that the Split Mountain lineament, the KCF, and the Durrwood Meadows swarm plane are members of an eastward-migrating imbricate fault system. Vertical offset within the KCF region, therefore, could have begun with initiation along a Split Mountain fault sometime after 40 Ma (most likely in Miocene time), continued along the KCF in Quaternary time, and finally migrated eastward to a blind fault 10 km east of the KCF. Other (U-Th)/He and geomorphic analyses indicate two discrete episodes of southern Sierra Nevada exhumation since 32 Ma (Clark et al., 2005). One clearly initiated at ca. 3.5 Ma and is related to the current phase of accelerated river incision in the southern Sierra Nevada. Evidence from cave sediments in the southern Sierra Nevada further support this event (Stock et al., 2004). We suggest the other episode of exhumation occurred at ca. 10 Ma, associated with the Greenhorn Mountains uplift (Figs. 2 and 3c) and initiation of normal motion along the KCF–Breckenridge–WWF system. This 10 Ma initiation of extension is probably linked to the ~600 m west-side-up offset along the KCF and Split Mountain lineaments (Fig. 3b).

Although Moore and du Bray (1978) and Ross (1986) point out the position of many recent earthquake foci close to the KCF, they did not find evidence of strike-slip disruption of the 3.5 Ma basalt that was reported to cap the KCF (Webb, 1936; Dalrymple, 1963). However, Ross (1986) later suggested that a rubbly weathering surface to the basalt could obscure small fault displacements. Indeed, our field investigations suggest that the basalt is fractured here (see **Field evidence of recent faulting**), and that it is in no way conclusive that the fault does not disturb the basalt.

Recent seismicity in the neighborhood of the KCF suggests current activity in the southern SNB (more under **Modern seismicity**). Furthermore, strain measurements across the KCF confirm ongoing deformation. A multicomponent laser interferometer strain meter was installed in the inactive Big Blue Mine tunnel north of Kernville, across what Vali et al. (1968) and Slade et al. (1970a, 1970b) mislabeled as the Kern River fault (the Kern River fault runs through the San Joaquin Valley; the strain meter was installed across the KCF). Through detection of a series of explosions from the Nevada test site, as well as tidal influences, winds, and microseismic activity, Slade et al. (1970b) determined that the fault, which they classify as clay gouge, acts as an elastico-viscous fluid. Strain across the KCF (3-4 x 10^{-8}, Slade et al., 1970b) is quite different than strain in the surrounding bedrock, and in general is 2-3 orders of magnitude greater than normal strain amplitude associated with microseismic activity. From Nov. 17-22, 1968, the strain meter recorded vertical shearing across the KCF that resulted in west-side-up slip between the bedrock and the fault zone.

South of the KCF, and in apparent continuation with it, are the Breckenridge and White Wolf faults (WWF). Study of the WWF places inception of its current pattern of motion at ca. 1.2 Ma (Stein and Thatcher, 1981), and the fault continues activity today, with earthquakes of M = 7.8 in 1952 and an earthquake swarm (maximum M = 3.6) in December 2003–January 2004. However, as discussed earlier, the WWF was clearly active as an oblique normal fault in late Oligocene-Miocene time (Goodman and Malin, 1988), and possibly originated as a transfer zone during rapid tectonic denudation of the southernmost SNB in Late Cretaceous time (Chapter 3). The current pattern of southeast-side-up reverse displacement is inverted from southeast side up normal displacement in Neogene time, and most likely reflects the recent phase of north-south directed shortening across the “Big Bend”–Transverse Ranges segment of the San Andreas plate juncture (Davis and Lagoe, 1988; Reid, 2006).

Regional fault motion, adjacent to southern Sierra Nevada

Evidence throughout the eastern margin of the Sierra Nevada microplate indicates that by mid-Late Miocene time, it lay in a generally extensional tectonic setting, moving ~15 mm/yr to the northwest relative to North America (Fig. 3b; Wernicke and Snow, 1998). We suggest (see **Discussion**) that such extension, as expressed by normal faulting along the current eastern edge of the Sierra Nevada, marks the inception of the Sierra Nevada microplate. Coincident initiation of the Garlock fault as an east-west transfer system within the greater B&R province (Davis & Burchfiel, 1973; Burbank & Whistler, 1987) further demarcated the nascent microplate at that time. Rocks that record local fault activity at the juncture of the Sierra Nevada frontal fault system with the Garlock fault (Fig. 1) are thus crucial to interpreting the early history of formation of the Sierra Nevada microplate. Such a record comes from the Ricardo Group, a 1,700 m thick sequence of Miocene volcanic and lacustrine sediments deposited between ~19-7 Ma in the El Paso basin (Figs. 2 and 3), where stratigraphic, radiometric and magnetostratigraphic data constrain the syndepositional structure and kinematics of the basin (Loomis and Burbank, 1988). The sediments document a change from volcanism and north-south extension with no net rotation at 17-15 Ma to sinistral slip on the Garlock fault and east-west extension north of the Garlock fault in the basin at 10-9 Ma, and the emergence of the southeastern Sierra Nevada as a sediment source and topographic upland by 8 Ma (Loomis and Burbank, 1988). Sediments of the Ricardo Group are divided into a lower volcanic unit and an upper sedimentary and volcanic unit that were deposited between ~18-8 Ma (Cox and Diggles, 1986; Loomis and Burbank, 1988). Vertical, east-west trending dikes cutting the lower unit and the underlying mid-Paleocene strata suggest a north-south extensional regime through ca. 15 Ma (Cox and Diggles, 1986; Loomis and Burbank, 1988; Monastero et al., 1997). This extension has been interpreted to arise from northward migration of the slab window beneath western North America. Indeed, several WNW trending lineaments in the southern SNB support north-south extension (Figs. 3a and 4). Change to east-west extension coincided with initiation of Garlock fault motion. This event has been placed at 10-7 Ma based on 15˚-20˚ counterclockwise rotation, imposed by sinistral fault motion, of upper unit sediments (Burbank and Whistler, 1987). North-south striking, 30˚-40˚ east-dipping normal faults with ~200-400 m of stratigraphic separation cut rocks as young as 9-8 Ma (Loomis and Burbank, 1988), suggesting a change to an east-west extensional regime around that time. At ~8 Ma, an increase in quartz and alkali feldspar grains in the sediment budget of the upper Ricardo Group unit indicates a felsic plutonic source area that Loomis and Burbank (1988) confidently identify as the SNB.

Onset of extension in the El Paso basin may have been contemporaneous with extension in the nearby Jawbone Canyon (Fig. 3b). A poorly constrained mid-Miocene age was assigned to this southern Sierra Nevada graben based on fossil vertebrates and plants (Dibblee, 1967). The basin is filled with tuff and tuff breccia, basalt, sandstone, and conglomerate (Dibblee, 1967). The position of graben-bounding normal faults – parallel to the trend of the KCF and perpendicular to the Garlock fault, which has been interpreted as an accommodating structure for Miocene extension in the region – kinematically correlates Jawbone Canyon with regional early to mid-Miocene extension. Slow exhumation rates of ~0.03 mm/yr from 55-11 Ma near Mt. Whitney (Fig. 2) suggest that exhumation related to extensional tectonics was limited to the southern Sierra Nevada until at least 11 Ma (Maheo et al., 2004). Around this time, geological evidence suggests that extension migrated up to the central to northern Sierra Nevada. At 12 Ma, the 700 km^2 Verdi-Boca basin near Reno, NV (Fig. 1) began to develop as a result of regional extension that affected much of the western B&R (Henry and Perkins, 2001). Low-magnitude east-west extension along steeply east-dipping normal faults is further constrained to have commenced at ca. 10 Ma for the southern Lake Tahoe region (Fig. 1; Surpless et al., 2002). In this area, unconformities in a volcanic sequence dated at 14-6 Ma that fills a paleo-canyon indicate reincision and vertical uplift of the canyon at 14-10 Ma, and at 10-6 Ma (DeOreo et al., 2004), suggesting onset of range-front faulting by ca. 10 Ma. In the Sonora Pass area, ~100 km to the south, syntectonic volcanism and transtensional faulting initiated at ca. 10.3 Ma, and continues to the Holocene (Rood et al., 2004). Widespread latitic volcanism constrained in age in this area to between 10.1–7.1 Ma is suggested by Rood et al. (2004) to mark a phase of rapid regional extension. Many of the Late Miocene faults just west of Lake Tahoe are sub-parallel to the modern range front, dip steeply, and exhibit significant west-side-up throw (Rood et al., 2004). Some of these structures cut Upper Pleistocene and last glacial maxima moraines, providing a direct structural and kinematic link between the Late Miocene system and the modern system.

