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THE SNAKE RANGE DÉCOLLEMENT: AN EXHUMED MID-TERTIARY DUCTILE-BRITTLE TRANSITION

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Abstract. The Snake Range décollement (SRD) in east-central Nevada separates supracrustal rocks extended by normal faulting from ductilely deformed igneous and metamorphic rocks. A well-known stratigraphy unaffected by earlier faulting permits analysis of both upper and lower plate strain leading to a better understanding of how vastly different rock types and deformational styles are juxtaposed along low-angle faults in metamorphic core complexes. Middle Cambrian to Permian upper plate rocks are cut by two generations of NE trending, east directed normal faults. Both generations were initiated as high-angle (60°) planar faults that flattened abruptly into the SRD and rotated domino style to low angles, yielding a total rotation of bedding of about 80-90°. Faulting is Tertiary in age as 35-m.y.-old volcanic rocks are involved and resulted in about 450-500% extension in a N55W-S55E direction. The SRD developed as a subhorizontal surface 6-7 km deep at the top of the Cambrian Pioche Shale. Lower plate granitic rocks and their late Precambrian-Cambrian metamorphic country rocks were involved in progressive ductile to brittle extension at low greenschist grade, forming a penetrative subhorizontal foliation and N55-70W lineation that increases in intensity eastward and upward toward the SRD. Stretching and thinning in the lower plate is coaxial and comparable in magnitude to upper plate extension, and is interpreted as synchronous. K-Ar ages ranging from 20 to 40 m.y. in the lower plate suggests the N. Snake Range represents a Tertiary thermal anomaly. We conclude that the SRD developed as a ductile-brittle transition zone at 6-7 km depth. Gravity data suggests that the gently domed SRD is cut by younger Basin and Range faults, but the geology of adjacent ranges suggests that the SRD does not continue more than 60 km in any given direction. The lack of stratigraphic omission across the SRD rules out large amounts of movement on a surface that originally cut downsection, and we suggest that extensional detachment faults such as the SRD can be developed locally as boundaries between brittlely extended rocks and underlying ductile extension and intrusion.

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INTRODUCTION

Gently dipping detachment faults in metamorphic core complexes of the U.S. Cordillera juxtapose brittlely deformed

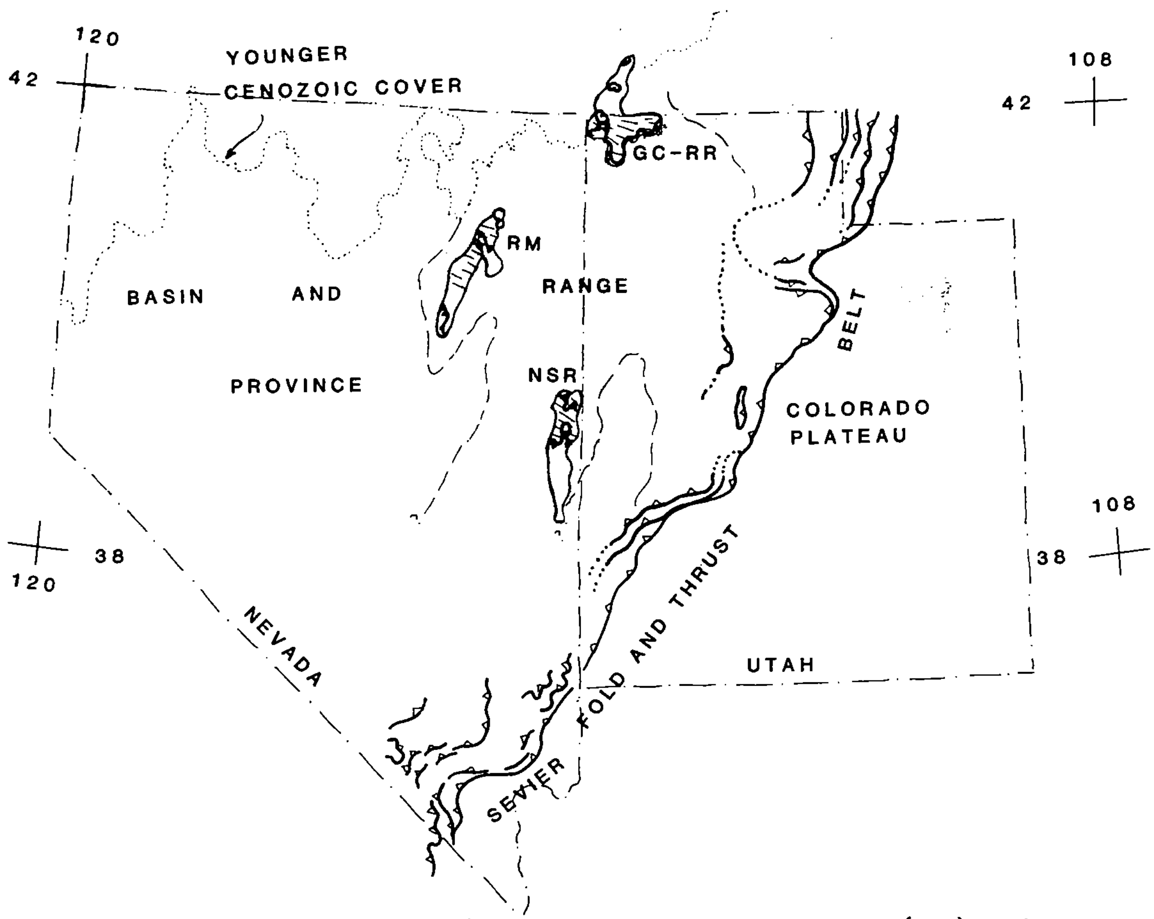


Fig. 1: Index map showing location of the northern Snake Range (NSR), Ruby Mountains (RM), and Grouse Creek-Raft River (GC-RR) metamorphic core complexes with respect to the Sevier fold and thrust belt. Lower plates of core complexes show lineations developed parallel to the direction of extension. Shaded areas represents highly extended region in NE Nevada and adjacent Utah. Data from Compton (1980), Snoke (1980), and King (1969).

supracrustal rocks and underlying metamorphic and igneous rocks inferred to have originated at much deeper levels (see review by Coney (1979) and papers by Crittenden et al. (1980). The age and tectonic significance of this striking juxtaposition are topics of current and lively debate.

Prior to geochronologic evidence for a Tertiary age, the detachment faults in these terranes were commonly interpreted as Mesozoic thrust faults. For example, Misch (1960) speculated that the Snake Range décollement in east-central Nevada (Figure 1) represented a regionally extensive shearing off fault whose frontal breakthrough occurred far to the east as one of the thrusts of the Sevier fold and thrust belt (Miller, 1966).

Hose and Danes (1973) and Hintze (1978) also assigned a Mesozoic age to the Snake Range décollement but recognized that overlying rocks had been drastically thinned. They proposed that east-central Nevada and Utah represented an uplifted, extended hinterland behind a gravity-driven thrust belt to the east.

Other workers in the northern Basin and Range province have applied a gneiss dome model to core complexes. Armstrong (1968a) described deep seated Mesozoic mantled gneiss domes in the Albion Range, Idaho, that were later affected by Tertiary uplift and denudation. Howard (1980) and Snoke (1980) suggested that the attenuation of rocks beneath the Ruby Mountains décollement (Figure 1) was related to the formation of a Mesozoic abscherungszone between mobile infrastructure and allochthonous brittle suprastructure. Compton et al. (1977), Compton (1980) and Todd (1980) concluded that the Raft River-Grouse Creek core complex (Figure 1) formed by the gravitational denudation of a rising gneiss dome, but documented that both the ductile and brittle deformation was largely Tertiary, not Mesozoic, in age. Similarly, new data from the Ruby Mountains highlight the role of Tertiary ductile deformation and magmatism in the formation of the Ruby Mountains décollement (Snoke et al., 1982).

Within the context of Tertiary extensional tectonics, several models have been proposed for detachment faults in metamorphic core complexes. G. A. Davis et al. (1980) interpreted the Whipple Mountains detachment fault in southern California as the sole of an extensive, far-traveled gravity slide complex. Wernicke (1981) introduced the concept of an 'extensional allochthon' whereby the juxtaposition of supra- and midcrustal rocks is effected along a very low angle zone of simple shear that ultimately involves the entire crust. G. H. Davis (1980) and Hamilton (1982), though differing in the specifics of their models, envision detachment faults as the boundary between an upper crust extended by normal faulting and underlying crustal blocks or lenses that have been pulled apart along ductile shear zones. Rehrig and Reynolds (1980) linked supracrustal extension above detachment faults to underlying, deeper seated penetrative stretching and dilation by intrusions.

In order to evaluate the validity of these models, two basic questions must be answered: (1) How does the age, magnitude, and geometry of the strain in the upper plate of detachment faults compare with that of the lower plate? (2) What is the sense and amount of relative movement between upper and lower plate rocks along detachment faults and how extensive are such faults? Unfortunately, in most metamorphic core complexes, superimposed thermal and structural events have obscured the answers to these questions.

This paper focuses on the age, three-dimensional extent, and tectonic significance of the northern Snake Range décollement (NSRD) in east-central Nevada. The northern Snake Range is particularly well suited for testing models of detachment faulting because (1) a straightforward miogeoclinal stratigraphy in both the upper and lower plates of the NSRD permits an accurate analysis of the strain that has affected these rocks, and (2) the demonstrable lack of predetachment faulting deformation in this region makes structural and stratigraphic relations across the NSRD unambiguous and allows estimation of paleodepths.

