The Laurel-Convict fault, eastern Sierra Nevada, California: A Permo–Triassic left-lateral fault, not a Cretaceous intrabatholithic break

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ABSTRACT

The Laurel-Convict fault is a prominent, northwest-striking, high-angle fault exposed in Paleozoic rocks of the Mount Morrison pendant in the eastern Sierra Nevada of California. The fault zone averages 25–50 m in width and consists of narrow, anastomosing domains of ductile deformation separating lenses of Paleozoic metasedimentary rock. The fault, which cuts structures in middle Permian metasedimentary rocks, is intruded by a relatively undeformed quartz porphyry felsite dike that has yielded a U-Pb zircon upper intercept age of 225 ± 16 Ma. Displacement on the Laurel-Convict fault is therefore constrained to the interval between middle Permian and Late Triassic. Displacement criteria, including curvature and offset of bedding in the fault zone, rare mesoscopic ductile shear indicators, and restoration of offset lower Paleozoic stratigraphy and structure across splay faults, all indicate a moderate amount of apparent left-lateral strike-slip displacement. Our data do not support previous interpretations of the Laurel-Convict fault as a thrust-faulted terrane boundary or a major right-lateral shear zone. The Laurel-Convict fault is not, therefore, an exposed segment of Intrabatholithic Break 3 (IBB3). Proposed Cretaceous right-lateral displacement of the Sr_i = 0.706 isopleth on IBB3 must be accommodated either east of the Mount Morrison pendant in the Owens Valley or west of the pendant in the eastern Sierra Nevada.

INTRODUCTION

Paleozoic metasedimentary rocks of the Mount Morrison pendant (Fig. 1) in the eastern Sierra Nevada of California are cut by the Laurel-Convict fault (Fig. 2), a prominent, northwest-striking, high-angle fault that is spectacularly exposed in cliffs on Laurel Mountain and the west face of Mount Morrison (Fig. 3). The very conspicuous field expression of this fault coupled with a lack of detailed study have led to widely differing interpretations of the fault's displacement history and regional significance.

The Laurel-Convict fault was defined originally by Rinehart and Ross (1964), who interpreted it as a left-lateral strike-slip fault on the basis of local curvature of bedding into the fault zone. Subsequently, the fault has been interpreted as a high-angle reverse fault (Russell and Nokleberg, 1977), a low-angle thrust fault subsequently rotated to a high angle (Nokleberg, 1983), and a right-lateral strike-slip fault (Kistler et al., 1980; Saleeby et al., 1986; Saleeby and Busby, 1993; Kistler, 1993). Nokleberg (1983) interpreted the Laurel-Convict fault as part of a major Triassic terrane boundary, separating unrelated rocks in his "High Sierra" and "Owens" terranes (Fig. 1). Recently, Kistler (1993) proposed that the Laurel-Convict fault is an exposed segment of a postulated regional fault zone called Intrabatholithic Break 3 (IBB3), interpreted to have Cretaceous right-lateral displacement of greater than 65 km based on an apparent offset of the Sr_i = 0.706 isopleth (Sr_i = initial ratio $^{87}Sr/^{86}Sr$) (Kistler and Peterman, 1973).

Our new work in the Mount Morrison pendant indicates that the Laurel-Convict fault is a left-lateral strike-slip fault of moderate displacement that was active between middle Permian and Late Triassic time (Greene et al., 1995). The fault is neither a terrane boundary nor a major right-lateral shear zone.

