2-1993

The Origin and Evolution of the Southern Snake Range Decollement, East Central Nevada

Allen J. McGrew
University of Dayton, amcgrew1@udayton.edu

TECTONICS, VOL. 12, NO. 1, PAGES 21-34, FEBRUARY 1993

THE ORIGIN AND EVOLUTION OF THE SOUTHERN SNAKE RANGE DECOLLEMENT, EAST CENTRAL NEVADA

Allen J. McGrew[1]
Department of Geology, Stanford University, Stanford, California

Abstract. Regional and local stratigraphic, metamorphic, and structural constraints permit reconstruction of the southern Snake Range extensional deformational system in east central Nevada. The dominant structure of the range, the southern Snake Range décollement (SSRD), operated during Oligocene and Miocene extensional deformation to exhume a footwall of multiply deformed metasedimentary and plutonic rocks. Intrusion of three plutons (~160 Ma, 79.1 ± 0.5 Ma, and 36± 1 Ma, respectively) and development of two cleavages preceded the onset of extensional deformation. Plastic deformation of lower plate metasedimentary rocks accompanied the early phases of regional extension and produced bedding-parallel grain shape foliations and WNW trending stretching lineations. These fabrics parallel the SSRD even in low-strain domains, suggesting that a significant component of pure shear strain probably accompanied noncoaxial deformation associated with motion on the SSRD, consistent with other lines of evidence. Meanwhile, hanging wall rocks were greatly extended by at least two generations of tilt block-style normal faults soling into the SSRD, with the earlier faults antithetic to the SSRD and the later faults dipping in the same direction as the SSRD. A retrodeformed regional cross-section sequence illustrates plausible alternative schemes for reconstructing the southern Snake Range extensional system. In one scheme, the SSRD forms as a crustal scale stretching shear zone separating an upper plate that extends on steeply inclined normal faults from a lower plate that stretches by penetrative flow. In the other, lower plate deformation incorporates a component of coaxial stretching, but the SSRD also functions as a conventional shear zone accommodating through-going displacement between opposing plates. In either case, as tectonic unroofing proceeds, differential isostatic unloading induces the SSRD to rotate to steeper dips as it migrates into the frictional sliding regime, thus enabling it to remain active as a brittle normal fault until it finally rotates to its present shallow inclination. In either scenario, cross-section constraints suggest that total extension accommodated by the SSRD was probably between 8 km and 24 km.

[1] Now at Geologisches Institut, Eidgenössische Technische Hochschule Zürich (The Swiss Federal Institute of Technology at Zürich), Zürich, Switzerland.

Paper number 92TC01713.
0278-7407/93/92TC-01713$10.00

INTRODUCTION

The origin, kinematic significance and geometrical evolution of shallowly inclined normal fault systems are fundamental issues in extensional tectonics. Regionally extensive faults that juxtapose nonmetamorphic sedimentary rocks in their hanging walls against plastically deformed crystalline rocks in their footwalls command special attention because they offer rare opportunities to characterize kinematic linkages between contrasting structural levels. These faults, commonly known as detachment faults, are the subjects of much controversy. This paper presents new data bearing on the nature and origin of one such fault, the southern Snake Range décollement (SSRD) of east central Nevada [Misch, 1960; Whitebread, 1969]. Currently, debate on the nature and origin of detachments focuses on a few critical questions such as those outlined below.

What magnitudes of displacement typify offsets across detachment faults? Because detachment faults typically juxtapose distinctly different structural levels, it is commonly difficult or impossible to identify the piercing points or cutoffs necessary to constrain displacements, although several studies report relationships that seem to require tens of kilometers of offset [e.g., Stewart, 1983; Reynolds and Spencer, 1985, Davis and Lister, 1988; Wernicke et al., 1988]. Occasionally this circumstance gives rise to radically different estimates of displacement for the same fault system, as in the case of the northern Snake Range décollement (NSRD) where published estimates of displacement vary from less than a few kilometers [Gans and Miller, 1983; Miller et al., 1983; Gans and Miller, 1985] to approximately 60 km [Bartley and Wernicke, 1984; Wernicke and Bartley,1985]. Because the SSRD may originally have been laterally continuous with the NSRD, the retrodeformed cross-section presented here may be relevant to the above controversy.

What fundamental kinematic function do detachment faults play in accommodating lithospheric extension? One popular viewpoint holds that detachments represent discrete, through-going crustal shear zones [e.g., Wernicke, 1981; Davis, 1983], while others see detachments as components in anastomosing shear zone networks [e.g., Kligfield et al., 1984; Hamilton, 1987] or as regionally developed decoupling zones between the seismogenic upper crust and deeper structural levels where penetrative stretching and pluton emplacement accommodate extension [e.g., Eaton, 1982; Miller et al., 1983; Gans et al., 1985; Gans, 1987]. In any case, because such models predict contrasting strain patterns and deformational histories, observations in the southern Snake Range provide important tests of the viability of some of the competing interpretations.

How does the inclination of detachment faults vary during the kinematic evolution of extensional systems? A particularly important issue in the debate surrounding detachment faults concerns whether they formed and were seismically active at the dips at which they are now observed, or whether they subsequently rotated to their contemporary shallow inclinations (for example, Wernicke [1981] versus Jackson and McKenzie [1983]). Additionally, in recent years so-called "rolling hinge models" have introduced a new perspective on the geometrical evolution of normal fault systems [e.g., Wernicke and Axen, 1988; Buck, 1988]. For instance, in the Wernicke and Axen model, detachment systems form as aseismic, shallowly inclined plastic shear zones in the middle crust and rotate to steeper dips as the footwall is uplifted in response to negative isostatic loading due to tectonic unroofing. Consequently, the detachment can continue to function as a steeply inclined seismogenic normal fault until the hingeline of isostatic flexure migrates through a given fault segment rotating that segment back to shallow dip. As in most detachment systems, the rotational history of the SSRD is particularly difficult to constrain, but it is possible to evaluate the geometrical viability of alternative interpretations.

GEOLOGIC SETTING

Situated in east central Nevada (Figure 1), the southern Snake Range (site of Great Basin National Park) was mapped previously at a scale of 1:48,000 by Whitebread ([1969]. In addition, plutonic rocks in the area have been extensively investigated, and abundant K-Ar, Rb-Sr, and U-Pb age data are available [Lee et al., 1968, 1970, 1981, 1982, 1984, 1986a, 1986b; Lee and Van Loenen, 1971; Lee and Christiansen, 1983a, b; Miller et al., 1988]. For this study, the structurally complex northeastern flank of the range was re-mapped at a scale of 1:24,000 by the author and by the 1984 Stanford Geological Survey led by E. L. Miller (map reproduced here at a scale of 1:48,000, Plate 1).

Located in the hinterland of the Late Cretaceous Sevier orogenic belt, the southern Snake Range exposes a broad, north trending anticlinorium bounded to the west by the Butte synclinorium and to the east by the Mesozoic-aged Confusion Range structural trough (CRST, exposed in the Burbank Hills; Figure 1). The southern Snake Range décollement (SSRD) forms the dominant structural feature of the range and dips 10°-15° eastward beneath southern Snake Valley, a narrow (8 km wide) basin that separates the southern Snake Range from the relatively simple structure and well-known stratigraphy of the Burbank Hills to the east [Hintze, 1960; Anderson, 1983]. The upper plate of the SSRD exposes a severely attenuated, normal-fault-bounded mosaic of various nonmetamorphic to slightly recrystallized

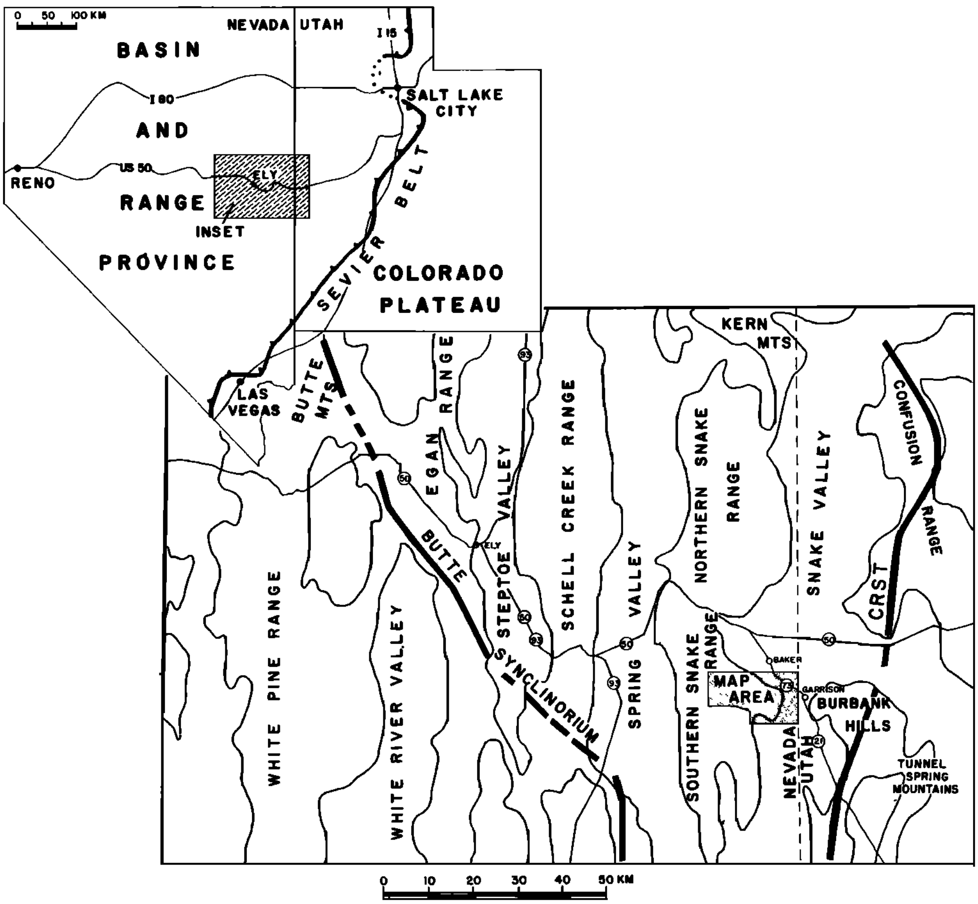


Fig. 1. Locality map showing the study area relative to some important Mesozoic structural trends: the Sevier orogenic belt, the Butte synclinorium, and the Confusion Range structural trough (CRST). In particular, note the apparent deflection of the Butte synclinorium relative to the CRST, probably as a result of Cenozoic extension.