REGIONAL SETTING

The Snake Range and surrounding region was the site of relatively continuous continental shelf sedimentation from the Late Precambrian through the early Triassic (Stewart and Poole, 1974; Hose and Blake, 1976). During this timespan, about 10-12 km of strata were deposited above thinned Precambrian crystalline rocks (Figure 2).

Mesozoic thrust faults are well documented to the east in the Sevier orogenic belt (Armstrong, 1968b) and to the west in western Nevada (Speed, 1978) but did not breach the surface in east-central Nevada (see Armstrong, 1972, and discussion by Gans and Miller (1983). The principal evidence for this is that early Tertiary rocks rest disconformably and exclusively on upper Paleozoic strata. Beneath the early Tertiary unconformity, conformable sections that span the entire Upper Precambrian to late Paleozoic interval effectively rule out regional Mesozoic décollement at any of the present levels of exposure (see discussion by Gans and Miller (1983)). Thus, 'stratigraphic depths' within the miogeocline are an accurate estimate of Mesozoic to early Tertiary 'structural depths'.

At shallow levels, Mesozoic shortening of small magnitude is recorded by gentle folds in upper Paleozoic strata, whereas at deeper structural levels, upper Precambrian and locally Lower to Middle Cambrian strata were intruded by plutons and penetratively deformed during regional dynamothermal, greenschist to amphibolite grade metamorphism (Misch, 1960; Misch and Hazzard, 1962; Gans and Miller, 1983). The Snake Range lies within a much broader belt of mid-Tertiary extension and mountain ranges within this belt are

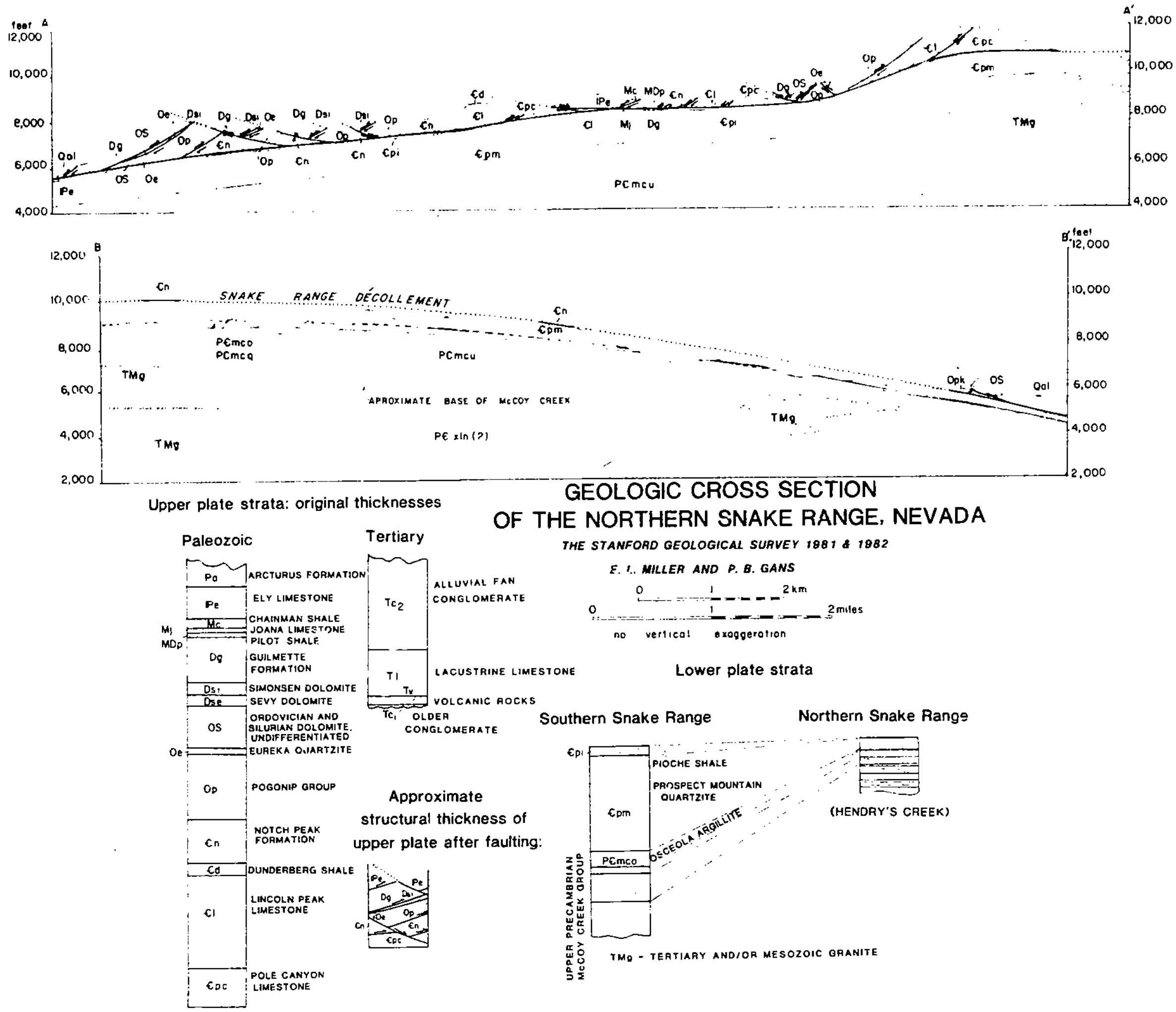


Fig. 2. Geologic cross section and summary of upper and lower plate stratigraphy, northern Snake Range. Symbols as in Plate 1.

characterized by complex arrays of imbricate low- and high-angle normal faults (Gans and Miller, 1983).

The Geology of the Northern Snake Range

Portions of the Snake Range were previously mapped by Drewes (1958), Nelson (1959), Whitebread (1969), Hose and Blake (1976), and Hose (1981). The Snake Range décollement was first described by Hazzard et al. (1953) and has prompted additional interpretations by Misch (1960), Armstrong (1972), Coney (1974), Hose and Whitebread (1981), and Wernicke (1981). Our views differ from these workers and are based on two summers of mapping by Miller, Gans, and the Stanford Geological Survey in the Snake Range, mapping in adjacent ranges by Gans (1982; Gans and Miller, 1983), and gravity surveys of the region encompassing the Snake Range by Garing.

In the northern Snake Range, vast expanses of penetratively stretched Upper Precambrian and Lower Cambrian metasedimentary rocks and granitic plutons of unknown age are exposed beneath the northern Snake Range decollement (NSRD). Lithologic contacts and foliation in the lower plate are structurally concordant to the gently arched NSRD which generally follows the top of the Lower Cambrian Pioche Shale (Figure 2 and Plate 1). In contrast, Middle Cambrian to Permian and Tertiary strata in the upper plate are broken and tilted by imbricate normal faults that do not cut the decollement.

Upper Plate Faulting

Geometric relations. The geometry of upper plate faults is best documented in the southwestern part of the northern Snake Range, where the upper plate is largely preserved. Exposures of the NSRD to the north, east, and in a window along the Negro Creek drainage constrain its subsurface geometry and provide critical views of the relations between upper plate faults and the décollement (Figure 2 and Plate 1).

Despite the extremely complex map pattern, a systematic structural style is evident in the upper plate. Structural sections that 'young' to the west are repeated eastward on east dipping faults (Figure 2 and Plate 1). Older, west dipping faults within these structural sections typically omit units. The two generations of faults are even more apparent in cross section (Figure 2). The younger faults are spaced approximately 1 km apart, dip 10 to 20° eastward, and merge with but do not offset the NSRD. The older faults are more closely spaced, dip 10° to 30° westward, and are truncated by either the NSRD or the younger faults. In three dimensions, the upper plate faults resemble faults in the Egan Range described by Gans (1982) and Gans and Miller (1983). They define shovel-shaped scoops that are 1.5-5 km across but are relatively planar in the direction of movement.

Hanging wall strata are displaced eastward relative to footwall strata on both generations of faults. The younger faults are clearly down-to-the-east normal faults, whereas the older faults presently have apparent reverse offset. The younger faults typically juxtapose upper Paleozoic formations on lower Paleozoic formations. Their actual offsets (0.2-2.0 km) are generally much less than their stratigraphic offsets (up to 4 km) because they displace sequences that were previously attenuated by the older faults.

Bedding attitudes in the upper plate are variable. Most strata strike N10E to N45E and dip northwest, but the amount of tilting ranges from 0 to 90° or even overturned (Figure 2). Bedding tilts are generally low in incompetent units and near faults. Tilts become progressively steeper away from fault planes, and the steepest westward dips occur in the more massive limestone units between widely spaced faults. Only these steepest dips reveal the true amount of westward rotation and the original bedding-to-fault angles; all lesser dips are demonstrably the result of normal drag on upper plate faults.

Faulting is more complex in the Miller Basin area (Plate 1), where domains of conjugate, down-to-the west faults and southeastward tilting occur as well as domains of down-to-the-east faults. High-angle strike-slip fault zones separate domains of opposite tilting. South of Miller Basin, faults become more widely spaced and the total amount of extension appears to diminish rapidly (Plate 1 and Figure 3).