The apparent coincidence of initial northwest-southeast directed extensional faulting recorded at roughly 10 Ma along numerous locations of the modern eastern Sierra Nevada region, as well as the contemporaneous inception of the Garlock fault, suggests that the Sierra Nevada microplate formed as a distinct tectonic block, or microplate, at this time (Fig. 3b). In the northern Sierra Nevada such initial extension occurred within the axial zone of the ancestral Cascades arc, whereas in the south such faulting extended beyond the known southern limits of the ancestral arc. Inasmuch as the Great Valley (greater SJV) forearc basin is defined as an integral part of the Sierra Nevada microplate (Argus and Gordon, 1991), one would predict the existence of a stratigraphic imprint of microplate inception in the valley. The Neogene Great Valley forearc basin was typified by subaerial, arc-derived strata along its northern (Sacramento Valley) segment, whereas the southern (SJV) segment remained mainly under marine conditions through much of Cenozoic time. A distinct Upper Miocene (10-8 Ma) Sierra Nevada basement-derived regional marine sand sheet does accent much of the entire Great Valley’s Neogene stratigraphic record, however (Hoots et al., 1954). In addition to the Upper Miocene Santa Margarita formation within the SJV stratigraphy, its lateral equivalent, the San Pablo formation, marks the only known post-Paleogene marine incursion to have embayed along the axis of the Sacramento basin (Repenning, 1960). Such an incursion could represent the initial linear subsidence pattern of the basin that was coupled to the initial westward tilting of the Sierra Nevada microplate at the time of its inception. The widespread evidence for eastern Sierra Nevada frontal faulting and

Garlock fault transfer faulting at ca. 10 Ma matches well with the Late Miocene reactivation of the KCF as a high-angle normal fault. The KCF stands as a unique feature, breaking partway through the interior of the Sierra Nevada microplate, as the microplate gained its distinct, otherwise lithosphere-scale coherent character.

Modern seismicity

Several earthquakes of $M \geq 3.0$ have occurred along or near the KCF in the recent past (Figs. 3c and 4). The most pronounced recent seismic activity, the Durrwood Meadows earthquake swarm, consists of more than 2,000 earthquakes, many of which were $M \geq 3.0$, and the largest of which was $M = 4.9$, in the Kernville area between October 1983 and May 1984 (Jones and Dollar, 1986). The swarm lies ~10 km east of the KCF and spans a discrete, 100 km long N-S trajectory between latitudes 35˚20′ N and 36˚30′ N. Its focal mechanisms are consistent with pure normal faulting (Jones and Dollar, 1986; Unruh and Hauksson, in review). All of the calculated earthquake depths were between 0 and 7 km, and all but one $M > 3.0$ occurred between 4.0 and 5.9 km. The KCF plane does not project into the swarm, thereby excluding the possibility that the main KCF trace is the plane along which this swarm occurred. Furthermore, the swarm occupies a vertical plane with no evidence of ground breakage. However, it is likely that the activity took place along a related strand of the KCF system. The focal mechanisms resolved by Jones and Dollar (1986) show predominantly north-south-striking slip planes, which is in agreement with the main strike of the KCF. On Nov. 14, 2005, a $M = 2.9$ earthquake occurred at the latitude of Lake Isabella at ~7 km depth and ~3 km east of the main KCF trace. The ~70˚E dip of the KCF in this location projects directly to the hypocenter of this earthquake.

Ross (1986) reported a series of earthquakes that were centered near Kernville in 1868, the largest of which was later tentatively assigned an $M = 6.5$ (Barosh, 1969). This series of events was reported to have more than 500 aftershocks, and the source was assumed to be the KCF (Treasher, 1948). At the northern extent of the KCF, at 36˚37′ N, these earthquakes triggered a rock slide that dammed a section of the Kern River, forming a lake. However, Ross (1986) suggested that these earthquakes also likely originated 10 km east of the KCF, and were related to the Durrwood Meadows swarm. The 1868 events, as well as other seismic swarms near the KCF, likely originated along a linear trend 10 km east of the main fault trace. This linear trend is proposed to link to the WWF to the south, and has been interpreted over the years to constitute a westward migration of B&R-style extension (Lockwood and Moore, 1979; Jones and Dollar, 1986; Niemi, 2003; we visit this subject in detail below). However, the southern extent of the belt of seismicity lies well east of the WWF (Fig. 4), suggesting it belongs to another fault plane altogether.

Offset along the KCF

The KCF is a prominent lineament for the main 130 km of its length. At its southern extent, just north of Walker Basin, it has been proposed to connect with the Breckenridge fault, which in series appears to connect with the WWF (Ross, 1986). Our field investigations reveal that the principal damage zones of each of these structures are in structural continuity. At its northern end, the main KCF trace ends at 36˚40′, and from that latitude to 36˚45′ N, Moore and du Bray (1978) mapped five small, right-lateral faults with a net total of 2.4 km of dextral separation. Although the timing of the right-lateral separations in this area is poorly constrained, these faults lie within a 6 km-wide zone roughly on strike with the main KCF trace, suggesting that the KCF dies out to the north by branching into several smaller faults.

Offset along the KCF is difficult to determine, but strike-slip displacement along the fault has been estimated by correlating apparently offset plutonic and metamorphic rocks. Moore and du Bray (1978) and Ross (1986) relied on mismatched boundaries of seven plutons as young as 80 Ma to estimate offset across the KCF. Apparent dextral offset increases from 6.5 km in the north (Moore and du Bray, 1978) to 16 km south of Lake Isabella (Ross, 1986) and increases southward by 0.2 km/km. These estimates are possibly flawed for the following reasons: 1) pluton boundaries are typically irregular, and therefore not as reliable offset markers as conventional stratigraphic markers; 2) most pluton-pluton and pluton-metamorphic contacts strike sub-parallel to the KCF and dip both steeply and moderately, like the KCF, and thus do not provide reliable piercing points across the fault; 3) it is difficult to differentiate late, brittle offset of pluton margins from earlier, ductile motion; and 4) most measurements assume purely strike-slip motion, with no vertical offset. However, evidence points to early components of substantial vertical motion along the PKCF between ca. 95 and 85 Ma, during batholith emplacement (Chapter 3). Inasmuch as dextral shear is evident in rocks as old as 95 Ma (Saleeby et al., 2006), the details of the earlier slip history have been obliterated by large-volume plutons emplaced between 92 and 85 Ma (Saleeby et al., in review). The PKCF has been documented to have a 10˚ pitch line, indicating a modest vertical slip component (Busby-Spera and Saleeby, 1990; Chapter 3), and we present evidence here for further vertical slip along the KCF.

Moore and du Bray (1978) mapped the KCF from 36˚ N to its northern end at 36˚40′ N. Offset along the KCF was thus roughly quantified for its northern portion, north of Kernville and 36˚ N, but remained disputed south of Kernville until Ross (1986) established that major sense of motion on the southern portion of the fault was also right-lateral, and estimated 16 km of dextral-sense offset along its southern segment. In a comment on the Moore and du Bray study (1978), Lensen (1979) pointed out that net slip along a fault can result in apparent lateral offset while true motion is vertical. Moore and du Bray (1979) replied that the dips on the pluton boundaries on either side of the KCF are between 55˚ and 70˚, which would require vertical offsets between 14.3 and 27.5 km. However, this assumes that the KCF is a constant vertical plane (which it is not). Furthermore, we show that KCF motion consists of a combination of dip and strike slip with widely different net slip components having operated at different times. In addition, the Breckenridge fault to the south appears to show more than 1,000 m of west-side-up normal dip-slip displacement (Ross, 1986), and the WWF even further south has a well-documented history of changing kinematics. Surface rupture patterns of the 1952 Tehachapi earthquake and CALCRUST seismic reflection data indicate that the WWF is currently undergoing reverse sinistral displacement (Buwalda and St. Amand, 1954; Goodman and Malin, 1992), which is inverted from Neogene age southeast-side-up oblique normal displacement. Structural continuity of the WWF–Breckenridge–southern KCF principal damage zone further suggests that the WWF–Breckenridge segments of the system also date back to Late Cretaceous time.

Short-term strain studies across the KCF led Vali et al. (1968) to conclude that the west side of the KCF is currently moving north. But after some years of observation, Slade et al. (1970a) reinterpreted this data as a transient pattern of movement followed by a reversal in direction, which may result from shearing due to tidal forces with no net slip. Slade et al. (1970b) determined that relative motion between bedrock and the fault zone is in the vertical direction. They suggest that motion along the KCF arises from forces perpendicular to the fault as a whole, and conclude that the "block" of crust between the San Andreas fault and the Kern River acts as a rigid body for vertical deflections of up to 6×10^{-6} radians (~4 mm) before deforming internally. It seems unlikely that this segment would act as a rigid block, as the Sierra Nevada front area to the west and the adjacent Bakersfield arch have experienced widely distributed, mainly high-angle normal faulting from mid-Neogene to Recent time (Nugent, 1942). Although Vali et al. (1968) did not suggest a rate at which the 4 mm of vertical deflection takes place, if the motion is restricted to the region of the KCF, over millions of years this strain could amount to appreciable offset.

In general, the apparent vertical offset along the KCF appears to increase southward (see **Field evidence**, below). This is in agreement with the assessment by Moore and du Bray (1978) that the KCF dies out to the north by branching into several smaller faults, and with their estimates of increasing strike-slip displacement from north to south. As mentioned earlier, southward-increasing strike-slip displacement probably reflects an increasingly oblique component to the predominantly dextral displacement. The apparent increase in Quaternary vertical offsets along the KCF supports a generally southward-increasing vertical slip pattern to the KCF.

Geomorphic and geophysical data indicate that the KCF coincides with a zone of Quaternary, and at least locally Holocene, seismicity. Geomorphic and stratigraphic relations in the adjacent San Joaquin Valley to the west, as well as evidence of fault activity along the eastern Sierra Nevada region from at least the El Paso basin in the south to the Tahoe area in the north, as mentioned earlier, further suggest that such activity reaches back as far as latest Miocene time. Evidence supports deformation of the southern part of the Sierra Nevada microplate, along the KCF system, since inception of the microplate at ca. 10 Ma.