sedimentary rocks, including fragments of a thick, carbonate-dominated miogeoclinal sequence and overlying tuffaceous Tertiary marls and conglomerates (Plate 1). By contrast, the lower plate of the SSRD exposes a thick, stratified sequence of Late Proterozoic to Middle Cambrian quartzites and schists overlain by a thin horizon of white marble mylonite. Intruding this sequence are three well-dated plutons of Late Jurassic, Late Cretaceous, and early Oligocene age, respectively. Relationships between these plutons and country rock are critical in establishing the chronology of deformational and metamorphic events in the study area (see below). Lower plate quartzites in the eastern part of the map area were strained and recrystallized during Tertiary deformation, but relict sedimentary features including cross bedding, rare conglomeratic horizons, and primary compositional layering are preserved. Grain shape foliation in these rocks is oriented perceptibly parallel to bedding and to the SSRD, and mean mineral elongation lineation (L_e) is oriented approximately 105°, 3° (Plate 1 and Figure 2a). Finally, the SSRD, lower plate bedding, and lower plate foliation are all gently folded about an axis oriented approximately 102°, 6°, essentially parallel to grain shape lineation (Figure 2a).

In many respects the structural framework outlined above resembles that of the northern Snake Range [Miller et al., 1983; Gans and Miller, 1983; J. Lee et al., 1987], but the rank of peak metamorphism and the extent and intensity of mylonitic deformation are much lower in the southern Snake Range than to the north. Although Miller et al. [1983] suggested that the NSRD and SSRD are unrelated structures, subsequent mapping indicates that younger faulting in the Sacramento Pass area between the two ranges obscures the structural relationship between the two surfaces, and they may once have been laterally continuous (E. L. Miller, personal communication, 1986). Consequently, comparison of these two ranges may offer important insights into the origin of a regionally important low angle structure.

PRE-EXTENSIONAL TECTONIC HISTORY

In the eastern part of the map area, Tertiary extensional deformation largely obscures the earlier deformational history, but in the western part of the study area pre-extensional fabric relationships are well preserved. The oldest deformational fabric in the southern Snake Range is a penetrative cleavage (S_1) that is gently inclined with respect to bedding and forms a north trending intersection lineation (L_{0x1}). Andalusite and pseudomorphosed staurolite porphyroblasts in the contact aureole of the Snake Creek-Williams Canyon pluton overprint this cleavage, and hornfels textures locally obliterate it. Dating of this zoned tonalitic to granitic pluton by U-Pb zircon, K-Ar hornblende, K-Ar muscovite, and Rb-Sr methods narrowly constrains its age at approximately 160 Ma (Figure 3) [Lee et al., 1968, 1970, 1981, 1986b]. Consequently, formation of the S_1 cleavage must at least slightly predate 160 Ma, although Miller et al. [1988] suggest that S_1 deformation broadly coincided with pluton emplacement. Metamorphic grade in

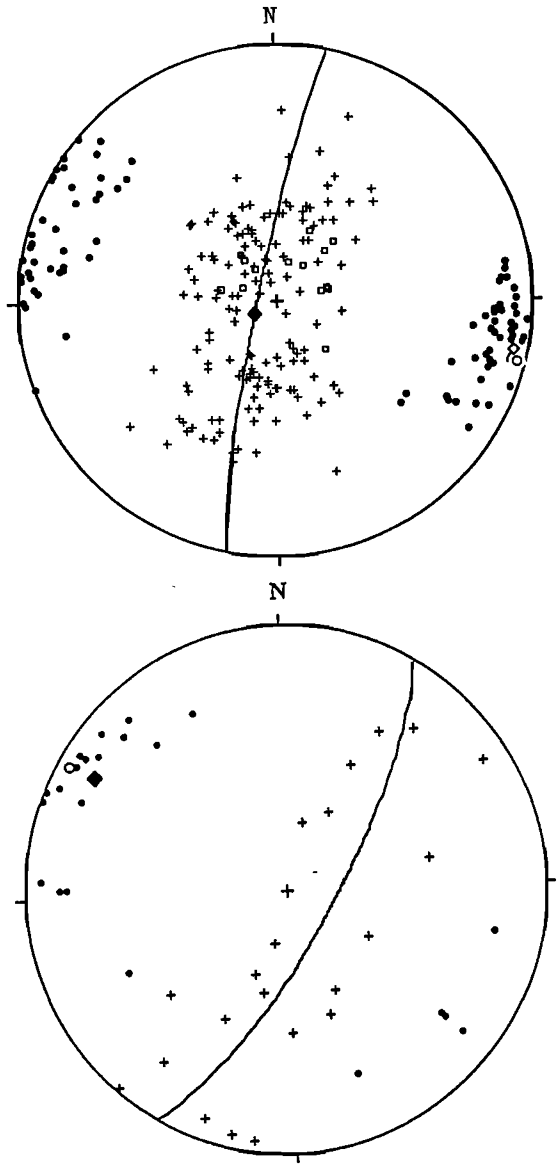


Fig. 2. Stereoplots of selected structural data from the southern Snake Range (Schmid equal-area net, lower-hemisphere projection). (a) Grain shape lineations (solid circles, N=94) with mean lineation vector indicated by open circle (105°, 3°); poles to grain shape foliation (crosses, N=162) with mean orientation indicated (solid diamond), and with best fit great circle and pole to best fit great circle plotted (open diamond, 102°, 6°); and poles to SSRD (open squares, N=14). (b) L_{0x2} intersection lineation (solid circles, N=22) with mean lineation vector indicated by open circle (301°, 5°); and poles to S_2 crenulation cleavage (crosses, N=21) with best fit great circle and pole to best fit great circle plotted (solid diamond, 302°, 15°).

the contact aureole of the Snake Creek-Williams Canyon pluton increases from greenschist facies to amphibolite facies over a distance of approximately 1.5 km, representing the peak metamorphic grade attained in the map area (Figure 3).

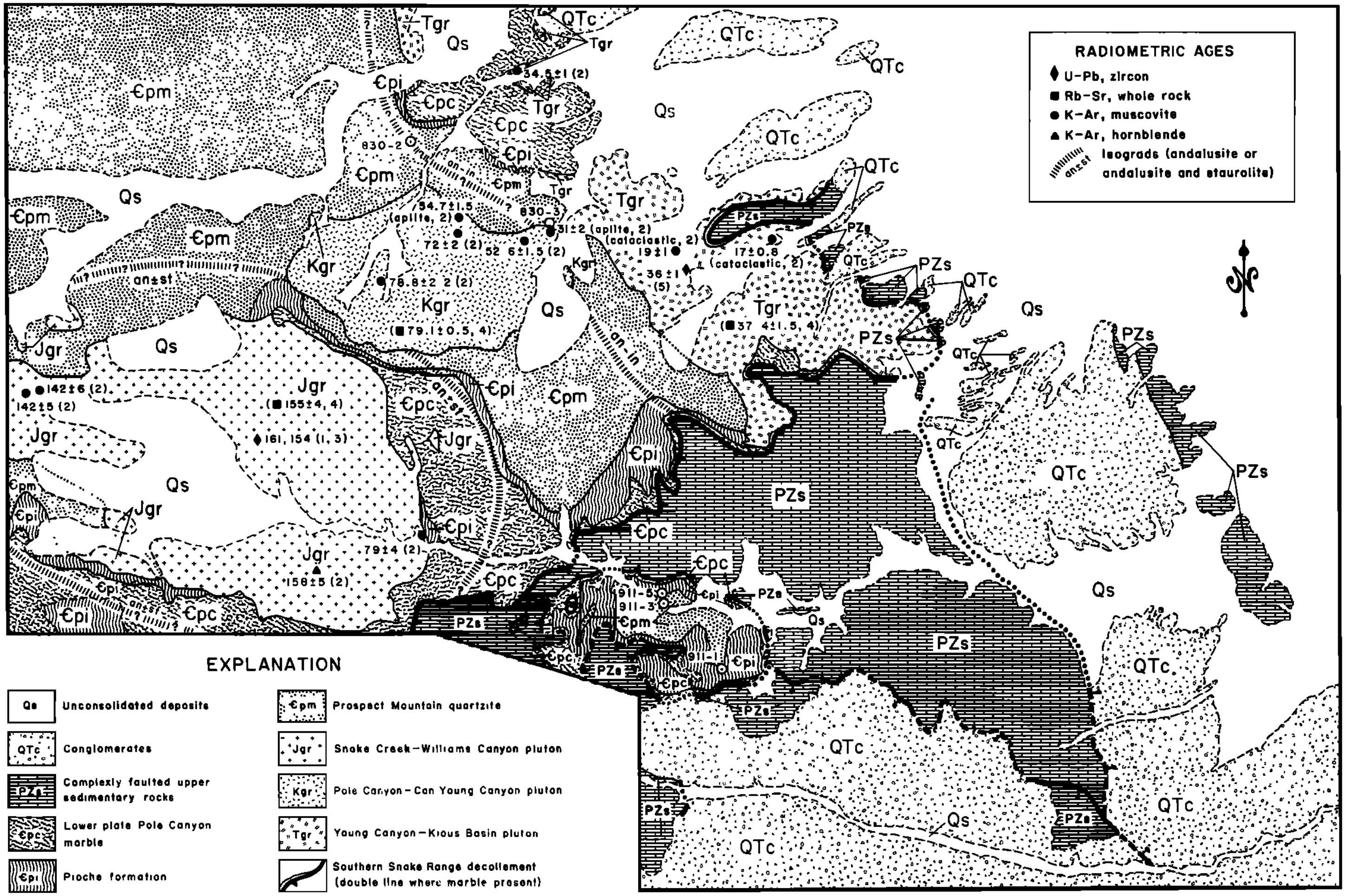


Fig. 3. Generalized geologic map of the southern Snake Range showing approximate locations of andalusite and andalusite + staurolite isograds surrounding the Tertiary and Jurassic plutons, respectively, and locations of previously published radiometric age determinations in the map area. References are 1, Lee et al. [1968]; 2, Lee et al. [1970]; 3, Lee et al. [1981]; 4, Lee et al. [1986b]; and 5, Miller et al. [1988]. Also shown are sample localities from area north of the Cretaceous pluton for finite strain samples 830-2 ($x:y:z = 3.1:1.0:0.7$, $k = 5.3$) and 830-3 ($x:y:z = 2.4:1.0:0.7$, $k = 3.5$).

