

Text and references to accompany NBMG Field Studies Map 20

GEOLOGY OF THE LITTLE HORSE CANYON QUADRANGLE, NEVADA AND UTAH

by
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INTRODUCTION

The Snake Range, in eastern White Pine County, Nevada, is a 150-km-long, north-trending mountain range in the northern Basin and Range province (fig. 1). Sacramento Pass divides the range into two main parts, the northern and southern Snake Range. The Little Horse Canyon Quadrangle is located on the eastern flank of the northern Snake Range and includes portions of the Horse Canyon, Little Horse Canyon, and Smith Creek drainages (fig. 2). The relief is impressive, rising nearly 2 km from the Lake Bonneville beach terraces on the east to the higher peaks on the west. This part of the range is much dryer than equivalent elevations on the western side,

because it lies in the rain shadow of Mount Moriah and the high western ridge crest. Main access into the part of the northern Snake Range covered by this quadrangle is via the northern Snake Valley road, a well maintained gravel road that heads north from the intersection of U.S. Highway 50 and State Route 487 in Nevada to Trout Creek in Utah. Several secondary dirt tracks provide access to the mouth of Smith Creek and Horse Canyon.

The northern Snake Range includes the Mount Moriah Wilderness Area, which was established in 1989, and lies north of the Great Basin National Park. The steep-walled canyons and rugged ridge crests of the northern Snake Range provide access to The Table, an unusual plateau at 11,000 feet (3,350 m) and

Mount Moriah at 12,067 feet (3,678 m), forming some of the most scenic hiking country in the Basin and Range province. The broad, arch-like physiography of the northern Snake Range is shaped by its geology, which is unique compared to other mountain ranges in the region. The northern Snake Range is now considered a classic example of a Cenozoic "metamorphic core complex" (for example, Coney, 1979). The most prominent structural feature of the range is the northern Snake Range décollement (NSRD), a low-angle fault that juxtaposes an upper plate of complexly normal-faulted Paleozoic and Tertiary strata against a lower plate of ductilely attenuated metasedimentary and igneous rocks (figs. 2 and 3). The NSRD defines a north-trending asymmetric dome with about 5,000 feet (1.5 km) of structural relief (fig. 4). The age, origin, and tectonic significance of the NSRD have been topics of continuing debate since the fault was first described by Hazzard and others (1953) and Misch (1960). Although the origin of the NSRD and core complex

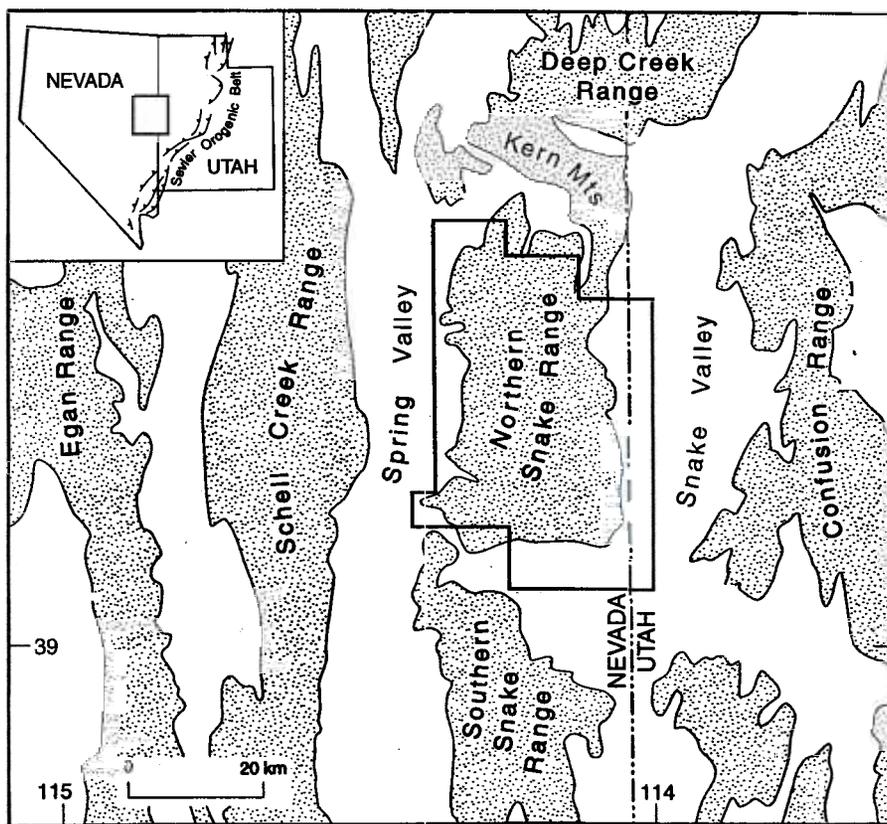


Figure 1. Index map of east-central Nevada and west-central Utah showing location of the Snake Range with respect to surrounding mountain ranges in the northern Basin and Range province, western United States.

