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Kinematic and dynamic analysis of a low-angle strike-slip fault: the Lake Creek fault of south-central Idaho

AUDREY D. HUERTA

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.

and

DAVID W. RODGERS

Department of Geology, Idaho State University, Pocatello, ID 83209, U.S.A.

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Abstract—A large, low-angle strike-slip fault with significant offset is present in south-central Idaho. The 40+ km long Lake Creek fault is oriented N50°W, 30°SW and has a slip vector 18 km long, plunging 2° to N55°W. Slip was determined by restoring the offset of a map-scale fold trough. Thus, the fault is a dextral-normal fault with predominant dextral strike-slip and minimal normal dip-slip displacement.

The present-day gentle dip of the fault appears to be the original dip since older folds and coeval to younger dykes in the area are not tilted. Several hypotheses for the origin of the low-angle fault are tested. Field and kinematic data support the interpretation that the fault formed as a low-angle strike-slip fault, not as a reactivated thrust fault nor in association with other regional fault systems.

Based on fault array analysis and published experimental fault studies, the Lake Creek fault is interpreted to have formed as a low-angle strike-slip fault owing to a nearly axial compressive state of stress with a subhorizontal σ_1, and crustal anisotropy induced by NW-trending folds and SW-dipping axial planar cleavage. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Regionally extensive, low-angle strike-slip faults are virtually unrecognized in the Earth's upper crust. Instead, strike-slip faults are commonly observed or inferred to be subvertical (Biddle & Christie-Blick 1985), except where minor splays create flower structures (Harding 1985) or older low-angle faults become reactivated. In this paper we present evidence for the existence of a large, low-angle strike-slip fault in central Idaho, and discuss the factors which account for its unique geometry and dynamics. While vertical strike-slip faults are adequately explained by Anderson's theory of faulting (Anderson 1951), this theory cannot explain the formation of, or slip along, low-angle strike-slip faults. To understand the development of low-angle strike-slip faults, we follow Bott (1959), who proposed that the relative magnitudes of all three principal stresses as well as crustal anisotropies will determine the fault mechanics.

Gently dipping, laterally extensive faults have been mapped throughout south-central Idaho. Previously interpreted as top-to-the-NE Mesozoic thrust faults (Umpleby *et al.* 1930, Dover 1981, 1983) the faults are now recognized as top-to-the-NW oblique-slip faults with components of normal slip and dextral shear (Kim 1986, Wust 1986, Burton 1988, Link *et al.* 1988, Turner & Otto 1988, 1995, Burton *et al.* 1989, Batatian 1991). One low-angle fault is the Lake Creek fault (Fig. 1), which cuts folded Paleozoic strata for 40 km along strike. In this paper we report the results of our 1:24,000 scale mapping and structural analysis of the Lake Creek fault, in which we determined its slip vector and factors which resulted in dextral movement on the low-angle fault.

LAKE CREEK FAULT

Portions of the Lake Creek fault were previously mapped as a Cretaceous thrust fault by Umpleby *et al.* (1930), Dover (1969, 1981, 1983), Hall (1985) and Link *et al.* (1988). Burton (1988) mapped over 10 km of the central Lake Creek fault, and Batatian (1991) mapped another 8 km of the northern Lake Creek fault. Burton (1988) first proposed that the Lake Creek fault was a normal fault with tens of kilometers of displacement, based on younger on older juxtaposition of strata across the fault, NW-trending slickenlines on the fault surface, and a significant facies change within Pennsylvanian–Permian strata across the fault. Huerta (1992) described the geometry and documented the strike-slip movement history of the Lake Creek fault.

Map relations

The trace of the Lake Creek fault extends for more than 40 km from the crest of the Boulder Mountains to the southern flank of the Pioneer Mountains (Fig. 1). The fault is delineated by an abrupt change in strati-