Overprinting the penetrative S_1 cleavage described above is a weak, sporadically occurring S_2 crenulation fabric. L_{0x2} intersection lineation trends consistently northwestward throughout the map area, but bedding to cleavage angles and dip directions of S_2 vary, suggesting subsequent fanning about an axis oriented approximately 301°, 5° (Figure 2b). At thin section scale, the S_2 cleavage cuts and rotates chlorite porphyroblasts that grew during the 160 Ma metamorphic event, thus placing an upper bound on the age of deformation. In contrast, andalusite porphyroblasts that grew in the contact aureole of the 36 Ma Young Canyon-Kious Basin pluton (see below) statically overprint and therefore postdate the S_2 cleavage. Accordingly, the timing of S_2 deformation is only broadly bracketed between 160 Ma and 36 Ma in the southern Snake Range; however, Miller et al. [1988] suggest on the basis of regional relationships that S_2 fabric development probably coincided broadly with Cretaceous plutonism. Consequently, a 79.1 ± 0.5 Ma Rb-Sr whole rock isochron and a 79.7 Ma K-Ar muscovite age for the Pole Canyon-Can Young Canyon pluton in the north central part of the map area may give the best estimate for the age of S_2 cleavage development [Lee et al., 1970, 1986a] (Figure 3). In contrast to the Late Jurassic and Oligocene plutons, this distinctive muscovite phenocrystic two-mica granite produced minimal contact metamorphic effects, including sericitization of Jurassic-aged andalusite porphyroblasts and growth of new chlorite in the immediate contact aureole.

The final stage of plutonism in the southern Snake Range involved emplacement of the Young Canyon-Kious Basin pluton in the northeastern part of the map area (Plate 1). A 36 ± 1 Ma U-Pb zircon age [Miller et al., 1988] and a 37.4 ± 1.5 Ma Rb-Sr whole rock isochron [Lee et al., 1986b] constrain the age of this intrusion (Figure 3). Garnet, poikiloblastic andalusite, and biotite aggregates forming pseudomorphs after earlier chlorite porphyroblasts characterize peak metamorphism in the immediate contact aureole of this pluton, and, as noted above, these assemblages statically overprint earlier deformational fabrics. In contrast to the relatively pristine older plutons to the west, the main phase of the Young Canyon-Kious Basin pluton is rather severely deformed and hydrothermally altered in the footwall of the SSRD (see discussion of lower plate strain below). Lee and Van Loenen [1971] mapped a fault contact between the severely deformed main phase and a much less deformed "aplitic" phase exposed on the northwestern side of Kious Basin, but mapping conducted for this study indicates that both the magnitude of deformation and the mineralogy of the pluton change gradationally across a narrow transition zone (Plate 1) [McGrew, 1986].

EXTENSIONAL TECTONISM

Overprinting and locally obscuring the earlier deformational history outlined above is the major extensional deformational event that is largely responsible for the present-day structural configuration of the southern Snake Range, including the most prominent structure of the range, the southern Snake Range décollement (SSRD). Several lines of evidence indicate an Oligocene to Miocene age for the SSRD. Most significantly, the SSRD either cuts or merges with upper plate normal faults that themselves cut and offset Tertiary-aged strata, including 29.5-30.6 Ma tuffs of the Needles Range Group [Armstrong, 1972; Best and Grant, 1987]. In addition, involvement of the 36 Ma Young Canyon-Kious Basin pluton in deformation that appears to be associated with activity on the SSRD places an upper bracket on the age of footwall strain (see discussion of lower plate strain below).

In addition to the above lines of evidence, the southern Snake Range exhibits a monotonic decrease in K-Ar muscovite ages from 79 Ma in the western part of the Pole Canyon-Can Young Canyon pluton to a minimum of 17 Ma immediately beneath the SSRD in the Young Canyon-Kious Basin pluton (Figure 3) [Lee et al., 1970]. The youngest K-Ar muscovite ages originate from cataclastically deformed and hydrothermally altered parts of the main phase of the Tertiary granite [Lee et al., 1970, 1984], and anomalously low $\delta^{18}O$ and δD values from the samples yielding the youngest K-Ar ages suggest that hydrothermal white mica rather than primary muscovite was dated [Lee et al., 1984]. Consequently, the anomalously young K-Ar ages within the Tertiary granite probably record mineral growth and/or Argon loss associated with hydrothermal activity that may have accompanied the late stages of movement on the SSRD.

Character of Lower Plate Strain

The SSRD is well exposed in the eastern part of the map area where it typically overlies a thin horizon of white marble mylonite that accommodated unquantified but potentially large shear strains. Beneath the marble mylonite lies a thick sequence of less intensely strained and mostly nonmylonitic quartzites and subsidiary schists characterized by bedding parallel grain shape foliations and well-developed stretching lineations oriented approximately 105°, 3°, parallel to similar lineations in the northern Snake Range that are Oligocene to early Miocene in age (Figure 2a) [Lee and Sutter, 1991]. Toward the west these grain shape fabrics gradually give way to ESE trending slickenlineations on bedding surfaces, and the degree of transposition of older fabrics diminishes such that S_1 and L_{1x0} (a north trending intersection lineation) are increasingly preserved. In the east these older fabrics are preserved primarily by inclusion trails in ESE rotated chlorite porphyroblasts that grew prior to the final stage of deformation (Figure 4a).

The age of the final stage of lower plate strain is constrained primarily by the deformation of the 36 Ma Young Canyon-Kious Basin pluton. Distributed cataclastic deformation along a complex system of small-scale shear surfaces accomodates most of the strain within the 36 Ma pluton, but mylonitic fabrics and solid state foliations occur locally within the outcrop area of this granite, and in some localities intrusive apophyses into the deformed country rock carry the same WNW trending grain shape lineation that characterizes surrounding quartzites. In thin section, the deformed Tertiary granites typically show greenschist facies mineral assemblages including chlorite, secondary epidote, and

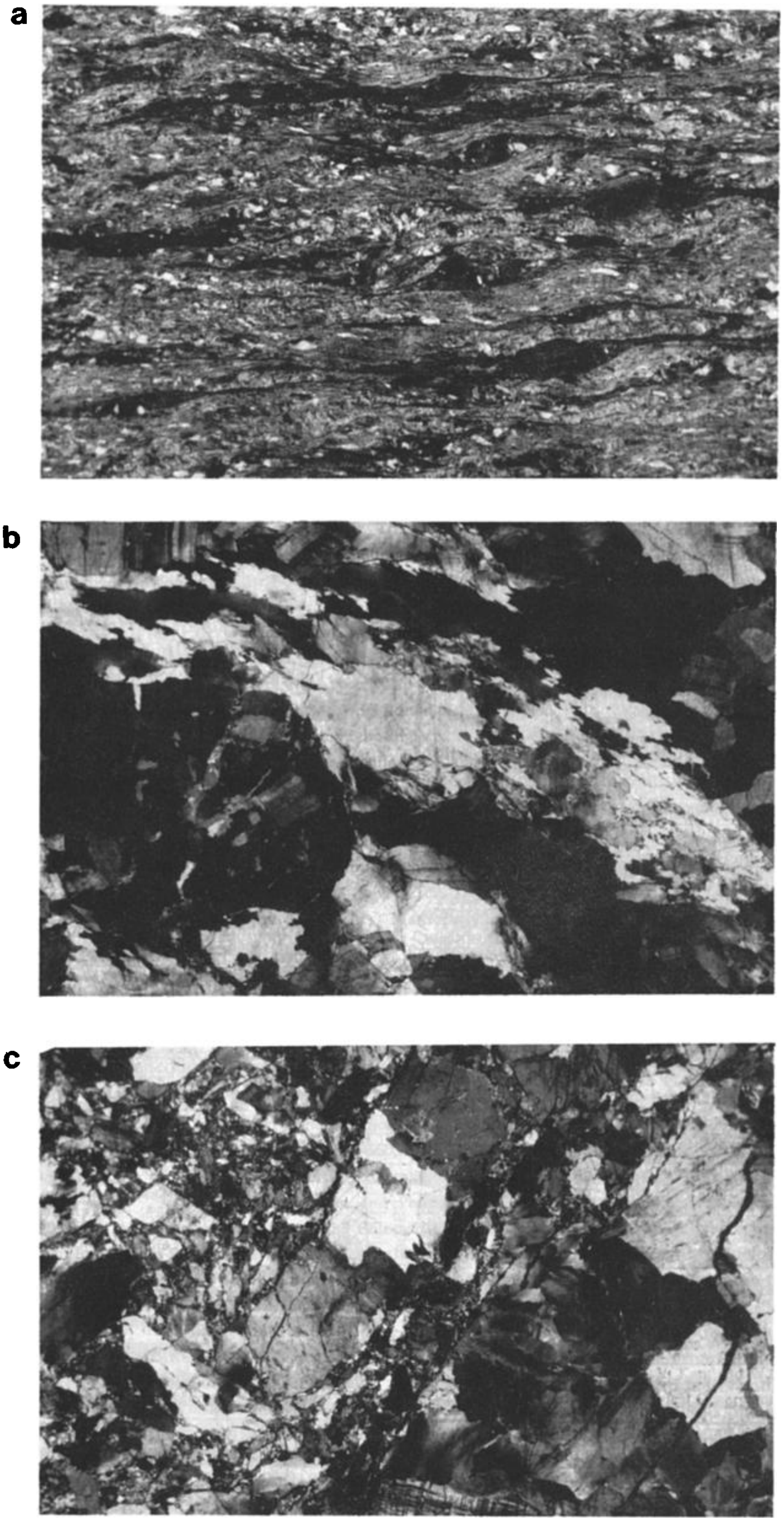


Fig. 4. (a) ESE-lineated mylonitic chlorite schist from Snake Creek window showing sigmoidal chlorite porphyroblasts that grew during earlier metamorphism and were subsequently rotated in an apparent top-to-the-east sense (dextral in this photograph) during Oligocene deformation (plane light). (b) Plastically deformed Tertiary granite (note sutured, polygonized, and dynamically recrystallized quartz; see text for additional discussion) (crossed nicols). (c) Intensely comminuted zone in cataclastically deformed Tertiary granite (contrast with Figure 4b; see text for additional discussion) (crossed nicols).