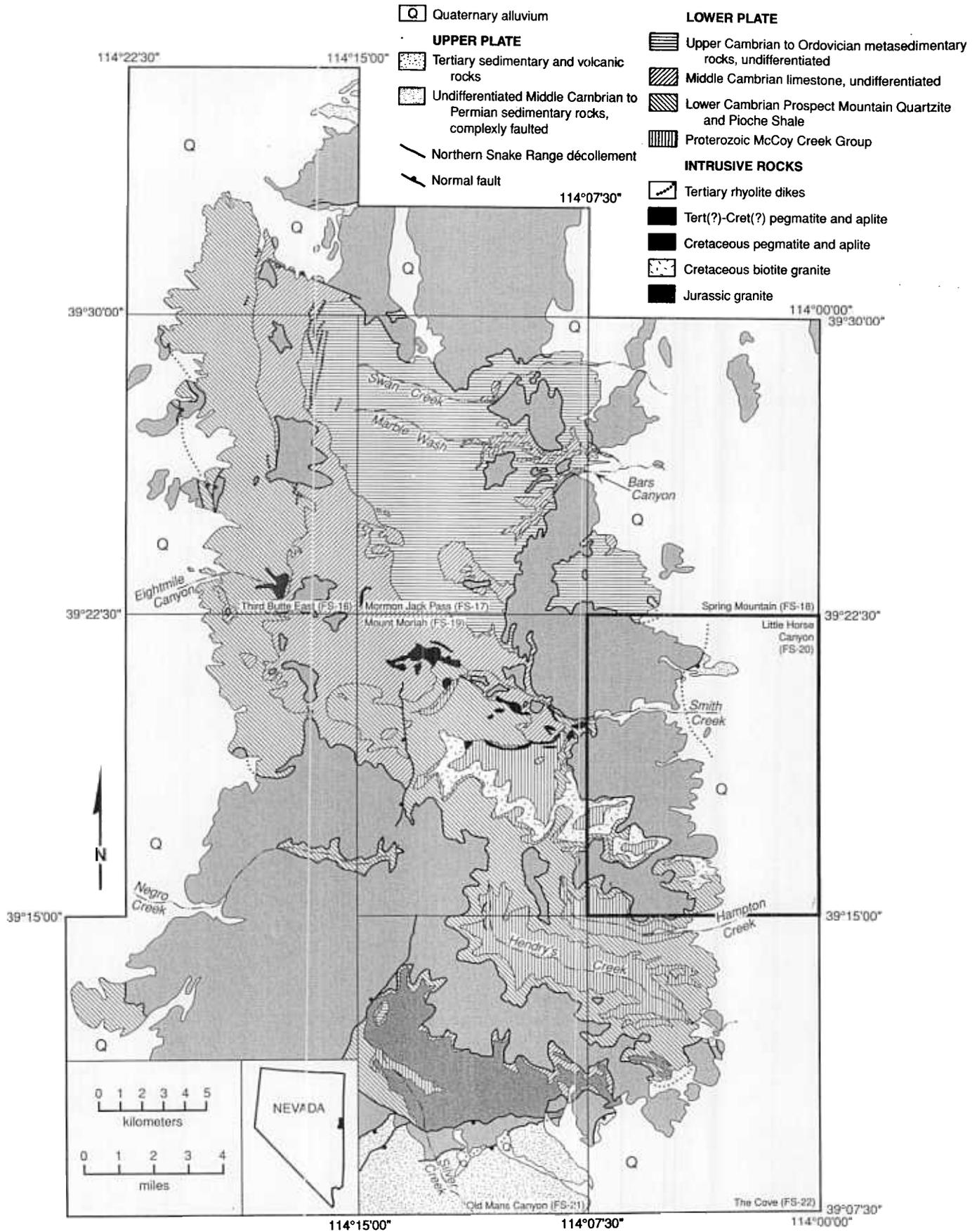


Figure 2. Index map of the northern Snake Range showing simplified geology and location of mapped 7.5-minute quadrangles.