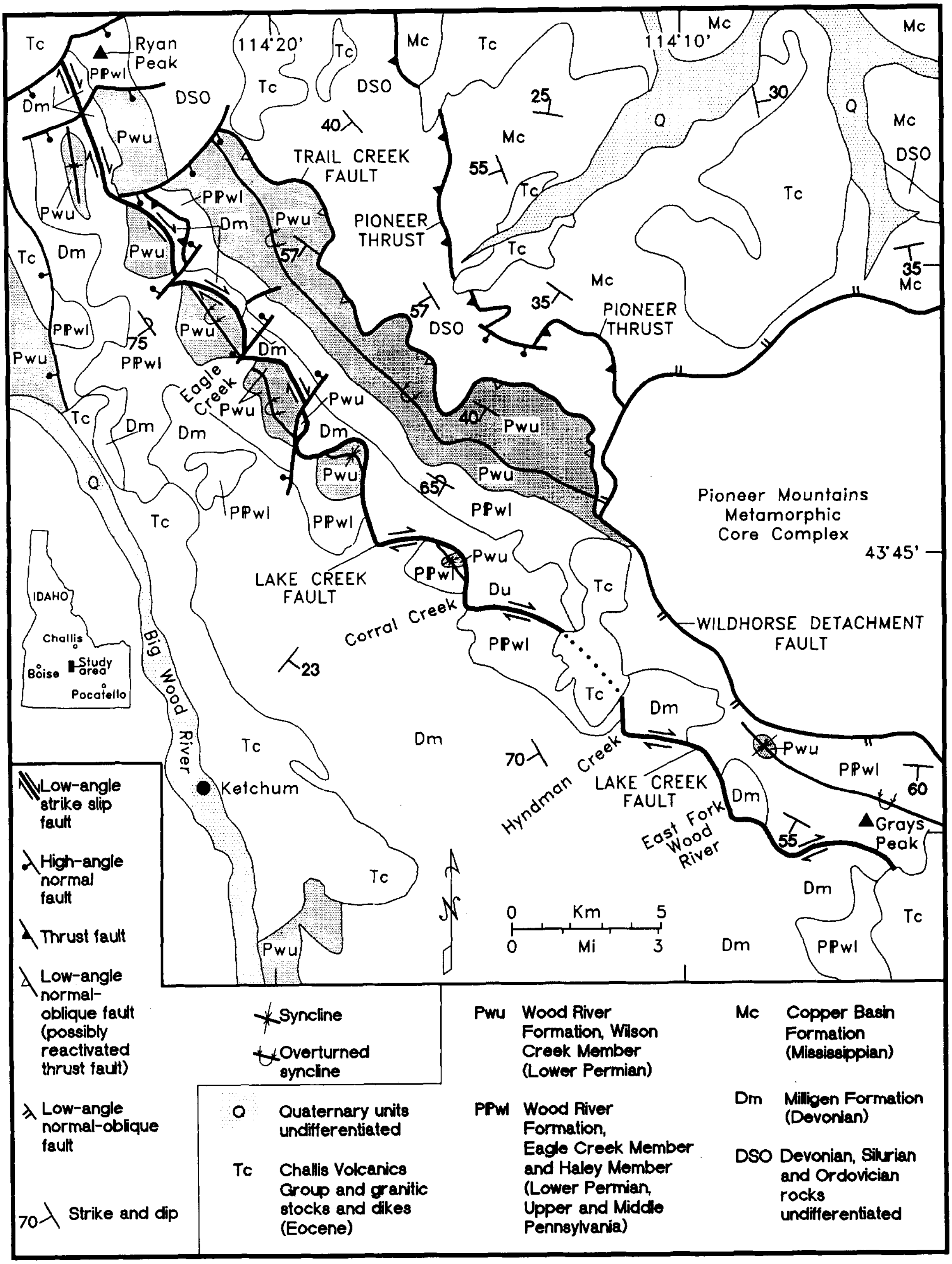

Fig. 1. Simplified geologic map of Lake Creek fault in south central Idaho. (Modified from Rodgers *et al.* 1995.)

graphic units and bedding attitudes, and in places is characterized by breccia, mineralized quartz veins and polished surfaces (Burton & Link 1989, Batatian 1991). The fault cuts the Devonian Milligen Formation and the Pennsylvanian–Permian Wood River formation (composed of the lower Hailey and Eagle Creek Members and upper Wilson Creek Member) (Mahoney *et al.* 1991), and is overlain by volcanic flows and cut by rhyolite dykes of the Eocene Challis Volcanic Group.

The Lake Creek faults juxtaposes strata in both younger-on-older and older-on-younger configurations (Fig. 1). Along the northern extent of the Lake Creek fault, Paleozoic sedimentary rocks structurally overlie coeval or older units. In this area the fault has been previously interpreted as a thrust fault (Umpleby *et al.* 1930, Dover 1981, 1983), a normal fault (Burton 1988), or a normal-oblique fault (Batatian 1991). Along the southern half of its trace, the Lake Creek fault places Devonian strata over Pennsylvanian–Permian strata, and was originally mapped as a thrust fault (Umpleby *et al.* 1930, Dover 1981, 1983). In areas where the fault puts Milligen Formation on Milligen Formation the fault had been previously unrecognized, because the monotonous lithology and polyphase deformation of the Milligen Formation obscured the structure.

The northern end of the fault is concealed by extensive Eocene lava flows and hypabyssal intrusive rocks. The southern end of the fault is overlapped by volcanic units of probable Eocene age.