secondary white mica. In addition, quartz commonly shows extensive subgrain development and sutured grain boundaries (Figures 4b and 4c). Finally, thin zones of intensely comminuted and cataclasized rock frequently cut earlier plastic fabrics, implying a plastic to brittle evolution similar to that of many other Cordilleran metamorphic core complexes (Figure 4c).

These abundant small-scale cataclastic zones form a complicated kinematic system, with most shear surfaces striking approximately northward and most slickenlineations oriented nearly parallel to dip, yielding a mean motion plane oriented approximately 80°, 77° (Figure 5; the motion plane is defined as the plane containing slickenlineation and the the shear surface normal). Where stepped slickensurfaces preserve a clear sense of offset, normal-sense displacement appears to predominate, suggesting an ENE trending extension direction that contrasts somewhat with the average slip line indicated by the orientation of L_e in surrounding quartzites (105°, 3°). Consequently, the extension direction may have varied by as much as 30° during the course of the extensional history. Approximately 65% of shear surfaces in the granite dip toward the east while the remainder dip westward, suggesting that the bulk deformation path may have incorporated a significant component of pure shear deformation as well as a component of east directed noncoaxial strain (an inference reinforced by relationships described below).

In order to evaluate alternative interpretations of the kinematic history of the SSRD, it is particularly important to constrain the strain path characterizing deformation of lower plate rocks. As noted previously, the mylonitic marbles immediately subjacent to the SSRD probably record significant amounts of noncoaxial strain, and sporadically occurring mylonitic schists at depths as great as 100 m beneath the SSRD exhibit porphyroclast asymmetries that may record ESE directed shear (Figure 4a). However, despite the evidence for ESE directed noncoaxial strains noted above, deformational fabric relationships and quartz c axis fabric data from lower plate rocks suggest that the deformation path probably deviated significantly from end member simple shear strain. Particularly important is the observation that bedding and deformational fabrics are oriented perceptibly parallel to the SSRD throughout the lower plate. A simple shear strain interpretation can explain the observed parallelism between foliation and the SSRD only if shear strains are systematically high throughout the lower plate (Figure 6). In relatively low strain domains, foliation (and possibly bedding) should be inclined at discernible angles to the shear zone boundary unless a component of pure shear strain is superimposed. By contrast, coaxial strains operating beneath a shallowly inclined shear zone should result in foliations paralleling the shear zone boundary even in low-strain domains. Consequently, the persistent parallelism

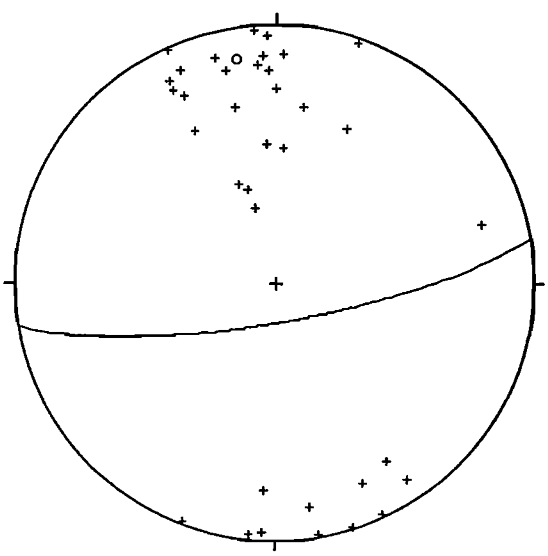


Fig. 5. Stereoplot of poles to motion planes for shear surfaces in deformed Tertiary granite [Marshak and Mitra, 1988]. Sense of displacement on shear surfaces is often uncertain, so poles are not plotted as directed line segments, but normal-sense displacement characterizes most surfaces where sense of slip can be determined. Approximately 65% of shear surfaces dip eastward, and 35% dip westward. Great circle indicates orientation of mean motion plane. N=38.

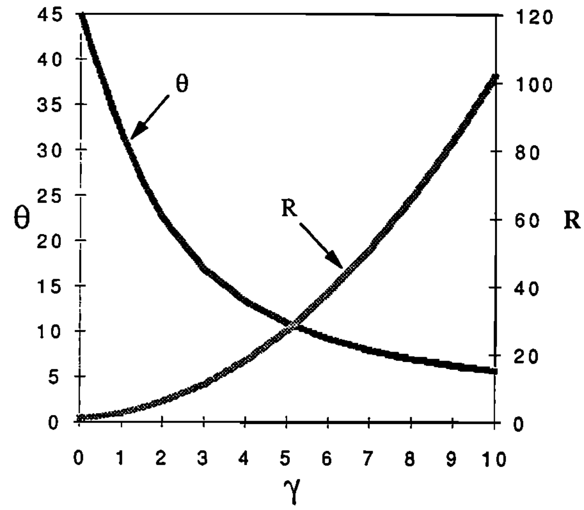


Fig. 6. Plot of foliation to shear zone angle (θ′) as a function of shear strain (γ) and ellipticity of the strain ellipse (R) for the case of end member simple shear strain [cf. Kligfield and others, 1983]. Measured finite strains in the lower plate of the southern Snake Range show values of R < 5 (see Figure 3), and even directly beneath the Southern Snake Range décollement (SSRD) thin section observations on deformed quartzites suggest that finite strains probably did not appreciably exceed this value. Consequently, strains in the southern Snake Range were probably too low to give rise to the observed parallelism between foliation and the SSRD by strict simple shear strain alone. A modest component of pure shear strain in addition to the noncoaxial strains that undoubtedly affected lower plate rocks could give rise to the observed fabric relations.

between grain shape fabrics, bedding, and the SSRD even at relatively deep structural levels where the rocks are neither mylonitic nor strongly strained argues against a strict simple shear strain origin for lower plate deformational fabrics.

Unfortunately, the finite strain values needed to quantify this argument are difficult to constrain in the southern Snake Range. Nevertheless, thinning of the Cambrian Pioche Formation (Cpi) from approximately 120 m in the less deformed northwestern part of the range to 80-90 m directly beneath the SSRD suggests the possibility of 25-33% tectonic thinning of lower plate units in the map area (although it should be noted that initial stratigraphic variations could also account for some or all of this thickness variation; Stanford Geological Survey, unpublished data, 1982 and 1984). A more rigorous estimate of finite strain in the lower plate is provided by R_f-ϕ' analysis of rare conglomeratic horizons found in quartzites north of the Cretaceous pluton, yielding finite strain values of 3.1 : 1.0 : 0.7 and 2.4 : 1.0 : 0.7 corresponding to k values of 5.25 and 3.5, respectively (placing them well within the field of apparent constrictional strain on a Flinn diagram) [Ramsay and Huber, 1983] (Figure 3). Without more extensive data, it is impossible to evaluate whether these strain values truly record regional constrictional strain or whether they merely reflect local perturbations in the boundary conditions of plastic flow near the more resistant Cretaceous pluton. In any case, despite the nonmylonitic character and relatively low strains of these rocks, the XY plane of the strain ellipsoid parallels bedding as does foliation throughout the map area, suggesting a significant component of pure shear strain parallel to lower plate bedding as discussed above (Figure 6). This inference accords well with the general lack of composite fabrics and other asymmetric microstructures in metamorphic tectonites at depth beneath the SSRD. In addition, quartz c-axis fabrics from beneath the SSRD generally show well developed crossed girdle patterns with very weak, ESE directed senses of asymmetry, suggesting that a significant component of pure shear strain accompanied ESE directed noncoaxial deformation [McGrew, 1986].

Cross-section Construction and Restoration

Plate 2 presents a sequential cross-section reconstruction illustrating two contrasting scenarios for the large-scale geometrical evolution of the southern Snake Range extensional system. The choice of an appropriate line of section presents an immediate problem in cross-section construction as several lines of evidence suggest that the slip line may not have been constant throughout deformation. As noted previously, the slip line implied by the orientation of lower plate stretching lineation (mean L_e = 105°, 3°; Figure 2) differs from that implied by motion plane analysis of cataclastic shear surfaces in the Tertiary granite (mean motion plane = 80°, 77°; Figure 5). In addition, upper plate normal faults define two separable generations characterized by opposing dips and slightly different strike orientations, with the earlier generation of west dipping faults generally striking 155° - 160° while the later, east-dipping faults usually strike approximately N-S (see Whitebread [1969] as well as Plate 1). The line of section shown in Plate 2 minimizes the need for projection from outside the plane of section and represents a compromise between the slip lines suggested by the various criteria outlined above. While the lack of a consistent slip line introduces a degree of uncertainty to cross-section restoration, this uncertainty is probably relatively small compared with some of the uncertainties discussed below. In the sections that follow I detail the key constraints and assumptions incorporated into the construction of Plate 2.