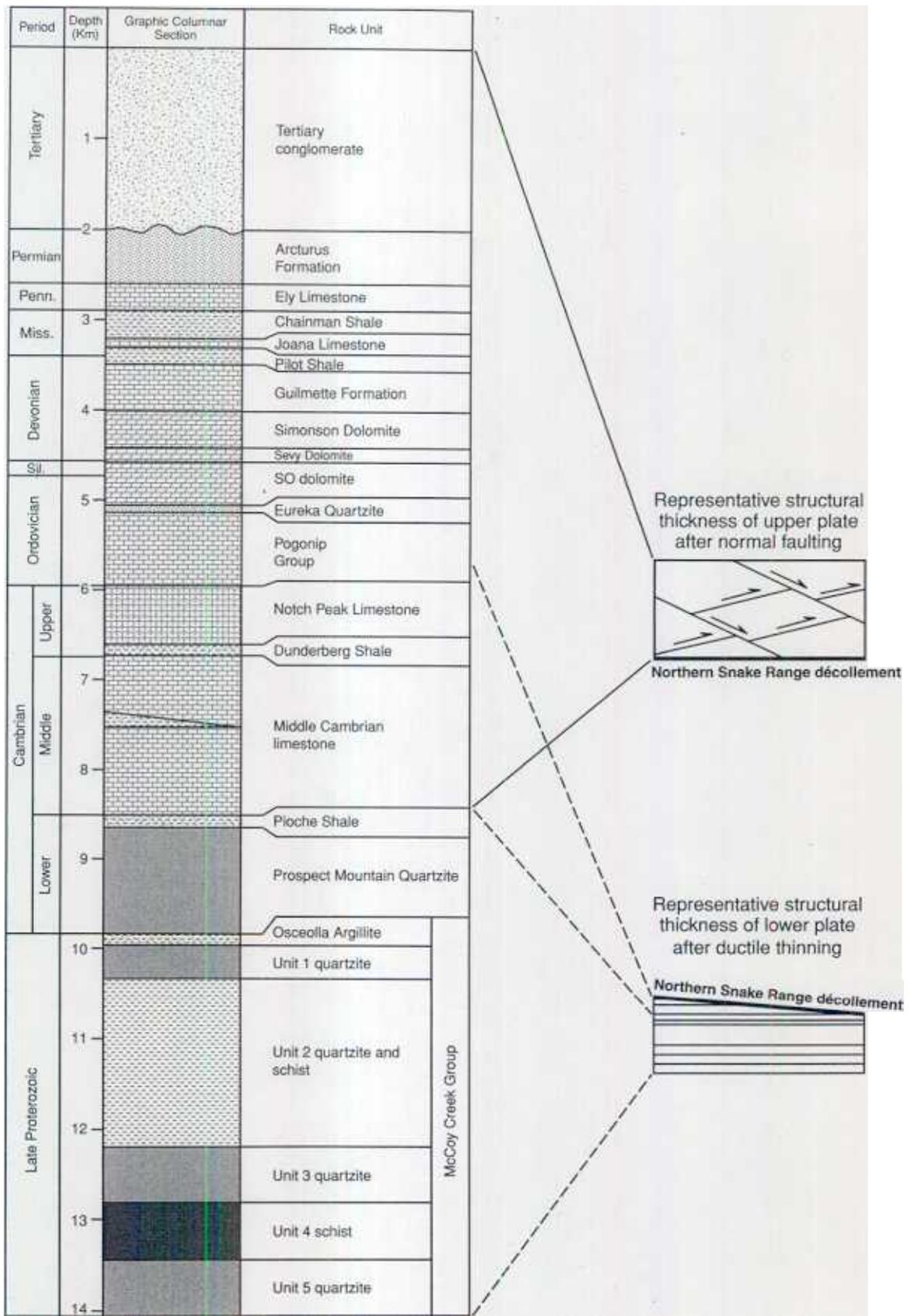


Figure 3. Representative stratigraphic column for the Snake Range and environs. Representative structural thicknesses for upper plate and lower plate rocks after normal faulting and ductile thinning.

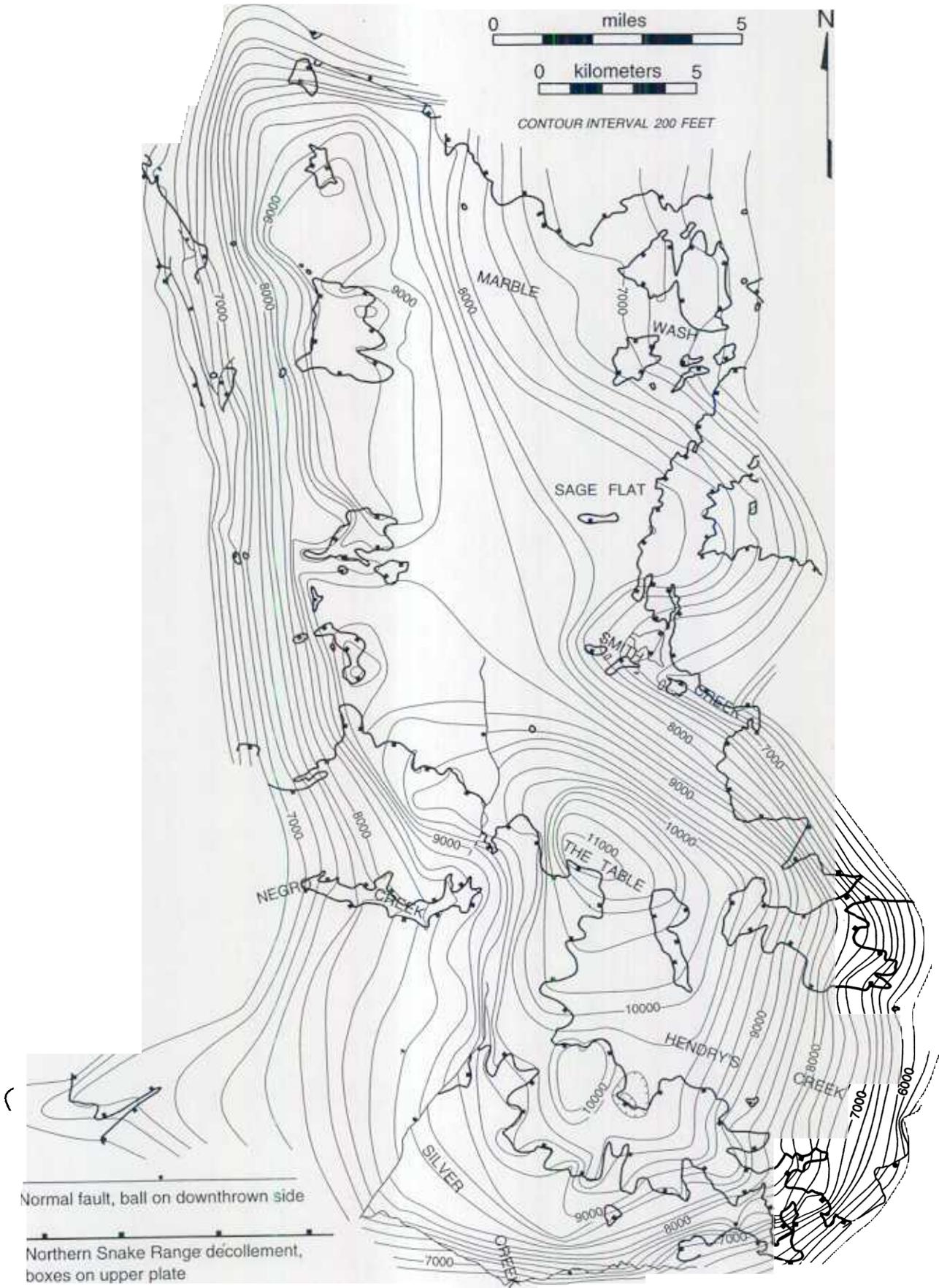


Figure 4. Structure contour map of the northern Snake Range décollement (from Lee, 1990).

detachment faults in general remain controversial, there is general agreement that these complexes provide excellent exposure of both brittle and ductile structures formed as a result of large-magnitude crustal extension.

GEOLOGIC SETTING AND PREVIOUS WORK

Both the northern and southern Snake Range are underlain primarily by Late Proterozoic to Permian miogeoclinal shelf strata deposited along the subsiding western continental margin of North America. Miogeoclinal strata in the footwall of the NSRD range in age from Late Proterozoic to Ordovician and generally define a broad, north-trending antiform. These rock units are relatively unfaulted but record a polyphase history of ductile deformation, metamorphism, and intrusion. The hanging wall or upper plate of the NSRD includes Middle Cambrian to Permian miogeoclinal rocks, as well as Tertiary sedimentary and volcanic rocks. In striking contrast to the lower plate, these rocks are little metamorphosed but highly faulted and tilted by multiple generations of normal faults (fig. 3).