Kinematic interpretations. The fact that movement on relatively planar, high-angle faults in the upper plate was accommodated by a subhorizontal detachment plane at depth requires that stratal rotation must have accompanied upper plate faulting. Figure 4 illustrates a sequence of faulting and tilting events that would result in the present bedding and fault attitudes. These simplified sequential cross sections do not attempt to show the effect of normal drag. The first generation of faults originated as east dipping, high-angle (50° to 60°) normal faults that subsequently rotated 'domino style' (Thompson, 1960; Morton and Black, 1975) to low angles. Second-generation faults also originated as high-angle faults and were superimposed on previously faulted and tilted strata. As the second-generation faults rotated to low angles, segments of the first-generation faults were rotated through horizontal into westward dips, thus causing the apparent reverse offsets. Note that the toes of the first generation faults were rotated away from the NSRD, whereas higher segments were rotated downward and are presently truncated by the decollement. Nonetheless, the first-generation faults must have interacted with the same basal detachment because they affect the entire range of stratigraphic units in the upper plate. Later doming of the NSRD probably added an additional 5° to 10° of westward tilt to the Negro Creek area.

If both generations of faults originated at the same angle with respect to horizontal, then the average angular difference between them (40°)

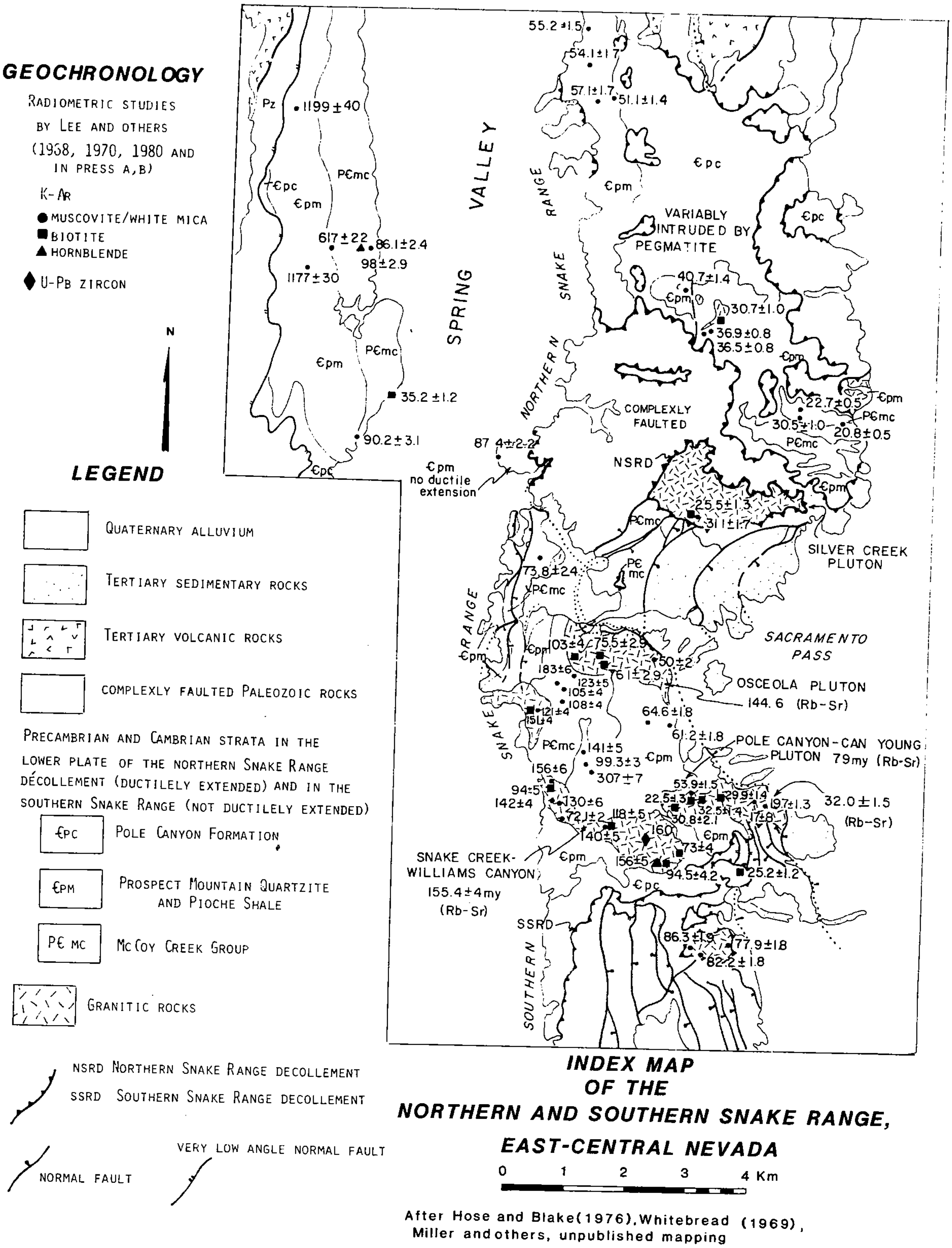


Fig. 3. Index map of the northern and southern Snake Range, Nevada, showing location of published radiometric dates.

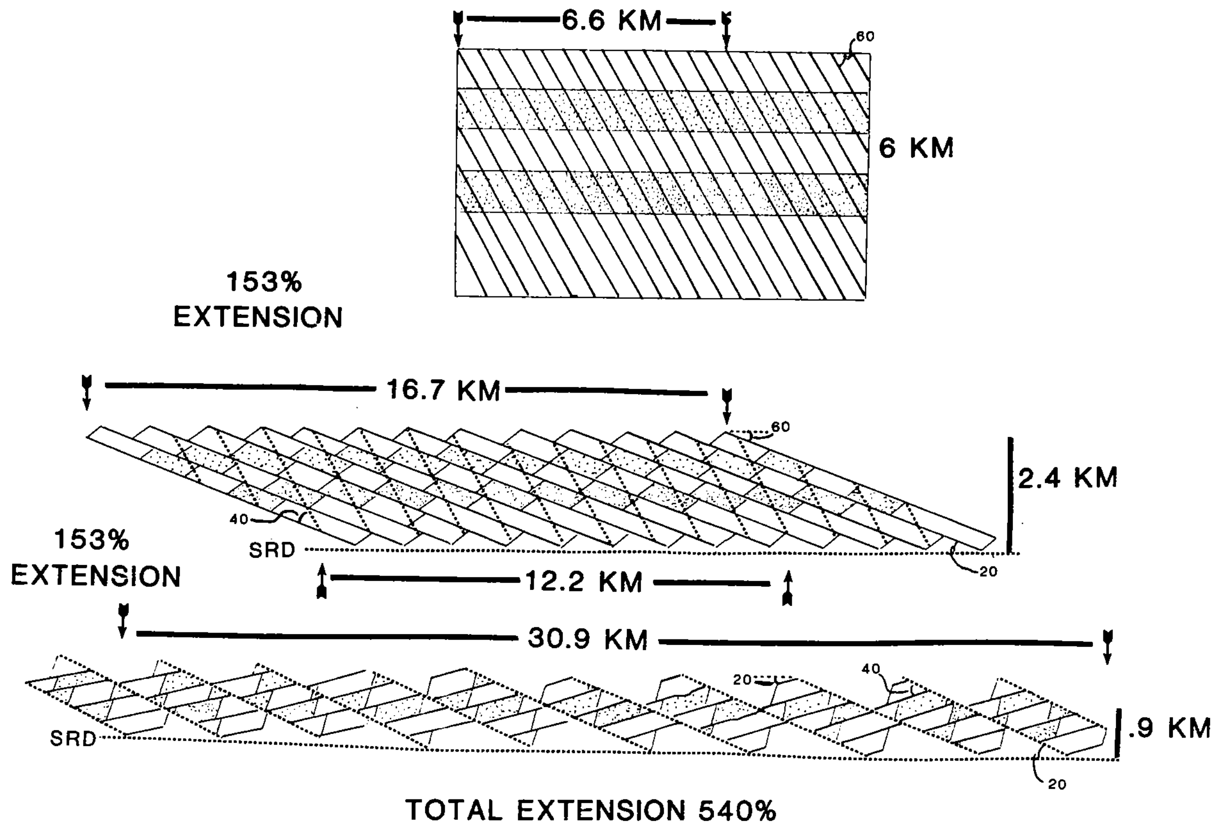


Fig. 4. Simplifed geometric model showing how two generations of upper plate faults interact with the decollement (SRD) to produce the bedding and fault attitudes observed in the Snake Range.

is precisely the amount of rotation that occurred on the older faults alone. Once these faults had rotated to dips as low as 20°, the resolved shear stress on the fault planes apparently no longer exceeded the frictional resistance to movement, and a new generation of high-angle normal faults was developed.

Large bedding-to-fault angles at all stratigraphic levels in the upper plate indicates that both generations of faults originally intersected the NSRD at high angles (50° to 60°). Space problems at the toes of fault blocks were apparently relieved by (1) brecciation of the more massive lithologies, (2) warping and folding of less competent units, and (3) low-angle splays at the toes of major fault blocks (see discussion by Gans and Miller 1983). The third process may have been particularly important during movement on the younger, more widely spaced faults as segments of older, rotated faults were reactivated.

<u>Direction of extension in the upper plate</u>. The direction of extension of the upper plate on the west flank of the Snake Range was estimated to be N55W-S55E. Poles to bedding planes form a diffuse great circle whose pole is oriented about N35E and subhorizontal (Figure 5) parallel to the strike of normal faults. These bedding attitudes are compatible with tilting and/or drag folding along southeast directed dip-slip movement faults. Similarly, the orientation of the sides of 'scoops' or 'shovels' and the trends of strike-slip faults between conjugate domains of faulting suggest NW or SE directed movement on upper plate faults.