Pre-extensional structural geometry. Several observations suggest that prior to the onset of extensional deformation the southern Snake Range probably resembled the Burbank Hills a few kilometers to the east, i.e., gently folded, but lacking severe structural disruption or profound duplication of section at the structural levels now exposed.

1. No significant older-on-younger fault relationships occur anywhere in the southern Snake Range.
2. Andalusite-bearing metamorphic assemblages in the contact aureoles of Mesozoic and Tertiary plutons are compatible with stratigraphic reconstruction of the miogeoclinal overburden but seem difficult to reconcile with wholesale duplication of the upper crust, at least at structural levels above the southern Snake Range.
3. Despite striking contrasts in deformational style, no evidence exists to demonstrate profound omission of either stratigraphic section or metamorphic grade across the SSRD.
4. As emphasized first by Armstrong [1972] and later by Gans and Miller [1983] pre-extensional Tertiary rocks throughout east central Nevada are everywhere deposited with minor angular discordance on upper Paleozoic or younger rocks.
5. As illustrated in Plate 2, upper plate fault geometries can be restored without invoking severe pre-extensional structural disruption.

However, it should be noted that the extent to which the above arguments apply to surrounding areas such as the northern Snake Range is an issue of continuing controversy [Bartley and Wernicke, 1984; Gans and Miller, 1985; Wernicke and Bartley, 1985; Lewis et al., 1992]. Furthermore, none of these points bear on the possibility that Mesozoic thrust faults may exist beneath the deepest levels exposed in the southern Snake Range. In fact, the occurrence of Mesozoic deformational fabrics in the lower plate suggests increasing structural involvement at depth, both in the southern Snake Range and in surrounding areas [Miller et al., 1988].

Geometrical evolution of the SSRD. As with other major detachment faults, constraining the inclination of the SSRD through time presents a particularly challenging and important problem in cross-section construction. At present, the SSRD dips <15° eastward throughout the southern Snake Range, but requiring the SSRD to maintain such dips throughout its history would give rise to serious mechanical problems and incongruency with numerous observations on the character of active normal-fault seismicity throughout the world [Jackson, 1987]. Angular relationships with lower plate strata provide some constraints on possible initial orientations of the SSRD. Throughout the eastern half of the range the SSRD parallels lower plate units, and regional reflection seismic data suggest that this pattern continues toward the east, with the Snake Range décollement paralleling the western limb of the CRST (COCORP Utah Line 1) [Allmendinger et al., 1983]. Because regional stratal dips probably did not exceed 20°-30° at the onset of extension (see above), this segment of the SSRD probably could not have originated with steep dips.

Nevertheless, mapping by Whitebread [1969] indicates that toward the west the SSRD cuts up-section across footwall strata with an angular discordance of approximately 30°, thus opening the possibility that the SSRD may originally have steepened toward the west as shown in Plate 2. The rotation of this segment of the SSRD to shallower dip could occur either by rotation in the hanging wall of the Schell Creek fault several kilometers to the west [Gans et al., 1985] or because of isostatic adjustments accompanying deformation [Buck, 1988, Wernicke and Axen, 1988]. By contrast, a similar isostatic mechanism could serve to rotate the initially shallowly dipping segment of the SSRD first to steeper angle and then back to shallow dip as the inflection point of isostatic uplift migrates through the region of interest [cf. Spencer, 1984; Wernicke and Axen, 1988].

The role that isostasy may have played in the tectonic evolution of the SSRD is difficult to evaluate from an empirical point of view because absolute variations in elevation of the Earth's surface during the course of orogenesis are notoriously difficult to constrain [England and Molnar, 1990]. However, both the Tertiary unconformity data referred to previously [Gans and Miller, 1983] and the palinspastic reconstruction shown in Plate 2 require that the Cambrian Pioche Formation was buried to paleodepths in excess of 6 km beneath the Earth's surface at the onset of Tertiary extension. At present, this same formation is exposed at the crest of the southern Snake Range, at least 6 km above its contemporary position beneath both the Burbank Hills to the east and the southern Schell Creek Range to the west (Plate 2) [Hose and Blake, 1976]. Mesozoic folding probably accommodated only part of this differential uplift, with the remainder occurring during Tertiary exhumation, most likely as a result of isostatic adjustments. In any case, reconstruction of Plate 2 without any uplift of lower plate rocks in the southern Snake Range relative to surrounding areas would result in a retrodeformed section showing > 4 km of vertical relief over a lateral distance of < 5 km. For these reasons, Plate 2 assumes that space problems between the hanging wall and the footwall of the SSRD were accommodated in part by footwall uplift as well as by hanging wall collapse [cf. Wernicke and Axen, 1988].

Geometry of upper plate faults. In the southern Snake Range, restoration of complicated upper plate fault geometries poses another challenging problem. Map relationships in the southern Snake Range imply two families of upper plate faults, an older generation of relatively closely spaced, west dipping faults and a younger generation of more widely spaced, east dipping faults. Although the east dipping faults do not clearly cut the west dipping faults in the area of Plate 1, such cross cutting relationships are exposed in adjacent areas mapped by Whitebread [1969] to the south. Because of a lack of exposed cutoffs, reconstruction of upper plate faults relies entirely on restoration of upper plate fault blocks to inferred pre-extensional stratigraphic positions. Fortunately, involvement of a well-known pre-extensional stratigraphy facilitates this mode of reconstruction.

The involvement of a well-known stratified sequence also places important constraints on regional fault reconstruction. Specifically, the Middle Cambrian Pole Canyon limestone (Cpc) is preserved both in the hanging wall and in the footwall of the SSRD (Plates 1 and 2). Consequently, the exposure of a complete section of this formation in the lower plate in the western part of the map area effectively defines a footwall cutoff. As a result, the upper plate Pole Canyon limestone must have originated less than ~14 km west of its present position (Plate 2).

Lack of control on the precise fault geometries underlying and bounding southern Snake Valley presents additional problems for regional cross-section construction (Plate 2). The nature of cross cutting relationships between the range-bounding fault and the SSRD is a particularly important uncertainty. Alam and Pilger [1987] and Alam [1990] report that proprietary seismic data obtained from Unocal for southern Snake Valley image moderately dipping reflectors that may correspond to the SSRD. If so, then the SSRD must steepen beneath the western side of Snake Valley as shown in Plate 2 (a possibility that accords well with the rolling hinge model described above). However, a plausible alternative interpretation is that these reflectors record the geometry of the range front fault rather than the SSRD, in which case the SSRD must be truncated by the range-bounding structure. Nevertheless, this alternative interpretation probably would not greatly alter the gross cross-section geometry beneath southern Snake Valley, although the magnitude of extension accommodated by the SSRD would decrease slightly.

An equally important uncertainty concerns the geometry of upper plate faults beneath southern Snake Valley. Fortunately, the narrowness of southern Snake Valley and the relatively well known structure and stratigraphy of the adjacent Burbank Hills provide constraints ameliorating this problem. Plate 2 illustrates an upper plate fault geometry beneath southern Snake Valley that is plausible but necessarily speculative. Nevertheless, whatever the precise fault geometry underlying Snake Valley, the narrowness of the basin serves to limit the magnitude of error associated with this uncertainty because extension within the upper plate across Snake Valley can be no less than 0 km and no greater than the width of the valley (8 km).

Nature and geometry of lower plate strain. Regardless of how the uncertainties discussed above are resolved, differing cross-sections are possible depending on the kinematic behavior attributed to the SSRD. For instance, if a strict in situ extension model is invoked [e.g., Miller et al.,1983], then thinning and nearly coaxial stretching of lower plate units directly beneath the SSRD must fully accommodate upper plate extension at any given point along the detachment. On the other hand, if a strict simple shear model is invoked [e.g., Wernicke, 1981; Bartley and Wernicke, 1984], then the final geometry of lower plate units depends on the distribution and magnitude of shear strain and the initial orientation of lower plate strata relative to the shear zone boundary. As outlined earlier, lower plate strain relationships in the southern Snake Range seem to preclude either end-member interpretation, but between these two extremes a broad spectrum of plausible scenarios exists, including some that resemble the end-member interpretations.

In short, it seems likely that some but not all of the extension in upper plate rocks was accommodated in situ by penetrative stretching directly beneath the SSRD. Consequently, the SSRD may well have acted as a "stretching shear zone" in the sense of Means [1989], with the detachment functioning at least in part to maintain strain compatibility between a relatively rigid upper plate and a lower plate that was stretching plastically as deformation proceeded. Plate 2 illustrates both an end-member stretching shear zone interpretation of the SSRD (solid lines) and a hybrid interpretation in which the SSRD functions in part as a stretching shear zone and in part as a more conventional through-going shear zone (broken lines). In the first case stretching of lower plate rocks by homogeneous plane strain completely accommodates displacement of upper plate rocks, whereas in the second case lower plate stretching accommodates only part of the displacement on the SSRD, with the remainder being taken up by through-going shear.

In either case, as extension migrates eastward through time, portions of the lower plate lying to the west experience unroofing and hence cooling and cessation of plastic deformation at an earlier stage than do areas to the east (compatible with the K-Ar cooling age patterns recognized by Lee et al. [1970]). Accordingly, the more protracted history of plastic deformation in the east results in a west-to-east strain gradient in lower plate units such as that depicted for the end-member stretching shear zone interpretation in Plate 2. While exposures of lower plate rocks are not sufficiently extensive to document such a strain gradient in the southern Snake Range, a strikingly similar strain pattern is well documented in the northern Snake Range [J. Lee et al., 1987].

