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Structural Evolution of the Central Schell Creek Range, White Pine County, Nevada

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by

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ABSTRACT

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The central Schell Creek Range (SCR) in eastern Nevada records some of the oldest extensional faulting in the eastern Great Basin. The geometries and kinematics of these early normal faults are poorly documented in this portion of the range, yet they have major implications for the shallow levels of the northern Snake Range metamorphic core complex and faults within major extensional accommodation zones. New detailed 1:12,000 scale geologic field mapping and structural analysis has documented six separate tilt domains along with numerous high- and low-angle, east- and west-dipping-normal faults. Two of the largest and oldest faults are the low-angle, west-directed, Majors Place Detachment (MPD), and the low-angle, east-directed, Schell Peaks Detachment (SPD). These faults along with their hanging wall splays have thinned the exposed rocks underlying the range from 7 km to 2-3 km. The stratigraphy in the footwall of the SPD and MPD is sub-parallel to faults and is largely unmetamorphosed. The SPD

has top-to-the-east displacement and shows a switch in the tilt polarity in the hanging wall from west-tilted in the south to east-tilted in the north. The MPD is a west-directed normal fault, and, based on Ar^{40}/Ar^{39} analysis of footwall rocks and syntectonic ignimbrites in the hanging wall of the MPD (Gans and Norman, in prep.), was active between 35-40 Ma. The MPD cuts hanging wall structures of the SPD implying the SPD is older than the MPD. The SPD and MPD are cut by a second generation of high-angle normal faults associated with the modern range bounding fault system.

The data presented here suggests a three stage model for the structural evolution of the central SCR. 1) Cretaceous shortening created ~NNE trending folds across the eastern Great Basin. 2) Extension, beginning in the Eocene, forming closely spaced normal faults – the SPD and MPD. The SPD and MPD possibly exploited the limbs of a pre-existing antiform transecting the SCR. The east-directed SPD exploited the east-dipping limb and the west-directed MPD exploited the west-dipping limb. 3) Miocene and younger range bounding normal fault systems at a high angle to bedding and cut the low-angle faults within the range.

1. Introduction:

Classic Basin and Range topography of western North America is characterized by normal fault-bounded blocks forming north-south trending mountain ranges with adjacent flat bottom valleys. However, the present-day structural style only records the latest phase of deformation from middle Miocene to the present. Many ranges record a longer structural history with multiple generations of deformation including Mesozoic folding and Cenozoic normal faulting. The central Schell Creek Range (SCR) is located in the heart of the Basin and Range Province, directly east of Ely, Nevada near the Nevada-Utah border (Fig 1, 2). This alpine range is 200-km-long, reaches elevations in excess of 3600 meters, and has diverse flora and fauna including Bristlecone pines and large herds of elk and deer (Fig 3). Geologically the range is significant for two reasons: 1) The central portion of the range straddles an extensional accommodation zone where there is an along-strike reverse in polarity of extensional faulting and tilting (Fig 2). North of this zone bedding dips westward and is cut by east-directed normal faults, whereas to the south, bedding dips to the east and is cut by west-directed faults. This geometry holds true for older generations of faults within the range and for younger, basin-bounding-normal faults and; 2) The SCR lies directly west of, and in the up-dip direction of the northern Snake Range Décollement (NSRD), a major detachment fault associated with the northern Snake Range metamorphic core complex. However, the correlative footwall units are unmetamorphosed and unstrained in the SCR compared to the northern Snake Range, and thus provide an opportunity to investigate the shallow levels of a major extensional fault.

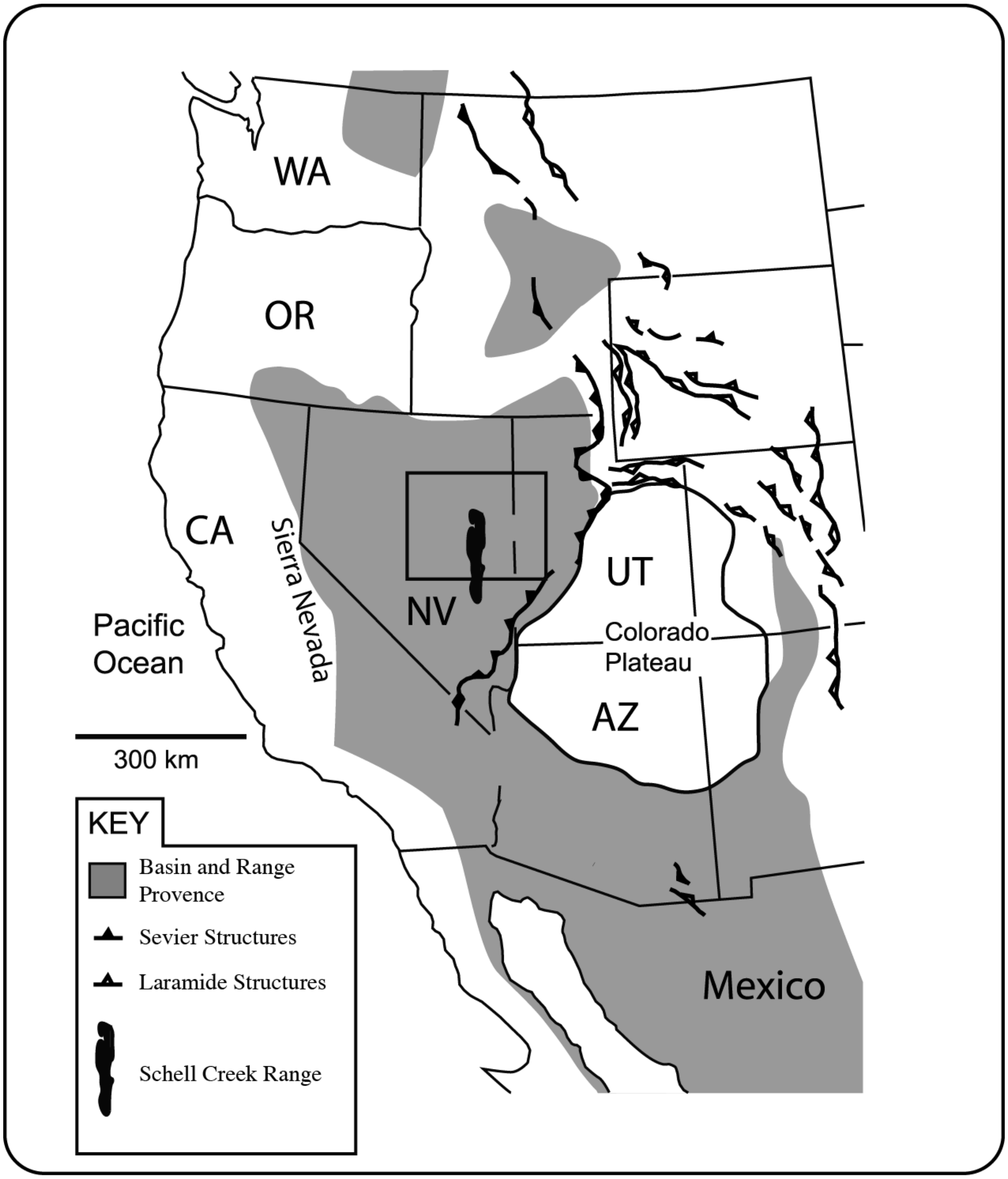


Fig 1 Index map of western North America showing some of the major tectonic elements and the location of the SCR. Redrawn from the study by Cooper et. al, 2010, modified from the studies by Coney, 1980; and Wernicke, 1992.

The SCR is underlain by a nearly 15 km-thick section of Paleozoic shallow marine carbonates and clastic sedimentary rocks associated with the miogeocline of western North America (Stewart and Poole, 1974), as well as sparse Tertiary volcanics and sedimentary rocks. These rocks have been highly faulted and tilted by multiple generations of normal faults that currently have steep to gentle dips.

The two most important faults in the central Schell Creek Range are the low-angle, west-directed Majors Place Detachment (MPD), and the (east-directed) Schell Peaks Detachment (SPD). Both faults separate highly faulted hanging wall from fairly coherent footwalls that are largely unmetamorphosed except for the deepest structural levels of the MPD that have reached temperatures between 400^{o} to 450^{o} C (Gans and Norman, in prep.). Although these structures had previously been identified (Young, 1960; Drewes, 1967) and mapped; their timing, magnitude of displacement and kinematics remain poorly understood.

This study addresses the structural history of the central Schell Creek Range with an emphasis on understanding the kinematics, geometry, and timing of extensional structures in the in the range, particularly the pre-Miocene extension history. Understanding the earliest phases of extension and the geometries of faults in the Basin and Range Provence improves our understanding of continental rifts and the early phases of Basin and Range extension.