<u>Amount of extension in the upper plate</u>. We have estimated the amount of extension in the upper plate for the Negro Creek area by three independent methods:

1. Sequentially restoring the faults along our line of cross section (Figure 6) yields approximately 125%

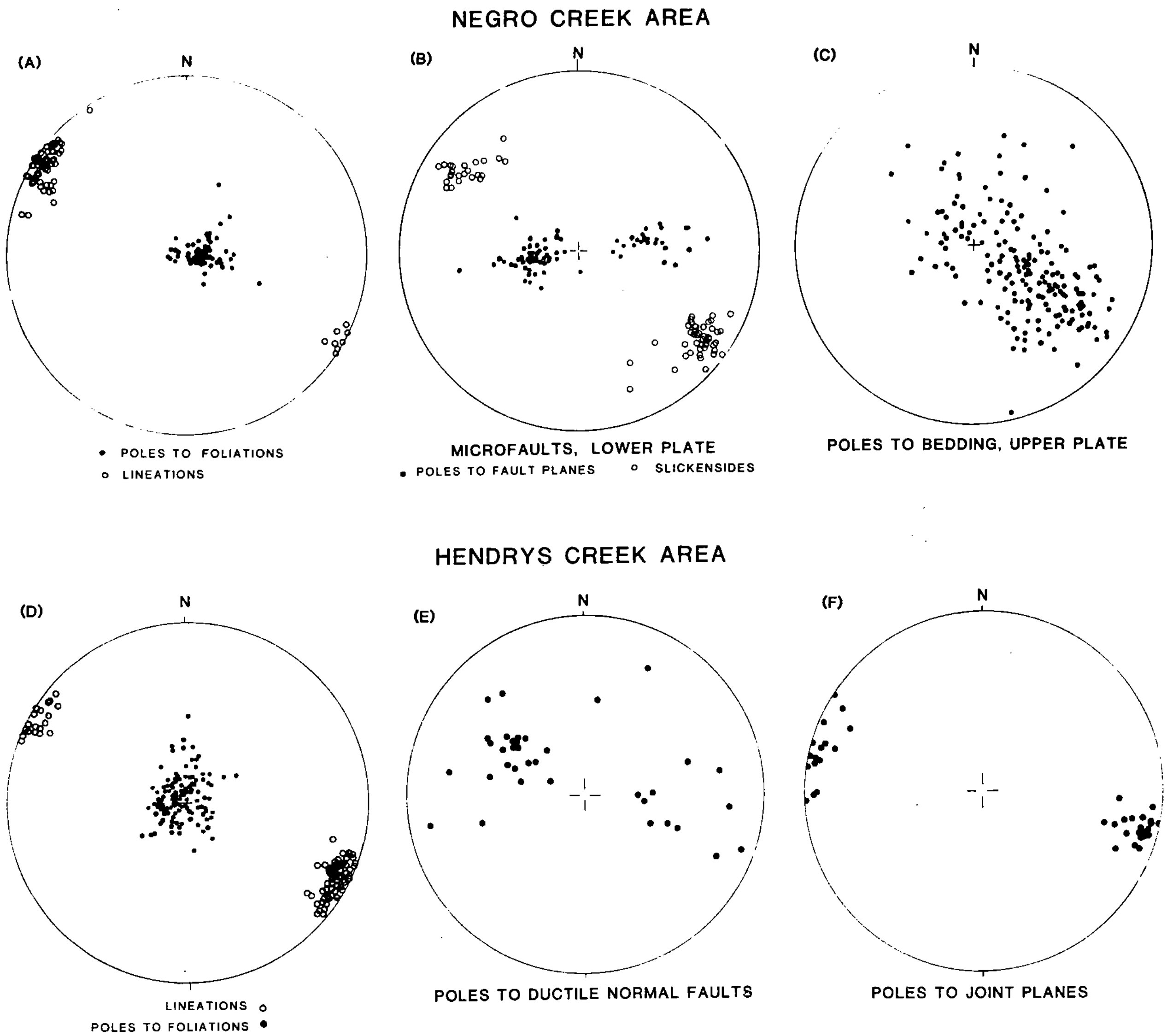


Fig. 5. Selected structural data from the northern Snake Range (lower hemisphere equal area projection). (a.) Attitude of foliation and lineation in the lower plate of the NSRD, Negro Creek area. (b.) Late-stage ductile-to-brittle microfaults in the Prospect Mountain Quartzite, Negro Creek area. (c.) Poles to bedding in the upper plate, Negro Creek area. (d.) Attitude of lower plate foliation and lineations in the middle reaches of Hendry's Creek. (e.) Poles to closely spaced or penetrative conjugate ductile normal faults (extensional cleavage) in McCoy Creek Group schist units along Hendry's Creek. Here, the east dipping set is best developed. (f.) Poles to joint planes, youngest of mesoscopic structures, lower plate rocks in Hendry's Creek. For location of Negro and Hendry's Creek, see Plate 1.

extension by second generation faults and 155% extension by first generation faults for a total of 480% extension (i.e., ((2.55 x 2.25) - 1.0) x 100 = 480%). This method has obvious problems because of the immense amount of small-scale faulting, brecciation, and folding that has changed the shape of the larger fault slices.

2. Our best estimate of the average structural thickness of the upper plate after normal faulting but prior to

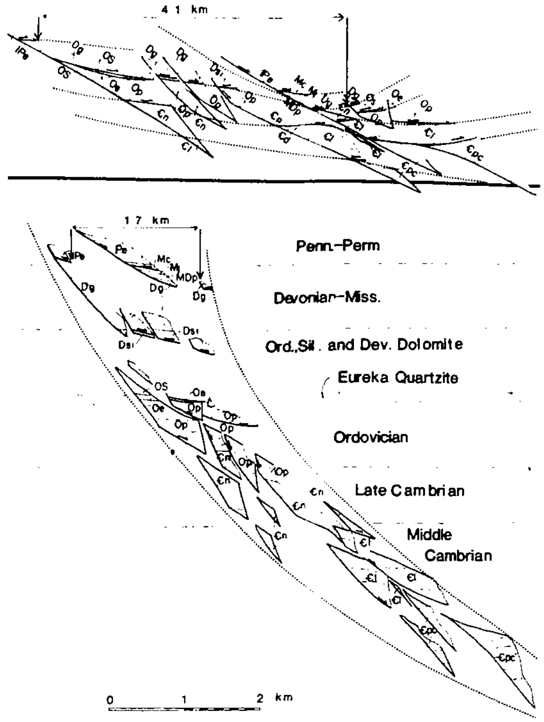


Fig. 6. "Cut and paste" restoration of Snake Range upper plate faults along cross section A-A'. Unit symbols serve as in Figure 2 and Plate 1. Heavy solid lines are second-generation faults, dashed lines are early generation faults. Erosion and change of shape due to brecciation, folding and small-scale faulting is largely responsible for the imperfect match across fault planes.

erosion is approximately 1.1 km compared to an original stratigraphic thickness of 6-7 km (Figure 2), similar to values calculated by Hose (1981). Assuming constant-volume plane strain, this change in thickness is equivalent to about 450% extension.

3. Calculation of the percent extension by using bedding-to-fault angles and the amount of tilting (Figure 6)(Thompson, 1960) yields 153% extension by both generations of faults for a total of 540% extension. This estimate is probably somewhat excessive because it does not account for deviations from two simple generations of faults or for the internal deformation in fault blocks.

Considering the large uncertainties in all of these estimates, we are impressed by how closely they agree. We conclude that 450-500% is a reasonable, perhaps even conservative, estimate of the amount of extension in the upper plate of the northern Snake Range.

Age of upper plate extension. The best constraints on the age of upper plate faulting come from the Tertiary rock sequence exposed in the Sacramento Pass area (Figures 2 and 3, and Plate 1). This sequence has been described by Hose and Blake (1976), Hose and Whitebread (1981) and most recently by S. Grier (1983; manuscript in progress, 1983). Here, 35-m.y.-old volcanic rocks rest depositionally on only upper Paleozoic strata. Overlying lacustrine and alluvial fan deposits contain debris derived from late Precambrian to Permian miogeoclinal strata, Mesozoic(?) plutons, and Tertiary rocks, suggesting that they were deposited synchronously with nearby faulting and uplift. The sequence does not, however, contain clasts derived from the lower plate of the NSRD. The Tertiary rocks in Sacramento Pass are cut by imbricate normal faults that merge with the NSRD (Hose and Whitebread, 1981)(Figure 3 and Plate 1) and geometrically resemble the second generation of faults in the Negro Creek area. The younger age limit for these faults is unknown. This data is consistent with relations in adjacent ranges that bracket much of the normal faulting in east-central Nevada as Oligocene (Gans, 1982; Gans and Miller, 1983). We differ with Hose and Whitebread (1981) in that we see no evidence for significant faulting and uplift prior to the deposition of the basal Tertiary units.

Lower Plate Deformation

Introduction. In marked contrast to the upper plate, rocks beneath the NSRD are relatively flat-lying and are not cut by faults (Figure 2 and Plate 1). Instead, they reveal a complex history of magmatism, metamorphism, and ductile deformation that ended with a transition into a brittle regime. Argon 40/Ar 39 and U-Pb dating in the northern Snake Range are presently underway; at this time it is not clear what proportion of the high grade metamorphism and plutons are Mesozoic or Tertiary. Most K-Ar mineral dates from lower plate rocks are between 20 and 40 m.y. old (Lee et al., 1968, 1970, 1980, and in press a,b), (Figure 3) but these dates may in part reflect Tertiary reheating of older metamorphic rocks and plutons.