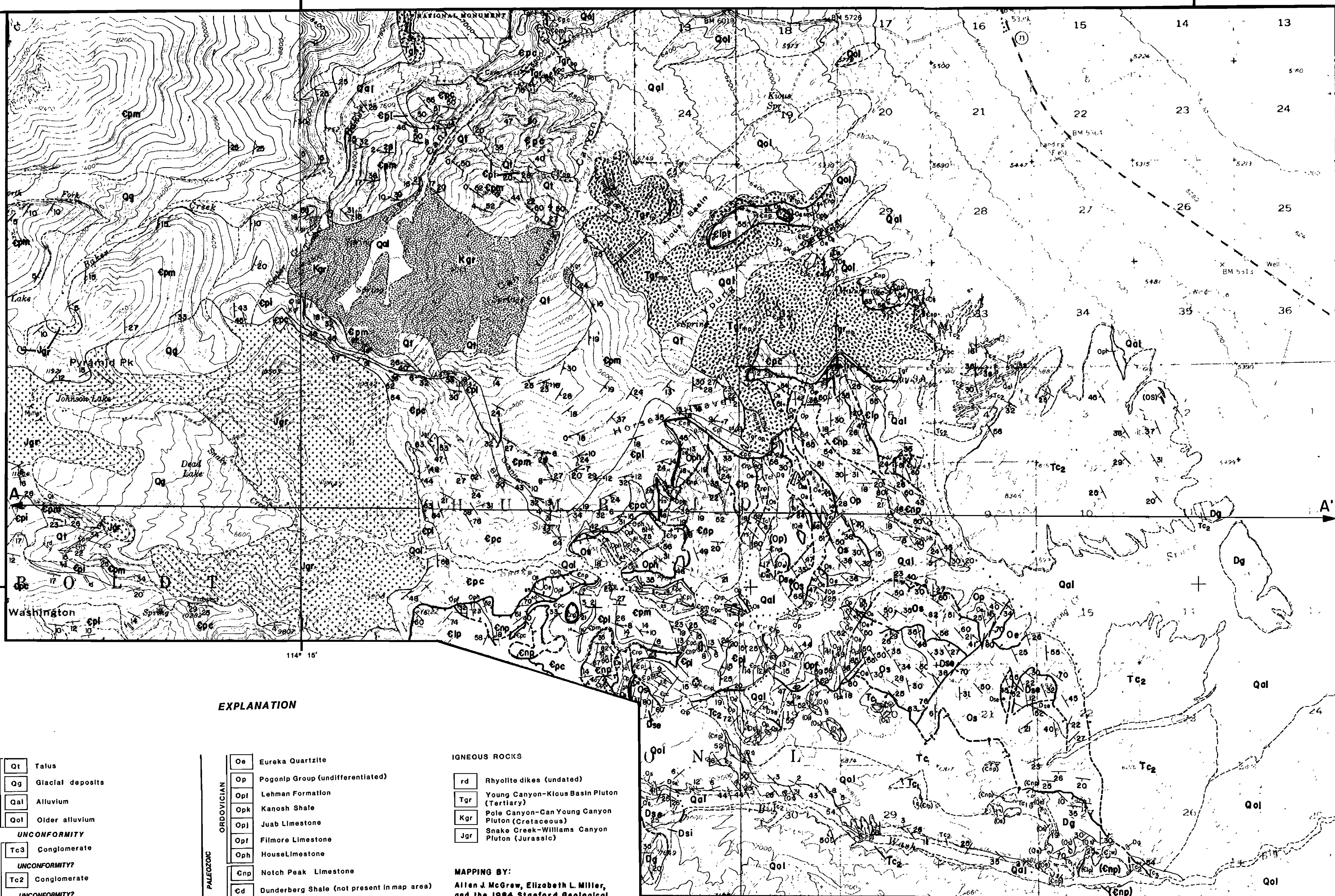
While bearing much in common with in situ extension interpretations previously advanced for the northern Snake Range décollement [Gans and Miller, 1983; Miller et al., 1983], it should be noted that the end-member stretching shear zone interpretation developed above differs in that it requires a large component of uniform-sense noncoaxial strain parallel to the SSRD. For example, in the western part of the cross-section the upper plate accommodates at least 120% extension whereas the lower plate accommodates no more than 65% extension, thus requiring substantial down-to-the-east displacement on the SSRD.

Cross-section reconstruction. The cross-section restoration illustrated in Plate 2 is balanced with respect to area but does not conserve line lengths or stratigraphic thicknesses due to the deformational mechanisms assumed. To wit, lower plate units were assumed to stretch and thin plastically during deformation and so cannot conserve line length. In addition, lateral differences in vertical uplift accompanying deformation were accommodated by vertical simple shear. In upper plate rocks, space problems developing between adjacent fault blocks during extension were accommodated insofar as possible by rigid body rotations (a line length conservative process resembling the tilt block models of Proffett [1977], Gans and Miller [1983], and other authors). However, as numerous authors have pointed out, it is not possible to completely accommodate space problems between fault blocks by rigid body rotation alone [e.g., Wernicke and Burchfiel, 1982], and so internal deformation by inclined simple shear was utilized to accommodate residual space problems as necessary (a process that does not conserve line lengths) [White et al., 1986; McGrew and Crews, 1990]. The reconstruction shown in Plate 2 yields an estimate of total extension of approximately 19 km between the central part of the southern Snake Range and the hingeline of the CRST. Assuming different kinematic mechanisms or contrasting cross-section parameters can give rise to different estimates of extension, but extension probably lies between 8 km and 24 km provided that the footwall cutoff of the Cambrian Pole Canyon Formation is honored and that an upper plate fault reconstruction resembling that shown in Plate 2 is adopted.

DISCUSSION AND CONCLUSIONS

In the preferred scenario developed in Plate 2, the SSRD initates as a plastic stretching shear zone separating an upper plate that deforms by frictional sliding on steeply inclined normal faults from a lower plate that deforms by penetrative stretching and pluton emplacement [cf. Miller et al., 1983; Means, 1989]. As illustrated, a major east dipping normal fault resembling modern range front fault systems governs upper plate deformation during the early phases of extension, with an array of closely spaced down-to-the-west normal faults antithetic to the master fault accommodating hanging wall collapse [cf. White et al., 1986]. As extension proceeds, tilt block rotation of the antithetic system results in dramatic attenuation of upper plate rocks, thus applying a negative isostatic load to footwall rocks and ultimately resulting in relative uplift of the lower plate and back-rotation of the master normal fault in the western part of the extended terrain [cf. Zandt and Owens, 1980, Buck, 1988]. Meanwhile, as areas to the west are relatively uplifted, adjacent segments of the SSRD that were originally shallowly dipping must become more steeply inclined and thus can remain active as tectonic unroofing carries them upward into the frictional sliding regime [cf. Wernicke and Axen, 1988]. Perhaps net lateral flow of deep crustal material out from beneath less extended adjacent areas could help accommodate such differential vertical motions [cf. Gans, 1987]. In any case, as unroofing proceeds from west to east, upper plate faults and the SSRD itself eventually rotate to sufficiently shallow angles that further slip becomes impossible due to frictional resistance, and as a result new steeply dipping faults must form, tracking unroofing toward the east. Meanwhile, portions of the lower plate in the western part of the area experience unroofing earlier and pass through Ar closure temperatures earlier than in the east (possibly contributing to the eastward decrease in K-Ar muscovite cooling ages recognized by Lee et al., 1970]. In other words, updip portions of the extensional system become defunct as down-dip portions of the system toward the east continue to accommodate extension.

PLATE I



EXPLANATION

CENOZOIC

QUATERNARY

- Qt — Talus
- Qg — Glacial deposits
- Qal — Alluvium
- Qol — Older alluvium

UNCONFORMITY

TERTIARY

- Tc3 — Conglomerate

UNCONFORMITY?

- Tc2 — Conglomerate

UNCONFORMITY?

- Tc1 — Conglomerate

UNCONFORMITY

PALEOZOIC

DEVONIAN

- Dg — Guilmette Formation
- Dsi — Simonson Dolomite
- Dse — Sevy Dolomite

SIL.

- OS — Undifferentiated Laketown (Silurian) and Fish Haven (Ordovician) Dolomite

PALEOZOIC

ORDOVICIAN

- Oe — Eureka Quartzite
- Op — Pogonip Group (undifferentiated)
- Opl — Lehman Formation
- Opk — Kanosh Shale
- Opj — Juab Limestone
- Opf — Filmore Limestone
- Oph — HouseLimestone

CAMBRIAN

- Ꞓnp — Notch Peak Limestone
- Ꞓd — Dunderberg Shale (not present in map area)
- Ꞓjw — Johns Wash Limestone
- Ꞓlp — Lincoln Peak Formation
- Ꞓpc — Pole Canyon Limestone
- Ꞓpl — Pioche Formation
- Ꞓpm — Prospect Mountain Quartzite

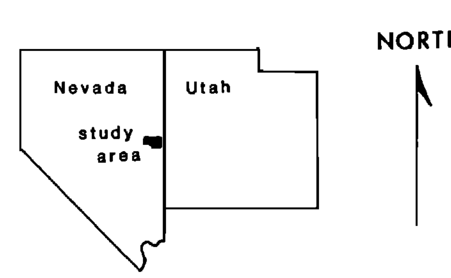
IGNEOUS ROCKS

- rd — Rhyolite dikes (undated)
- Tgr — Young Canyon-Kious Basin Pluton (Tertiary)
- Kgr — Pole Canyon-Can Young Canyon Pluton (Cretaceous)
- Jgr — Snake Creek-Williams Canyon Pluton (Jurassic)

MAPPING BY:

Allen J. McGrew, Elizabeth L. Miller, and the 1984 Stanford Geological Survey: B. Aaron, L. Baugh, A. Bryer, S. Brokken, A. Campbell, D. Clark, C. Duncan, P. Gans, C. Gazis, S. Grant, P. Lewis, A. McGrew, K. Merino, E.G. Miller, E.L. Miller, S. Munn, K. Shanks, and A. Tomlinson.