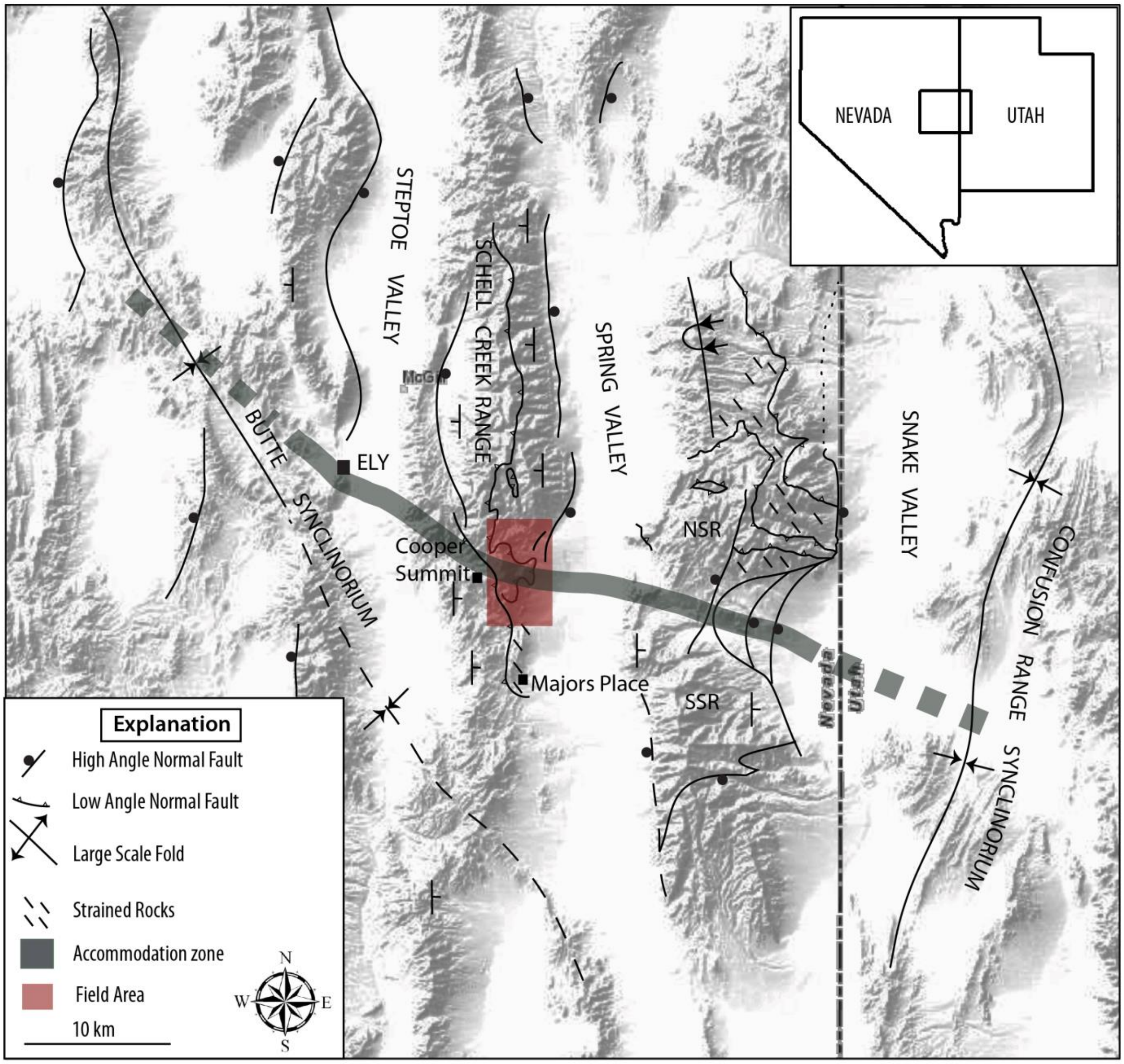


Fig 2. Tectonic index map of east central Nevada showing the approximant location of range bounding faults, Low angle detachment faults, large-scale folds, accommodation zone, and the field area in the central Schell Creek Range. Maps modified from: Hose and Blake, 1976; Gans and Miller 1983; Miller et. al, 1999

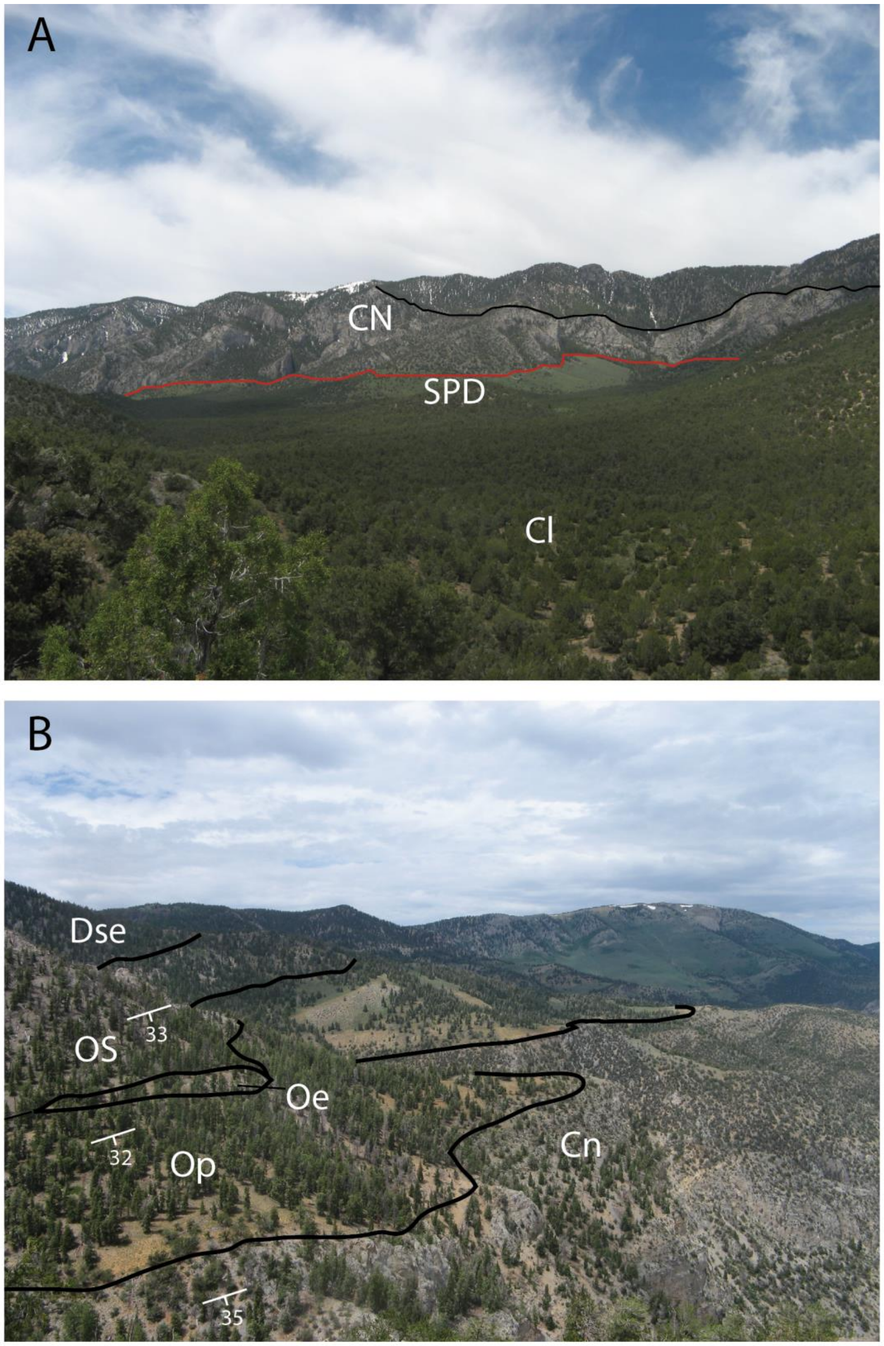


Fig 3. Selected view shots of the eastern flank of the central Schell Creek Range. A) View looking southwest of field area: forested slope in foreground is underlain by silty limestone of the middle Cambrian Lincoln Peak Fm. Rugged cliffs in background formed mainly by upper Cambrian Notch Peak Formation and lie in the hanging wall of the Schell Peak Detachment (SPD) (red line). Black line is the lowest west-directed fault in the hanging wall of the SPD. B) View northward of the north-east portion of mapping area illustrating pseudo-stratigraphy created by an imbricate stack of west directed normal faults in the hanging wall of the SPD. Cl = Cambrian Lincoln Peak Fm. Cn = Cambrian Notch Peak Fm. Op = Ordovician Pogonip Group, Oe = Ordovician Eureka Quartzite. OS = Ordovician Silurian Dolomite Undifferentiated. Dse = Devonian Sevy Dolomite.