Fault geometry and displacement

The trace of the Lake Creek fault over rugged topography constrains the three-dimensional geometry of the fault surface. The fault is a sub-planar surface with a consistent N50W ± 10° strike and a SW dip. Although the dip varies along strike from 37° to 10° it does not vary significantly up or down dip over the typical (450 m) to maximum (1 km) vertical exposures in the study area. The fault is cut by younger, NNE-striking faults that are coincident with several drainages (Umpleby *et al.* 1930, Dover 1981, Kim 1986, Burton 1988, Batatian 1991, Huerta 1992, Burton & Link 1995).

The amount and direction of slip along the Lake Creek fault is indicated by the displacement of folded strata of the Milligen and Wood River Formations. Within the footwall of the Lake Creek fault is the eastern limb, hinge zone and portions of the western limb of a distinctive map-scale syncline (Figs 1 and 2). The syncline is close to open, with subvertical to gently SE-plunging hinges, and an axial surface which strikes NW and is steeply inclined to the SW. Within the hangingwall of the Lake Creek fault is the western limb, hinge zone and portions of the eastern limb of a fold with comparable geometry. Nowhere else in the region are there folds with such large amplitudes or which extend for such a great distance. Since the synclines contain the same stratigraphic units and have similar geometries and are cut by the Lake Creek fault, we interpret them as the same fold which was obliquely cut and displaced along the fault.

The intersections of synclinal troughs with the Lake Creek fault provide piercing points used to determine net slip along the fault (Fig. 2). We elected to use the troughs defined by the stratigraphic contact of the lower and upper members of the Wood River Formation, because this contact is the most extensive and easily mapped in the region. Although the actual piercing points defined by this folded contact were removed by erosion, structure contours of the contact were constructed to define the synclinal folds and locate the piercing points. In the hangingwall, structure contours of the Lake Creek fault and the lower–upper contact (Fig. 2) were projected a short distance south of Corral Creek to locate the piercing point. In the footwall, extrapolation of contours for a distance of 8 km south of East Fork Wood River yields a piercing point between Grays Peak and East Fork Wood River.

The two piercing points are inferred to represent the same point prior to movement on the Lake Creek fault. The calculated slip vector is 18 km long, trends N55°W, and plunges 2°NW (Fig. 2). Note that after restoration of the 18 km of displacement, the footwall fold geometry matches that of the hangingwall. Along the majority of the fold, the folds are close and overturned to the east (Fig. 2, cross-sections A–A′ and AA–AA′) except at two locations: the hangingwall syncline is open and upright near Lake Creek (Fig. 2, cross-section B–B′), and the footwall syncline is open and upright near East Fork Wood River (Fig. 2, cross-section BB–BB′). The good match of these cross-sections presently located 18 km apart provides additional support of the net slip.

The calculated relative slip vector can be resolved into 18 km of dextral shear and less than 1 km of normal slip. As such, the Lake Creek fault is an oblique-slip fault with predominant dextral strike-slip displacement.

Age of movement

Initial movement on the Lake Creek fault postdates folding since the Lake Creek fault obliquely cuts across map-scale folds. Folds within the region are thought to be of Cretaceous age (Armstrong 1975, Skipp & Hait 1977, Dover 1981), prior to or coeval with metamorphism and plutonism associated with the emplacement of the Idaho batholith at ~95–85 Ma (Lewis *et al.* 1987, Johnson *et al.* 1988). Latest movement on the fault is constrained by cross-cutting Eocene igneous rocks including an andesite flow between Hyndman Creek and Corral Creek, volcanic flows at the south end of the fault trace, and a dacite dyke in the headwaters of Eagle Creek (Burton 1988). None of these rocks have been dated, but intermediate volcanism ceased throughout the region by 48 Ma (Fisher *et al.* 1992, Janecke & Snee 1993), indirectly providing a minimum age of faulting. Thus, available age constraints suggest that all movement on the Lake Creek fault occurred after folding at ~95–85 Ma and prior to volcanism at ~48 Ma.

Syn- to post-kinematic tilting

The Lake Creek fault is unusual because it is a gently-dipping strike-slip fault. To determine if the fault was tilted NE from a subvertical dip to its present one, the attitudes of Eocene dykes and Cretaceous folds were analyzed.