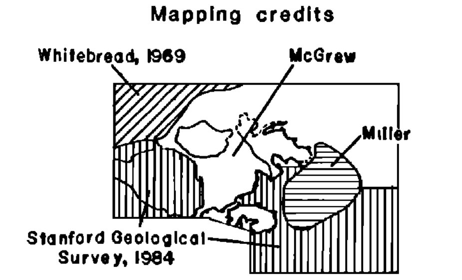
Compiled by Allen J. McGrew



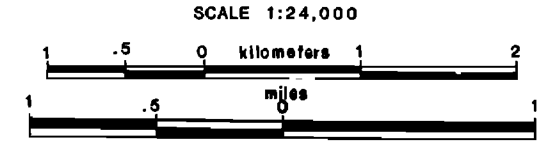
MAP SYMBOLS

- Cotacts: Broken where inferred, queried where uncertain, dotted where concealed.
- Gradational Contacts.
- Faults: Strike and dip of fault plane, trend and plunge of slickenside lineations. (26 29)
- The Southern Snake Range Decollement, teeth on upper plate.
- Slide blocks of Paleozoic lithologies hosted in Tertiary stratigraphic section. ((Ꞓnp))
- Strike and dip of beds (upright and overturned). (32, 63)
- Strike and dip of bedding-parallel foliation with trend and plunge of grain shape lineation. (22, 12)

Mapping credits



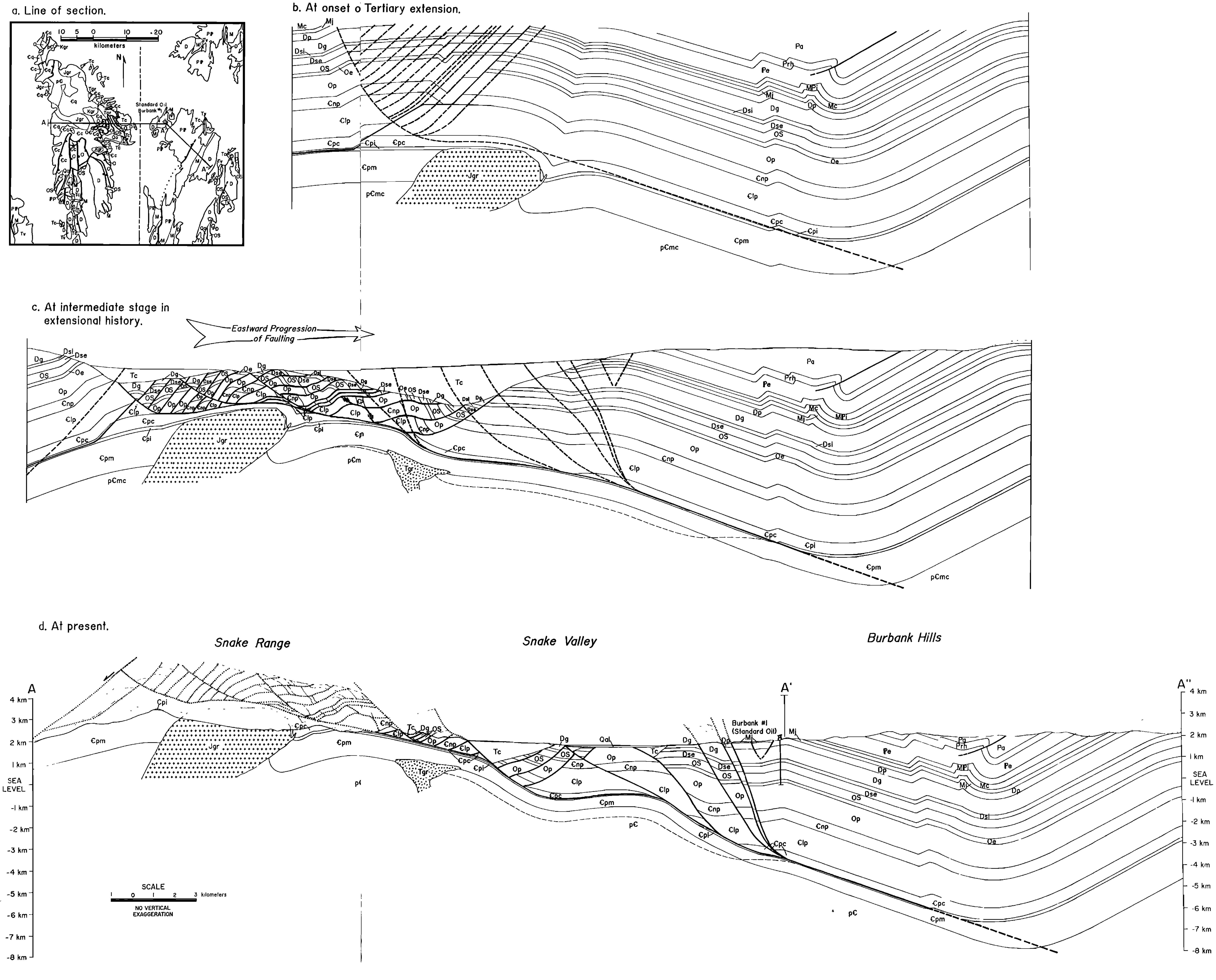
SCALE 1:24,000



contour interval 40 feet

GEOLOGIC MAP OF PART OF THE SOUTHERN SNAKE RANGE, NEVADA

PLATE II. Retrodeformed regional cross-section sequence illustratng likely structural evolution of the SSRD.
Units as in Plate I with the addition of: pCmc - McCoy Creek Grup, Dp - Pilot Shale, Mj - Joanna Limestone, Mc - Chainman Formation, MPi - Illipah Formation, Pe - Ely Limestone, Prh - Rib Hill Formation, Pa - Arcturus Formation.



Although Plate 2 illustrates a plausible scenario for the structural evolution of the southern Snake Range, it should be evident that certain elements in this scenario are more speculative than others. Among the most poorly constrained elements in this scenario are the initial dip of the SSRD in the western part of the cross-section, the nature of cross cutting relationships between the SSRD and the range front structure, and the precise geometry of lower plate units to the east of the southern Snake Range. The dip of the SSRD at intermediate stages in its evolutionary history and the precise effect of isostatic compensation on the evolution of this geometry present other major elements of uncertainty.

Nevertheless, despite important uncertainties, several points can be made with some confidence. The SSRD formed as a plastic shear zone some time after emplacement of the 36 Ma Young Canyon-Kious Basin pluton, but by the time it ceased to be active (probably before 17 Ma, at least in the Snake Range proper) it was probably functioning as a brittle normal fault. While the initial dip of the SSRD is uncertain along the western flank of the range, it very probably formed at shallow inclination parallel to lower plate strata in the east. In the upper plate, an early generation of westward dipping faults and a later generation of eastward dipping faults clearly accommodated great extension, and attenuation of hanging wall rocks ultimately produced dramatic unroofing and relative uplift of lower plate rocks compared to surrounding areas. Such differential vertical movements are difficult to explain except in the context of isostasy. Finally, penetrative stretching of lower plate rocks directly beneath the SSRD appears to have accommodated at least part of upper plate extension, but a substantive component of ESE directed shear is also present. Consequently, the SSRD probably played a dual kinematic role, acting in part to transfer displacement down dip toward the east and in part to resolve relatively localized strain mismatches between a relatively rigid upper plate and a plastically stretching lower plate.

Acknowledgements. Elizabeth L. Miller provided particularly invaluable advice and support during the course of this work. In addition, the 1984 Stanford Geological Survey contributed much basic data and many important insights to this study. Excluding the author, the participants in this field camp were: Bill Aaron, Lisa Baugh, Adam Bryer, Shana Brokken, Tony Campbell, Doug Clark, Claire Duncan, Phil Gans, Carey Gazis, Stanley Grant, Peter Lewis, Karen Merino, Eric Miller, Steve Munn, Kirby Shanks, David Stahl, Andy Tomlinson, Jack Whittimore, and Elizabeth Miller (leader of SGS). Phil Gans, Jeff Lee, and Jim Wright provided many useful discussions, and Karen Merino and Heidi S. McGrew provided especially important field and other assistance. Peg Brown provided valuable assistance in drafting. John Bartley, Tekla Harms, and Richard Allmendinger provided thorough and useful reviews. Funding for this project came in part from general grants from ARCO and SOHIO, in part from NSF grant EAR 8418678 to E. L. Miller et al., and in part from a Stanford Geology Department graduate fellowship.

REFERENCES

Alam, A.H.M. Shah, Crustal extension in the southern Snake Range and vicinity, Nevada-Utah: An integrated geological and geophysical study, Ph.D. thesis, La. State Univ., Baton Rouge, 126 pp., 1990.

Alam, A.H.M. Shah, and R.H. Pilger, Jr., Extension of the southern Snake Range Décollement beneath the southern Snake Valley based on reflection seismic data: Basin and Range Province, Nevada-Utah, *Geol. Soc. Am. Abstr. Programs, 19,* 568, 1987.

Allmendinger, R.W., J.W. Sharp, D. Von Tish, L. Serpa, L. Brown, S. Kauffman, J. Oliver, and R.B. Smith, Cenozoic and Mesozoic structure of the eastern Great Basin province, Utah, from COCORP seismic-reflection data, *Geology, 11,* 532-536, 1983.

Anderson, R.E., Cenozoic structural history of selected areas in the eastern Great Basin, Nevada-Utah, *U.S. Geol. Surv. Open File Rep., 83-504,* 47 pp., 1983.

Armstrong, R.L., Low-angle (denudational) faults, hinterland of the Sevier Orogenic Belt, eastern Nevada and western Utah, *Geol. Soc. Am. Bull., 83,* 1729-1754, 1972.

Bartley, J.M., and B. Wernicke, The Snake Range décollement interpreted as a major extensional shear zone, *Tectonics, 3,* 647-657, 1984.

Best, M.G., and S.K. Grant, Oligocene and Miocene volcanic rocks in the central Pioche-Marysvale igneous belt, western Utah and eastern Nevada: Stratigraphy of the volcanic Oligocene Needles Range Group in southwestern Utah and eastern Nevada, *U.S. Geol. Surv. Prof. Pap., 1433A,* 1-28, 1987.

Buck, W.R., Flexural rotation of normal faults, *Tectonics, 7,* 959-974, 1988.

Davis, G.A., and G.S. Lister, Detachment faulting in continental extension; Perspectives from the southwestern U.S. Cordillera, in Processes in Continental Lithospheric Deformation, edited by S.P. Clark, Jr. et al., *Geol. Soc. Am. Spec. Pap., 218,* , 133-159, 1988.