Lower plate metasedimentary rocks are amphibolite grade, and the metamorphism appears to increase both with depth and to the north. Pelitic units in the lowermost part of the Cambrian Pioche Shale along the west flank of the range contain the assemblage staurolite-garnet-muscovite-biotite-quartz. At a deeper stratigraphic level on the east flank of the range, the Osceola Argillite contains kyanite-muscovite-biotite-quartz and locally garnet (Rowles, 1982). It is noteworthy that on the basis of their stratigraphic position, these assemblages appear to have formed at a significantly shallower depth (6-8 km) than the experimentally derived minimum depths (e.g., Holdaway, 1971).

Both in outcrop and in thin section, this high grade metamorphic fabric is clearly cut by or transposed into parallelism with a penetrative subhorizontal foliation which developed at lower metamorphic grade (Rowles, 1982). The older, higher grade metamorphism could be Mesozoic in age, like mid-Jurassic fabrics described in late Precambrian rocks in adjacent ranges (Misch, 1960; Gans and Miller, 1983). However, the younger K-Ar dates from the Snake Range suggest it may well be as young as Tertiary. The strain associated with the younger deformation is so intense that the orientation of older fabrics and magnitude of older strain can no longer be ascertained in the map area. Furthermore, it is unclear what the relationship of plutons are to this metamorphism, as they too have been intensely deformed by this younger event.

Plutons in the lower plate are principally granitic in composition. The largest of these, the Silver Creek pluton (Plate 1), grades from a 2-mica granite margin to a biotite granodiorite interior and, in its eastern exposures includes minor hornblende diorite. Swarms of muscovite-garnet bearing pegmatite dikes intrude both the plutons and metasedimentary rocks and locally comprise up to 80% of the lower plate. Although pegmatite dikes are common immediately below the decollement, they are not present in exposures of the upper plate.

<u>Progressive (Ductile to Brittle) Extension</u>. Superimposed on all lower plate metamorphic and igneous rocks is a younger penetrative subhorizontal foliation and lineation that increases in intensity both eastward and upward toward the decollement. This deformation was accompanied by retrograde low greenschist grade metamorphism. In the westernmost exposures of lower plate(?) Prospect Mountain Quartzite (Figure 3 and Plate 1), foliation and lineation are weakly developed, whereas on the east flank of the northern Snake Range, stratigraphic sequences originally about 3 km thick have been ductilely thinned to less than 0.5 km (Figure 2 and Plate 1). Highly attenuated, mylonitic sections of Pioche Shale and the very basal part of the Pole Canyon Limestone are present nearly everywhere beneath the decollement (Figure 2), but are often too thin to be shown on our geologic map (Plate 1). Although lower plate strain diminishes away from the decollement, it does not die out within the present levels of exposure. Since the original thickness and the amount of strain of deeper McCoy Creek Group rocks is unknown, depth to Precambrian crystalline basement is speculative (Figure 2).

In detail, lower plate strain is quite complex and heterogeneous. At the low greenschist grade conditions under which deformation occurred, quartz behaved ductilely while feldspars and micas behaved brittlely. Micas in schist units are either kinked (if the older metamorphic layering is at an angle to the younger subhorizontal fabric), or have been mechanically rotated into parallelism with the new fabric. Metamorphic porphyroblasts such as garnet, staurolite and kyanite are kinked, pulled apart, or rotated, but trains of inclusions in these minerals still preserve an older fabric (Rowles, 1982). Granitic rocks and pegmatite dikes are variably deformed depending on their quartz to feldspar ratio, grain size and/or dike attitude. The plutons, because of their high feldspar content, are in general less deformed than metasedimentary country rocks and have essentially behaved as giant 'augen' during deformation. The only rocks that are not involved in lower plate

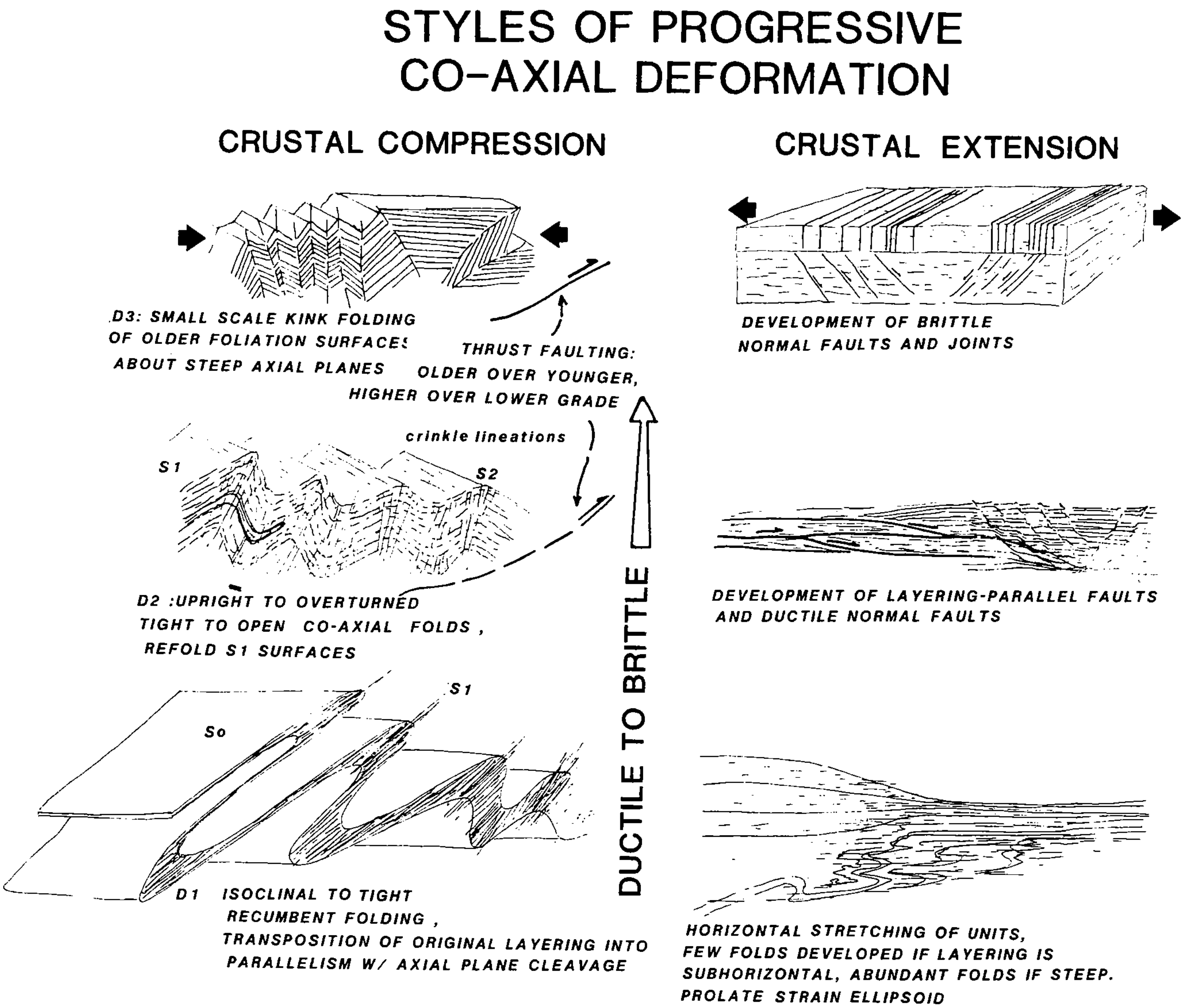


Fig. 7. Comparison of ductile to brittle progressive deformational fabrics produced during compression and extension.

deformation are rare, fine-grained quartz porphyry dikes that cut the subhorizontal fabric yet in one locality are truncated by the NSRD. Similar quartz porphyry dikes are locally present in the upper plate and are involved in the faulting.

Mesoscopic structures associated with the subhorizontal fabric in the lower plate record ductile to brittle progressive extension (Figures 5 and 7). Stretched pebbles and mineral grains indicate extension in a NW-SE direction and flattening in a vertical direction. The direction of stretching in the lower plate rocks of the NSRD varies from N55W on the west side of the range to N70W on the east side. Aspect ratios of stretched pebbles in McCoy Creek Group strata on the east flank of the range are commonly of the order of 8-10: 1:0.1. Occasional mesoscopic and, more rarely, map-scale folds are present in the lower plate. Folds in the Hampton Creek area (Plate 1) have been described by Rowles (1982). Here, fold axes are everywhere subparallel to the direction of extension, and are overturned both to the north and south. Most of these folds probably formed during extension and reflect (1) local changes in the magnitude and configuration of the intermediate and minor strain axes, and/or 2) superposition of the extensional strain ellipsoid on originally nonhorizontal layering (Rowles, 1982).

Late stage brittle structures such as microscopic and mesoscopic ductile normal faults, brittle normal faults and joints in the lower plate indicate a NW-SE direction of extension, parallel to the direction of mineral grain and pebble elongation (Figure 5). East dipping mesoscopic and microscopic ductile normal faults are sometimes preferentially developed over their west dipping conjugate sets, particularly along the east flank of the range.

The ductile to brittle progressive deformation recorded in lower plate rocks of the Snake Range is similar to extensional fabrics described by G. H. Davis (1980) in many of the Arizona metamorphic core complexes, and unmistakably different from that typically developed in rocks during progressive compressional deformation (Figure 7).