Field evidence of recent faulting

Detailed and regional field mapping has revealed substantial evidence of recent activity along the KCF. The geomorphology of South Fork Valley, the valley partially filled in by Lake Isabella after damming of the Kern River in 1952, indicates recent west-side-up motion along the KCF. Several cores used to construct a cross section along the southern end of Lake Isabella reveal that up to 30 m of Quaternary sediments of South Fork Valley are trapped immediately east of the KCF, suggesting that the KCF acted as a dam against which thick alluvium has built up against the footwall of the fault (Figs. 5 and 6). Active alluviation of South Fork Valley is evident in the burial of mountainous topography east of Lake Isabella. Southwest of Lake Isabella, the Kern River deeply incises basement rocks across the footwall of the KCF.

Several north-south-oriented fault scarps also indicate recent motion along the KCF. Starting at the southern end of the KCF, in Havilah Valley, a well-developed, linear ridge ~1 km long and with ~2 m of relief indicates west-side-up displacement (Fig. 6a).

To the east, alluvium fills a flat valley that ends abruptly at the west-bounding ridge, but drainage that has incised perpendicularly into the ridge is not offset and therefore indicates no appreciable active strike-slip motion along the KCF. Approximately 17 km north of Havilah, Engineer Point in Lake Isabella is a fault scarp (Fig. 6b) that projects northward for ~500 m before it disappears under water. At this location, a cross section based on cores, borings, trenches, and seismic refraction data indicates ~30 m of Quaternary fill is trapped immediately east of the KCF, resulting from at least that much vertical displacement along the fault (Fig. 5). At Cannell Creek, 15 km north of Engineer Point, a subdued scarp stretches 2 km northward along the trace of the KCF. Again 20 km further north, at Brush Creek, a prominent scarp displaces rock that is identical on both sides of the KCF, thus eliminating the possibility of preferential erosion along dipping planes. There is at least 2 m of apparent vertical displacement in this location. The scarp extends for 10-20 km, and though it appears to continue to the north, it is covered first by alluvial valley fill and then by a paved road that runs parallel to the projection of the scarp, thereby obscuring its possible expression. The valley fill is not offset, and thus post-dates major activity along this segment of the KCF. The upper surface of the valley fill is probably less than 5,000 years old (Page, 2005). Then again, ~7 km north of Brush Creek, another prominent scarp is evident along the Rincon Trail toward Durrwood Creek, near latitude 36˚ N (Fig. 6c), and at this location, we also document a well-preserved expression of the KCF, which places Cretaceous granitic basement rocks against a Quaternary debris flow deposit (Fig. 6c; Nadin and Saleeby, 2001). Along this debris flow–basement rock contact, the basement rock has a pervasive brittle shear fabric that is concordant with the KCF. The fault contact is isolated on a low, broad hill, precluding the possibility of a buttress unconformity between Quaternary sediments and a pre-existing topographic high. Furthermore, the fault plane strikes N 05˚ E, in agreement with the focal mechanism slip planes of the Durrwood Meadows swarm, and it dips 80-85˚ E.

Continuing northward along the KCF, and approaching its northern reach near latitude 36˚15′ N, the fault is evident in a series of elongate, flat green meadows aligned in the midst of rugged topography (Trout Meadows, Fig. 6d). Alluvium filling these meadows is trapped on the downthrown (east) side of west-side-up faulting of the KCF, but again, lack of fresh scarps in these meadows suggests any recent displacement is small or occurred thousands of years ago. Similarly, alluvial fans that overlie the KCF to the north lack fresh scarps. However, there is fresh evidence of recent seismic activity in the vicinity of the KCF in the upper Kern Canyon. The Kern River was dammed during rockslides triggered by earthquakes in 1868, forming Kern Lake (Townley and Allen, 1939; Ross, 1986), which persists to today. The slide deposit resulted from failure of the adjacent rocky slope to the east; an estimated 0.2 cubic km of material fell, leaving a scar 1100 m wide, 200 m high, and 900 m deep into the cliff. This earthquake was probably on the KCF or on an adjacent fault to the east, possibly along the same plane as the 1983-84 Durrwood Meadows swarm (Ross, 1986).

The most commonly cited evidence for lengthy quiescence of the KCF, as mentioned before, lies in a 3.5 Ma basalt flow that was reported to cap the fault (Webb, 1936; Dalrymple et al., 1963). However, these investigators concentrated on evidence for major strike-slip motion along the KCF, and may have therefore overlooked clues of minor vertical displacements. The basalt flow is difficult to get to, as it is adjacent to the steep Kern Canyon and accessible only via lengthy, rugged trails or by helicopter. But a recent helicopter trip to the flow, focusing on this subtlety, yielded field evidence that the KCF does indeed displace the volcanic rocks. The generally bold outcrops of basalt west of the fault end suddenly in a gully where deeply weathered basalt has small-scale shears along the trace of the KCF (Fig. 6d). The lava is sheared and fractured above the fault (Fig. 6d), and the surface of the flow appears to be displaced about 5 m, up on the west (Fig. 6d). This apparent displacement is degraded to a gentle slope, and no fresh scarp is evident on the top of the flow, suggesting again that the most recent displacements have been small or occurred thousands of years ago.

Discussion

Geodetic and GPS data from the Sierra Nevada–Great Valley block (Sierra Nevada microplate) indicate that the plate is moving N 36˚ W (Argus and Gordon, 1991) to N 47˚ W (Bennett et al., 2003) with respect to stable North America. Relative motion in the B&R province transitions from east-west extension in the central portion to northwest-southeast right-lateral shear across the westernmost B&R (Argus and Gordon, 1991; Dixon et al., 1995; Wernicke and Snow, 1998; Bennett et al., 1999, 2003; Niemi et al., 2004). This shearing likely arises from coupling of the Sierra Nevada microplate to the Pacific plate (Wernicke and Snow, 1998), and accommodates ~20% of Pacific–North American relative plate motion (Sauber et al., 1994; Thatcher et al., 1999; Bennett et al., 1999, 2003; Dixon et al., 2000), with all B&R–Sierra Nevada motion ascribed to dextral shears between rigid blocks. Indeed, the Sierra Nevada microplate has long been regarded as a rigid block (Argus and Gordon, 1991; Dixon et al., 1995, 2000; Wernicke and Snow, 1998; Bennett et al., 1999, 2003), despite evidence of internal strain (Lockwood and Moore, 1979; Bennett et al., 2003). Bennett et al. (2003) document more rapid movement in southern Sierra Nevada GPS sites than in those to the north. Furthermore, two GPS stations that straddle the SNB show differential motion: Station LIND, west of the SNB, is moving northwest with a westward component of ~11 mm/yr, while station ARGU, east of the SNB, is moving northwest with a westward component of ~7.8 mm/yr (Bennett et al., 2003). A rather large (18 +/- 4 nstr/yr) westerly increase in N 40˚ W directed motion across the microplate supports right-lateral shear associated with fault zones that bound the region (including the Walker Lane seismic belt, Fig. 3c). However, the strain and differential GPS movement could also arise from spatially variable forces acting within the SNB lithosphere or along its base (Bennett et al., 2003). Lockwood and Moore (1979) proposed that post-Miocene deformation internal to the Sierra Nevada microplate, documented by several conjugate microfault sets, is related to late Cenozoic extension of western North America. Unruh and Hauksson (in review) also interpret background seismicity in the southeastern Sierra Nevada, east of longitude 118.5˚W, to indicate some deformation within the microplate. This region is characterized by thinner crust (~35 km) and higher heat flow (32-57 mW/m^2) than in the foothills to the west, where crustal thickness is 41 km and heat flow is 18-21 mW/m^2 (Ruppert et al., 1998; Saltus and Lachenbruch, 1991).

Deformation within the Sierra Nevada microplate has been ascribed to 1) westward migration of the edge of B&R extension (Jones and Dollar, 1986; Saltus and Lachenbruch, 1991; Surpless et al., 2002; Niemi, 2003; Rood et al., 2004), 2) westward propagation of fault initiation from post-11 Ma movement on the Sierra Nevada Frontal

Fault (Maheo et al., 2004), and 3) delamination of the high-density mantle lithosphere from beneath the batholith (Saleeby and Foster, 2004; Unruh and Hauksson, in review). We pursue here the idea that recent, west-side-up vertical motion along the KCF reflects lithospheric response to forces initiated in Miocene time and continuing to the present. Wernicke and Snow (1998) document two significant changes in Sierra Nevada microplate motion with respect to the Colorado Plateau since middle Miocene time, based on paleomagnetic data from the Spring Mountain block in the western B&R. Between 10 and 8 Ma, motion slowed from >20 mm/yr to ~15 mm/yr, and then slowed again to the contemporary rate of 11 mm/yr. These changes in plate motion, which correspond with an increasing northwesterly trajectory and the slowing of motion along faults in the western B&R, could also reflect an increase in fault activity closer to the eastern Sierra Nevada front. Such activity is well documented along the eastern Sierra Nevada. At ca. 12 Ma, the 700 km^2 Verdi-Boca sedimentary basin, north of modern-day Lake Tahoe, formed as a result of east-west extension across what was to become the Sierra Nevada–B&R boundary (Henry and Perkins, 2001). A switch from north-south extension in early-mid Miocene time to east-west extension in mid-late Miocene time is also documented in the sediments of the El Paso basin and linked to the transition of the western North American plate boundary from a subduction zone to a transform fault (Glazner and Schubert, 1985; Loomis and Burbank, 1988) with northward passage of the Mendocino triple junction (Atwater, 1970). Tectonic uplift following the passage of the triple junction from the latitude of the El Paso basin at 17 Ma (Glazner and Loomis, 1984) occurred in the El Paso basin and to the west, in the San Joaquin basin (Loomis and Glazner, 1986). Ingersoll (1982) also suggested that east-west extension in Southern

California may be related to the migration of the triple junction via reorientation of lithospheric stresses to the south. A horizontal maximum extension direction of N 61° W within the SNB is documented along conjugate microfaults, some of which cut late Miocene volcanic dikes (Lockwood and Moore, 1979). Rerouting of the Kern River and high-angle faults of the Kern River front and Bakersfield Arch (Nugent, 1942) further support westward migration of extensional tectonics as early as late Miocene time.