2. PREVIOUS WORK

Previous work in the Schell Creek Range includes detailed studies of specific areas (Young, 1960; Drewes, 1967; Gans and Miller, 1983; Gans et al, 1985) and several regional studies (Misch, 1960; Armstrong, 1972; Coney, 1974; Gans et al 1985; Miller et al, 1989; Miller et al, 1999). The understanding of the structural evolution of the range has evolved, with early workers suggesting all low-angle faults in the range were Mesozoic thrust faults associated with crustal shortening (Misch, 1960; Dechert, 1967; Drewes, 1967). Young (1960) carefully mapped a large portion of the northern Schell Creek Range north of the study area, and although he referred to many of the low-angle faults as thrusts, he recognized that all the faults place younger rock units on older, omit large amounts of stratigraphic section, and argued that they were Tertiary because the Tertiary sedimentary and volcanic rocks appeared to be deformed as much as the Paleozoic units that underlie them. The first detailed geologic map of the central SCR that includes the present study area was made as part of the USGS 15' quadrangle (Drewes, 1967). Drewes work was the first to describe the local stratigraphy and accurately recognize and map the major structures in the range. His mapping and many cross-sections highlighted the complexities within the range and the abundant low-angle and high-angle faults. He interpreted the large low-angle faults as Mesozoic thrusts, in accordance with the thinking of the time (Misch, 1960). Areas where Tertiary rocks were faulted against Paleozoic rocks were attributed to reactivation of Mesozoic structures (Drewes, 1967). Armstrong (1972) reinterpreted many of the low-angle thrusts of the central SCR as normal faults which he called "Denudation Faults" because they place younger stratigraphy on older and appear to truncate the Tertiary sections. Although it is now widely accepted that the low-angle faults in the Schell Creek Range are Tertiary normal faults, there is still considerable debate regarding their precise age and original orientation. One group of researchers postulates that the low-angle faults initiated and slipped at dips of < 30 degrees (Wernicke, 1981; Wernicke, 1985; Hose and Danes, 1973; Hintze, 1978). The second argues for multiple generations of high angle (60^{o}) planner rotational (domino style) normal faults. Gans and Miller (1983) conducted a regional study across the northern Egan Range, SCR and Snake Range to understand the structural style of Basin and Range extension in east central Nevada. Their study documented multiple generations of normal faults and they concluded that many of the low-angle faults had rotated from high angle ‘domino-style’ to their present orientation.

The relationship between the low-angle faults of the SCR and the well-known “detachment faults” in the Snake Range metamorphic core complex to the east is particularly controversial. Asymmetric folds in strained and metamorphosed middle Cambrian units in the footwall of the Majors Place Detachment were interpreted by Coney (1976) to indicate that the hanging wall had been displaced towards the southwest. He correlated this fault with the Snake Range Décollement and suggested that the upper plate rocks had moved radially off a large dome located at the northern Snake Range. A high-resolution seismic line across Spring Valley and detailed mapping to the north in the SCR and northern Snake Range suggest that the Northern Snake Range Décollement (NSRD) projects under Spring Valley where it is cut by the Schell Creek Range Fault and reemerges at the crest of the Schell Creek Range (Gans et al, 1985). I refer to this fault as the Schell Peaks Detachment (SPD). In the Snake Range this fault has unequivocal top-to-the-east displacement (Miller, et. al, 1983)

Existing timing constraints on faulting in the Schell Creek Range come from fission-track thermochronology of zircon and apatite, north of the study area and argon thermochronology from the Cooper Summit and Majors Place area (Fig 2). Apatite and zircon fission track ages in the deepest structural levels along the eastern flank of the SCR range from 126 ± 10 Ma (Zr) to 13.1± 2.3 (Ap), with clusters around 17 Ma suggesting the Schell Creek Range Fault began slipping between 15-20 Ma (Miller et al, 1999). Preliminary $^{40}Ar/^{39}Ar$ thermochronology and geochronology from the footwall of the MPD and from a suite of syntectonic ignimbrites near Cooper Summit suggest that slip on the MPD occurred between 40 and 35 Ma (Gans and Norman, in prep.)

3. GEOLOGIC FRAMEWORK

Bedrock exposures in the eastern Great Basin consist mainly of Paleozoic shallow marine clastic and carbonate sedimentary rocks with minor Tertiary sedimentary and volcanic rocks (Hose and Blake, 1976). The Mesozoic geologic history of eastern Nevada is still poorly understood but was apparently characterized by modest amounts of supra-crustal shortening, with widespread metamorphism and plutonium at deeper levels (Armstrong, 1972; Gans and Miller, 1983; Miller et al, 1989.) Evidence for Mesozoic shortening includes large, open and recumbent folds in the Butte Range, Northern Snake Range and Confusion Range (Fig. 2). During the Cenozoic, much of eastern Nevada was extended by a factor of 3 or more in a WNW-ESE direction (Gans and Miller, 1983).

Extension is recorded by multiple generations of normal faults within the ranges as well as the modern-range bounding faults, steep tilts (block rotations) of Paleozoic and Tertiary strata, thick extensional (half graben) basin fill deposits and the exhumation of deeper structural levels (Gans and Miller, 1983; Gans et al, 1985). The precise age(s), magnitude(s), and kinematics of Cenozoic extension in the eastern Great Basin are topics of ongoing research. Available data indicate major episodes of extension in both the late Eocene and Miocene (Miller et al, 1999; Gans, 2001).

4. STRATIGRAPHY:

The central Schell Creek Range area examined in this study is underlain primarily by Cambrian to Pennsylvanian clastic and carbonate rocks of the western North American miogeoclinal succession. Previous mapping by Drewes (1967) generally followed the stratigraphic nomenclature used in the eastern Great Basin (eg. Hose and Blake, 1976) with the exception of Upper Cambrian to Upper Ordovician units, which he grouped into one "Cambrian-Ordovician Limestone" unit (Drewes, 1967, p. 16). In this study, I adopted the same stratigraphic nomenclature of Hose and Blake (1976). In addition, I divided some formations into informal members and divided the Cambrian-Ordovician limestone unit of Drewes (1967) into the more generally accepted Cambrian Johns Wash Formation, Cambrian Notch Peak Formation, and Ordovician Pogonip Group (Fig 4). No attempt was made to separate the Pogonip Group into its individual formations due to structural complexity. Thicknesses of each unit were measured from map and cross sections where the most-complete and least-faulted sections are preserved. Brief descriptions of the each unit are provided below.

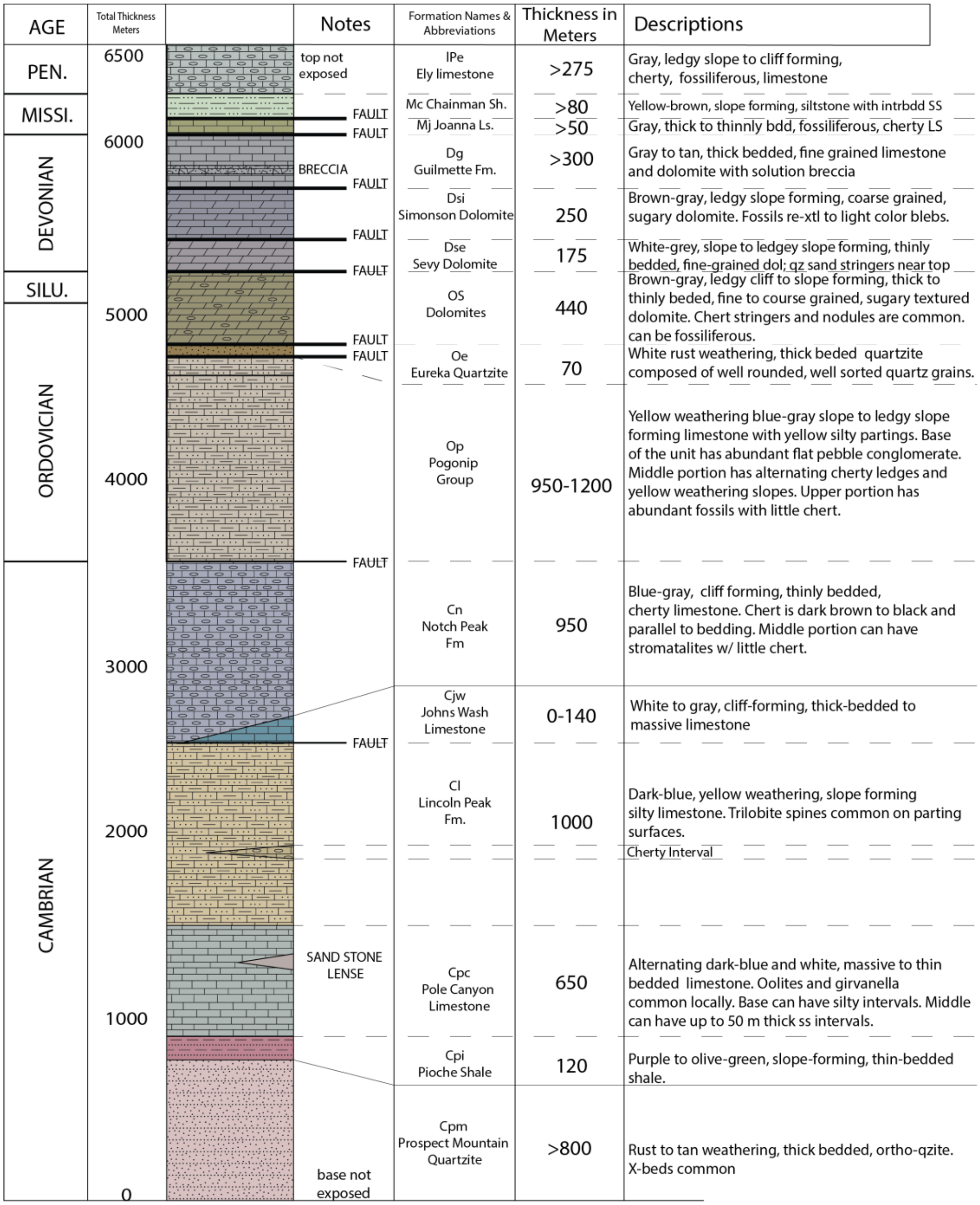


Fig 4. Composite columnar section of the Schell Creek Range mapping area. Maximum exposed thicknesses of each unit are illustrated but note that many of the sections have faulted contacts and are incomplete.