Geology of the Mount Morrison Pendant

The Mount Morrison pendant consists of Cambrian through Devonian metasedimentary rocks structurally juxtaposed against Mississippian through Permian metasedimentary rocks across the Laurel-Convict fault (Fig. 2) (Rinehart and Ross, 1964; Greene and Stevens, 1994; Stevens and Greene, 1994, 1995; Wise, 1996). Triassic and Jurassic metavolcanic rocks structurally overlie the metasedimentary rocks to the southwest (Morgan and Rankin, 1972; Bergeron, 1992). As defined by Stevens and Greene (1995), the lower Paleozoic section consists of interbedded black siliceous argillite and medium gray marble of the Cambrian–Ordovician(?) Mount Aggie Formation; black siliceous argillite and less common quartzite of the Ordovician Convict Lake Formation; green and white banded calc-silicate hornfels of the Silurian to Lower Devonian(?) Aspen Meadow formation; light gray calcareous quartz sandstone of the Middle Devonian Mount Morrison Sandstone; and black phosphatic chert, argillite, and gray calcareous sandstone of the Late Devonian Squares Tunnel Formation. The upper Paleozoic section consists of dark gray siliceous argillite and fine-grained micaceous sandstone of the Mississippian Bright Dot Formation; medium gray banded marble of the Pennsylvanian to Early Permian Mount Baldwin Marble; and variously interbedded siliceous and calc-silicate hornfels of the Permian Mildred Lake Hornfels, Lake Dorothy Hornfels, and Bloody Mountain Formation (Rinehart and Ross, 1964; Willahan, 1991).

The lower Paleozoic section is generally north-striking and overturned, dipping steeply to the east (Fig. 2). The section is imbricated by north-striking faults interpreted to be overturned thrust faults and contains steeply plunging, map-scale folds (Greene and Stevens, 1994). Predominantly bedding-parallel, spaced to locally slaty cleavage is developed in argillaceous rocks; tight, mesoscopic folds are locally prominent in thin-bedded units (Rinehart and Ross, 1964; Russell and Nokleberg, 1977; Wise, 1996). The

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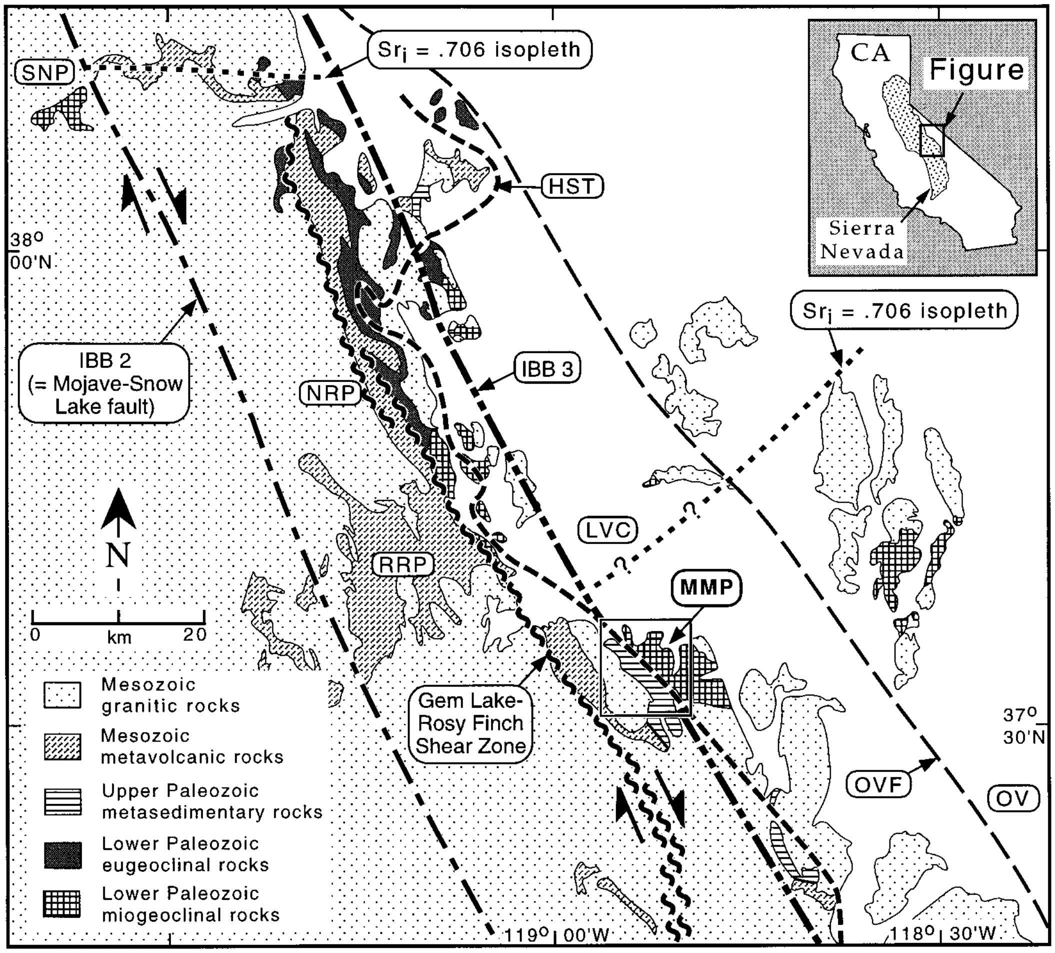