The timing of capture of the Kern River, which is well recorded in the stratigraphy of the southern SJV (Bandy and Arnal, 1969; Reid, 2006), is a critical constraint on the initiation of west-side-up displacement along the Breckenridge-Kern Canyon fault system. This late Miocene event, in conjunction with the Holocene scarps, signals the sluggishness with which this high-angle fault system is moving. Dismemberment of the Verdi-Boca basin at ca. 3 Ma (Henry and Perkins, 2001), in conjunction with extension-related basaltic volcanism and a period of renewed exhumation and erosion in the southern Sierra Nevada (Stock et al., 2004; Maheo et al., 2004; Clark et al., 2005), are consistent with the Plio-Pleistocene reactivation of the KCF system. The late Neogene–Recent high-angle displacements along the KCF and along parallel structures are patchy along the entire trace of the fault, and in places the faults appear to bifurcate into parallel imbricate sets. This could signal relatively low overall strain, although the strain field has clearly persisted (or reappeared over a lengthy time interval) and localized deformation along a crustal flaw that has continued activity since Cretaceous time. The patchy reactivation patterns, and their punctuated intervals of activity as guided by the (P)KCF system, pose the possibility that such high-angle faulting is not simply the expression of the Plio-Pleistocene propagation of B&R extension into the region.

Recent analysis of the southern Sierra Nevada seismogenic field from inversion of focal mechanisms suggests that seismogenic deformation in the region (near latitude 36° N) is characterized by horizontal plane strain in two directions, i.e., oblate flattening (Unruh and Hauksson, in review). Furthermore, a well-defined east-to-west transition from dextral strike-slip faulting in the Walker Lane belt (Fig. 3c) to horizontal extension and crustal thinning in the southern Sierra Nevada microplate led Unruh and Hauksson (in review) to conclude that southern Sierra Nevada deformation is isolated and localized. The zone of extensional deformation lies directly east of the "Isabella anomaly," a high-velocity anomaly in the upper mantle interpreted to result from convective descent of the Sierra Nevada mantle lithosphere deeper into the mantle (Fig. 3c; Benz and Zandt, 1993; Saleeby et al., 2003; Zandt et al., 2004; Jones et al., 2004; Boyd et al., 2004).

Studies of mantle evolution beneath the southern SNB, as documented in mantle xenolith suites, basaltic volcanism, and geophysical data, indicate that the high-density mantle lithosphere that formed beneath the batholith during Cretaceous arc magmatism has been in the process of being convectively removed over the past ca. 8–5 Ma (Ducea and Saleeby, 1998; Saleeby et al., 2003; Zandt et al., 2004). The sub-Sierra Nevada mantle lithosphere appears to have been mobilized westward as it gathered into a "drip" structure and descended into the deeper mantle beneath the southwestern Sierra Nevada and adjacent SJV. Recent motion along high-angle faults in the southern SNB could reflect a widespread response to these mantle processes. Analyses of southern Sierra topography suggest that the most recent uplift in the southern Sierra is related to the ascent of buoyant asthenosphere into the region vacated by the drip (Ducea and Saleeby, 1996; Saleeby and Foster, 2004: Jones et al., 2004; Clark et al., 2005). Furthermore, analysis of depositional patterns in the western Sierra Nevada–Great Valley transition zone indicate that a region of accelerated subsidence overlies the descending drip (Saleeby and Foster, 2004). Dynamic models of convective instabilities predict such subsidence, as well as coupled uplift marginal to the drip, above the area vacated by the high-density material that sourced the drip (Bindschadler and Parmentier, 1990; Pysklywec and Cruden, 2004). These models further predict substantial basement warping across the subsidence–marginal uplift zone, thereby posing a possible alternative mechanism for the more recent phase of activity along the KCF and neighboring structures.

Late Neogene–Holocene (?) high-angle faulting of relatively low magnitude is widespread in the southern Sierra Nevada region. This includes important petroleum trap structures of the Bakersfield Arch and the related Kern River fault, with numerous neighboring parallel structures that step up into the Sierra Nevada (Nugent, 1942; Maheo personal communication), and the faults of the Kern Canyon system (Figs. 3c and 4). An alternative interpretation to the more recent movement of the Kern Canyon system arising from more far-field effects of the B&R extensional tectonism is that these and the other high-angle structures noted above have and are accommodating basement warping over the mantle drip. Specifically, the Sierra Nevada basement between the KCF and the Kern River fault is anomalously elevated in comparison with other regions of the western Sierra Nevada, and has the appearance of a broad horst (Greenhorn Mountains horst, Figs. 2 and 3c). The Greenhorn Mountains lie within the predicted peripheral uplift zone of the drip. The relatively low-magnitude, high-angle slip history recorded for the Walker Basin and Split Mountain segments of the Kern Canyon system (Fig. 3b), the discontinuous scarps of the KCF (Fig. 6), and the Durrwood Meadows earthquake swarm (Figs. 3c and 4) may be interpreted as an imbricate high-angle fault system that is assisting in the accommodation of basement warping along the peripheral uplift zone of the mantle drip.

In this scenario, the Pliocene to Recent phase of southern Sierra Nevada uplift is dynamically linked to the convective removal of the high-density mantle lithosphere from beneath the southern SNB (Saleeby and Foster, 2004; Clark et al., 2005; Unruh and Hauksson, in review). Uplift increases the gravitational potential energy of the region, leading to horizontal tensile stresses that thin the lithosphere (Artyushkov, 1973; Unruh and Hauksson, in review). In this model the KCF system is a preferred locus for deformation related to crustal thinning and basement warping, owing to the inherent weakness of the high-angle fault system dating back to Late Cretaceous time.

Conclusions

Geological field investigations and geophysical evidence point to recent activity in the southern Sierra Nevada and adjacent areas that may be a response to removal of the mantle lithosphere in this area. Fresh fault scarps and Quaternary sediment-filled valleys along the length of the KCF, (U-Th)/He analyses showing ~600 m of west-side-up normal faulting along the KCF and a parallel lineament, and the 1980's Durrwood Meadow earthquake swarm all support patchy reactivation of the Kern Canyon–Breckenridge–White Wolf fault system in Cenozoic time. The stress field in the Sierra

Nevada microplate has certainly changed from the supra-subduction zone transpressional setting that gave rise to the ca. 95 Ma inception of motion along the (P)KCF system. Major faults in the southern Sierra Nevada express these changes: The general westward movement and overall extension of the Sierra Nevada microplate result in fault sets with apparent conflicting senses of motion. The WWF displays both sinistral and reverse motion, the Breckenridge fault just north of that displays normal or dextral oblique slip, and throughout (P)KCF history, movement has likely shifted from Early Cretaceous dextral oblique motion to Cretaceous strike-slip to primarily normal offset since Miocene time. The physical continuities of these faults suggest the WWF, Breckenridge fault, and KCF are parts of the same fault system, which probably initiated in Late Cretaceous time.

The WWF likely acted as a bounding structure to initial Kern River deposits as the river exited the Sierra Nevada via Walker Creek. The role of the KCF at this time is unclear, but capture of the Kern River by the modern, lower course Kern Canyon drainage suggests that the KCF was active as a west-side-up fault by ca. 10 Ma. During Miocene time, several extensional features developed throughout the batholith and adjacent areas, including volcanism in the Tahoe area and opening of the Verdi-Boca basin, the El Paso basin, and Jawbone Canyon. The KCF system, a high-angle fault system, was likely reactivated at this time of regional east-west extension. Post-40 Ma offsets of ~600 m on the KCF and an adjacent lineament are recorded in constant-elevation (U-Th)/He transects at the latitudes of Lake Isabella and Walker Basin. We interpret this activity to fall within the Miocene extensional setting of the batholith.

Basement incision west of the KCF and trapping of Quaternary alluvium from the east against the KCF support reactivation of the KCF as a normal fault in Quaternary time. Modest-relief scarps along the length of the KCF are apparent from near its northernmost extent – where a 3 Ma basalt cap has been sheared along the fault – to its southernmost extent in Havilah Valley. Along these scarps, Quaternary sediments are trapped in elongate valleys along the fault. At Lake Isabella, ~30 m of Quaternary fill trapped immediately east of the fault indicate at least this much vertical offset along the KCF in the Quaternary. However, Quaternary alluvium overlapping the fault at Lake Isabella and Havilah Valley suggests the KCF has lain quiescent for the past few thousand years. Deformation within the batholith may be migrating 10 km eastward, from the tract of the KCF to the narrow, north-south trending zone of active seismicity defined by the 1980's Durrwood Meadows earthquake swarm.