Eocene dykes north of Eagle Creek cut the Lake Creek fault and are present in its hangingwall and footwall. The dykes strike N, NW, E and NNE, and all dykes are subvertical (Dover 1983, Burton 1988, Batatian 1991). Further north, in an intrusive center near

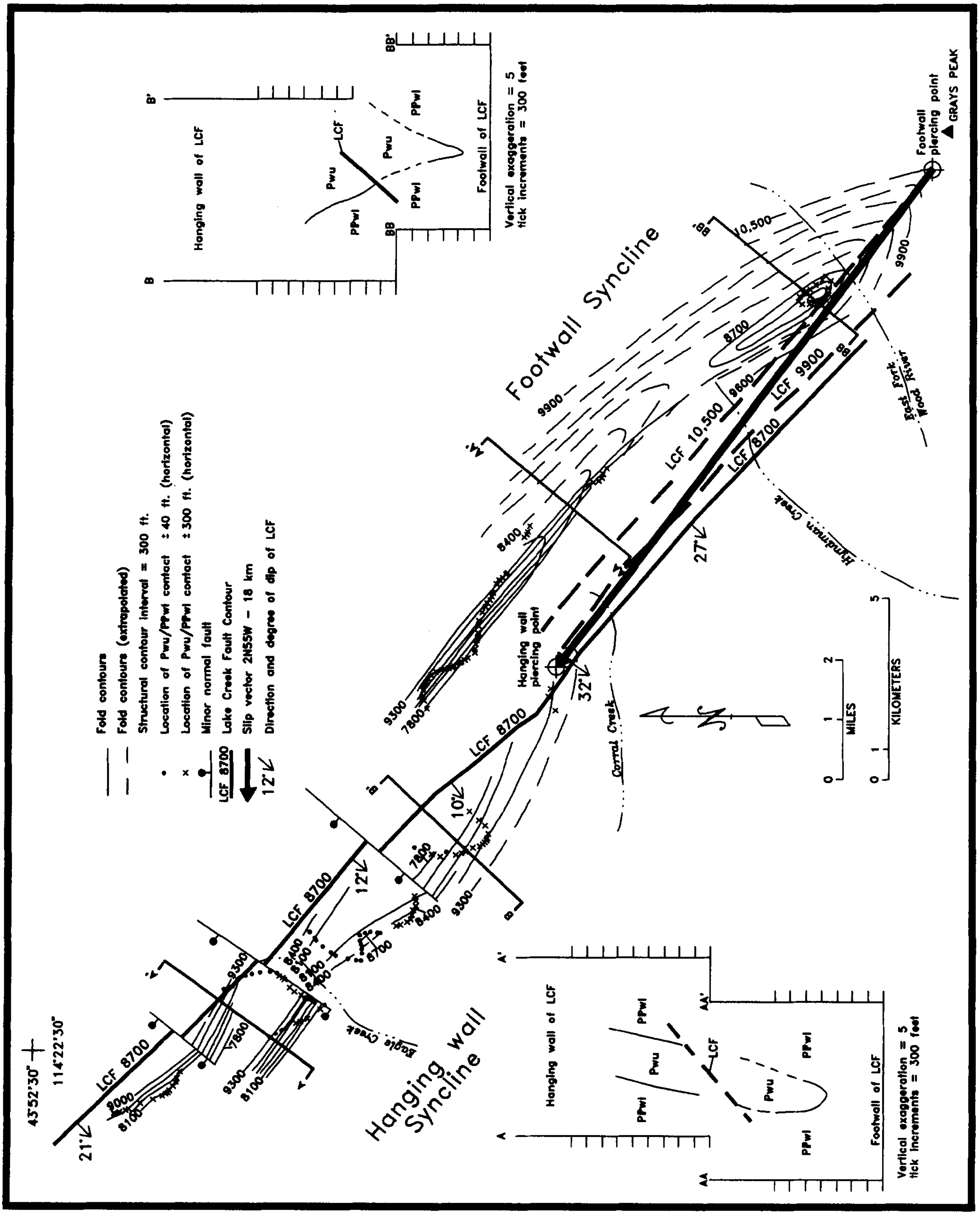
Fold contours
Fold contours (extrapolated)
Structural contour interval = 300 ft.
Location of Pwu/PPwl contact ± 40 ft. (horizontal)
Location of Pwu/PPwl contact ± 300 ft. (horizontal)
Minor normal fault
LCF 8700 Lake Creek Fault Contour
Slip vector 2N55W - 18 km
12° Direction and degree of dip of LCF
43°52'30"
114°22'30"
Hanging wall Syncline
Footwall Syncline
LCF 8700
LCF 10,500
LCF 9900
Hanging wall piercing point
Footwall piercing point
GRAYS PEAK
Eagle Creek
Corral Creek
Hyndman Creek
East Fork Wood River
21°
12°
10°
32°
27°
9300
9000
8100
7800
8400
8700
9900
10,500
A
A'
AA
AA'
B
B'
BB
BB'
Hanging wall of LCF
Footwall of LCF
PPwl
Pwu
LCF
Vertical exaggeration = 5
tick increments = 300 feet
MILES
KILOMETERS
0
1
2
5

Fig. 2.