Davis, G.H., Shear zone model for the origin of metamorphic core complexes, *Geology, 11,* 342-347, 1983.

Eaton, G.P., The Basin and Range Province: Origin and tectonic significance, *Annu. Rev. Earth Planet. Sci. Lett., 10,* 409-440, 1982.

England, P., and P. Molnar, Surface uplift, uplift of rocks, and exhumation of rocks, *Geology, 18,* 1173-1177, 1990.

Gans, P.B., An open-system, two-layer crustal stretching model for the eastern Great Basin, *Tectonics, 6,* 1-12, 1987.

Gans, P.B., and E.L. Miller, Style of mid-Tertiary extension in east-central Nevada, in Geologic Excursions in the Overthrust Belt and Metamorphic Core Complexes of the Intermountain Region, Nevada, Geological Society of America Guidebook Part 1, *Spec. Stud. Utah Geol. Miner. Surv., 59,* 107-160, 1983.

Gans, P.B., and E.L. Miller, Comment on "The Snake Range décollement interpreted as a major extensional shear zone" by John M. Bartley and Brian P. Wernicke, *Tectonics, 4,* 411-415, 1985.

Gans, P.B., E.L. Miller, J. McCarthy, and M.L. Ouldcott, Tertiary extensional faulting and evolving ductile-brittle transition zones in the northern Snake Range and vicinity: New insights from seismic data, *Geology, 13,* 189-193, 1985.

Hamilton, W., Crustal extension in the Basin and Range Province, southwestern United States, in Continental Extensional Tectonics, edited by M.P. Coward et al.,

Geol. Soc. Spec. Publ., London, 28, 155-176, 1987.
Hintze, L.F., Geology of the Burbank, Tunnel Spring and northern Needle Ranges, Millard and Beaver Counties, Utah, scale 1:48,000, Brigham Young Univ. Geol. Dep., Salt Lake City, Utah, 1960.
Hintze, L.F., Geologic Map of Utah, scale 1:500,000, Utah Geol. and Miner. Surv., Salt Lake City, Utah, 1980.
Hose, R.K., and M.C. Blake, Geology and mineral resources of White Pine County, Nevada, part 1, Geology, *Bull. Nev. Bur. Mines Geol., 85*, 105 pp., 1976.
Jackson, J.A., Active normal faulting and crustal extension, in Continental Extensional Tectonics, edited by M.P. Coward et al., *Geol. Soc. Spec. Publ., London, 28*, 3-18, 1987.
Jackson, J.A., and D.P. McKenzie, The geometrical evolution of normal fault systems, *J. Struct. Geol., 5*, 471-482, 1983.
Kligfield, R., J. Crespi, S. Naruk, and G.H. Davis, Displacement and strain patterns of extensional orogens, *Tectonics, 3*, 577-609, 1984.
Lee, D.E., and E.H. Christiansen, The mineralogy of the Snake Creek - Williams Canyon pluton, southern Snake Range, Nevada, *U.S. Geol. Surv. Open File Rep., 83-337*, 21 pp., 1983a.
Lee, D.E., and E.H. Christiansen, The granite problem in the southern Snake Range, Nevada, *Contrib. Mineral. Petrol., 83*, 99-116, 1983b.
Lee, D.E., and R.E. Van Loenen, Hybrid granitoid rocks of the southern Snake Range, Nevada, *U.S. Geol. Surv. Prof. Pap., 68*, 1-46, 1971.
Lee, D.E., T.W. Stern, R.E. Mays, and R.E. Van Loenen,, Accessory zircon from granitoid rocks of the Mt. Wheeler Mine area, Nevada, *U.S. Geol. Surv. Prof. Pap., 600-D*, D197-D203, 1968.
Lee, D.E., R.F. Marvin, T.W. Stern, and Z.E. Peterman, Modification of K-Ar ages by Tertiary thrusting in the Snake Range, White Pine County, Nevada, *U.S. Geol. Surv. Prof. Pap., 700-D*, D92-D102, 1970.
Lee, D.E., T.W. Stern, and R.F. Marvin, U-Th-Pb isotopic ages of zircon from the southern Snake Range, Nevada, *Isochron West, 31*, p. 25, 1981.
Lee, D.E., I. Friedman, and J.D. Gleason, The oxygen isotope composition of granitoid and sedimentary rocks of the southern Snake Range, Nevada, *Contrib. Mineral. Petrol., 79*, 150-158, 1982.
Lee, D.E., I. Friedman, and J.D. Gleason, Modification of delta D values in eastern Nevada granitoid rocks spatially related to thrust faults, *Contrib. Mineral. Petrol., 88*, 288-298, 1984.
Lee, D.E., J.S. Stacey, and L. Fischer, Muscovite phenocrystic two mica granites of northeastern Nevada are Late Cretaceous in age, in Shorter Contributions to Isotope Research, edited by Z.E. Peterman and D.C. Schnabel, *U.S. Geol. Surv. Bull., B1622*, 31-39, 1986a.
Lee, D.E., R.W. Kistler, and A.C. Robinson, The strontium isotope composition of granitoid rocks from the southern Snake Range, Nevada, in Shorter Contributions to Isotope Research, edited by Z.E. Peterman and D.C. Schnabel, *U.S. Geol. Surv. Bull., B1622*, 171-179, 1986b.
Lee, J., and J.F. Sutter, Incremental $^{40}Ar/^{39}Ar$ thermochronology of mylonitic rocks from the northern Snake Range, Nevada, *Tectonics, 10*, 77-100, 1991.
Lee, J., E.L. Miller, and J.F. Sutter, Ductile strain and metamorphism in an extensional tectonic setting: A case study from the northern Snake Range, Nevada, U.S.A., in Continental Extensional Tectonics, edited by M.P. Coward et al., *Geol. Soc. Spec. Publ., London, 28*, 267-298, 1987.
Lewis, C.J., J. Selverstone, and B. Wernicke, Deep burial depths for metapelites from the lower plate of the northern Snake Range decollement, Nevada, *Geol. Soc. Am. Abstr. Programs, 24*, 23, 1992.
Marshak, S., and G. Mitra, *Basic Methods of Structural Geology*, 446 pp., Prentice Hall, Englewood Cliffs, N.J., 1988.
McGrew, A.J., Deformational history of the southern Snake Range, Nevada, and the origin of the southern Snake Range décollement, M.S. thesis, Stanford Univ., 46 pp., Stanford, Calif., 1986.
McGrew, A.J., and S.G. Crews, A quantitative model for the geometrical evolution of multiple fault extensional systems, *Geol. Soc. Am. Abstr. Programs, 22*, A273, 1990.
Means, W.D., Stretching faults, *Geology, 17*, 893-896, 1989.
Miller, E.L., P.B. Gans, and J. Garing, The Snake Range décollement: An exhumed mid-Tertiary ductile-brittle transition, *Tectonics, 2*, 239-263, 1983.
Miller, E.L., P.B. Gans, J.E. Wright, and J.F. Sutter, Metamorphic history of the east-central Basin and Range province: Tectonic setting and relationship to magmatism, in *Metamorphism and Crustal Evolution of the Western United States: Rubey Volume VII*, edited by W.G. Ernst, pp. 649-682, Prentice Hall, Englewood Cliffs, N. J., 1988.
Misch, P., Regional structural reconnaissance in central-northeast Nevada and some adjacent areas: observations and interpretations, in Guidebook to the Geology of East-central Nevada, pp. 17 - 42, Intermt. Assoc. Pet. Geol. and Eastern Nev. Geol. Soc., 11th Ann. Field Conf., Salt Lake City, Utah, 1960.
Proffett, J.M., Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting, *Geol. Soc. Am. Bull., 88*, 247-266, 1977.
Ramsay, J.G., and M.I. Huber, *The Techniques of Modern Structural Geology*, vol. I, *Strain Analysis*, 307 pp., Academic, San Diego, Calif., 1983.
Reynolds, S.J., and J.E. Spencer, Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona, *Geology, 13*, 353-356, 1985.
Spencer, J.E., Role of tectonic denudation in warping and uplift of low-angle normal faults, *Geology, 12*, 95-98, 1984.
Stewart, J.H., Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwestward, *Geology, 11*, 153-157, 1983.
Stewart, J.H., and J.E. Carlson, Geologic Map of Nevada, scale 1:500,000, U.S. Geol. Surv., Reston, Va., 1976.
Wernicke, B., Low angle normal faults in the Basin and Range province: Nappe tectonics in an extending orogen, *Nature, 291*, 645-648, 1981.
Wernicke, B., and G.J. Axen, On the role of isostasy in the evolution of normal fault systems, *Geology, 16*, 848-851, 1988.
Wernicke, B., and J.M. Bartley, Reply to comment by Phillip B. Gans and Elizabeth L. Miller, *Tectonics, 4*, 417-419, 1985.
Wernicke, B. and B.C. Burchfiel, Modes of extensional tectonics, *J. Struct. Geol., 4*, 105-115, 1982.
Wernicke, B., G.J. Axen, and J.K. Snow, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada, *Geol. Soc. Am. Bull., 100*, 1738-1757, 1988.
White, N.J., J.A. Jackson, and D.P. McKenzie, The relationship between the geometry of normal faults and that of the sedimentary layers in their hanging walls, *J. Struct. Geol., 8*, 897-909, 1986.
Whitebread, D.H., Geologic Map of the Wheeler Peak and Garrison Quadrangles, Nevada and Utah, scale 1:48,000, *U.S. Geol. Surv. Misc. Field Stud. Map, I-578*, 1969.
Zandt, G., and T.J. Owens, Crustal flexure associated with normal faulting and implications for seismicity along the Wasatch Front, Utah, *Bull. Seismol. Soc. Am., 70*, 1501-1520, 1980.

A. J. McGrew, Geologisches Institut, Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology at Zurich), CH-8092 Zürich, Switzerland.

(Received October 5, 1989;
revised June 26, 1992;
accepted July 21, 1992.)