It is likely that ancient fundamental structures such as the (P)KCF system become reactivated to accommodate changes in stress, and the KCF appears to be reactivated as an integral extensional feature of the modern Sierra Nevada deformational field. This reactivation is ascribed to either westward migration of B&R extension or to more localized effects related to the removal of the eclogitic root of the batholith. The potential of B&R-related extension should be determined via assessment of local GPS movement across the SNB. Paucity of this information leads readily to the interpretation of stress associated with the most recent phase of KCF motion as related to a local phenomenon, rather than to the far-field effects of B&R extension. Right-lateral strike-slip shear dominates the stress field between the southern B&R and the Sierra Nevada, suggesting that the Sierra Nevada microplate is somehow separated from B&R-related movement, at least at this southern latitude. Movement within the southern part of the Sierra Nevada microplate, at least, is dominated by horizontal extensional stresses, which we assign to the local phenomenon of mantle lithosphere delamination beneath the southern Sierra Nevada. Reactivation of the Kern Canyon Fault at several discrete times over the past 100 Myr indicates that deformation readily localizes along pre-existing crustal weaknesses, and supports the idea that well-developed, sub-vertical fabrics have a tendency to reactivate, particularly in extension. Geological and geophysical anomalies provide evidence for active deformation in the southern 150 km of the Sierra Nevada microplate.

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FIGURE CAPTIONS

1. Location map showing California (CA), Nevada (NV), and the geological and geographical features referenced throughout the text. The box shows the location of Figures 2 and 3.

2. Digital elevation model (DEM) of the southern Sierra Nevada. Locations of major faults shown in red: Kern Canyon–Breckenridge–White Wolf; Proto-Kern Canyon; Edison; Kern River. Also shown are locations of: Kern River and Walker Creek; Lake Isabella, South Fork Valley, and Walker Basin; the Little Kern basalt flow; the abandoned Bena channel; Havilah; and photo locations lettered a-d (Fig. 6).
3. Series of reconstructions of the southern Sierra Nevada, Miocene–Recent. Note the north arrow in A for orientation.
   a) Early Miocene (ca. 25-12 Ma) Kern Canyon–Breckenridge–White Wolf fault transfer system for extensional faulting, possibly related to migration of slab window. The Kern River exited through modern-day Walker Creek, depositing the Bena submarine fan into the Maricopa sub-basin of the San Joaquin Valley. The WWF acted as a bounding structure to the fan at this time. Numerous WNW trending lineaments in the southern SNB, as well as the opening of the El Paso basin and normal faulting in the Tejon embayment suggest north-south extension, possibly related to slab window migration.
   b) Late Miocene (ca. 10 Ma) extensional remobilization of the Kern Canyon–Breckenridge fault system. The Kern River was captured by its modern lower course drainage during west-side-up reactivation of the Kern Canyon fault. Garlock fault initiation, opening of the Jawbone Canyon graben, early extensional faulting of Owens Valley, appearance of the Split Mountain lineament and reactivation of the neighboring Kern Canyon fault as a normal fault reflect a switch to east-west extension.
   c) Model of Mid-Pliocene to Holocene (ca. 3.5-0 Ma) surface response to mantle lithosphere removal. Recent seismicity outlines normal faulting in the San Joaquin Valley, including Tulare basin and the Bakersfield arch. Subsurface

faulting in the valley has been related to convective removal of the mantle lithosphere (the mantle drip), the surface projection of which is outlined. Within the batholith, east-west extension is manifest in subdued normal faulting along the Kern Canyon fault, possibly related to the 1983-1984 Durrwood Meadows earthquake swarm. Normal faulting in the batholith is segregated from dextral strike-slip faulting of the Owens Valley and Walker Pass regions.

4. DEM of the southern Sierra Nevada showing the locations of major faults (red), and lineaments (yellow). WWF = White Wolf fault, BF = Breckenridge fault; KCF = Kern Canyon fault, SNFF = Sierra Nevada frontal fault, GF = Garlock fault. Also shown are M>2 earthquakes in the vicinity of the KCF since 1983. The Durrwood Meadows earthquake swarm is a pronounced north-south trending zone of seismicity with pure normal fault focal mechanisms. The surface projection of the mantle drip is shown for reference.

5. A cross section across the south shore of Lake Isabella, showing ~30m of Quaternary alluvium of South Fork Valley trapped east of the west-side-up Kern Canyon fault (KCF). A thin layer of alluvium overlaps basement rock just west of the fault, suggesting the fault is inactive. Cross section based on rock cores, soil borings, trenches, and a seismic refraction study. Data courtesy of Page (2005).

6. Aerial and field photos documenting recent activity along the Kern Canyon fault (KCF). Arrows indicate north direction.
   a) In Havilah Valley, a subdued fault scarp traps Quaternary alluvium east of the west-side-up KCF. The scarp is dissected, suggesting the fault is inactive.
   b) Engineer Point, a peninsula in Lake Isabella, is a west-side-up fault scarp along the KCF. East of the KCF, Quaternary alluvium of South Fork Valley ponds against the fault (see Fig. 6).
   c) Along the Rincon trail, west-side-up faulting is evident in this high-relief fault scarp. At C*, Cretaceous granitic basement west of the KCF is in fault contact with Quaternary alluvium to the east.

d) Evidence of recent activity in i) apparent west-side-up offset of the Little Kern basalt flow (star indicates location of Figures Diii and Div), ii) elongate meadows along the KCF, such as Trout Meadows, again trapping Quaternary alluvium east of the fault, iii) blocky outcrops of basalt west of the KCF, and iv) immediately east of photo Diii, the basalt is deeply weathered and sheared, and forms a gully along the trace of the KCF.

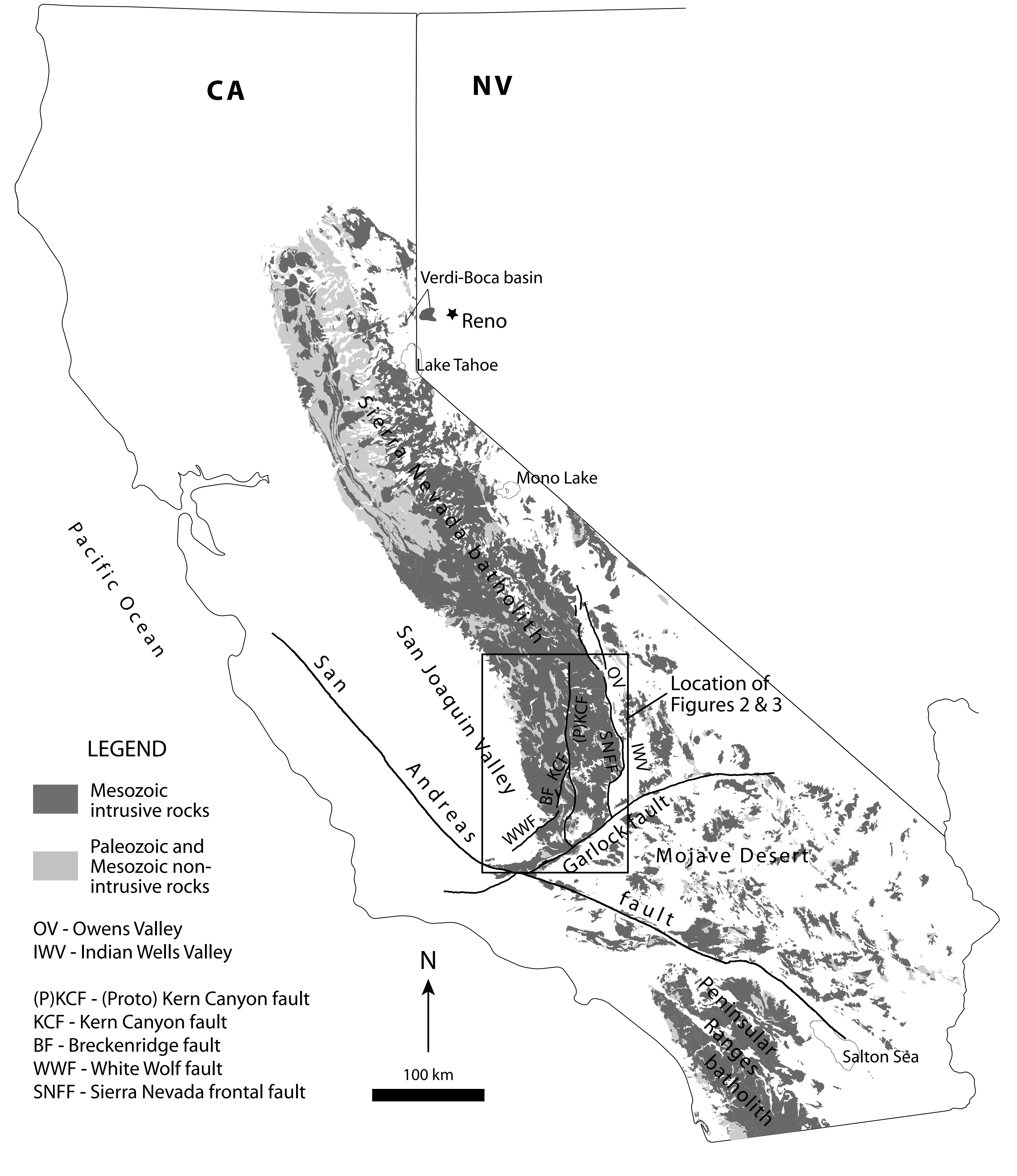
CA
NV
Verdi-Boca basin
Reno
Lake Tahoe
Mono Lake
Sierra Nevada batholith
Pacific Ocean
San Joaquin Valley
San Andreas fault
Garlock fault
Mojave Desert
Location of Figures 2 & 3
OV
IWV
SNFF
(P)KCF
KCF
BF
WWF
Peninsular Ranges batholith
Salton Sea
N
100 km
LEGEND
Mesozoic intrusive rocks
Paleozoic and Mesozoic non-intrusive rocks
OV - Owens Valley
IWV - Indian Wells Valley
(P)KCF - (Proto) Kern Canyon fault
KCF - Kern Canyon fault
BF - Breckenridge fault
WWF - White Wolf fault
SNFF - Sierra Nevada frontal fault