Ryan Peak, dacite dykes are vertical to steeply SE-dipping while younger E-striking rhyolite dykes are subvertical (Batatian 1991). Since the dykes intruded at shallow levels and cross-cut bedding we conclude that the orientation of the dykes was controlled by an Andersonian stress field, and were originally subvertical. Thus, the attitudes of dykes indicates that there has been no tilting within the area since their emplacement at ~50–47 Ma.

If the Lake Creek fault had originally been steeply dipping, and was subsequently tilted to its present-day gentle SW dip, the axial planes of the Cretaceous folds would also have been tilted. Cretaceous map scale folds in both hangingwall and footwall now have vertical to steeply SW-dipping axial planes (Dover 1983, Rodgers *et al.* 1995), but if they were tilted, their axial planes would have originally dipped NE, yielding W-vergent folds. However, large-scale W-vergent folds are uncommon in the region (Dover 1981, 1983, Rodgers *et al.* 1995). Hinges of map-scale and outcrop-scale folds are subhorizontal to gently (<20°) SE plunging (Rodgers *et al.* 1995). These hinges may indicate minor (5–10°) tilting to the SE, but such tilting would have had little effect on the attitude of the Lake Creek fault. Thus, the available data indicate the Lake Creek fault formed as a low-angle fault.

FAULT DYNAMICS

To examine the state of stress associated with slip along the Lake Creek fault, fault and striation orientations were analyzed using the methods of Angelier (1979) and Aleksandrowski (1985). Minor faults within 2000 m of the Lake Creek fault were studied regardless of their style or orientation. The faults are irregularly spaced and show offsets less than the thickness of stratigraphic units (i.e. offsets less than a few 100 m). Figure 3(a) shows that the trends of fault striations are generally scattered, but concentrations exist at N60°W and at S60°W. Poles to faults are also scattered with a notable lack of steeply dipping, N60°W-striking faults (Fig. 3b).

Fault and striation data were used to calculate slip linears (Fig. 3d) and M-poles (Fig. 3g). Slip linears do not show a consistent trend (Fig. 3d), while M-poles are broadly distributed throughout the north and south quadrants (Fig. 3g). Field observations and study of Fig. 3 support the interpretation that two fault sets were measured. Fault set 1 is characterized by slip linears that consistently trend NW (Fig. 3e) and M-poles that are concentrated within 20° of a N30°E, 75°SE great circle (Fig. 3h). Most striations of fault set 1 plunge gently to moderately to the NW and SE (Fig. 3b), while fault planes strike NE and dip moderately to steeply to the NW and SE (Fig. 3e). Fault set 2 is characterized by slip linears that consistently trend NE (Fig. 3f) and a concentration of M-poles plunging 0° ± 20° (Fig. 3i). Striations of fault set 2 plunge gently to the NE and SW (Fig. 3c), while a number of faults strike N30°W (Fig. 3f). Some faults of set 2 were observed in the field to be normal faults. Striations associated with one fault set were never found superimposed on the other fault set, evidence that each fault set accommodated a single stage of movement. Cross-cutting relations between the fault sets were not observed, but kinematic analysis (discussed below) suggests that fault set 1 is older.

Fault set 1 and the Lake Creek fault show similar slip linear and M-pole orientations (Fig. 3), suggesting they are kinematically similar. Assuming that the Lake Creek fault and fault set 1 are related, we follow the methods of Aleksandrowski (1985) to interpret the orientation of principal stresses associated with movement on the Lake Creek fault. Aleksandrowski (1985) noted that if M-poles form a great circle distribution, then: (a) the great circle contains σ_2 and either σ_1 or σ_3; (b) the pole to the M-pole great circle is coincident with either σ_1 or σ_3; and (c) the slip linears point toward σ_1 or the σ_1–σ_2 plane. The slip linear of the Lake Creek fault points toward the pole to the M-pole great circle (Fig. 3h), suggesting the pole is σ_1 and therefore the M-pole great circle contains σ_2 and σ_3. To locate σ_2 we could follow Anderson's (1951) theory of faulting and assume that the Lake Creek fault plane contained σ_2, so that σ_2 is located where the M-pole great circle intersects the trace of the Lake Creek fault (Fig. 3h). Alternatively, it may not be appropriate to assume that σ_2 is the fault plane (Bott 1959), and that σ_2 may be located along the M-pole great circle in the center of concentration in the NE quadrant (Fig. 3h) (Aleksandrowski 1985). Distinguishing the two cases may be unimportant because the slightly diffuse great circle of M-poles implies that the ratio $(\sigma_1 - \sigma_3)/(\sigma_2 - \sigma_3)$ was approximately 10, or in other words that the magnitude of σ_2 was much closer to σ_3 than to σ_1 (Aleksandrowski 1985). Based on the above analysis, we propose that the state of stress during movement along the Lake Creek fault was approximately one of axial compression, in which σ_1, oriented 15°/N60°W was an order of magnitude larger than σ_2 and σ_3, which were oriented in a N30°E, 75°SE plane (Fig. 3h).