Figure 1. Generalized geologic map of the central eastern Sierra Nevada, showing the location of major roof pendants and proposed regional faults. Boxed inset shows location in California. Other box indicates area of Figure 2. Abbreviations: HST—High Sierra/Owens terrane boundary of Nokleberg (1983), IBB2 and IBB3—Intrabatholithic Break 2 and 3 of Kistler (1993), LVC—Long Valley caldera, MMP—Mount Morrison pendant, NRP—Northern Ritter Range pendant, OV—Owens Valley, OVF—proposed dextral fault in Owens Valley of Stevens and Greene (1995), RRP—Ritter Range pendant, SNP—Snow Lake pendant. Modified from Nokleberg (1983), with data from Kistler (1993) and Greene and Schweickert (1995).

upper Paleozoic section displays map-scale and outcrop-scale open folds with horizontal, northwest-trending hinge lines. The Laurel-Convict fault and several splays northeast of the main fault strand, are prominently exposed through the central part of the Mount Morrison pendant (Fig. 2). The McGee Creek fault, a poorly exposed fault with a similar orientation and timing of displacement, is located east of the Laurel-Convict fault and may be related to it (Wise, 1995, 1996).

DESCRIPTION OF THE LAUREL-CONVICT FAULT

The Laurel-Convict fault is northwest striking, vertical to very steeply northeast dipping, and exposed over a distance of about 9 km in the Mount Morrison pendant. The fault is cut on the southeast by the Late Cretaceous Round Valley Peak Granodiorite and is covered to the northwest by Quaternary sedimentary and volcanic rocks of the Long Valley caldera. The main strand of the Laurel-Convict fault primarily juxtaposes lower Paleozoic rocks against upper Paleozoic rocks. Subsidiary splay faults offset stratigraphic units and structures in the lower Paleozoic section. The fault is well exposed (although relatively inaccessible) in very steep slopes on the west face of Mount Morrison (Fig. 3), where it places the lower Paleozoic Convict Lake, Aspen Meadow, and Mount Morrison Formations against the Mississippian Bright Dot Formation. The fault cuts bedding in both the lower Paleozoic and upper Paleozoic sections (Figs. 2 and 3).

The main fault zone averages between 25 and 50 m in width, and the zone of ductile deformation is sharply bounded on both sides (Fig. 3). The fault zone consists of narrow, anastomosing zones of ductile deformation separating lenses of less deformed metasedimentary rocks. Highly cleaved, silicified, and hydrothermally altered zones of ductile deformation average 50 to 100 cm in width. Lenses of metasedimentary rock are 2 m to 10 m wide and 25 m to greater than 100 m long. Lenses are parallel to the fault zone and appear to consist of “shuffled” slices of both upper Paleozoic and lower Paleozoic rocks. The most prominent metasedimentary rocks in the fault zone are lenses of calcareous sandstone derived from the Mount Morrison Sandstone that contain metamorphic mineral assemblages including quartz–diopside–grossular garnet, quartz-diopside-wollastonite, and calcite-wollastonite.