Cambrian System

4.1 Lower Cambrian Prospect Mountain Quartzite (Cpm):

The Cpm is best exposed at the mouth of Cleve Creek and consists of a pink- to gray, rust weathering, talus-covered, ledgy slope to cliff-forming quartzite with a minimum exposed thickness of 800 meters. Quartzite beds range in thickness from 40-120 cm and are separated by mm- to cm-thick beds of olive to purple colored shale; they contain planar and trough cross-beds. The quartzite is typically fine- to medium-grained, well-rounded, and locally contains up to 15% feldspar. North of the study area and in adjacent ranges, complete sections of the Prospect Mountain Quartzite are approximately 1200 m-thick and conformably overlie the Pre-Cambrian McCoy Creek formation (Young, 1960; Hose and Blake, 1976). The upper contact is mapped at the top of the last thick quartzite bed directly below the Pioche shale.

4.2 Cambrian Pioche Shale (Cpi):

The Pioche Shale is a recessive slope-forming unit that is best exposed on the hills south of Cleve Creek (Plate 1) with a complete section measuring approximately 120-meters thick. The unit is often expressed as a sage-covered, brown- to maroon-weathering slope separating the Prospect Mountain Quartzite from the Pole Canyon Fm. Outcrops are sparse and consist of a purple to olive-green, thinly-bedded (8 mm-4 cm) argillite and fine-grained, impure, micaceous-sandstone and siltstone. The lower portion of the unit contains interbeds of quartzite (2-40 cm thick), whereas the upper portion of the unit often contains thinly bedded silty micaceous dark-blue to khaki colored limestone.

4.3 Cambrian Pole Canyon Formation (Cpc):

The Cpc is a 650-meter-thick, cliff to ledgy-slope forming limestone. A complete section is exposed south of Cleve Creek and at the mouth of Cooper Canyon. The Cpc is characterized by alternating bands of light-blue, gray, and nearly white, massive- to thinly-bedded limestone. Color banding ranges in thickness from 10s of meters to cm in scale and can be mottled. Isolated oolitic and girvanella-rich intervals and rare trilobites can be found near the base of the unit. The lower part of the Cpc contains occasional intervals of thinly bedded (1-4 cm) blue to red limestone with red-orange silty partings, but most is massive- to thick-bedded. A lenticular interval up to 50 meters thick of moderately well-sorted, brown- to red, micaceous-sandstone interbedded with silty limestone is exposed near Cleve Creek (Fig 5). In some areas the Cpc limestone is replaced by irregular bodies of coarse-grained, sugary-textured dolomite. In the vicinity of Cooper Canyon the Cpc is weakly strained, as evidenced by oolites stretched in a NE direction with an X:Y:Z ratio of approximately 2:1:1. The upper contact of the Pole Canyon formation grades abruptly into silty limestone of the Lincoln Peak Fm. over a few cm.

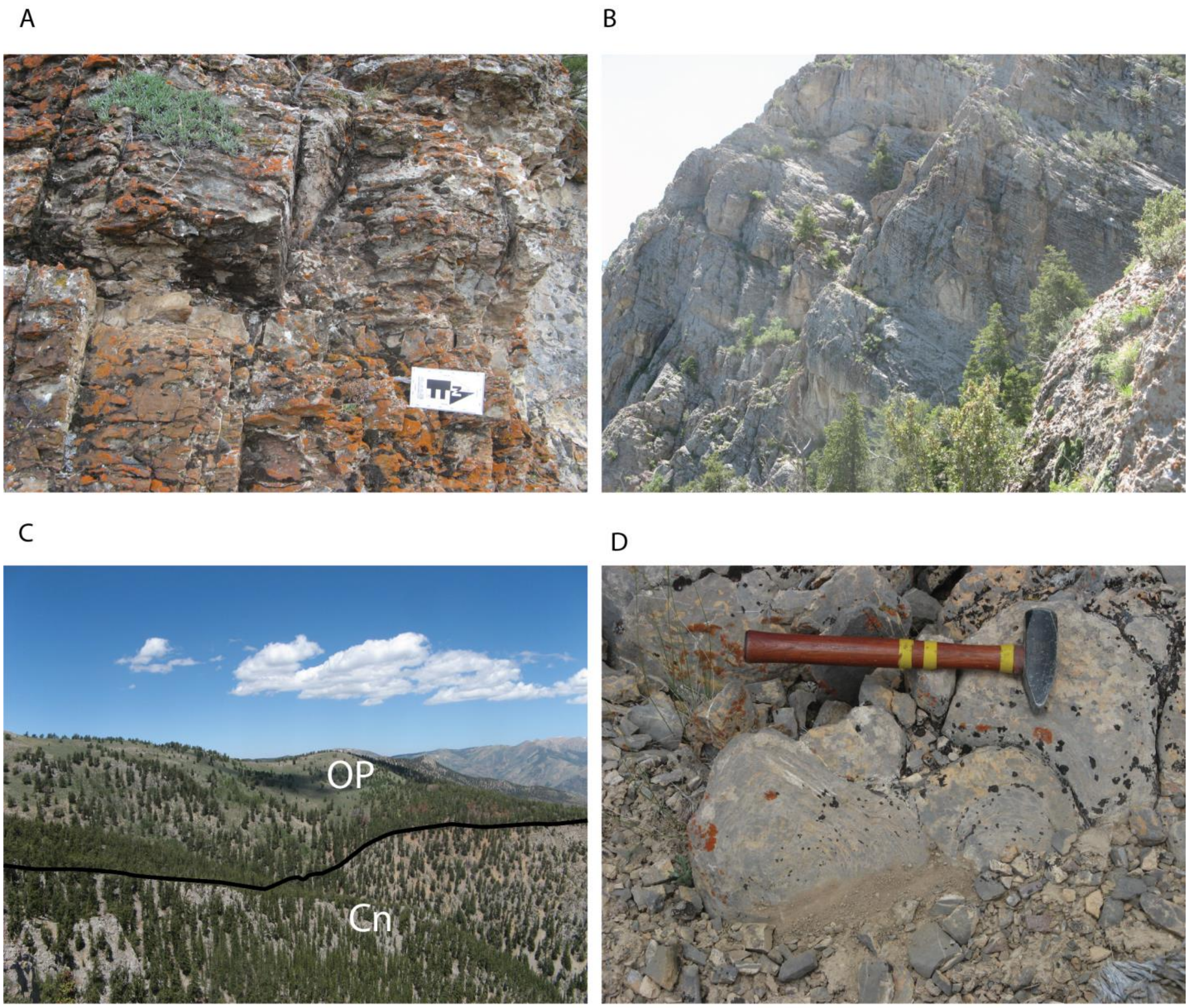


Fig 5. Selected views of Paleozoic miogioclinal units in the central Schell Creek Range. A) Sandstone interval within the Cambrian Pole Canyon Limestone (scale bar arrow = 10cm) . B) Typical Cliff of Cambrian Notch Peak Formation C) View to the NW of the faulted contact between the Cambrian Notch Peak Formation (Cn) and Ordovician Pogonip Group (Op). Note the abrupt change from cliff forming limestone to the yellow slope and ledgy slope forming silty limestone of the Pogonip Group. D) Top view of stromatolites from the middle of the Notch Peak Formation.

4.4 Cambrian Lincoln Peak Formation (Cl):

The Lincoln Peak Fm. is a blue- to brown, slope- to ledgy-slope forming limestone that makes up the forested foothills along the eastern flank of the SCR. A nearly complete section of the Cl, ~1000 meters thick, is exposed near Cooper Canyon. The Cl is generally very poorly exposed and densely forested by piñon pines and junipers. Outcrops consist of small ledges or isolated knobs and are most common along drainages and ridges. The majority of the formation is characterized by regolith of blue, brown, and yellow limestone plates suspended in yellow-brown soil. Outcrops are mainly blue- to grey, thinly-bedded (1-4 cm) limestone with yellow mottled-silty partings. Trilobite spines are common in silty partings. Isolated massive resistant ledges of limestone up to 2 meters thick occur sporadically. Near Cleve Creek, the Lincoln Peak Fm. contains a 10 m thick resistant ledge (mapped as Cl_2) composed of thinly bedded limestone and layered brown chert nodules up to 2 cm thick and spaced 4-10 cm apart. The Cl_2 thins to the south where it eventually pinches out after several 100 meters of continuous outcrop (plate 1). In neighboring ranges in White Pine County the Cl ranges in thickness from 1200-1400 meters.