Figure 1

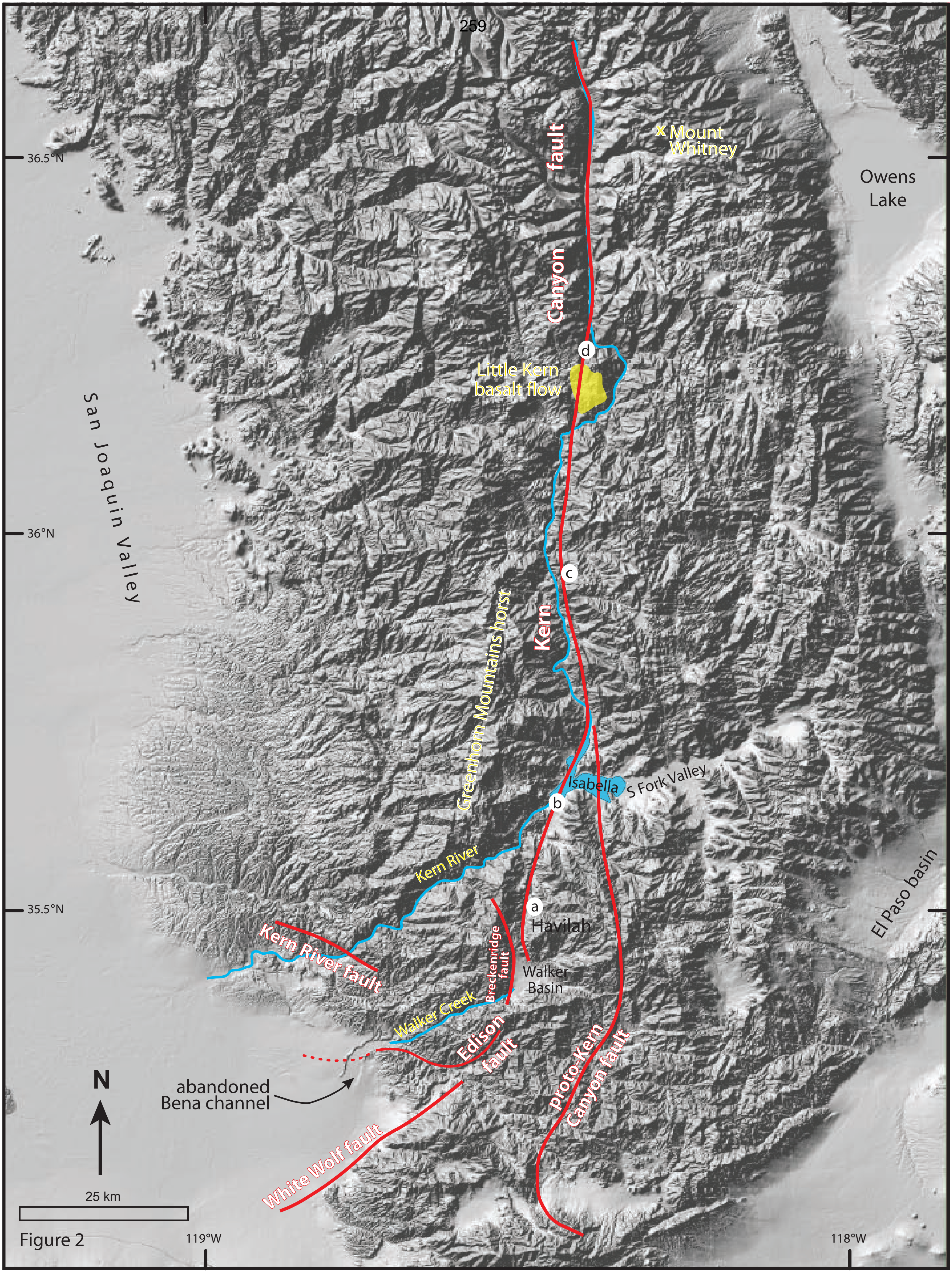
36.5°N
36°N
35.5°N
119°W
118°W
Mount Whitney
Owens Lake
San Joaquin Valley
Kern Canyon fault
Little Kern basalt flow
d
c
b
a
Greenhorn Mountains horst
Isabella
S Fork Valley
Kern River
Havilah
Walker Basin
Breckenridge fault
Kern River fault
Walker Creek
Edison fault
proto-Kern Canyon fault
abandoned Bena channel
White Wolf fault
El Paso basin
N
25 km

Figure 2

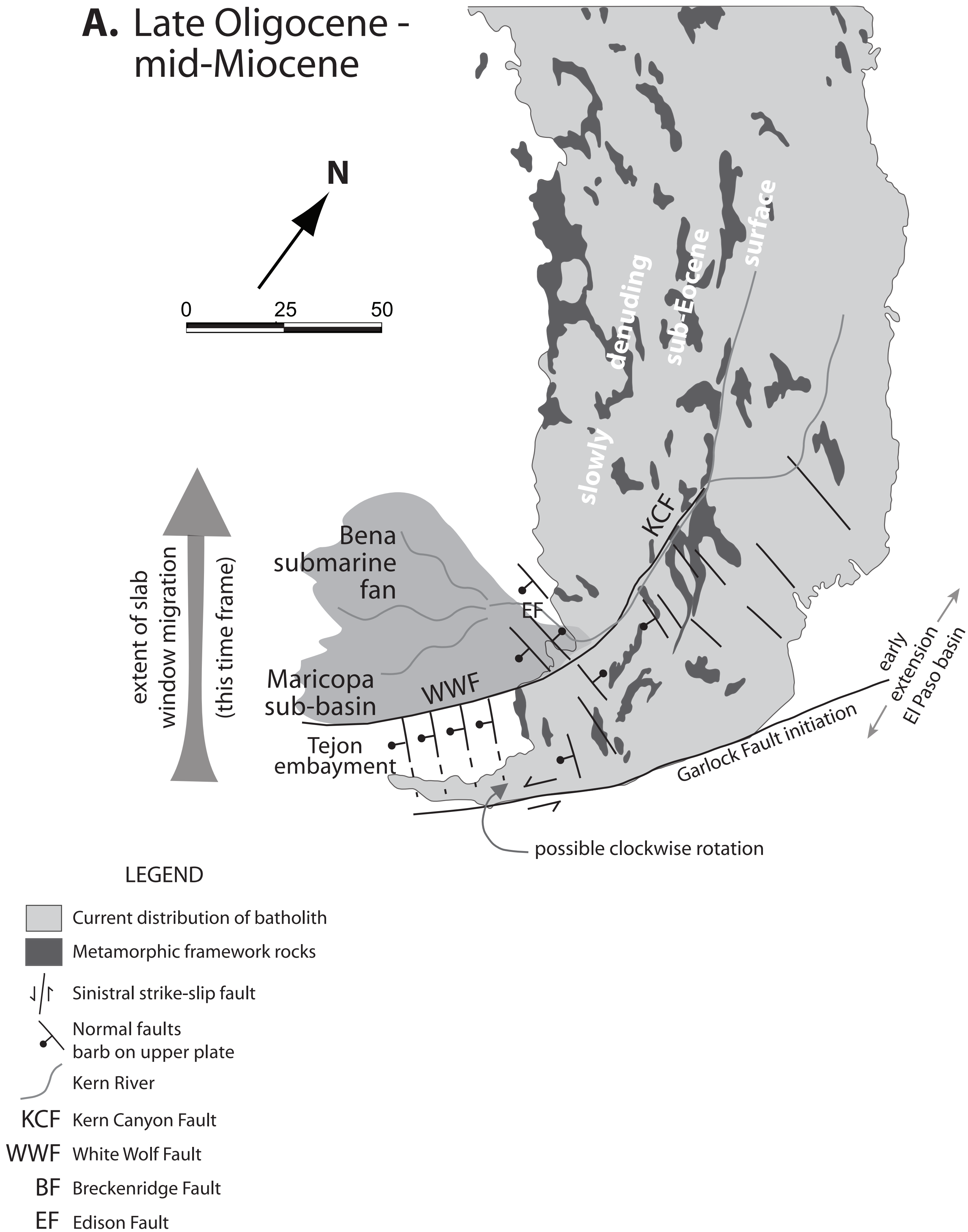
A. Late Oligocene - mid-Miocene
N
0
25
50
slowly
denuding
sub-Eocene
surface
KCF
Bena
submarine
fan
EF
Maricopa
sub-basin
WWF
Tejon
embayment
extent of slab
window migration
(this time frame)
early
extension
El Paso basin
Garlock Fault initiation
possible clockwise rotation
LEGEND
Current distribution of batholith
Metamorphic framework rocks
Sinistral strike-slip fault
Normal faults
barb on upper plate
Kern River
KCF Kern Canyon Fault
WWF White Wolf Fault
BF Breckenridge Fault
EF Edison Fault