A quartz porphyry felsite dike that is 10 to 50 m wide and at least 7 km long is present along much of the main strand of the Laurel-Convict fault (Fig. 2). Felsite has also intruded splays of the main fault zone northeast of Laurel Canyon and in the cirque southeast of Mount Morrison. The felsite is undeformed except for minor, strike-parallel spaced cleavage that is defined by locally developed, thin parallel fractures that probably are related to Mesozoic contractional deformation. The felsite dike was intruded after displacement on the fault ceased, and it seals the fault zone.

Sense of Displacement

On the west face of Mount Morrison, bedding in the Mount Morrison Sandstone has been dragged into the Laurel-Convict fault zone with a left-lateral sense of displacement (Fig. 3), as originally noted by Rinehart and

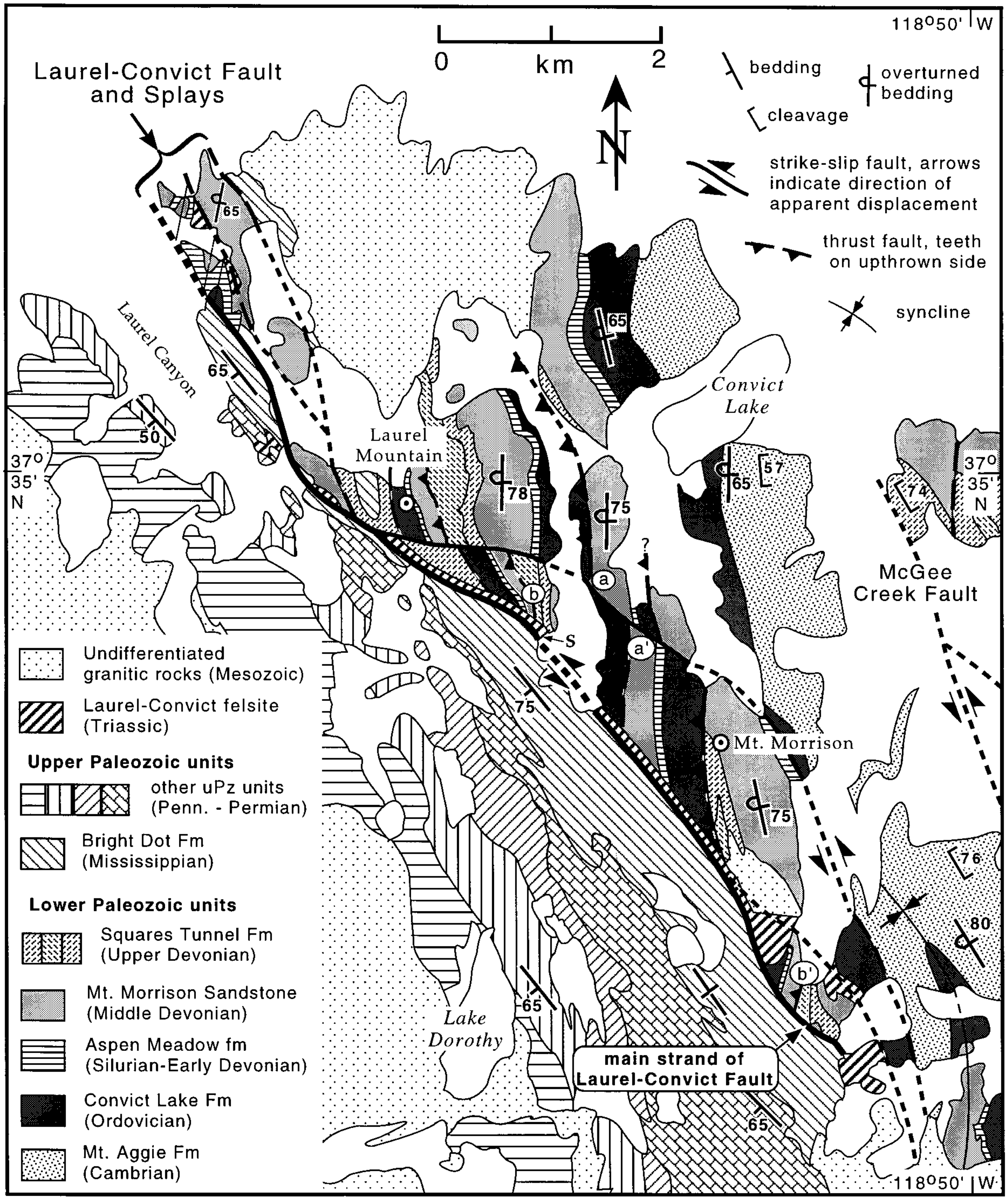

Figure 2. Generalized geologic map of the Laurel-Convict fault and splays in the Mount Morrison pendant. Circled letters indicate offset stratigraphic and structural successions; a matches with a′, and b matches with b′. S indicates location of the U-Pb sample. Geology modified substantially from Rinehart and Ross (1964).

Ross (1964). Also visible in Figure 3 is a dark block of the Mount Morrison Sandstone (labeled "a′") which has been displaced left laterally with respect to the layer labeled "a." Such displacement indicators are rare in the main fault zone, however, and the dissimilar stratigraphic sections juxtaposed across the main strand of the Laurel-Convict fault do not provide piercing points that permit determination of the overall sense of displacement.