4.5 Cambrian Johns Wash (Cjw):

The Johns Wash Limestone conformably overlies the Lincoln Peak Fm. A complete section north of Cooper Canyon is 140-meter thick and consisting of thickly-bedded, massive, gray- to white, ledgy-slope to cliff-forming limestone. It is distinguished from the overlying Notch Peak Fm. by the lack of chert and by being the first cliffs above the

Cl. The Cjw appears to thin to the north and near Kolcheck basin. Here a nearly complete section of Cn is exposed and the underlying Cjw is represented by only a few thin ledges between the Lincoln Peak Fm. and Notch Peak Fm.

4.6 Cambrian Notch Peak Formation (Cn):

The Notch Peak Fm. is a blue-gray, cliff-forming limestone with a minimum thickness of 950 m. The unit is well exposed throughout the study area and forms most of the major cliffs along the eastern flank of the range (Fig. 5). The unit is characterized by thinly bedded (1-7 cm thick) limestone with yellow to red silty parting and bedding-parallel black to brown and gray chert nodules 1-5 cm thick. The chert is a strongly layered with individual nodules 10-30 cm long spaced 2-5 cm apart. The lower 400 m consists of blue gray, mostly thinly-bedded limestone with 0.5-4 cm thick bedding-parallel chert nodules. The percentage of chert varies laterally from 40% in thin bedded limestone to 0% in massive thick bedded limestone. Fossils are rare in the lower portion of the unit. Above the cherty interval, is several hundred meters of thinly bedded, silty limestone that is locally stromatolitic, (Fig. 5) with minimal chert and occasional beds of flat-pebble-limestone conglomerate in a silty limestone matrix. The middle member can be fossiliferous with localized fragments of trilobites, brachiopods, and other unidentified fossils in a lavender limestone. The upper 250 meters consists of a blue-gray, thinly bedded, cliff forming, and cherty limestone, very similar to the lower 400 m. The contact of the Notch Peak Fm. with the overlying Pogonip Group varies from gradational with alternating cherty ledges with silty slopes to abrupt.

Ordovician System

4.7 Ordovician Pogonip Group (Op):

The Ordovician Pogonip Group is a 950-1200 m thick slope- to ledgy-slope forming limestone that is generally fault bounded. It is best exposed in the vicinity of Cave Mountain where a nearly complete section is located. Throughout the northwest portion of the study area the Pogonip Group is expressed as a ~100-meter wide, fault-bounded strip forming a small bench above the Notch Peak Formation (Fig. 3). The lower part of the unit forms a yellow-weathering slope, covered in sage and dense groves of pine trees. Sparse outcrops are characterized by blue-gray weathering, clast supported, flat-pebble-limestone conglomerates. Clasts are 2-10 cm in diameter and 0.5-2 cm thick, and enclosed in a yellow weathering silty limestone matrix. The middle portion of the unit consists of alternating 10 meter thick cherty limestone ledges and yellow weathering slopes. The ledges are characterized by blue gray, thinly-bedded (1-4 cm) limestone with tan, pink, and brown chert nodules. Stromatolites are locally abundant. Chert nodules in the Op are up to 30 cm thick and 50 cm wide are generally larger than the underlying Notch Peak Fm. The upper 100 m of the Pogonip Group is only exposed in small fault bounded slivers south of Cleve Creek Baldy and consists of brownish yellow, fossiliferous, calcareous shale and a blue fossiliferous limestone with yellow silty partings. The upper portion of this unit tends to be richly fossiliferous and includes fossils of bryozoan, brachiopods, gastropods, crinoids, corals, and ostracods.

4.8 Ordovician Eureka Quartzite (Oe)

The Ordovician Eureka Quartzite consists of a 70-m-thick, white-colored, rust-weathering, thickly-bedded quartzite that forms ledgy slopes or cliffs. A nearly complete section of the unit is exposed 8 km south of Cleve Creek Baldy. Beds are typically less than 1 m thick but are difficult to recognize due to the compositional homogeneity and extensive fractures. The Oe is often found as brecciated fault-bounded slivers along major faults. These slivers range in size from 2 to 100 m along strike and are typically 2-3 times longer then they are thick. The Oe is an extremely pure orthoquartzite composed of well rounded, well sorted, 0.25-1 mm sized quartz grains. Slopes below the unit are often littered with talus and large blocks of the quartzite. The upper contact of the Oe with the OS dolomite is gradational over a few meters and is characterized by interbeds of sandy, brown dolomite with white quartzite that grades into the gray and brown dolomite of the OS.

4.9 Ordovician Silurian Dolomites undifferentiated (OS)

In other parts of the eastern Great Basin the Ordovician-Silurian dolomite has been divided into the Ordovician Fish Haven Dolomite and Silurian Lake Town Dolomite (Hose and Blake, 1975). In the study area, the units were mapped as a single unit because of their similar characteristics, extensive faults, and breccia. In the study area, a maximum (faulted) section of OS dolomite is 440 meter thick and consists of chocolate-brown to gray, ledgy slope to cliff forming dolomite. The unit is generally well exposed, with 2-50 cm thick beds of massive, coarse to fine grained, sugary textured dolomite.

Conspicuous stromatolite-rich horizons up to 1-meter-thick occur in isolated beds in the lower portion of the unit. The middle to upper portion of the unit has abundant brown to gray to black chert nodules and stringers, locally forming 20-meter high cliffs of silicified dolomite. Textural variations within the unit range from very fine-grained dolomicrite, to coarse-grained, sugary dolomite and colors vary from gray to brown. Bedding ranges from massive and thick-bedded to thin-bedded dolomite with closely spaced mm scale silty laminations. The unit is best distinguished from the other middle Paleozoic dolomites by having chert, stromatolite and typically being more massive and coarse grained.

Devonian System

4.10 Devonian Sevy Dolomite (Dse)

The Devonian Sevy Dolomite consists of a 175-meter-thick, slope to ledgy-slope forming, thinly-bedded (5-100 cm), well laminated, gray to white, fine-grained, sugary-textured, dolomite. Occasional bands of light to dark brown fine- to coarse-grained dolomite are locally present in the upper and lower portion of the unit. Slopes of the Dse typically have few outcrops and are nearly devoid of any sage brush. One of the most diagnostic features of the Dse is brown- to rust-weathering, cm scale beds and stringers (5 cm - 1 m thick) of well-rounded, well sorted, frosty textured, 0.5-1 mm sized quarts sand grains in the middle to upper portion of the unit. Although the sand grains give the host beds a brown a brown weathered color, in hand sample the clear well rounded sand grains are suspended in white to gray dolomite matrix.

4.11 Devonian Simonson Dolomite (Dsi)

The Simonson Dolomite consists of a 250-meter-thick, brown to gray, ledgy-slope forming, thinly bedded (5-50 cm), and medium- to coarse-grained, recrystallized, dolomite. The lower portion of the unit consists of a massive brown to dark-gray, sugary textured dolomite that is fossil poor. The contact between the Dse and Dsi is drawn at the base of the first thick (>10 m) interval of coarse-grained sugary dolomite. The middle to upper portions of the unit consists of planar bedded, conspicuously laminated, dark to light brown dolomite that contains locally abundant fossils including: gastropods, corals, bryozoans, and mm scale trace fossils. One of the distinguishing features of the Dsi is that fossils have recrystallize to a white to gray colored, mm scale blebs that are lighter in color than the dark brown dolomite. Intervals of dark gray limestone 2-5 m thick separated by 5-10 m thick sections of dark brown dolomite occur in the upper part of the formation.

4.12 Devonian Guilmette Formation (Dg)

The Devonian Guilmette is exposed in the west-northwest portion of the study area and only includes the lower member of the formation. The Dg has a minimum thickness of 300 m in the study area, but regionally it can be 700 m thick with three distinct members. The Dg is characterized by a blue-gray to buff cliff to ledge slope forming, thick-bedded (0.5-6 m thick) micritic limestone with abundant solution collapse breccias in the lower portion of the unit. These breccias can be up to 100 m thick and characterized by monolithologic limestone clasts in a red to yellow silty limestone matrix. Rare fossils are present in the lower portion of the unit and include gastropods, crinoids, and corals.

Mississippian System

4.13 Mississippian Joana Limestone (Mj)

The Joana Limestone is exposed in a small klippe in the north central portion of the study area (Plate 1) and as a series of slivers along the Majors Place Detachment in the southwest. Only the middle to upper portion of the Mj is exposed and is characterized by a blue to gray, cliff-forming, thick- to thinly-bedded (5cm-100cm), fossiliferous, cherty limestone. Several intervals of bedding parallel-brown to black chert nodules 4-10 cm thick and spaced 5 cm apart occur near the base. The limestone itself is composed mainly of sand-sized fossil fragments giving the unit a grainy look on weathered surfaces. The upper portion of the unit is thinly bedded and fossil rich, with abundant well preserved fossils including rugose corals, colonial corals, crinoids, brachiopods, bryozoans, and gastropods. The top of the unit abruptly grades into thinly bedded yellow weathering shale of the Mc.

4.14 Mississippian Chainman Shale (Mc)

The Mississippian Chainman Shale is only exposed in a few places in the study area and no complete sections exposed are preserved. Detailed descriptions of this unit are provided by Drewes (1967) and Hose and Blake (1976). The Mc is a 80 m thick, yellow-weathering slope-former composed of thinly bedded shale (mm-cm scale) with interbeds of brown sandstone beds less than 1 meter thick. Outcrops of this unit are rare and its presence is only inferred from the distinctive float. In Cooper Canyon, the Mc sits in the hanging wall of the MPD and is highly faulted and sheared by top-to-the-west normal faults. The upper contact of the unit is gradational over 2-3 meters with silty limestone of the overlying Ely Limestone.