Figure 3a

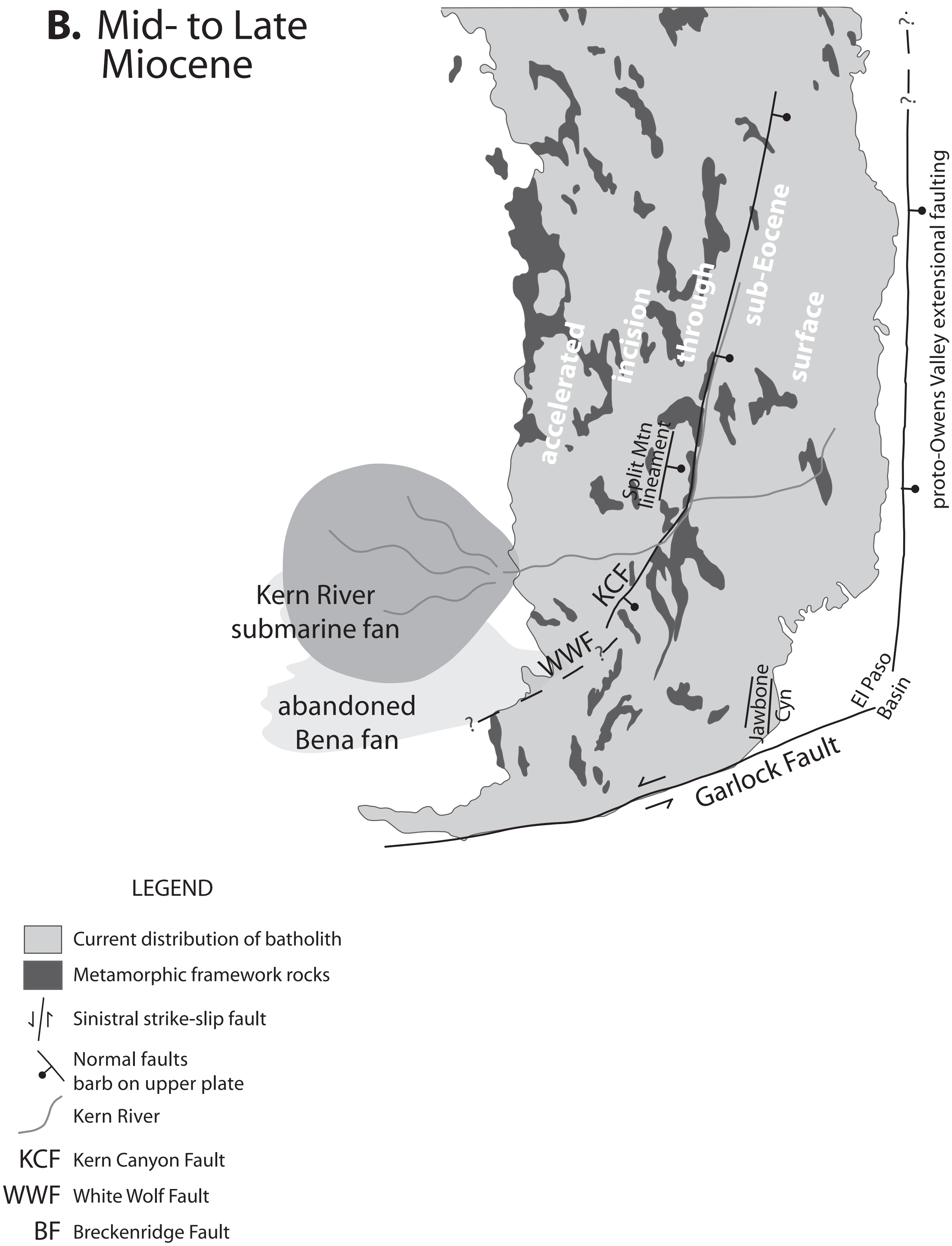
B. Mid- to Late Miocene
accelerated incision through sub-Eocene surface
proto-Owens Valley extensional faulting
Split Mtn lineament
KCF
WWF
Kern River submarine fan
abandoned Bena fan
Jawbone Cyn
El Paso Basin
Garlock Fault
LEGEND
Current distribution of batholith
Metamorphic framework rocks
Sinistral strike-slip fault
Normal faults barb on upper plate
Kern River
KCF Kern Canyon Fault
WWF White Wolf Fault
BF Breckenridge Fault

Figure 3b

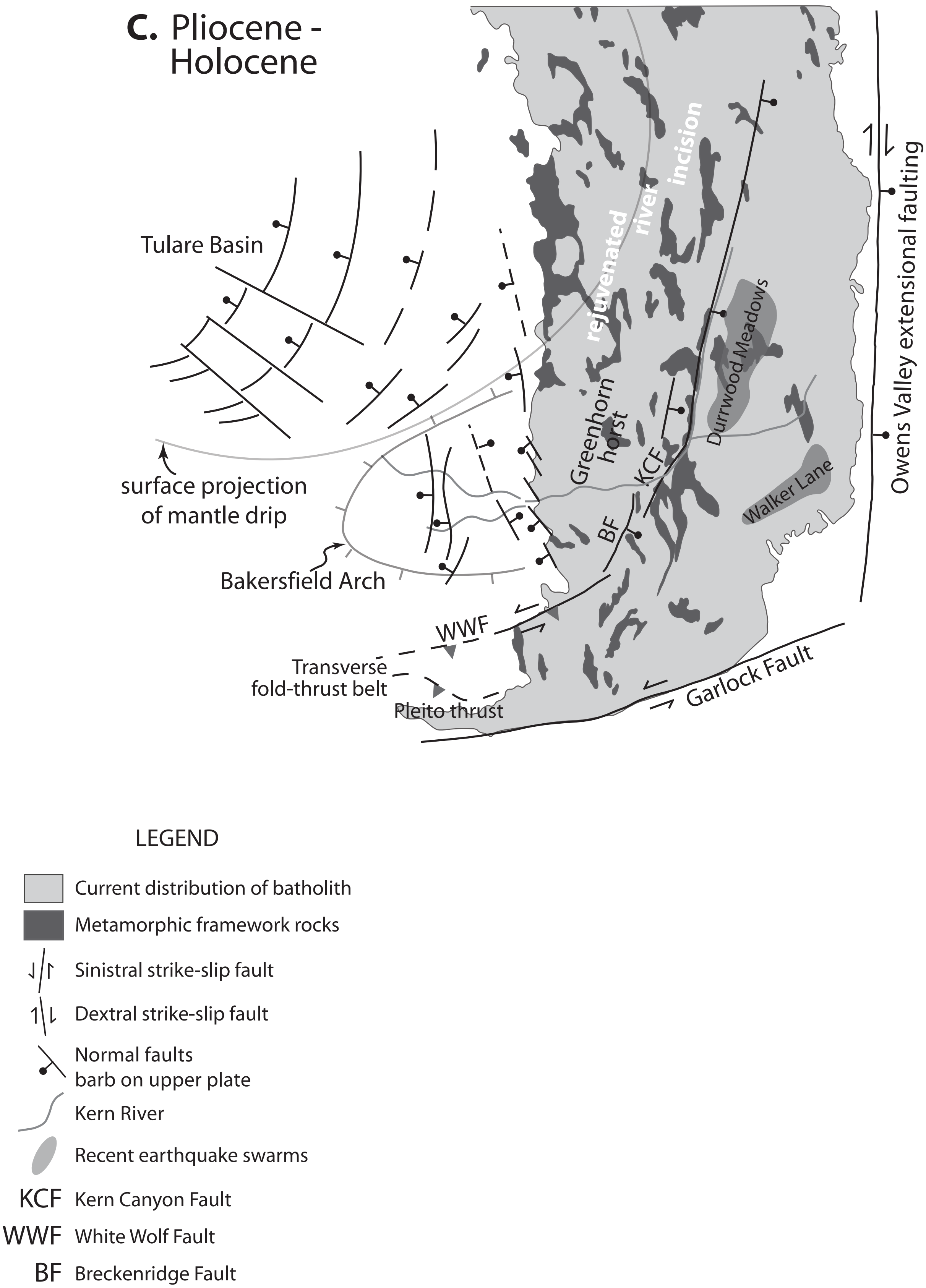
C. Pliocene - Holocene
Tulare Basin
rejuvenated river incision
Greenhorn horst
KCF
BF
Durrwood Meadows
Walker Lane
Owens Valley extensional faulting
surface projection of mantle drip
Bakersfield Arch
WWF
Transverse fold-thrust belt
Pleito thrust
Garlock Fault
LEGEND
Current distribution of batholith
Metamorphic framework rocks
Sinistral strike-slip fault
Dextral strike-slip fault
Normal faults barb on upper plate
Kern River
Recent earthquake swarms
KCF Kern Canyon Fault
WWF White Wolf Fault
BF Breckenridge Fault