In many ways, the evolution of ideas concerning the origin of the NSRD charts the progress of our understanding of the extensional history of the Cenozoic Basin and Range province as a whole. Until the early 1970s, most low-angle faults like the NSRD in the western United States were mapped as thrust faults. The Snake Range décollement was first described by Hazzard and others (1953). A more detailed study of the geology of the northern Snake Range by Misch (1960) and Misch and Hazzard (1962) followed as part of a regional survey of the geology of eastern Nevada. They noted that the major structure in the northern Snake Range was a low-angle "décollement" that separated an "autochthon" of strongly metamorphosed rocks from an "allochthon" of faulted and folded, but largely unmetamorphosed, carbonate rocks. Nelson (1966, 1969) mapped the northern end of the range as part of a regional mapping project that included the Kern Mountains and southern Deep Creek Range. He mapped the décollement of Misch (1960) and identified lower-plate schists and marbles as metamorphosed equivalents of Proterozoic and Cambrian-Ordovician miogeoclinal units and upper plate rocks as Cambrian to Permian carbonate rocks and younger Tertiary rocks. Nelson proposed that rocks in the lower plate (his "autochthon") recorded three deformational events, the youngest of which involved the generation of mylonites and formation of folds that he assigned to the Mesozoic. He believed that these structures were associated with east-directed thrusting along the décollement horizon. The position of the Snake Range in the hinterland of the Cretaceous Sevier orogenic belt (fig. 1) led these and later workers to relate the low-angle "décollement faulting" in the northern Snake Range to Mesozoic thin-skinned thrust faulting further east, where the NSRD represented the basal shearing-

off plane for these thrusts (Misch, 1960; Miller, 1966). However, Hose and Danes (1973) and Hintze (1978) recognized that the deformation in the upper plate was dominated by normal faulting and attenuation of the stratigraphic section rather than by shortening and thickening of the rock column. This led them to propose a model wherein the Snake Range and environs where uplift and extension in the hinterland was linked to coeval shortening in the foreland via a basal detachment fault now exposed as the NSRD. Armstrong (1972) was the first to suggest that many of these faults might be Tertiary rather than Mesozoic in age, and therefore unrelated to Mesozoic thrust faulting. Armstrong specifically cited geochronologic and stratigraphic relations from the southern Snake Range as some of his principal evidence for a Cenozoic age for the Snake Range décollement. Coney (1974) suggested that at least some of the lower plate deformation in the northern Snake Range might be related to the Snake Range décollement. He studied folds in marble mylonite beneath the NSRD and proposed "quaquaversal" or radial sliding of upper plate down the flanks of the dome.

Hose and Blake (1976) compiled a 1:250,000-scale geologic map of White Pine County which included the first published geologic map of all of the northern Snake Range, based on their reconnaissance mapping. They mapped the low-angle NSRD in its entirety, which they described as separating a lower plate of undifferentiated Lower Cambrian quartzites and pelites and Middle Cambrian marbles from an upper plate of complexly faulted Middle Cambrian to Permian carbonate rocks. Hose and Blake (1976) proposed that two metamorphic and deformational events were recorded in lower plate rocks, a post mid-Jurassic to pre-early Eocene intrusive and high-grade metamorphic event followed closely by a low-grade metamorphic event associated with the development of a strong penetrative foliation and west-northwest-trending mineral elongation lineation. This was followed by post-early Eocene movement along the NSRD and associated faulting in the upper plate. As part of the Wilderness RARE II study, additional mapping of the southern part of the northern Snake Range was carried out at a scale of 1:62,500 (Hose, 1981). This publication pointed out the magnitude of structural thinning of upper plate units by normal faulting. Wernicke (1981), in an influential paper on the geometry and kinematic significance of extensional detachment faults, cited the Snake Range décollement as a key example of a large-displacement, eastward-rooting low-angle normal fault.

Studies in the northern Snake Range by geologists based at Stanford University began in 1981. Miller and others (1983) and Gans and Miller (1983) suggested that the basic structural relationships in the northern Snake Range were best explained as extensional in origin and Cenozoic in age. For the first time, the Late Proterozoic lower plate units in the central and

southern part of the range were identified and correlated, bringing to light the large amount of strain or attenuation of these rock units by ductile deformational processes. The upper plate units were shown to have been affected by multiple generations of predominantly east-dipping normal faults, and it was pointed out that over much of the range there appeared to be near stratigraphic continuity between the oldest units present above and youngest units present below the décollement. These and other relations led Miller and others (1983) to question the need for significant displacement on the décollement and to propose instead that the NSRD originated as a subhorizontal ductile-brittle transition zone between a brittlely extending upper plate and a ductilely stretching lower plate. This interpretation was challenged by Bartley and Wernicke (1984), who proposed instead that the NSRD represented a low-angle normal fault or shear zone with 60 km or more displacement that brought lower plate rocks up from a deeper thrust plate in the Sevier belt to the east. In their model, the lack of stratal omission between upper and lower plate rock units cited by Miller and others (1983) was strictly fortuitous. Gans and Miller (1985) responded to this alternative interpretation by citing additional regional stratigraphic and structural relations that created difficulties with their proposed model.

Further studies in the northern Snake Range expanded our geologic mapping and utilized structural and kinematic analyses, seismic reflection profiling, metamorphic petrology, and extensive geochronology and thermochronology in order to place constraints on the amount of displacement and initial angle of the NSRD, as well as the age of lower plate deformation and its geometric and kinematic relationship to the evolving NSRD (Rowles, 1982; Gans and Miller, 1983; Grier, 1983; Miller and others, 1983; Gans and others, 1985; Geving, 1987; Lee and others, 1987; Miller and others, 1987; Miller and others, 1988; Miller and others, 1989; Gans and others, 1989; Huggins, 1990; Lee, 1990; Lee and Sutter, 1991; Lee, 1995). Our geologic mapping at scales of 1:12,000 and 1:24,000 over a 12-year period (1981-1992) was the first detailed mapping to be completed in the range. During the first half of this project, mapping was carried out on 1:16,000 black and white and 1:24,000 color aerial photographs and compiled upon orthophotog quadrangles because topographic maps were not yet available for the region.