Amount of extension in the lower plate. We have estimated the amount of extension in the lower plate by the change in thickness of the Lower Cambrian Prospect Mountain Quartzite. Undeformed Prospect Mountain Quartzite sections in adjacent ranges are typically 1200 m thick. On the east flank of the northern Snake Range, complete sections of this unit are generally only 100-200 m thick. On the west side of the range, the base of the Prospect Mountain Quartzite is not exposed. However, the reduction in average bedding thickness (from 45 cm to 15 cm) suggests that it has been thinned to approximately one third its original thickness. An average of 330% extension across the range was derived by restoring the Prospect Mountain Quartzite to its original thickness while preserving its cross-sectional area.

Age of lower plate extension. The age of lower plate extension is not yet bracketed radiometrically, but we strongly suspect that it is Tertiary and synchronous with upper plate normal faulting. Indirect arguments that support this age assignment include (1) the similarity in magnitude and precise parallelism of lower and upper plate strain axes, (2) anomalously young Tertiary K-Ar mica ages from all rock types in the lower plate as compared to non-stretched but equivalent structural levels in adjacent ranges (Figure 3), and (3) well-documented mid-Tertiary ages for identical fabrics in the nearby Raft River Range and Ruby Mountains (Compton et al., 1977; Snoke et al., 1982).

The northern Snake Range décollement. The northern Snake Range décollement is an extremely sharp break between brittlely and ductilely deformed rocks. In most places, the same formation (Pole Canyon Limestone) is present immediately above and below this fault. Assuming that lower plate stretching was synchronous with upper plate faulting, then the NSRD represents an exhumed mid-Tertiary, ductile-brittle transition zone. Irregular zones of ductile deformation and recrystallization in the lower portions of upper plate fault slices (Pole Canyon Limestone) suggest that, initially, the transition was fairly diffuse. As extension continued, the transition was rapidly localized within a narrow (probably less than 100 m) interval. Local shattering and brecciation of lower plate mylonitic rocks suggest that the NSRD ultimately evolved into a strictly brittle fault.

REGIONAL EXTENT OF THE SNAKE RANGE 'DUCTILE-BRITTLE TRANSITION ZONE'

Gravity Models of the Snake Range and Adjacent Valleys

The extent of the Snake Range décollement beyond the northern Snake Range can be inferred from subsurface data in the adjacent valleys and structural relations in adjacent ranges. We have compiled a Bouguer gravity anomaly map of the Snake Range and surrounding areas (Figure 8) in order to evaluate the geometry of the adjacent basins and to judge whether the associated 'Basin and Range' faults cut the NSRD. Bouguer anomaly values in the map region range from -250 to -150 mGaL; conspicuous northerly trending gravity lows correspond to valleys underlain by low density Tertiary and Quaternary

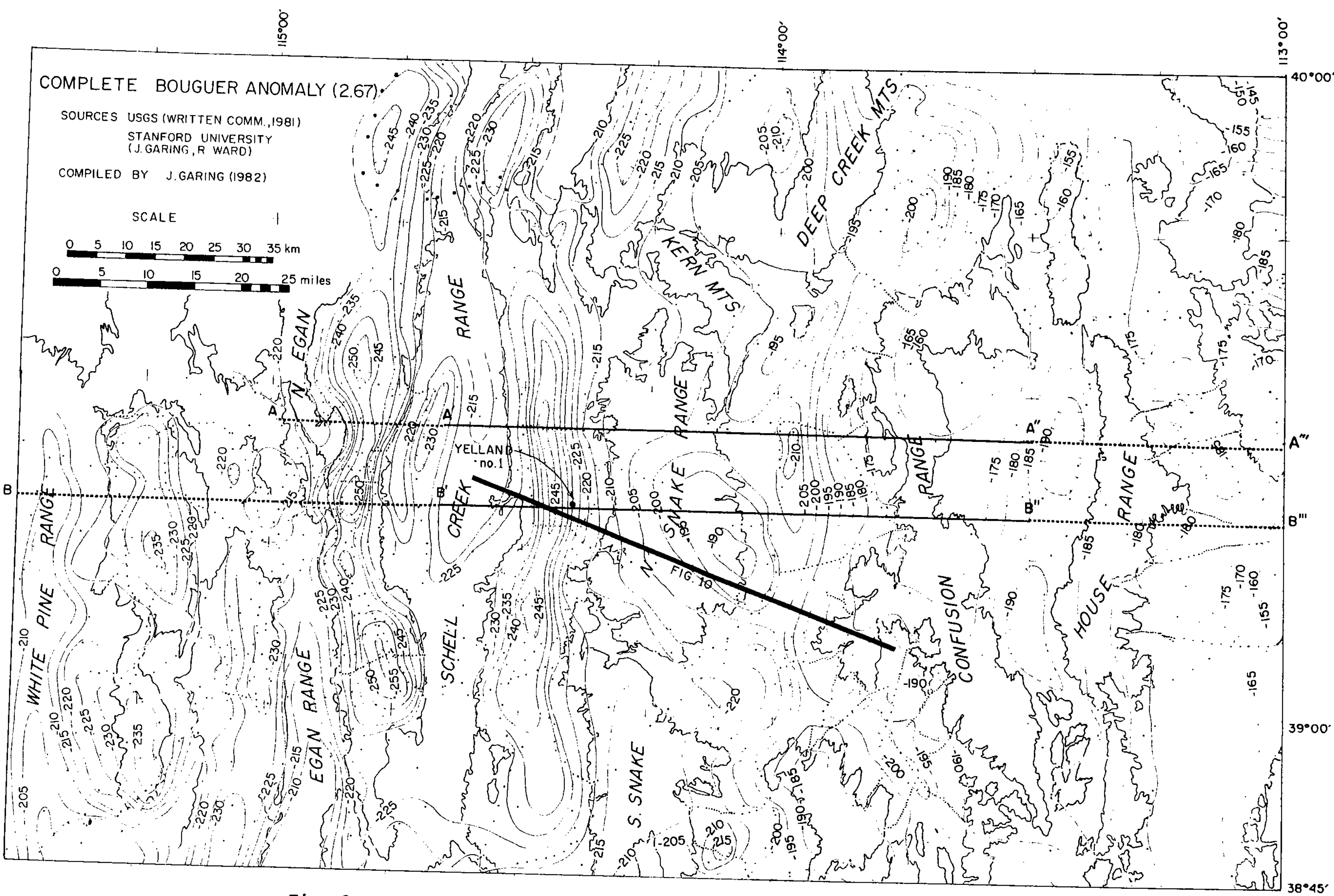
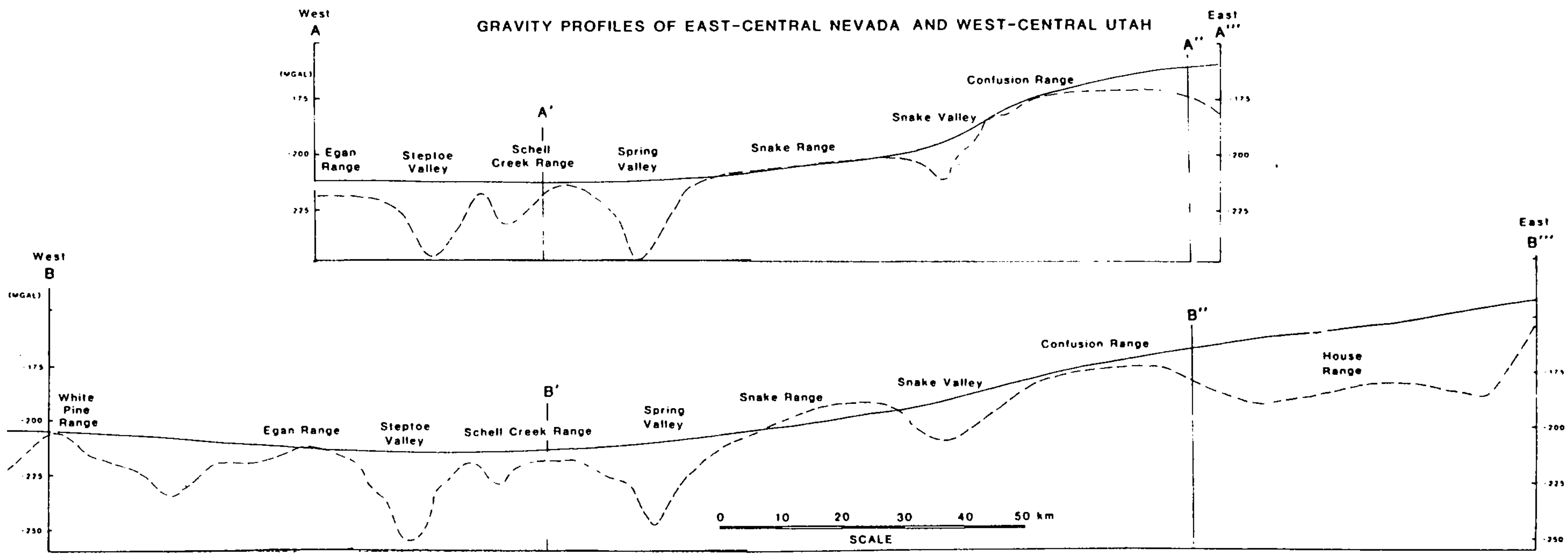


Fig. 8. Bouguer gravity anomaly map of the Snake Range and vicinity.