Figure 3c


263
-119°0'
-118°30'
-118°0'
36°30'
36°0'
35°30'
20 Km

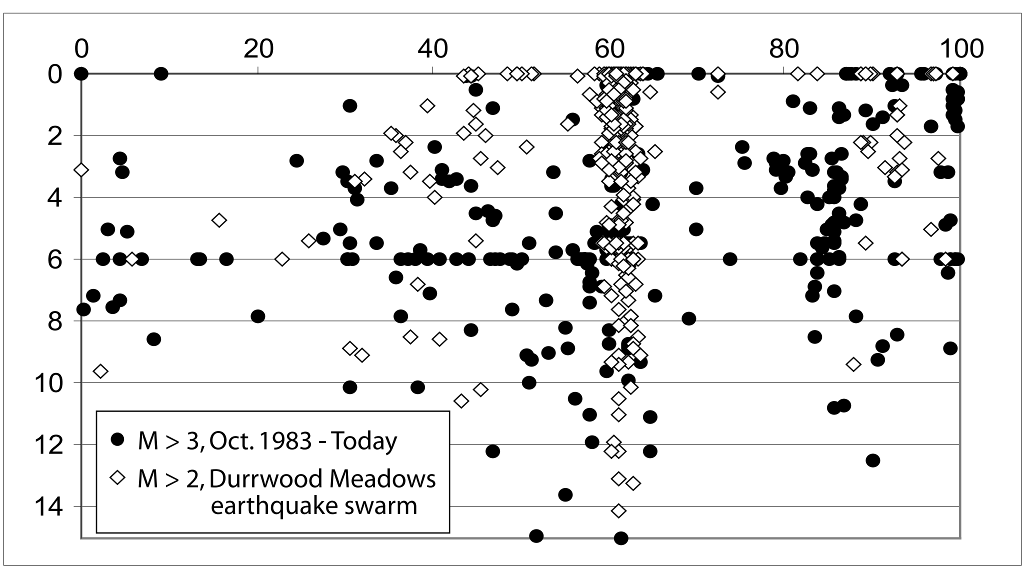
0
20
40
60
80
100
2
4
6
8
10
12
14
M > 3, Oct. 1983 - Today
M > 2, Durrwood Meadows earthquake swarm

Figure 4

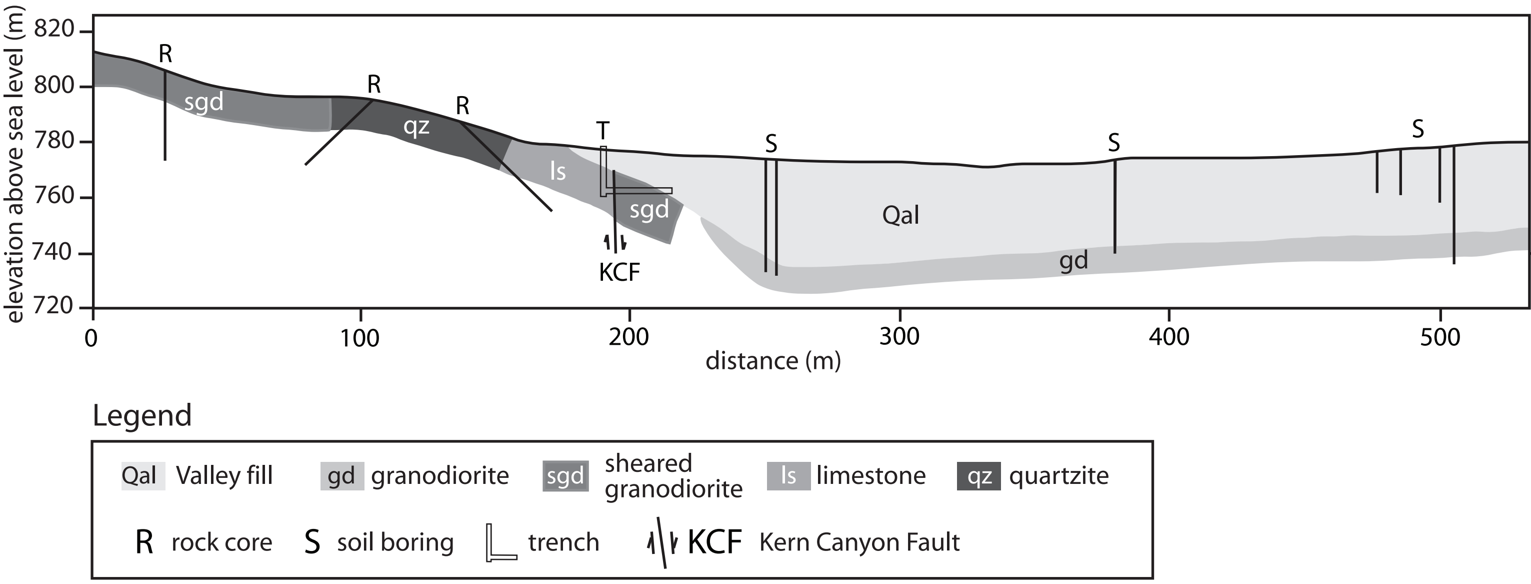
elevation above sea level (m)
820
800
780
760
740
720
0
100
200
300
400
500
distance (m)
R
R
R
T
S
S
S
sgd
qz
ls
sgd
KCF
Qal
gd
Legend
Qal Valley fill
gd granodiorite
sgd sheared granodiorite
ls limestone
qz quartzite
R rock core
S soil boring
trench
KCF Kern Canyon Fault

Figure 5

Figure 6 a, b, and c

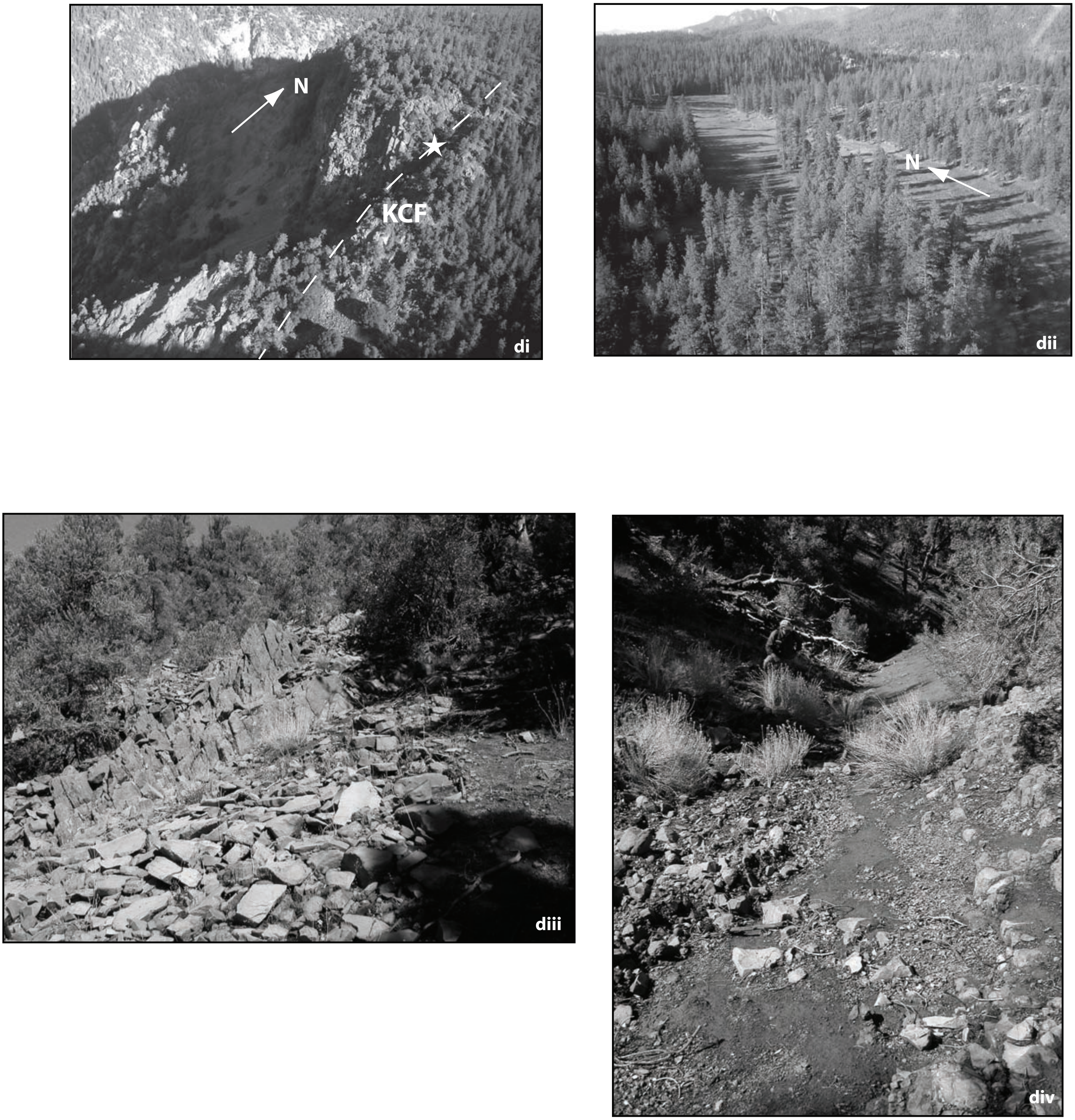

Figure 6d