Pennsylvanian system

4.15 Pennsylvanian Ely Limestone IPe

Only the base of the Pennsylvanian Ely Limestone is exposed in the study area and detailed descriptions of exposures due west of the study area are provided by Drewes (1967). The IPe consists of a gray, cliff- to ledgy slope forming, thickly-bedded (20 cm-2 m thick) cherty, fossiliferous limestone. Chert nodules have variable morphology from bedding parallel stringers of chert to large ellipsoidal chert nodules up to 30 cm across. In some beds, chert nodules have replaced large colonial corals and sponges up to 25 cm in diameter, with radiating septa preserved. Fossils are abundant in the Pennsylvanian Ely Limestone and included gastropods, crinoids, brachiopods, rugose corals, colonial coral, and bryazon. Yellow sandstone and siltstone intervals are present sporadically in the lower portion of the unit.

4.16 Quaternary Units:

Quaternary units underlie large expanses of the eastern foothills of the study area with isolated accumulations higher in the range. Eight separate Quaternary units have been mapped based on their characteristics and relative ages. Quaternary Older Gravel (Qog) is composed of unconsolidated sands and gravels of older terraces flanking the range that sit higher than the modern alluvial fan surface. These units covers a pediment surface and are interpreted to represent older alluvial fan and stream deposits that predate the most recent uplift of the range and or base level drop. The Qog is incised by modern stream channels and modern alluvial fans. Quaternary Older Alluvium (Qoal) is composed of unconsolidated sands, gravels, and boulders that represent older stream deposits. This unit generally forms terraces higher than the flanks of active stream channels. Quaternary Younger Gravel (Qyg) consists of unconsolidated-sands and gravels of modern alluvial fan. These include paleo-shoreline deposits associated with Pleistocene lakes. Quaternary Slide blocks Qsb are isolated locally derived coherent blocks of a single Paleozoic unit that have clearly moved down slope under the influence of gravity. Bedding can be coherent over large areas with brecciation restricted to the base. Quaternary landslide deposits (Qls) are locally derived accumulations of clast supported angular blocks. These deposits are typically monolithologic and sit at the base of topographic amphitheaters. Quaternary Glacial Moraine (Qm) deposits are found only east of Cleve Creek Baldly and include both lateral and terminal moraines associated with a small, Pleistocene, alpine glacier. Quaternary Talus (Qt) is composed of unconsolidated, locally derived, monolithologic, clast supported slopes and piles of angular cobbles and boulders at the base of steep cliffs. Quaternary Alluvium (Qa) generally unconsolidated sands, gravels, and conglomerates of active stream channels. Deposits are typically only a few meters wide.

5. Structure:

The structure of the central SCR is dominated by multiple generations of high and low-angle N-S to NNE-SSW trending normal faults (Fig. 6). These faults display a wide range of orientation and stratigraphic throw. The most significant structures in the study area include two

low-angle normal faults or "detachment faults", herein called the Schell Peaks Detachment (SPD) and Majors Place Detachment (MPD), and the modern range-bounding fault known as the Schell Creek Range Fault (SCRF) (Young, 1960). The SPD and MPD can be traced along strike for 60 km to 15 km respectively (Fig. 2). These faults typically place tilted and highly faulted rocks in the hanging wall against Middle to Lower Cambrian units in the footwall (Plate 1, 2). Bedding in the hanging wall is typically highly discordant to the underlying detachment, whereas bedding in the footwall is commonly sub-parallel to the overlying detachment (plate 2). The net effect of the two detachment faults and numerous hanging wall faults has been to structurally thin the brittle part of the crust to a fraction of its original thickness.

The low-angle detachment faults are cut by a younger generation of high angle, east-and west-dipping faults interpreted to be associated with the SCRF. North of the study area along the eastern range front, the SCRF has nearly 10 km of offset, estimated from seismic profiling across Spring Valley (Gans et al, 1985). Within the study area, the SCRF appears to break into splays and with a decrease in displacement southward based on the elevation of the range and the deeper stratigraphic levels exposed to the north.

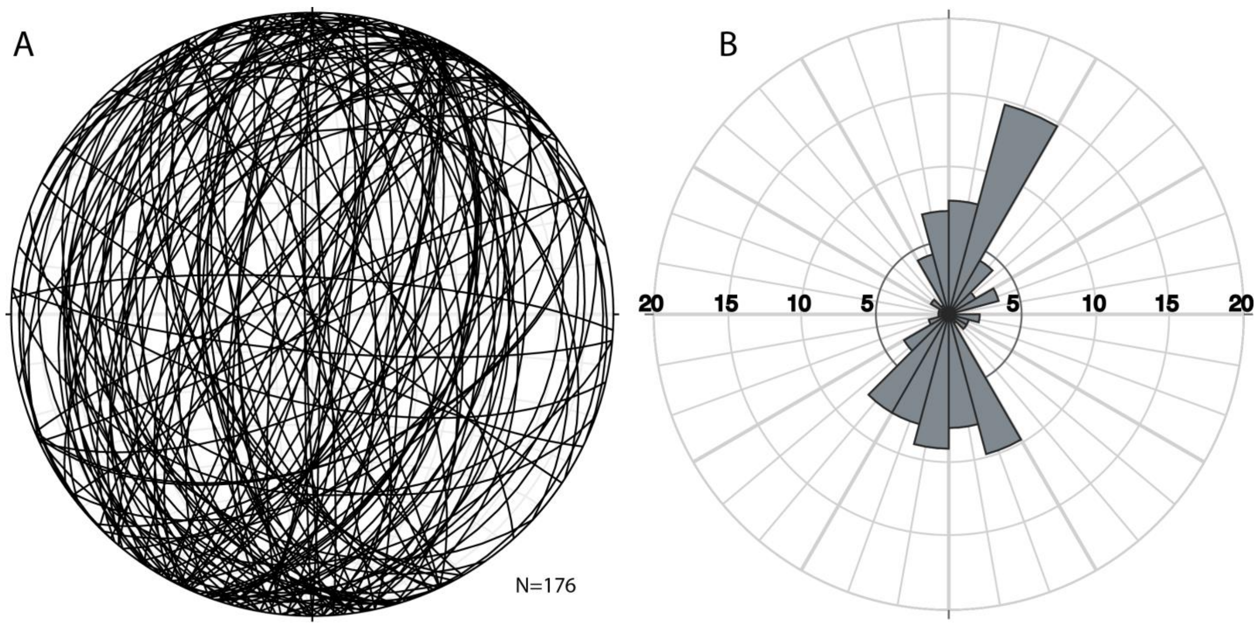
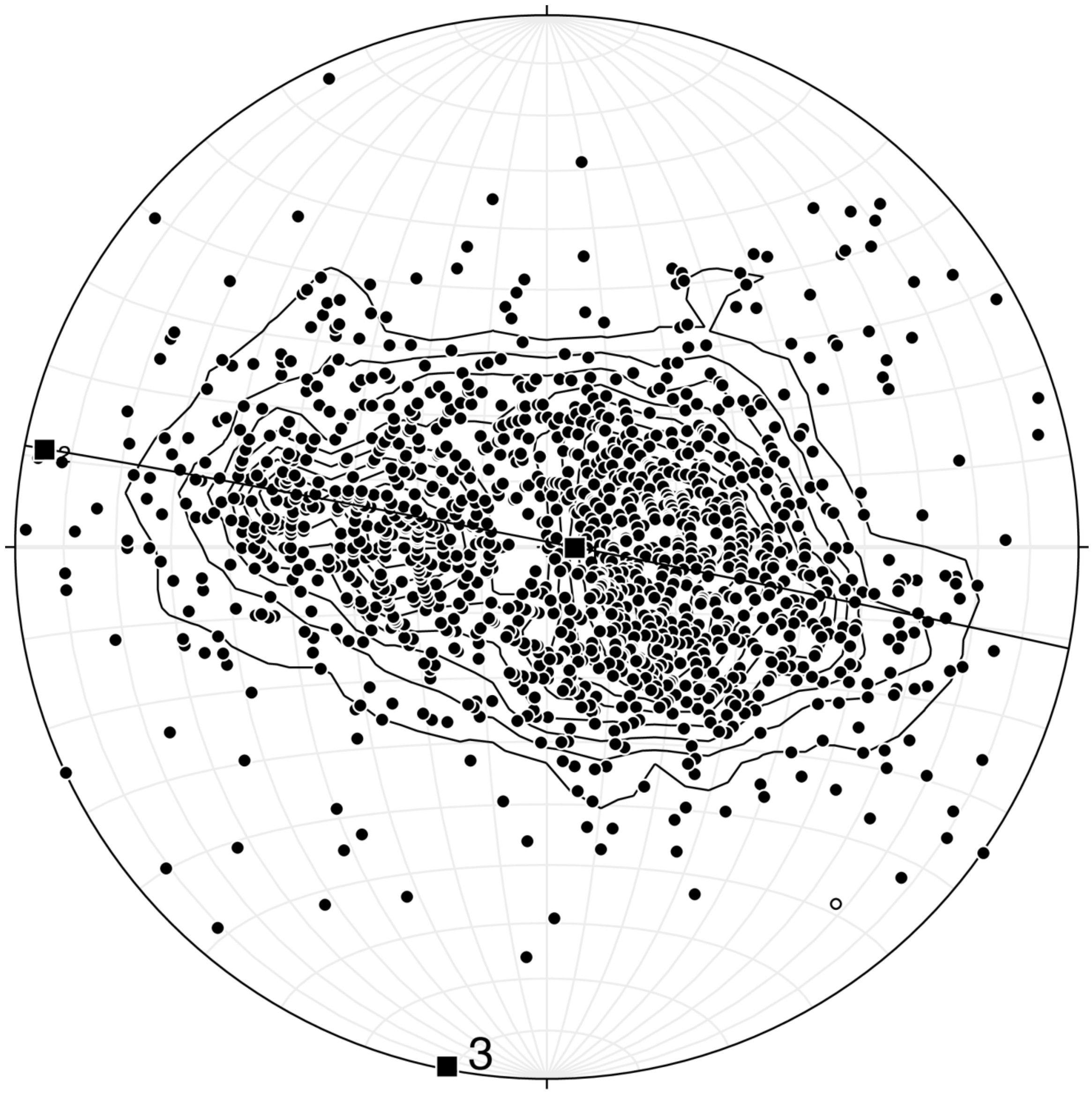