GRAVITY PROFILES OF EAST-CENTRAL NEVADA AND WEST-CENTRAL UTAH



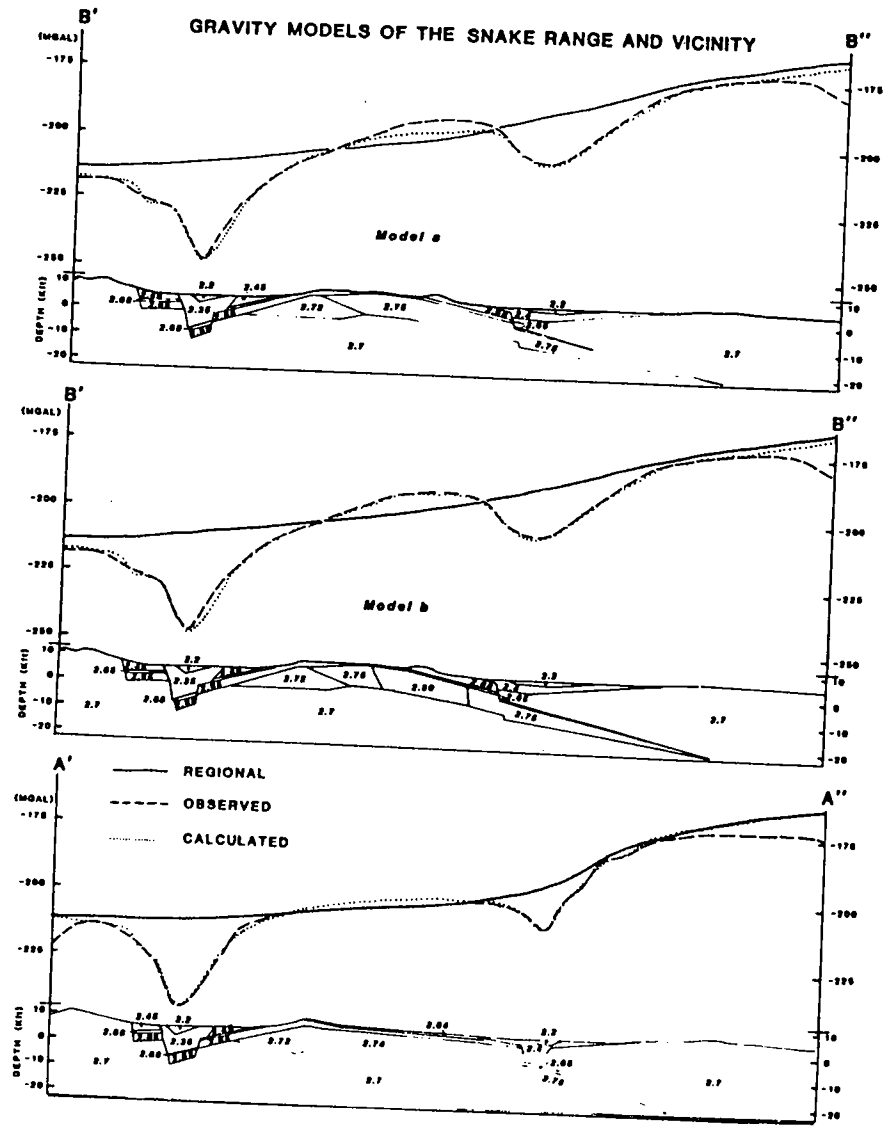


Fig. 9. Gravity profiles and models across the Snake Range and adjacent valleys, see Figure 8 for locations.

TABLE 1. Summary of Sample Densities for the Snake Range Region

Sedimentary and Metamorphic Rocks	Range of Densities	Number of Samples	Average
Quaternary Valley fill	2.1-2.4	well logs*	...
Tertiary Lake Deposits	2.375-2.59	3	2.49
Upper Plate Paleozoic Carbonate	2.57-2.76	9	2.68
Lower Plate Marble	2.59-2.85	8	2.66
Cambrian Prospect Mountain Quartzite	2.615-2.66	7	2.64
PC McCoy Creek Group			
Quartzite	2.64-2.655	2	2.65
Quartzose Schist	2.65-2.68	4	2.67
Schist	2.65-3.25	15	2.78
Igneous Rocks			
Hornblende diorite	2.895-2.925	4	2.91
Biotite granite	2.62-2.665	8	2.65
Muscovite-bearing granite pegmatite	2.57-2.64	2	2.61
Tertiary/Quaternary volcanic rocks	2.3-2.4	well logs*	...
Precambrian crystalline basement	...	...	2.7

Wells used: 1-20 Federal SE NW Sec 20 T12N R67E; #1 Yelland NW SE Sec 23 T17N R67E.

* Source of information: Dome Petroleum (written commmunication, 1982).

The relatively undeformed Paleozoic section beneath the Confusion Range was assigned an average density of 2.70 g/cm^3, while faulted and brecciated upper Paleozoic rocks in the Snake Range were assigned a density of 2.68 g/cm^3.

Mylonitic marble beneath the Snake Range decollement (Cambrian Pole Canyon Limestone) is modeled with a density of 2.64 g/cm^3, the sample normative value instead of the average density of 2.66 g/cm^3.

The density of the McCoy Creek Group is modeled as varying laterally as the schist to quartzite ratio increases eastward. Also, highest grade schists on the east flank of the Snake Range are more dense than any sample collected from equivalent units in the adjacent Schell Creek Range to the west.

A density of 2.70 g/cm^3 is used for inferred Precambrian crystalline rocks at depth which is the average for the United States calculated by Wollard (1962).

alluvial and lacustrine sediments. Within the intervening mountain ranges, the effect of the valley fill is reduced sufficiently for more regional gravity anomaly values to be measured. Relative gravity anomaly highs within the mountain ranges increase from west to east, suggesting a strong regional gradient in the Bouguer anomaly (Figure 9, B-B"). This regional trend is thought to be due largely to variations in thickness of the lithosphere beneath this region (Eaton et al., 1978; Thompson and Zoback, 1979). The regional gravity profiles in Figure 9 were qualitatively estimated and were not determined by our modeling which focuses instead on features in the upper 10 km of crust. Density assignments for the gravity models are based on measurements of rock samples collected in the ranges and density log data from wells in Spring Valley (Table 1). Our density models for the Snake Range follow our geological cross sections and exceptions to density assignments for particular lithologies are listed in Table 1.

The gravity low observed over Spring Valley is best fit by a model involving three high-angle normal faults that displace the pre-Tertiary basement surface (Figure 9). The most significant of these faults occurs along the flank of the Schell Creek Range and has a down-to-the-east displacement of approximately 6-8 km (Figures 9 and 10). Gravity data in Snake Valley to the east of the Snake Range suggests the presence of a down to the east range front fault with about 1.5 km or more of offset (Figure 9). According to our data, the thickness of basin fill, and thus the displacement along this fault, increases toward the north. If the NSRD extends beneath these valleys, it seems most likely that it is cut and offset by the high-angle Basin and Range faults.

Using the values listed and discussed in Table 1, the calculated gravity anomaly (model a) along line B'-B" does not fit the observed Snake Range anomaly well and implies that the model needs more mass beneath the east side of the range. An alternate density model for section B'-B" is shown (model b) with mass added in order to generate a calculated anomaly that matches the observed anomaly. The added mass could be due to more mafic intrusive rocks at depth, either within the metasedimentary sequence or in the underlying crystalline basement. Alternatively, the added mass could be explained by a greater percentage of particularly dense garnet-staurolite schist in the McCoy Creek Group (d max = 3.25 gM/cm^3, Table 1).

Section A'-A", on the other hand, requires a reduction in the mass of the density model for a match between the observed and calculated gravity anomalies. The excess mass could be removed by lowering the density assignment for the McCoy Creek Group rocks, suggesting a decrease in the schist:quartzite ratio northward, or could be due to the presence of lower density granitic plutons at depth (d = 2.65 g/cm^3).

Westward continuation of the NSRD

Yelland Well #1 in Spring Valley (Figure 8) penetrated 1650 m of Quaternary and Tertiary deposits and 150 m of Paleozoic rocks before reaching quartzite at a depth of 1800 m. (Dome Petroleum, private communication, 1982). This depth is compatible with the projected depth of the NSRD based on its attitude along the west flank of the Snake Range, and compatible with our gravity data that suggests no major faults cut the decollement along this side of the valley (Figure 10), but we do not know if this quartzite is penetratively stretched. Further west, an impressively thick 30°-45° west dipping section of Precambrian McCoy Creek Group and Prospect Mountain Quartzite is exposed along the east flank of the Schell Creek Range (Misch and Hazzard, 1962; Young, 1960; Drewes, 1967; Hose and Blake, 1976) (Figure 10). These rocks are not ductilely extended like their counterparts in the lower plate of the northern Snake Range, and are in places conformably overlain by Pioche Shale and Pole Canyon Limestone. In the Conners Pass Area, Drewes (1967) mapped low-angle younger on older faults within the middle Cambrian portion of the section (the 'Schell Creek Thrust') and between Cambrian and Ordovician strata. Further north, Hose and Blake (1976) mapped a low-angle fault within the Pole Canyon Limestone along part of the range. If either of these faults represent the westward continuation of the NSRD, it has cut upsection and has lost its Snake Range character in that it no longer juxtaposes brittlely and ductily stretched rocks. However, these faults may not be 'basal detachments' like the NSRD but rotated 'upper plate' type faults that have locally dragged bedding into parallelism with the fault planes. To the north of our line of section, McCoy Creek Group strata are clearly involved in down-to-the-southeast normal faulting and have steep (up to 50°) westward tilts, suggesting that they overlie a deeper detachment