Splay faults northeast of the main fault zone cut stratigraphy and structure in the lower Paleozoic section (Fig. 2), and restoration of offsets on these splays shows a consistent apparent left-lateral sense of displacement. For example, 500 m of apparent left-lateral offset across the splay fault northwest of Mount Morrison is indicated by the offset of a north-striking thrust fault that places Convict Lake Formation structurally over Mount

Figure 3. View of the Laurel-Convict fault looking southeast from Laurel Mountain. Banded rocks on left are Devonian Mount Morrison Sandstone, massive appearing unit on right is Mississippian Bright Dot Formation. Center of fault zone is occupied by a quartz porphyry felsite dike. Block a′ is offset from bed a. Vertical relief ≈1000 m.

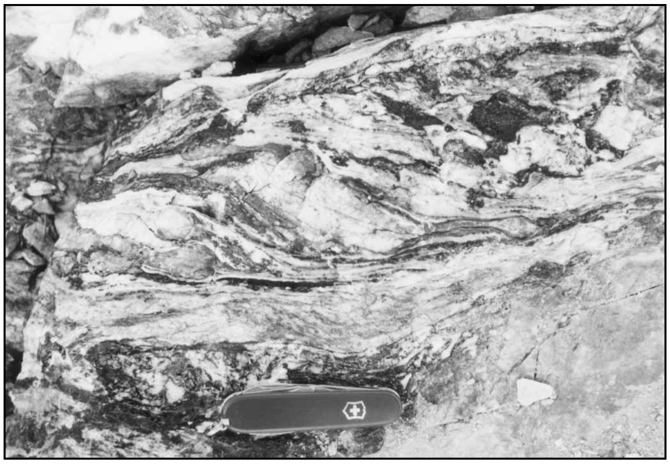

Figure 4. Ductile deformation of marble around silicic porphyroclasts indicating left-lateral shear, exposed in the Laurel-Convict fault south of Mount Morrison. Outcrop surface is approximately horizontal, north is toward the upper left. Knife is 9 cm.

Morrison Sandstone (a–a′ in Fig. 2). Structures and stratigraphic units with similar offsets are present southeast of Laurel Mountain and north of Mount Morrison, where a drag fold involving the Aspen Meadow formation also indicates a component of left-lateral displacement. Stratigraphic units in all these areas dip steeply to the east; large vertical displacements (on the order of 2000 to 3000 m) would be required to produce the observed offsets with dip-slip motion.