Our studies have shown that lower plate rocks consist of metamorphosed Late Proterozoic to Lower Cambrian quartzites and pelites and Middle Cambrian to Ordovician marbles that correlate in a straightforward fashion to less deformed and metamorphosed sections in the adjacent Schell Creek, Deep Creek, and southern Snake Ranges. Jurassic and Cretaceous granitic plutons and Tertiary dike swarms intrude lower plate units. Lower plate rocks record at least three metamorphic and deformational events. The first

metamorphic event, of Jurassic age, is best preserved along the southern flank of the northern Snake Range. Here, Late Proterozoic and Lower Cambrian quartzites and metapelites have been intruded and contact metamorphosed by a mid-Jurassic plutonic complex (Miller and others, 1988). Structural fabrics associated with this event are strongly overprinted by superimposed Cretaceous and Cenozoic fabrics. The second metamorphic event, of Late Cretaceous age, affected a much broader region of the lower plate. A series of mineral-in isograds mapped along the eastern side of the range indicates that the grade of metamorphism increases from greenschist to amphibolite facies from south to north and with structural depth in the succession (Geving, 1987; Huggins, 1990). A Late Cretaceous pegmatite and aplite dike swarm was intruded during this metamorphic event, which has been dated at about 82-78 Ma (Huggins and Wright, 1989; Huggins, 1990). Structural fabrics associated with this metamorphic event have also been strongly overprinted by Cenozoic fabrics, making their analysis and interpretation difficult. However, on the northwestern flank of the range, Tertiary strain decreases and eventually dies out. Here, west-dipping foliations, minor thrust faults, and a map-scale fold now inferred to be of Cretaceous age (Lee, 1990; P. B. Gans, 1992, unpubl. data) are preserved. Lower to upper greenschist-facies metamorphism of Eocene to Miocene age (Lee and Sutter, 1991; Lee, 1995) strongly affected much of the lower plate, causing retrogression of older mid-Jurassic and Late Cretaceous metamorphic assemblages. The Tertiary metamorphic event was accompanied by vertical thinning and horizontal stretching, resulting in a subhorizontal, bedding-parallel mylonitic foliation and west-northwest-trending stretching lineation. This foliation is axial planar to isoclinal, recumbent folds in the northern half of the range. Strain associated with this youngest event increases dramatically from west to east across the range. Mesoscopic, microstructural, and petrofabric studies on lower plate rocks were utilized by Lee and others (1987) to modify the pure shear model proposed by Miller and others (1983). Lee and others (1987) proposed a strain path whereby pure and simple shear (top to the east) acted in unison and in sequence in the lower plate and that this strain was intimately tied to the evolution of the NSRD, ultimately leading to slip along this surface in the brittle regime (see also Gans and others, 1985). Structural studies by Gaudemer and Tapponnier (1987) were used to promote a model whereby lower plate deformation occurred entirely by simple shear. The question of simple versus pure shear remains controversial (Lee and others 1987), as most structural and petrographic observations used to resolve these questions do not yield unique interpretations. Important questions still remain regarding the exact age of development of lower plate fabrics, whether they are developed as a consequence of pure and/or simple shear, and what

the exact kinematic relation is between these fabrics and the evolving NSRD.

In the overlying upper plate, unmetamorphosed to weakly metamorphosed Middle Cambrian to Permian carbonate rocks have been attenuated by at least two sets of imbricate normal faults whose exact ages remain poorly constrained but are at least in part Eocene(?)–Miocene in age. In the Sacramento Pass area and at the northern end of the northern Snake Range, Tertiary fanglomerate, lacustrine deposits, and volcanic rocks are cut by normal faults that merge along strike with the NSRD, demonstrating a Tertiary age for much if not all of the extensional faulting (Gans and others, 1989). Parts of the upper plate of the NSRD are characterized by a systematic history of east-directed normal faulting that resulted in successive northward tilting about a common axis in response to WNW–ESE extension, parallel to that recorded by the ductile deformational fabrics in the lower plate (Miller and others, 1983). However, the amount of strain indicated by these faults and the amount of rotation related to faulting varies across the range, as does the direction of tilting or rotation. Movement along the NSRD during the time span of upper plate faulting is geometrically required, as none of the upper plate faults actually cut and offset the NSRD. Motion along the NSRD is believed to have been top-to-the east and resulted in the juxtaposition of the less metamorphosed and mostly younger upper plate rocks down upon the more highly metamorphosed and generally older lower plate rocks. An important exception to this occurs in the northern part of the range where Middle Cambrian and younger rocks of the upper plate routinely overlie Upper Cambrian and locally Ordovician strata in a lower plate position.

We previously postulated that most of the movement on the NSRD was Oligocene to early Miocene in age (for example, Gans and Miller, 1983; Miller and others, 1983; Gans and others, 1985; Lee and Sutter, 1991). However, new thermochronologic and geologic data suggest that movement along the NSRD may have been episodic and occurred during the Eocene to middle Miocene. Multiple diffusion domain analyses of potassium feldspar Arrhenius data and $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra, and apatite fission-track studies suggest three rapid cooling events: 1) middle Eocene (48–41 Ma), 2) late Oligocene (30–26 Ma) and 3) early to middle Miocene (20–15 Ma) (Miller and others, 1989, 1990; Lee, 1995). These cooling events are interpreted to indicate diachronous exhumation of footwall rocks from beneath the NSRD. The spatial distribution of these cooling events suggest that the NSRD is a composite structure; the NSRD along the west flank of the range moved during the Eocene and Oligocene, and the NSRD along the east flank of the range moved during the early to middle Miocene (Miller and others, 1989, 1990; Lee, 1995). Field relations showing Miocene or younger sedimentary sequences along the northern, eastern and southern flanks of the

range are cut and tilted by a set of normal faults that we infer either to cut or to sole into the NSRD in the subsurface supporting the inferred early to middle Miocene exhumation event (Gans and others, 1989; Miller and others, 1989, 1990).