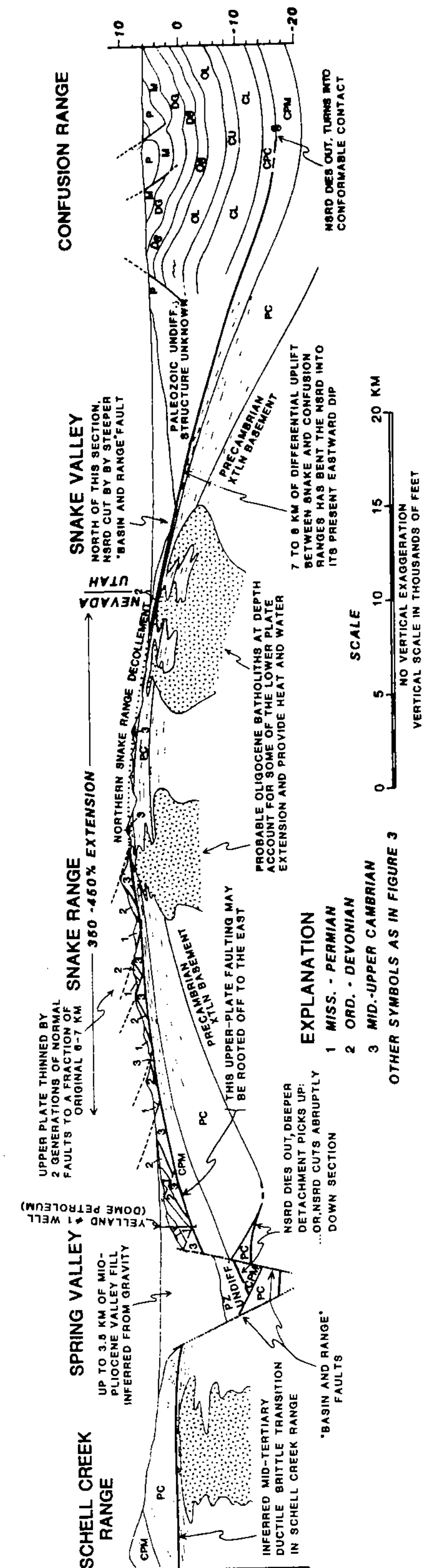


Fig. 10. Interpretive geologic cross section from the Schell Creek Range to the Confusion Range.

fault. We suggest that the NSRD dies out somewhere beneath Spring Valley and that a deeper mid-Tertiary ductile-brittle transition must underlie the Schell Creek Range (Figure 10).

Eastward Continuation of the NSRD

Paleozoic strata in the Confusion Range to the east of the Snake Range are involved in a broad, open synform (Hose, 1977) (Figure 10). Based on known stratigraphic thicknesses of miogeoclinal rocks, the depth to the top of the Cambrian Prospect Mountain Quartzite in the Confusion Range is approximately 7 km (Figure 10). The 7-9 km of differential uplift between the Confusion Range and the northern Snake Range originally pointed out by Hose (1981) might be accomplished either by a fault or by a large-scale upward bend or warp in the decollement surface. We do not know for sure whether the NSRD and the lower plate strain continue beneath the Confusion Range, but we interpret the lack of 'upper plate type' deformation in the Confusion Range as indicative that the decollement also dies out to the east. Further east in the House Range, conformable Lower to Middle Cambrian sections (Hintze, 1980) demand that if it extends that far it must cut downsection.

Northward and Southward Continuation of the NSRD

North of the map area (Figure 3), the décollement cuts stratigraphically up section, and marbles as young as Middle(?) Cambrian are present in a lower plate position (Nelson, 1959, Hose and Blake, 1976) (Figure 3). At the northernmost reaches of the Snake Range it dips gently (5° or less) northward beneath faulted Paleozoic strata that can be traced continuously into the Kern Mountains (Nelson, 1959, Hose and Blake, 1976). If the NSRD continues this far north, it may truncate the Cretaceous Kern Mountain pluton (Best et al., 1974; Lee et al., 1983) at depth, as upper plate strata of the NSRD are apparently intruded by the pluton.

Along the southern flank of the northern Snake Range, the NSRD plunges abruptly southward beneath the Sacramento Pass area (Figure 3, Plate 1). Here, late Precambrian and Cambrian strata are present in both upper and lower plate positions. The upper plate units are not ductilely deformed and can be traced southward to the southern Snake Range where they are in the lower plate of another 'décollement' mapped by Whitebread (1969). The southern Snake Range 'décollement' does not separate ductile and brittle deformation and cannot be structurally equivalent to the NSRD. Thus if the NSRD continues south from Sacramento Pass, it must cut to deeper structural levels, as both McCoy Creek Group strata and Prospect Mountain Quartzite in the northern part of the southern Snake Range are involved in upper plate type faulting.

Synthesis

Structural and stratigraphic relations in the northern Snake Range help constrain the kinematics of crustal extension that led to development of the Snake Range decollement. These relations provide important documentation of how supracrustal extension by high-angle normal faults is accommodated at depth. Rocks above the NSRD were extended approximately 450% in a NW-SE direction by two generations of high-angle normal faults that rotated to low angles as they moved. Relations in the Sacramento Pass area and in adjacent ranges (Gans and Miller, 1983; Grier, 1983) indicate that this faulting is largely mid-Tertiary in age. Rocks beneath the NSRD were penetratively stretched approximately 350% parallel to the direction of extension in the upper plate. The importance of dilation by plutons in the lower plate is as yet unknown. The coaxial nature of upper and lower plate deformation, together with K-Ar dates that indicate the northern Snake Range was anomalously hot during the mid-Tertiary, suggest that lower plate ductile extension was synchronous with upper plate normal faulting. We conclude that the NSRD represents a mid-Tertiary ductile-to-brittle transition zone.

The consistent stratigraphic position of the Snake Range décollement at the Pioche Shale-Pole Canyon Limestone boundary (Figures 2,10) indicates that it originated at 6-7 km depth and was originally subhorizontal. The precise amount and direction of movement of the upper plate with respect to the lower plate is enigmatic as there are no offset markers. Although the NSRD, like other core complex detachment faults, presently juxtaposes rocks that represent radically different structural levels and deformational styles, this juxtaposition can be explained by two generations of normal faults that thin the upper plate and by the collapsing of isograds by ductile thinning in the lower plate. We emphasize that there need not be a great amount of offset on the decollement as the amount of extension above and below is approximately the same! Thus extension by normal faulting in the upper plate may have been largely accommodated in situ by penetrative stretching and magmatism in the lower plate, similar to models proposed by Rehrig and Reynolds (1980), and Eaton (1982).

On the other hand, several arguments can be made for some movement on the NSRD:

1. The metamorphic grade of the youngest units in the lower plate may locally be appreciably higher than that of the oldest units in the upper plate.
2. The amount of extension in the upper plate appears to be somewhat higher than the amount of extension in the lower plate.
3. The overall assymmetry of lower plate deformation (Figure 2) and the preferential development of down-to-the-east normal faults is compatible with eastward movement of the upper plate with respect to the lower plate. In this view, a component of the extension in the upper plate along the west flank of the range and under Spring Valley may be rooted off to the east where the maximum lower plate strain occurs (Figure 10).
4. The observed strain gradient towards the decollement indicates that lower plate deformation may have involved a component of simple shear. If so, upper plate rocks would be increasingly allochthonous with respect to progressively deeper horizons in the lower plate. Alternatively, the gradient in penetrative stretching may simply reflect increasing dilation by plutons with increasing depth.

Although some movement may have occurred on the NSRD, there is strong evidence that this surface did not cut downsection in the direction of movement of the upper plate, a geometry required by Wernicke's (1981, 1982) model of 'low-angle, rooted normal faults'. Across the entire width of the range, the oldest unit at the toes of upper plate fault slices (Middle Cambrian Pole Canyon Limestone) is in stratigraphic continuity with the youngest unit in the lower plate (Lower Cambrian Pioche Shale). The lack of stratigraphic (i.e., structural) omission across the decollement effectively rules out large amounts of movement on a surface that originally cut downsection.

It is interesting to note that a similar lack of stratigraphic omission is evident in other metamorphic core complexes and may in fact characterize detachment faults in general. In the Ruby Mountains, the youngest intruded and deformed strata in the lower plate and the oldest "upper plate" strata are both Devonian in age (Snoke et al., 1982, Snoke, 1980) and in the Raft River Range these are both Permian in age (Compton et al., 1977). Howard et al. (1982) describe normal fault slices in Arizona-California that involve 10 km of crustal section, which is also the estimated depth of origin of lower plate rocks of the adjacent Whipple Mountains detachment fault (Davis et al., 1980, 1982).

Relations in surrounding areas suggest that the NSRD need not extend very far beyond the limits of the northern Snake Range. As a single detachment fault, it probably is not more than 60 km across in any given direction. We conclude that extensional detachment faults like the NSRD develop as subhorizontal boundaries at midcrustal levels between overlying rocks extended by normal faulting and underlying rocks that are penetratively stretched and intruded by plutons, similar to models proposed by Eaton (1982) and Rehrig and Reynolds (1980). These boundaries may develop as local dislocations and hence do not need to 'surface' or 'root' deep in the mantle.

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