Outcrop-scale ductile shear-sense indicators showing a component of left-lateral strike-slip are present locally on subhorizontal surfaces in the main fault zone. These include S-C fabric (in the sense of Ramsay and Huber, 1987) defined by cleavage and preferred orientation of grain aggregates, and rare sigma-type porphyroclast systems consisting predominantly of silicified clasts in a more calcareous matrix (Fig. 4). Lineations have not been observed in the fault zone, nor have unequivocal shear-sense indicators been observed in thin section. Elongate grains of wollastonite are randomly oriented and the mineral fabric generally indicates static recrystallization, presumably resulting from intrusion of the felsite dike into the fault zone.

Because of the lack of lineations in the fault zone and the sparse nature of mesoscopic shear-sense indicators, we cannot rule out the possibility of a component of dip-slip motion on the fault. Most observed shear-sense indicators, however, are on subhorizontal surfaces, suggesting that displacement is predominantly strike slip. The apparent left-lateral offset of steeply dipping stratigraphic units across the northeast splay fault (e.g., from a to a′ in Fig. 2) could result from southwest-side-up dip-slip displacement, but unrealistically large vertical displacement would be required to produce the 4.5 km of left-lateral separation between locations b and b′ in Figure 2 (discussed in the following section). Southwest-side-up dip-slip displacement would be required to produce the observed left-lateral separations in steeply east-dipping units juxtaposed across the splay faults. The main strand of the Laurel-Convict fault, however, places upper Paleozoic strata on the southwest side of the fault against lower Paleozoic strata on the northeast side of the fault, implying northeast-side-up displacement. These conflicting apparent offsets are difficult to reconcile with predominantly dip-slip motion, unless the splay faults record substantially different displacement than the main strand of the fault.

In summary, while we cannot preclude a component of dip-slip displacement on the Laurel-Convict fault, we consider that substantial dip-slip displacement is unlikely. We interpret the outcrop and map-scale features to collectively indicate that displacement on the Laurel-Convict fault was predominantly left-lateral strike slip, as originally suggested by Rinehart and Ross (1964).

Amount of Displacement

Restoration of stratigraphic offsets on the splay of the Laurel-Convict fault northwest of Mount Morrison indicates apparent left-lateral displacement of about 500 m. An isolated block near the southeast end of the Laurel-Convict fault (b′ in Fig. 2) consists of a distinctive stratigraphic succession of (from west to east) structurally overturned Convict Lake, Aspen Meadow, and Mount Morrison Formations apparently thrust over structurally upright Squares Tunnel and Mount Morrison Formations. This block is separated from the remainder of the Paleozoic section by intrusions of the quartz porphyry felsite, which we interpret to have intruded a splay of the Laurel-Convict fault. The succession in this block is anomalous with respect to surrounding units, but matches with a similar stratigraphic and structural succession present in a wedge-shaped block southeast of Laurel Mountain (b in Fig. 2). We therefore interpret the block at the southeast end of the Laurel-Convict fault to be offset 4.5 km to the southeast from the vicinity of Laurel Mountain. Together these offsets indicate a minimum apparent left-lateral displacement of about 5 km on the Laurel-Convict fault system.

The maximum displacement on the Laurel-Convict fault is unknown. As originally mapped (Rinehart and Ross, 1964) the fault was thought to juxtapose unrelated lower Paleozoic and upper Paleozoic stratigraphic sections, suggesting the possibility of very large displacement. Our recent mapping in the northwestern part of the Mount Morrison pendant, however, indicates that the Mississippian Bright Dot Formation is in fact present on both sides of the main strand of Laurel-Convict fault. On the west side of Laurel Mountain, the Bright Dot Formation is exposed in an overturned syncline(?) involving the Devonian Squares Tunnel Formation, and to the northwest the Bright Dot Formation occurs in structural slices east of the Mount Morrison Sandstone (Fig. 2).

The contacts between the lower Paleozoic section and these newly recognized upper Paleozoic rocks in the Mount Morrison pendant are poorly exposed and may be faults. In other pendants in the region, however (i.e., Bishop Creek and Log Cabin Mine pendants), depositional continuity between the Devonian and Mississippian sections is apparent (Stevens and Greene, 1994). Therefore, we interpret the lower and upper Paleozoic sections in the Mount Morrison pendant to be closely related. Displacement on the Laurel-Convict fault need not be large in order to juxtapose these rocks, although differences in the style of deformation on opposite sides of the fault suggest at least a moderate distance (a few tens of kilometers?) between the two blocks at the time of this deformation.