In summary, we now think that the combined data on the deformational history of upper and lower plate rocks indicate that the NSRD is a composite structure rather than a single fault; thus it was never simultaneously active over its entire mapped extent. East-dipping normal faults along the eastern flank of the range were likely active in mid-Miocene and later times and perhaps originated as steep faults that have since been rotated to present low dips. The high-strain rocks and mylonites of the lower plate may also represent more than one Tertiary event, but our studies have not been able to demonstrate this. Limiting factors include the resolution of available geochronologic techniques, the complex thermal and deformational histories of the minerals available for dating, and the inability of structural studies to distinguish more than one superimposed event if these are developed at low angles to one another. Clearly, the NSRD represents the end result of an involved history of extensional strain at both ductile and brittle levels of the crust and more than one episode of faulting is responsible for the exhumation of ductile extensional fabrics in the range. More sophisticated studies and modeling of existing data are necessary to fully understand the kinematic history and mechanics of deformation and faulting.

GEOLOGY AND STRUCTURAL HISTORY OF THE LITTLE HORSE CANYON QUADRANGLE

Bedrock exposures in the Little Horse Canyon Quadrangle are restricted to the western half of the quadrangle. The eastern half is underlain by an older alluvium pediment surface that dips gently eastward down to the highest Lake Bonneville beach terraces. The bedrock geology is dominated by Middle Cambrian to Devonian and Tertiary rocks of the upper plate of the NSRD. The northern Snake Range décollement dips about 10° eastward in the Little Horse Canyon Quadrangle and is well exposed along the walls of the deeper drainages. Unmetamorphosed Middle Cambrian to Devonian rocks of the upper plate underlie much of the rugged, high, western part of the quadrangle and constitute perhaps the best exposures of upper plate extensional fault complexes in the northern Snake Range. Metamorphosed and strongly deformed Eocambrian metasedimentary rocks and Cretaceous plutonic rocks crop out in lower plate windows in the deeply incised headwaters of Smith Creek, Horse Canyon, and Little Horse Canyon and have a well-developed mylonitic foliation and west-northwest-trending stretching lineation. Tilted Miocene sedimentary rocks are exposed locally along the eastern flank of the range and yield important insights on the youngest faulting responsible for uplift of the range.

Upper Plate Structure

The structural style of upper plate rocks in the Little Horse Canyon Quadrangle is similar to that for the northern Snake Range in general (Gans and Miller, 1983), with some important variations. All the upper plate units are cut by at least two and locally three superposed generations of faults. These faults all appear to be normal faults, because they consistently place younger rocks on older rocks and structurally thin the stratigraphic section to a small fraction of its original thickness. Faults are present at all scales, with displacements ranging from centimeters to kilometers. Only faults with offsets in excess of 50 m are shown on the map, but these appear to account for most of the upper plate strain. Upper plate units generally young westward and upward across the quadrangle, from predominantly massive Middle Cambrian rocks on the eastern flank of the range to Ordovician to Devonian strata along the high ridges and peaks in the western part of the quadrangle. A composite stratigraphic thickness of more than 5 km is represented by the rocks of the upper plate, but nowhere is there more than 1 km of relatively unfaulted stratigraphic section, and the maximum structural thickness of the upper plate is generally even less than that.

The upper plate in this quadrangle can be divided into two structural domains that are separated by an east-trending boundary approximately coincident with Smith Creek (see map). South of Smith Creek, upper plate units dip mainly to the west-northwest and are cut by two and locally three generations of normal faults (see map). These faults have predominantly top-to-the-east or -southeast displacement. North of Smith Creek, units dip mainly to the southeast and are cut by faults with predominantly top-to-the-northwest displacement. The boundary between these opposing tilt domains is poorly defined, but appears to be a kilometer-wide accommodation zone, rather than a discrete transfer fault. Within this zone, bedding attitudes are mostly south-dipping but extremely variable, and faults range from steep to low-angle, with varying senses of displacement. If there is any systematic structural style or sequence of faulting within this zone, we were not able to discern it.

In the southern domain, bedding dips mainly to the northwest, but dips range from vertical to subhorizontal. Much of this variability appears to be a consequence of local drag in the vicinity of faults. The more intact sections dip about 40 to 60° to the northwest. Older (Middle Cambrian) units of the upper plate tend to dip less steeply than younger strata, but it is not clear whether this is because the older rocks are actually less rotated by faulting or whether they have been affected by normal drag on the underlying NSRD. Along the eastern flank of the range, bedding locally rolls over from gently northwest-dipping to gently east-dipping, a feature we attribute to normal drag along a major east-dipping normal fault in this vicinity.

The oldest faults in the southern domain dip 20 to 30° westward and are at relatively low angles to bedding. This generation of faults has been identified with confidence only in Upper Cambrian and younger rocks. Top-to-the-east or -southeast displacement can be inferred from the fact that these faults omit section and generally dip less steeply than bedding and from the sense of drag on strata immediately adjacent to the faults. The next younger set of faults is sub horizontal, at high angles to bedding in Upper Cambrian and younger units of their hanging walls but generally at lower angles to bedding in the Middle Cambrian footwall rocks. Slickensides and stratigraphic offsets indicate top-to-the-southeast offsets of at least a kilometer on some of these. The youngest normal faults dip moderately eastward and are at high angles to bedding in both hanging walls and footwalls. These youngest faults may in part be synchronous with and related to the major east-dipping fault along the eastern flank of the range.