The state of stress associated with fault set 2 is interpreted from field observations of normal slip and the M-pole concentration (Fig. 3i) to be characterized by a subvertical σ_1, subhorizontal, NNW-trending σ_2 and a subhorizontal, ENE-trending σ_3. The offset and the orientations of principal stress axes are compatible with Neogene Basin and Range faulting recognized throughout the area.

Fig. 2. Structure contour map of contact between lower and upper members of Wood River formation near Lake Creek fault. Lake Creek fault location indicated by its 8700′ structure contour. Footwall contours show contact is folded into syncline that is upright in the southeast but overturned in the northwest. Hangingwall contours show contact is similarly folded but axial region of syncline is cut out by Lake Creek fault. Piercing points to restore fault offset are located where synclinal troughs are cut by fault. Fault slip vector shown by bold arrow. Cross-sections are stacked to illustrate restored syncline profile. (Modified from Huerta 1992).

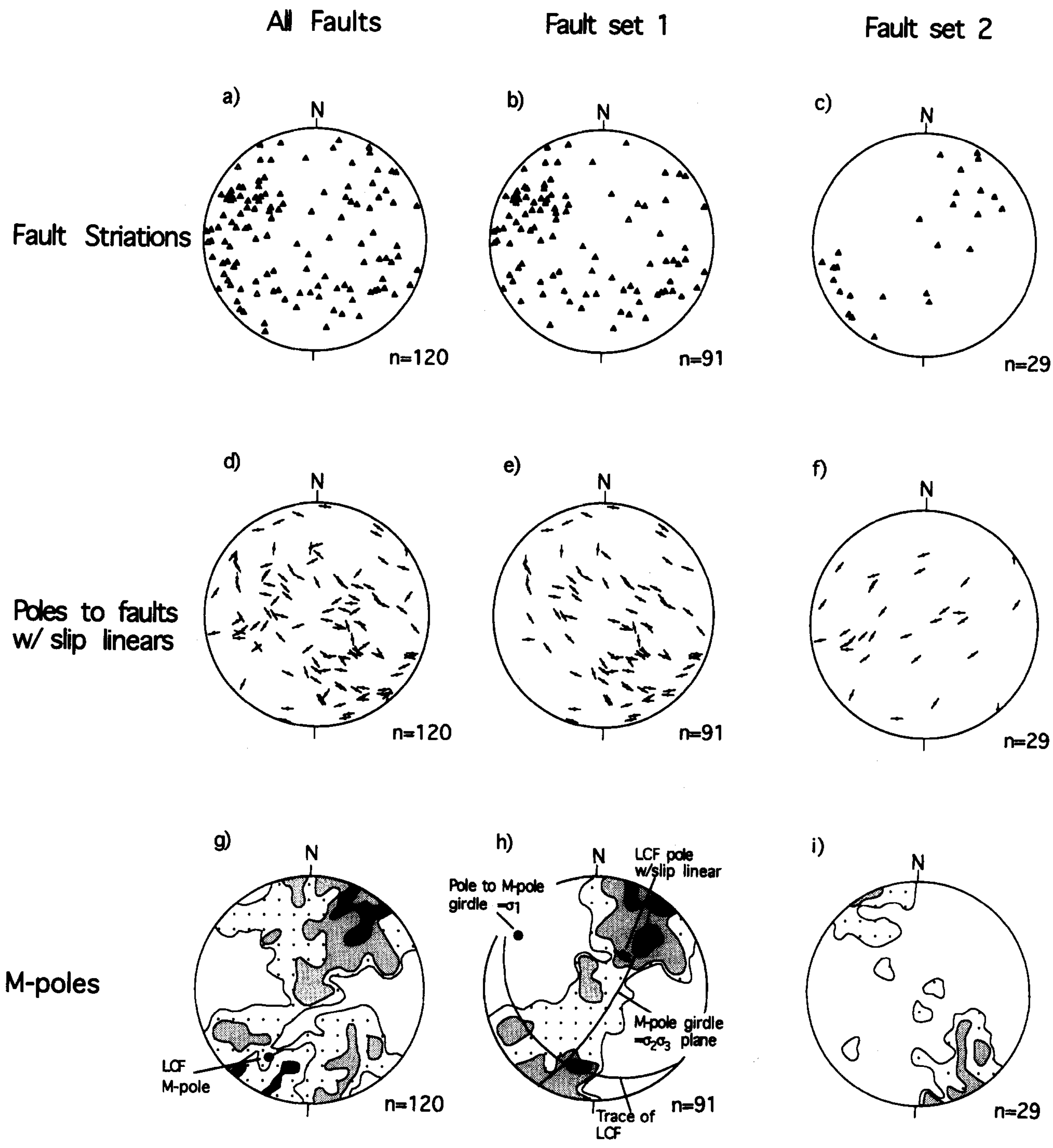

Fig. 3. Lower-hemisphere, equal-area projections of structural data measured on minor faults within 2 km of the Lake Creek fault; all faults (left column), fault set 1 (center column), and fault set 2 (right column). (a), (b) & (c) Fault striations. (d), (e) & (f) Poles to faults with slip linears calculated according to the method of Angelier (1979). (g), (h) & (i) Contoured diagram of poles to movement planes (M-poles) calculated according to the method of Angelier (1979). (g) Large circle represents M-pole of Lake Creek fault. Contour intervals are 0.4, 1.3, 2.9 and 4.6% per 1% area. (h) Contour intervals are 0.5, 1.6, 2.8, 3.9, 5.0 and 6.0% per 1% area. The slip linear and M-pole of the Lake Creek fault are shown. M-poles are concentrated along a N30°E, 75°SE great circle whose pole is indicated. The interpreted orientations of σ_1 and the σ_2–σ_3 plane are explained in the text. (i) Contour intervals are 1.6 and 4.8% per 1% area.

DISCUSSION

Origin of the Lake Creek fault

The gentle dip of the Lake Creek fault contrasts with the steep dip of most strike-slip faults (Wilcox *et al.* 1973, Freund 1974, Biddle & Christie-Blick 1985). Thus, it is important to determine if the Lake Creek fault formed as a regionally extensive low-angle strike-slip fault, or in association with other regional structures. Possible scenarios are that the Lake Creek fault formed as: (1) a reactivated thrust fault; (2) the side of a scoop-shaped normal fault; (3) a splay of a flower structure; or (4) a splay of the underlying Wildhorse detachment fault. Below we consider these possibilities but conclude that none satisfactorily address the evidence, and that in fact the Lake Creek fault developed as a regionally extensive low-angle strike-slip fault.