Fig. 6 A) Lower-Hemisphere stereonet plot of all fault planes (great circles) measured in the central Schell Creek Range. B) Rose diagram illustrates relative abundance of different fault plane azimuths (using right hand rule) highlighting the pre-dominates of NS to NNE-SSW trending faults.

5.1 Structural Domains:

Bedding orientations throughout the study area exhibit a great deal of variability, dipping into every quadrant and ranging from horizontal to vertical and even overturned (Fig 7). Nevertheless, the vast majority of bedding dips moderately to gently WNW or ESE. For example the Lower Cambrian sections in the eastern portion of the study area dip consistently moderately to gently WNW except where folded by small scale folds. The middle Cambrian through Devonian sections have more variation but are fairly consistent within individual domains. Bedding dips to the west and east with abrupt polarity flips along strike within the hanging wall of the SPD. To illustrate spatial variations in tilting, the study area has

been broken up into six structural domains, each of which exhibits distinct structural characteristics (e.g. bedding and faults orientations) (Fig. 8). The domain boundaries are either discrete faults or gradational over short distances. Each of the structural domains is described separately below.



All Bedding

Fig. 7 Contoured poles to all bedding measured in the central Schell Creek Range. Poles to bedding are distributed on a WNW-ESE great circle, reflecting an average rotation axis of 05/190. N=1425

Domain 1 consists of the Prospect Mountain Quartzite, Pioche Shale, and Pole Canyon Limestone in the northeast part of the study area (Fig. 8). These units lie in the footwall of the SPD, but unlike correlative units to the north and south, in this area bedding dips to the southwest with an average strike and dip of 136/18. The southwest dip instead of the typical westerly dip expressed in the rest of the SPD footwall is attributed to decrease in the displacement along the range front fault. North of the study area, the SCRF has 8-10 km of normal offset, whereas to the south, the SCRF has considerably less offset based on lower elevations of the range and a decreased thickness of basin fill in Spring Valley (Miller et al, 1983) A consequence of the decreased displacement to the south, is a differential uplift of the range and southwest dipping stratigraphy. Folding in domain 1 is restricted to the Pole Canyon Fm. and consists of occasional decameter scale folds that that have an average trend and plunge of 235/15.

Domain 2 encompasses Middle Cambrian units along the eastern flank of the range extending up into portions of Cleve Creek and lower Kolcheck Basin. This domain represents most of the footwall exposures of the SPD. Bedding generally dips to the west with an average strike and dip of 181/29 (Fig. 8), but is locally east-dipping due to the presence of numerous small scale, generally upright, N-S trending folds within the thin bedded Lincoln Peak Fm. The generally consistent westward dips of Domain 2 units is striking in light of the abrupt flips in polarity of tilting and faulting in the hanging wall of the SPD immediately to the west.

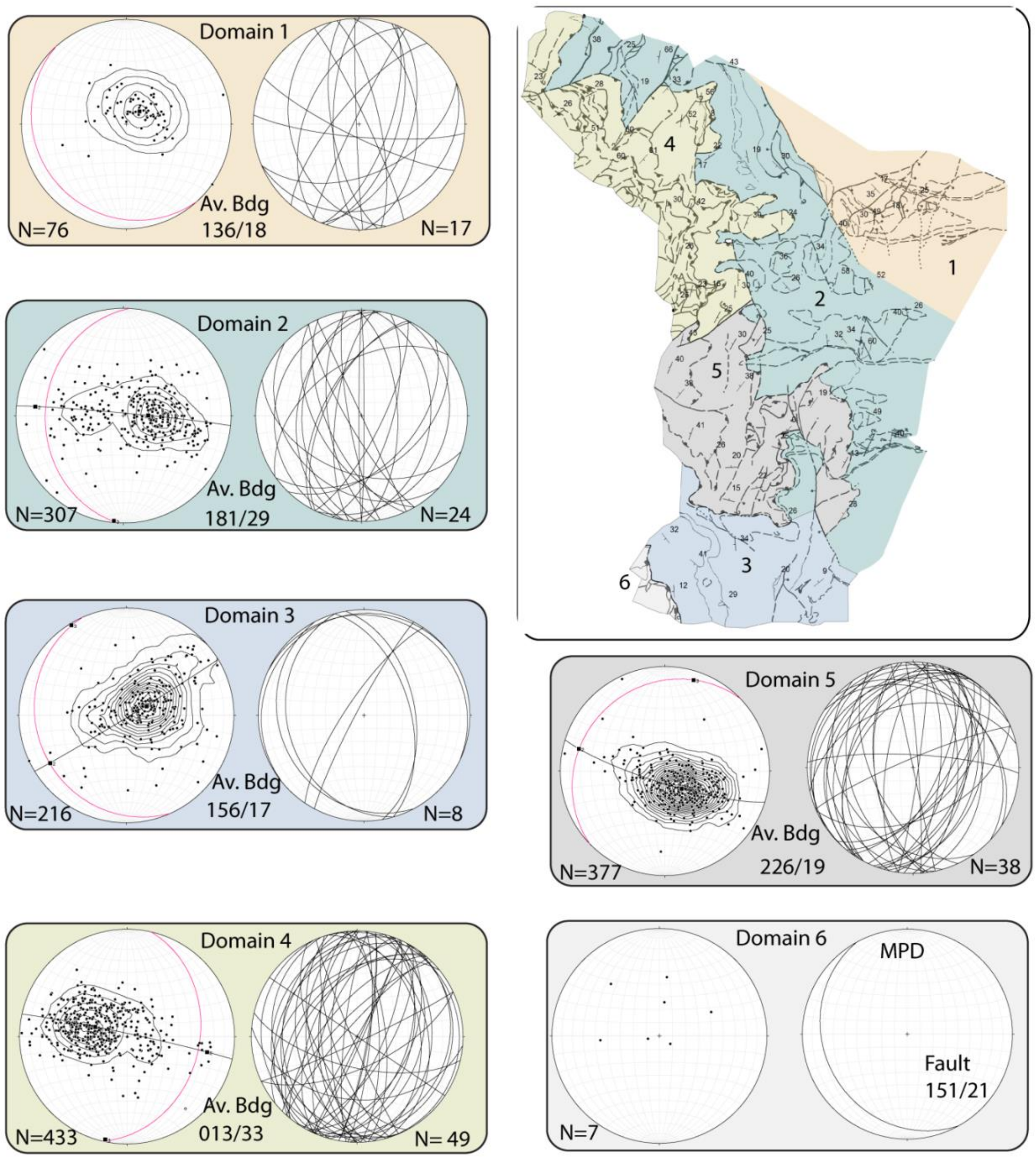


Figure 8 Structural data for the central SCR separated by structural domain. Plots are of lower-hemisphere stereonet projections of poles for bedding (left) and planes for faults(Right). rea 6 has only fault measurements on the MPD

Domain 3 is located in the southwest portion of the study area and encompasses Lower and Middle Cambrian units that generally dip southwest and, with an average strike and dip of 156/17 (Fig. 8) and are locally folded by meter scale folds trending NNW. Domain 3 is a continuation of Domain 2 with no major structures separating the two domains. These domains are distinguished by a transition from units which lie in the footwall of the SPD (Domain 2) to stratigraphically higher units which lie in the footwall of the structurally higher MPD (Domain 3). The SPD appears to die out a few km south of Cave Mountain as displacement on the MPD incresses southward. Near Majors Place farther to the south, units within the footwall of the MPD become increasingly strained and metamorphosed and exhibit a pervasive NW trending stretching lineation. Work by Gans and Norman (in prep.) has shown that the ductile fabrics exposed at Majors Place are likely late Mesozoic and were exhumed by slip along the MPD between 38-35 Ma.