The northern (east-tilted) domain of the upper plate in this quadrangle consists largely of Middle Cambrian rocks but is continuous with Upper Cambrian to Pennsylvanian rocks in the Mount Moriah Quadrangle to the west. Bedding dips are variable but average about 35° to the southeast and east. Most of the larger faults strike northeast, dip moderately northwest, and have clear top-to-the-northwest displacements as indicated by offset markers, drag features, etc. Many such faults are spectacularly exposed on the northern wall of Smith Creek Canyon. Because of the lack of distinctive marker beds within the thick Middle Cambrian section, it was generally not possible to determine exact offsets on many of these faults or to resolve different generations of faults, as in the southern domain. Nevertheless, at least two generations appear to be present, an older, more gently dipping set of normal faults and a younger, more steeply northwest-dipping set. Several faults of the younger set, including the major west-dipping fault that juxtaposes Upper Cambrian and younger rocks against Middle Cambrian rocks in the northwest corner of the quadrangle, sole into the NSRD.

A major east-dipping fault is exposed along the eastern flank of the northern Snake Range, approximately coincident with the eastern limits of bedrock exposure. This fault dips 10 to 30° eastward and is inferred to have at least several kilometers of offset, as it juxtaposes tilted Miocene conglomerates in the hanging wall against faulted and tilted Middle Cambrian and younger rocks in the footwall. The Miocene rocks in the hanging wall now dip about 25° westward and are interpreted to represent the syntectonic basin fill that accumulated during uplift of the range and movement on this fault. The range-front fault is clearly younger than much of the faulting within the range, including the NSRD, because: 1) it cuts previously faulted and tilted rocks in the footwall; 2) it continues uninterrupted across the domain boundary defined by the upper plate

fault systems; and 3) most important, it cuts conglomerate that contains clasts derived from the whole spectrum of upper plate units as well as from mylonitic, lower-plate marble, quartzite, and orthogneiss. The source of these lower-plate clasts can be confidently assigned to the headwaters of Smith Creek in the Mount Moriah Quadrangle to the west based on the distinctive clasts of Cretaceous orthogneiss and pegmatite exposed in this drainage. The conglomerate is inferred to be Middle Miocene or younger because the lower plate clasts yield fission-track ages of 20 to 15 Ma that record the rapid cooling and exhumation of the lower plate (Miller and others, 1990).

The succession of faulting and tilting events in the Little Horse Canyon Quadrangle is interpreted to reflect progressive extension of large magnitude. The direction of extension documented by faults in the upper plate of the NSRD is approximately N45W-S45E on the basis of slickenlines on many of the faults and the average direction of tilting in both the northern and southern domains. The direction of movement on the younger range-front fault appears to be more easterly. The ages of the various generations of faults are not well enough constrained to evaluate whether they formed in response to one progressive extensional event or whether they reflect distinct faulting episodes, perhaps widely separated in time. We interpret the northwest-dipping faults in the northern domain to be broadly synchronous with at least the first two generations of southeast-dipping faults in the southern domain because they document similar magnitudes and directions of extension, and there does not appear to be a consistent crosscutting relationship between faults of the two domains. Thus, the poorly defined northwest-trending boundary between the two structural domains is interpreted to be an accommodation zone that approximately parallels the extension direction and separates opposing, coeval tilt domains. The only constraint on the older generations of faults is that they are post-Paleozoic, although we suspect they must predate or be synchronous with rapid, Early to Middle Miocene cooling and exhumation of the lower plate (Miller and others, 1990; Lee, 1995). The youngest range-front fault must have continued to move during and after this Middle Miocene cooling, as it records the erosional breaching of the lower plate.

Lower Plate Structure

Eocambrian metasedimentary rocks and Cretaceous plutonic rock of the lower plate are exposed at low elevations on the flank of the range and in the bottom of Horse and Little Horse canyons in the southern part of the quadrangle. Metasedimentary rocks include quartzite and schist correlated with the three upper units of the Late Proterozoic McCoy Creek Group of Misch and Hazzard (1962), and the Lower Cambrian Prospect Mountain Quartzite and Pioche Shale, and marble correlated with the lower Middle Cambrian

Eldorado Limestone. Igneous rocks include a large biotite tonalite/granodiorite orthogneiss body known to be Early Cretaceous (Miller and others, 1988) and small leucogranite aplite and pegmatite bodies of Late Cretaceous age (Huggins and Wright, 1989). The scattered exposures of the Early Cretaceous orthogneiss (Kbg, also informally called the orthogneiss of Horse Canyon) all appear to be part of a single sill-like intrusive body, several hundred meters thick that extends at least 15 km in a west-northwest direction and several kilometers in a northeast direction. Its sill-like geometry is particularly obvious in the deeply incised headwaters of Horse Canyon and Little Horse Canyon, where both the upper and lower contacts are well exposed and dip very gently to the east or southeast. In detail, the intrusive contacts of the orthogneiss systematically cut upsection toward the north or northeast, and we suspect that much of its present sill-like geometry and west-northwest elongation is a reflection of the large magnitude of superimposed Tertiary strain.

Lower plate units are locally pervasively injected by dikes and sills of leucogranite, aplite, and pegmatite. Most of these are inferred to be Late Cretaceous in age and broadly synchronous with amphibolite-facies metamorphism (Huggins, 1990). These were described as "lit-par-lit" injections by Misch (1960), but are more likely a network of dikes and sills that have been strained into sill-like masses.

The lower plate rocks in this part of the Snake Range were metamorphosed at conditions ranging from amphibolite facies in the lower units to perhaps upper greenschist facies in the highest stratigraphic units. Metamorphic minerals present in schists of the McCoy Creek Group include garnet + staurolite + biotite + muscovite + plagioclase ± kyanite (Huggins, 1990). The impure marble contains high-Mg biotite and/or phlogopite/muscovite ± quartz ± calcite ± dolomite ± plagioclase ± tremolite/actinolite. The age of peak metamorphism is dated as Late Cretaceous (~75-82 Ma) based on U-Pb ages of monazite from amphibolite-facies pelite in the Hampton and Smith Creek areas (Lee and Fischer, 1985; Huggins and Wright, 1989).