(1) *Reactivation of a thrust fault.* If the Lake Creek fault is a reactivated thrust fault it should display a geometry and kinematic history compatible with other structures that accommodated shortening in the area. Thrust faults, which are rare in the region, generally strike N30°W, dip gently to the SW, and show NNE striations (Dover 1983, Rodgers *et al.* 1995). These features contrast with the geometry and deformational style of the Lake Creek fault, which strikes more westerly (N50°W) and has striations which mostly trend NW, and with fault set 1, which preserves no record of NE slip. In addition, the absence of intense ductile strain near the Lake Creek fault, particularly in its footwall, contrasts with high strain gradients generally observed near thrust faults (Protzman & Mitra 1990, Evans & Neves 1992).

Folds throughout the region typically trend more northerly (N0°W–N30°W) and are more steeply inclined (60–80°) than the N50°W, 30°SW Lake Creek fault. The only exception is along the central Lake Creek fault, where folds trend subparallel to the fault perhaps in response to an underlying lateral ramp (Rodgers *et al.* 1995). Furthermore, the Lake Creek fault cuts across a map-scale syncline (used as a piercing-point), indicating that the Lake Creek fault formed after folding. Based on these observations, the Lake Creek fault is not interpreted as a thrust fault that was later reactivated as a strike-slip fault.

(2) *The side of a scoop-shaped normal fault.* If the Lake Creek fault is the side of a curved, down-to-the-NW normal fault, it should display a curved geometry and features consistent with normal offset. The Lake Creek fault remains relatively planar throughout its 40 km length, and does not bend to a NE-striking, NW-dipping attitude. The fault does not cut downsection to the NW. The fault does not display a change of metamorphic grade across the fault or along strike within the footwall or hangingwall. These observations indicate that footwall rocks from deeper crustal levels were not uplifted due to normal slip. Because the Lake Creek fault does not bend, and does not juxtapose rocks of differing crustal levels, the fault is not interpreted to be the side of a scoop-shaped normal fault.