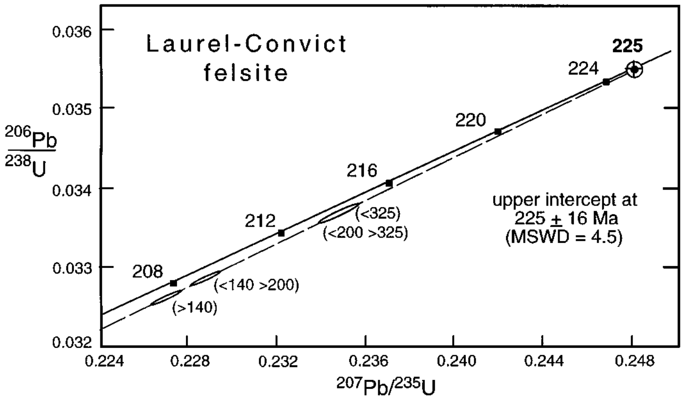

Figure 5. Concordia diagram for quartz porphyry felsite dike intruding the Laurel-Convict fault (see Table 1). Numbers in parentheses indicate the size fractions analyzed in standard mesh. Ellipses reflect 2-sigma error. Sample collected from outcrop on the west wall of Convict Creek canyon at lat 37°34′13″N, long 118°52′37″W (location plotted in Fig. 2).

Age of Displacement

The quartz porphyry felsite dike that intrudes the Laurel-Convict fault has yielded a U-Pb zircon upper intercept age of 225 ± 16 Ma (Fig. 5, Table 1), indicating that displacement on the fault must be Triassic or earlier. The Laurel-Convict fault cuts structures and stratigraphy in the upper Paleozoic section, as noted previously by Rinehart and Ross (1964). South and west of Laurel Mountain the Bright Dot Formation and overlying Mount Baldwin Marble are thinned and almost cut out along the fault (Fig. 2), and east of Laurel Canyon slivers of the Bright Dot Formation appear to be involved in splays of the Laurel-Convict fault (Fig. 2). The early Mississippian to middle Permian section is probably continuous, as indicated by depositional contacts, fossil age control, and the presence of similar structures throughout the section (Rinehart and Ross, 1964; Willahan, 1991). Thus, displacement on the Laurel-Convict fault occurred after deposition of the middle(?) Permian Bloody Mountain Formation and before intrusion of the felsite dike in the Late Triassic.

DISCUSSION

Offset stratigraphy, drag folds, and macroscopic ductile shear-sense indicators all support the interpretation that the Laurel-Convict fault is a left-lateral strike-slip fault. Offset stratigraphic and structural markers indicate that apparent displacement is greater than 5 km. The maximum displacement and its exact orientation are unknown, but the observation that upper Paleozoic rocks occur on both sides of the fault suggests that displacement is not large. Differences in the style of deformation across the fault, however, probably indicate at least some separation of the presently juxtaposed upper and lower Paleozoic rocks during an earlier period of contractional deformation. The fault was active after deposition of middle(?) Permian sedimentary rocks and before intrusion of a Late Triassic felsite dike.

These data preclude a number of previous hypotheses concerning the nature and age of the Laurel-Convict fault. The evidence for left-lateral strike-slip displacement and the presence of Mississippian Bright Dot Formation on both sides of the fault show that the fault is not a thrust-faulted terrane boundary as proposed by Nokleberg (1983), a conclusion consistent with recent studies to the north in the Northern Ritter Range pendant (Greene, 1995) and the Saddlebag Lake pendant (Schweickert and Lahren, 1993).