The lower plate units are generally right side up and in correct stratigraphic order but are highly attenuated. A gently east-dipping mylonitic foliation and a well developed east-southeast-trending mineral elongation lineation is present throughout the lower plate in this part of the range. This penetrative strain has attenuated the stratigraphic section to a small fraction of its original thickness. For example, the Prospect Mountain Quartzite is penetratively thinned to about 60 to 150 m, only 5 to 10% of its original 1200 m thickness (Miller and others, 1983; Lee and others, 1987). The majority of kinematic indicators (S-C fabrics, extensional crenulation cleavages, asymmetric augen and boudinage) suggest a top-to-the-east sense-of-shear, although the relative proportion of

coaxial and non-coaxial deformation in the lower plate is poorly constrained. The geometry, kinematics, and metamorphic conditions of the lower plate strain have been described and discussed by Lee (1990) and Lee and others (1987). Intraformational folding on scales ranging from centimeters to hundreds of meters is common, particularly in lower plate marble. Boudinage of more resistant layers (schist layers, dolomitic marble, calc-schist) on scales ranging from centimeters to hundreds of meters is also common.

Because the youngest deformation to affect the lower plate rocks in this area involves such large strain, any older fabrics (if they existed) have been effectively obliterated. Elsewhere in the northern Snake Range at least two distinct fabrics are present in lower plate rocks, an older one associated with peak metamorphism and inferred to be Mesozoic and a younger, high-strain, low greenschist facies fabric inferred to be Tertiary (Miller and others, 1983, 1987; Lee and Sutter, 1991). The high-strain fabric in the lower plate of this quadrangle presumably correlates with the younger (S₂) fabric elsewhere in the range, as it clearly postdates peak metamorphism (metamorphic minerals are pulled apart with new growth of chlorite-white mica in pressure shadows) and occurred at temperatures where calcite and quartz were behaving ductilely. However, it should be emphasized that the absolute age(s) of the high-strain deformation remains poorly constrained. Miller and others (1983) inferred it to be largely Oligocene and synchronous with extensional faulting in the upper plate, which at the time was

thought to be mainly Oligocene (Gans and Miller, 1983). Lee and Sutter (1991) carried out an ⁴⁰Ar/³⁹Ar study of primarily metamorphic white mica from the lower plate and also concluded that the mylonitic deformation was largely Oligocene on the basis of an approximately 37 Ma-age on rhyolite porphyry dikes that appeared to predate the deformation and 24- to 25-Ma ages of metamorphic micas interpreted to reflect post-deformational cooling of the lower plate. More recently, calculated thermal histories, based on multiple diffusion domain analyses of potassium feldspar ⁴⁰Ar/³⁹Ar age spectra, showed that lower plate rocks along the western part of the range did not drop below 300°C until 34 Ma, whereas lower plate rocks along the eastern flank did not drop below 300°C until 20 Ma (Lee, 1995). These results led Lee (1995) to conclude that the approximately 37-Ma undeformed rhyolite porphyry dikes along the western flank of the range postdated at least some mylonitic deformation and that mylonitic deformation along the eastern flank was pre-20 Ma. However, given all of the uncertainties (for example, correlation of fabrics and temperature(s) of deformation) the only firm minimum and maximum age brackets are provided by the age of peak metamorphism (latest Cretaceous) and the final cooling and exhumation of the lower plate at about 20 to 15 Ma (Miller and others, 1990; Lee, 1995).

Correlation of Upper and Lower Plate Rocks

Prior to Cenozoic faulting, Late Proterozoic to Paleozoic strata in the Little Horse Canyon Quadrangle

formed part of a regionally extensive sequence of miogeoclinal strata deposited on the subsiding western continental shelf of North America (Gans and Miller, 1983). Formational designations, thicknesses, and regional facies variations have been described by Drewes and Palmer (1957), Whitebread (1969), Hose and Blake (1976), and Stewart (1980), among others. In the Little Horse Canyon Quadrangle, Paleozoic rocks in the upper plate of the NSRD are complexly faulted, and many sections are incomplete. Similarly, Late Cambrian and Early Cambrian rocks in the lower plate of the NSRD are highly metamorphosed and deformed, and their present thicknesses are not representative of original stratigraphic thicknesses. Descriptions of the less metamorphosed and deformed counterparts of these units in the adjacent southern Snake Range can be found in Misch and

Upper plate, northern part of northern Snake Range

Єn Notch Peak Limestone	
Єd Dunderberg Shale	
Єm Middle Cambrian Limestone (undifferentiated)	Єm ₅
	Єm ₄
	Єm ₃
	Єm ₂
	Єm ₁

base not exposed

Upper plate, southern part of northern Snake Range

Єd Dunderberg Shale
Єl Lincoln Peak Formation
Єpc Pole Canyon Limestone

Lower plate, northern part of northern Snake Range

Єd Dunderberg Shale
Єr Raiff Limestone
Єmn Monte Neva Formation
Єe Eldorado Limestone
Єpi Pioche Shale
Єpm Prospect Mountain Quartzite

Lower plate, southern part of northern Snake Range

<i>top not exposed</i>
Єpc Pole Canyon Limestone
Єpi Pioche Shale
Єpm Prospect Mountain Quartzite

Figure 5. Stratigraphic nomenclature, unit designations, and correlations for Middle Cambrian upper and lower plate units across the northern Snake Range.

Hazzard (1962) and in Miller and others (1993), where the rationale for a somewhat different nomenclature than that used by Misch and Hazzard (1962) is discussed. The lower plate units and their correlation are described in greater detail by Løe (1990).

At the scale of the northern Snake Range, unit descriptions and formational names are not always consistent, because of real geographic variations in the stratigraphy. We have attempted to handle most of these in our legend of map units and stratigraphic column (fig. 3). Specifically, unit descriptions for the Middle Cambrian units vary in different parts of the northern Snake Range so we have further clarified our unit designations and their equivalence in figure 5.

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