(3) *A splay of a flower structure in a wrench fault system.* If the Lake Creek fault is a splay of a negative flower structure, then it should be associated with a wrench fault system and have offset consistent with flower structure formation (Harding 1985). However, no wrench fault system is apparent in the region (Worl *et al.* 1991, Rodgers *et al.* 1995), and the 40-km trace of the Lake Creek fault is an order of magnitude longer than recognized splays of flower structures (Harding 1985). These characteristics are not consistent with the interpretation that the Lake Creek fault is a splay of a flower structure.

(4) *A fault associated with development of the Wildhorse detachment fault.* Underlying the Lake Creek fault is a down-to-the-NW normal fault, the Wildhorse detachment fault, which separates mid-crustal rocks in the core of the Pioneer Mountains metamorphic core complex from overlying weakly to non-metamorphosed rocks (Wust 1986, O'Neal & Pavlis 1988). The detachment is made of two planar oblique-slip faults that intersect to form a fault surface shaped like a NW-plunging, antiformal kink fold. Although the strike of the Lake Creek fault is subparallel to the west side of the underlying Wildhorse detachment fault, the Lake Creek fault dips more gently. Thus, if the dips of the faults do not change at depth, the Lake Creek fault will not merge with the Wildhorse detachment, as it would if the two faults shared a branch line.

The stress regimes of the two faults are also incompatible. The Lake Creek fault accommodated almost pure strike-slip offset, during a stress regime with a NW-trending σ_1, while the Wildhorse detachment accommodated top-to-the-NW normal offset, indicating a stress regime with a NW-trending σ_3. Timing histories of the two faults are also different. The majority of movement on the Lake Creek fault occurred prior to ~48 Ma, while rapid cooling of the mylonite zone of the Wildhorse detachment from the 36–33 Ma indicate movement during this time (Silverberg 1990). In addition, minor NE-striking normal faults cross cut the Lake Creek fault, indicating that NW extension post-dated movement on the Lake Creek fault. Because of dissimilar geometries, stress regimes, and timing the Lake Creek fault is not interpreted to be associated with the Wildhorse detachment.

Since none of the above possibilities adequately address the data, we conclude that the Lake Creek fault did in fact form as a low-angle strike-slip fault. To explain the apparently anomalous gentle dip we propose that two factors, the state of stress and crustal anisotropy, controlled the fault geometry and kinematics.

Controls on low-angle strike-slip faulting

Fault array analysis provides evidence that the Lake Creek fault formed and slipped under a stress regime characterized by axial compression in which $\sigma_1 \gg \sigma_2 \cong \sigma_3$. Experiments with texturally homogeneous core samples have shown that fractures formed under axial compression (with σ_1 vertical) will strike at any azimuth while maintaining a 30° angle to σ_1. If σ_1 were subhorizontal, the array of possible faults would therefore include thrust faults that strike perpendicular to σ_1 and dip 30°, oblique slip faults whose strikes range from 90° to 30° to σ_1 and dips range from 31° to 89°, and strike-slip faults that strike 30° to σ_1 dip vertically.

The fault geometry most likely to form would depend upon factors other than the state of stress. Experimental faulting of anisotropic rocks indicates that fabric orientation will strongly influence fault orientation (Donath 1961). For example, compression of samples with σ_1 oriented 0–45° to a planar cleavage causes fracture subparallel to the cleavage (Donath 1961). This experimental result may be analogous to formation of the Lake Creek fault. The upper crust throughout this region has a strong linear anisotropy imparted by NW-trending map-scale folds. The folds involve very well-bedded mudstones, siltstones and sandstones that accumulated in a basinal environment. If σ_1 was everywhere subparallel to the NW-trending anisotropy, failure would have preferentially occurred subparallel to the linear weakness creating a NW-striking strike-slip fault.

While the dip of the Lake Creek fault would not be influenced by a horizontal linear anisotropy, it would be influenced by planar fabrics. Fold profiles displayed in Fig. 2 indicate that the upper crust does not have a throughgoing planar fabric defined by bedding. However, map-scale folds in the region are generally NE-vergent, and with increasing depth the fold should develop a penetrative, SW-dipping axial planar cleavage (a feature actually observed in uplifted strata in adjacent regions) (Rodgers *et al.* 1995). Furthermore, all four major faults in the region (Lake Creek, Trail Creek, Pioneer and western Wildhorse detachment faults) (Fig. 1) dip gently to moderately SW. We propose that the gentle dip of the Lake Creek fault was controlled by a pre-existing, mid- to upper-crustal planar anisotropy defined by SW-dipping axial planar cleavage.

We conclude that low-angle strike-slip faults can form in the earth's crust. If the Lake Creek fault is representative of such faults, at least two factors may act in concert to produce the low-angle geometry: a state of stress characterized by subhorizontal axial compression, and regional crustal anisotropies.

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