The Laurel-Convict fault cannot be a segment of the postulated regional shear zone called Intrabatholithic Break 3 (IBB3) (Saleeby et al., 1986; Saleeby and Busby, 1993; Kistler, 1993) because that shear zone is interpreted to be Cretaceous in age and to have had right-lateral displacement. Right-lateral offset of the $Sr_i = 0.706$ isopleth must therefore be accommodated on faults located east of the Mount Morrison pendant in Owens Val-

TABLE 1. ZIRCON DATA FOR THE LAUREL-CONVICT FELSITE

Fraction analyzed (mesh size)	Sample weight (mg)	U (ppm)	Pb (ppm)	Corrected Ratios			Radiogenic ratios			Isotopic ages (m.y.)		
				$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207/206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207/206}Pb$
nm, >140	5	767	24.7	0.09919	0.05070	0.000013	0.03263	0.22722	0.05050	207.0	207.9	218.0
nm, <140 >200	2.8	811	26.4	0.10080	0.05077	0.000017	0.03285	0.22884	0.05052	208.4	209.2	219.0
nm, <200 >325	4	801	26.7	0.10060	0.05069	0.000010	0.03372	0.23503	0.05055	213.8	214.3	220.1
<325	1.2	580	19.4	0.10352	0.05115	0.000039	0.03364	0.23456	0.05057	213.3	214.0	221.3

Note: Analyses completed at the Baylor Brooks Institute of Isotope Geology, San Diego State University, by Melissa Girty. Radiogenic lead corrected for blank ($^{206}Pb/^{204}Pb$ = 18.868; $^{207}Pb/^{204}Pb$ = 15.66; $^{208}Pb/^{204}Pb$ = 38.528) and 250-m.y.-old Stacey and Kramers (1975) initial lead ($^{206}Pb/^{204}Pb$ = 18.318; $^{207}Pb/^{204}Pb$ = 15.609; $^{208}Pb/^{204}Pb$ = 38.172). Mesh sizes are for sieved zircons. The three analyzed fractions indicated as nm were nonmagnetic at 1.8 amps and 1° slope on the Franz Laboratory Barrier Separator. Zircons were not leached or air abraded during sample preparation. Samples were spiked with a $^{208}Pb/^{235}U$ mixed spike. Dissolution and chemical separations were modified after Krogh (1973) using dissolution bombs described by Parrish (1987). Blank lead during the period of these analyses was less than 0.05 ng. Data were reduced using the programs and regression model 2 of Ludwig (1989). Uncertainties in Pb/U and Pb/Pb ratios for all four fractions are better than 0.2% (2-sigma), assuming the Stacey and Kramers initial Pb values are accurate for this rock. Lead and uranium ratios were normalized for mass fractionation based on repeated analyses of NBS Pb 981, Pb 983, and U-050. Decay constants used Lambda ^{238}U = 0.000155125 and Lambda ^{235}U = 0.00098485 decays per m.y. (Jaffey et al., 1971).

ley or west of the pendant in the eastern Sierra Nevada (Fig. 1). Stevens et al. (1995) have proposed a cryptic right-lateral fault with 65 km of displacement in Owens Valley based on the reconstruction of a Devonian submarine fan complex, and restoration of displacement on this fault would account for the offset of the $Sr_i = 0.706$ isopleth shown in Figure 1B of Kistler (1993). Some right-lateral displacement of the $Sr_i = 0.706$ isopleth may also be accommodated on the Gem Lake–Rosy Finch shear zone west of the Mount Morrison pendant (Greene and Schweickert, 1995), and on cryptic structures within the Cretaceous batholith (Fig. 1).

The Laurel-Convict fault provides the first field evidence for left-lateral strike-slip deformation in the central eastern Sierra Nevada during at least part of middle(?) Permian to Late Triassic time. This deformation may correlate with the later stages of a late Paleozoic left-lateral continental truncation proposed to have cut previous facies trends in the southwestern Cordillera and offset eugeoclinal rocks of the Antler orogenic belt from the central Sierra Nevada into the northern Mojave Desert (e.g., Walker, 1988; Stone and Stevens, 1988).

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