Domain 4 represents the east-tilted region within the hanging wall of the SPD in the NW portion of the study area. Upper Cambrian to Mississippian units exposed in this domain are cut by a set of closely spaced west-dipping imbricate normal faults and has been tilted to the east-southeast with an average strike and dip of 013/33. (Fig 8 Plate 2). Overall bedding is remarkably consistent considering the high density of faults. Local variations in bedding attitudes occur in the thinly bedded limestone units like the Notch Peak Fm. and Pogonip Group and are attributed mainly to drag adjacent to faults. A peculiar departure from the generally consistent east tilts in this domain is exhibited by a small isolated fault block of the Mississippian Chainman and Mississippian Joanna

Limestone in the Kolcheck Basin (Plate 1). These units dip west and are separated from the east dipping Notch Peak Fm. by a flat lying (east directed?) fault.

At the southern boundary between Domains 4 and 5, there is an abrupt change in bedding east to west dip over a distance of a few hundred meters. The transition is well exposed in a deeply incised canyon, 5.5 km south west of Cleve Creek recreational area (Plate 1).

Domain 5 is directly south of Domain 4 in the hanging wall of the SPD and is characterized by north to northwest dipping beds in the Notch Peak Fm. and Pogonip Group and east directed normal faults. Although this area is in the hanging wall of the east-directed SPD, bedding flipped from east-dipping to largely northwest dipping with an average strike and dip of 226/19. Accompanying this reversal in dip direction is a reversal in the polarity of fault from mainly west-directed to mainly east-directed. In the southern portion of Domain 4, bedding changes gradually towards a more northward dip over a distance of a few hundreds of meters. The promontory at Bastian Creek (Plate 1) has more irregular bedding attitudes due to abundant faults and small-scale north-south trending folds. Poles to bedding in this area define a broad girdle with an average trend and plunge to a fold axis of 020/30.

Domain 6 represents a small portion of the hanging wall of the MPD in the southwest corner of the study area and was not examined in detail. Near the MPD, units have highly scattered orientations and are cut by numerous small-scale faults. Farther to the south, Devonian to Pennsylvanian units in the hanging wall are consistently tilted to the east and repeated by west-directed imbricate normal faults (Drewes, 1967), similar to that observed in domain 4.

5.2 Faults

Overview:

Three generations of normal faults of different orientations have tilted and attenuated rocks exposed in the central Schell Creek Range. many of these faults are not well-dated, but available evidence suggests extensional faulting started in the Eocene (Gans and Norman, in prep.) and continued intermittently until the present. The majority of faults strike NS to NNE-SSW (Fig 6). High and low-angle faults within the range consistently place younger rocks on older and omit stratigraphic section. The net effect of the high and low-angle faults is to thin the nearly 7 km thick stratigraphic section of crust to ≤ 2-3 km. Most contacts between formations are faulted and few complete sections of any unit are preserved in the range. Faults are fairly obvious where they juxtapose different formations, but are difficult to trace through thick monotonous sections of the same formation (e.g. Notch Peak Fm.) or through poorly exposed units (e.g. Lincoln Peak Fm. and Pogonip Group). Only the largest and most obvious faults are depicted on Plate 1, but many smaller faults are also present. Fault planes are rarely exposed, but the location of faults are evident from the juxtaposition of dissimilar units, lines of trees, and truncation of layering. Where faults planes are exposed they form knife sharp polished surfaces with minimal fault gouge, but well developed cataclasite. Slickenlines on fault surfaces are almost never preserved because of the high susceptibility of carbonates to surface weathering.

As stated previously, the most significant faults in the study area, in terms of their inferred magnitudes of offset and continuity are the Schell Peaks Detachment (SPD), Majors Place Detachment (MPD), and Schell Creek Range Fault (SCRF). The SPD and MPD are older, presently low-angle normal faults, both of similar age but they differ in their stratigraphic position and inferred slip direction. Although these two faults are distinct surfaces, they both separate highly-faulted hanging wall from a footwall that is generally west-dipping and significantly less faulted. The SCRF along with the high-angle splays and conjugate faults associated with it, is the youngest fault system in the SCR.

5.3 Schell Peak Detachment

The SPD was first described by Young (1960) as being the structurally lowest "thrust" or low-angle fault, in a series of generally gently-west-dipping faults in the northern Schell Creek Range. The SPD first crops out approximately 55 km to the north and can be traced continuously for approximately 65 km to the vicinity of Cave Mountain and Cooper Canyon in the southern portion of the study area (Plate 1). For much of its trace, the fault lies just west of the crest of the range and near many of the high peaks of the SCR. The fault dips to the west at < 25 degrees in the north (Young, 1960; Gans et al, 1985) but rolls over to a gentle eastward dip, south of Cleve Creek (Plate 2). For most of its trace, talus from the steep cliffs of the Notch Peak Fm. in the hanging wall obscures the fault. The fault plane and footwall limestone immediately adjacent to the fault are locally replaced by jasperoid breccia. Although the fault is poorly exposed, its position is generally evident because the hanging wall is typically highly discordant to the footwall and there is significant stratigraphic omission across the fault.

The stratigraphic juxtaposition across the fault varies along strike. In the far NE portion of the study area the fault places Lincoln Peak Fm. in the hanging wall against the lower portion of the Pole Canyon Fm. in the footwall. The two units are in correct stratigraphic order and appear roughly concordant with the fault but are two thirds of their normal stratigraphic thickness. Directly south, in the Kolcheck Basin, the SPD places Notch Peak Fm. in the hanging wall on Pole Canyon Fm. in the footwall, with a minimum stratigraphic omission of 1500 meters of section across the fault at this locality. This is the largest separation along the SPD observed in the study area, but the total omission might, in part, represent multiple juxtaposition events including older structures (e.g. Kolcheck Basin fault). Southward of Kolcheck Basin, the SPD places Notch Peak Fm. on successively younger footwall units (Lincoln Peak Fm. or Johns Wash Fm.) suggesting progressively less displacement to the south.

The discordance between Notch Peak Fm. in the hanging wall and Lincoln Peak Fm. in the footwall changes from north to south. South of Cleve Creek for ~5 km, the Notch Peak Fm. in the hanging wall dips to the east and the Lincoln Peak Fm. in the footwall dips to the west (plate 2). South of this zone, both hanging wall and footwall units dip west between 10 to 30 degrees. The total stratigraphic omission across the fault is not that great, (<500 m) considering the discordance and magnitude of faults in the hanging wall.

It is difficult to precisely assess the sense and total amount of offset across the SPD due to the lack of well-defined hanging wall and footwall cutoffs and because of the flip in tilt polarity of the hanging wall units. To the north, the SPD clearly shows top-to-the-east displacement based on: 1) the fault cuts down section to the east in the footwall and places younger units on older; 2) imbricate splays in the hanging wall are generally east-directed and; 3) the sense of drag indicated by thin bedded silty limestones immediately adjacent to the fault. In the study area however, not all of these relationships hold true.(Young, 1960, Gans et. al, 1985) The hanging wall splays are both east-directed and west-directed and drag along the fault is ambiguous due to the abundant small-scale folds adjacent to the fault. Throughout the study area the SPD place younger rocks on older and appears to cut down in section to the east, even when faults in the hanging wall are west-directed. Based on the observation that the fault cuts down section to the east and places younger rocks on older I also interpret the SPD to be a top-to-the-east normal fault, but the total offset is unknown. This fault's geometric evolution will be discussed below.

The age of the SPD is poorly constrained with no geochronologic data to support timing or duration of fault slip. The best assessment of fault activity comes from cross-cutting relationships near Cave Creek and Success Summit east of the study area. Here hanging wall structures of the SPD are offset by the MPD demonstrating the SPD is older than the (38-35 Ma) MPD but there is no reliable maximum age for the fault.

Fig 9. Views of various faults in the central Schell Creek Range. A) View south at one of the more obvious low-angle faults cutting the Cambrian Notch Peak formation. B) View northeast of two splays of the Bastian Creek Fault. C) Low-angle fault cutting the Pole Canyon Limestone in the southeast portion of the study area. Note the well-developed cataclasite and polish fault plane. E) View south into the Kolcheck Basin of east tilted stratigraphy (dashed lines) cut by west directed faults. In this locality the SPD is cut by the Kolchek Basin Fault. F) View west of the complex structures in Kolchek Basin. Kolcheck Basin fault cuts the SPD and juxtaposes the Prospect Mountain Quartzite in the foot wall against the Lincoln Peak in the hanging wall. Also note the Cl, in the hanging wall of the SPD, is omitted on the south side of the canyon.

5.4 Hanging wall Structure of the Schell Peak Detachment

The exposed hanging wall of the SPD is composed of highly faulted and tilted sections of Cambrian Notch Peak Fm. to Devonian Guilmette Fm. In the northern portion of the hanging wall (Domain 4), the hanging wall includes an imbricate stack of four to five contiguous gently-west-dipping normal faults spaced at 100-500 m that can be traced along strike for approximately 6-7 km (Plate 1,2) with less abundant high angle east dipping faults. These faults typically bound map view strips composed of a single unit, creating a pseudo-stratigraphy of fault bounded units that appear in correct stratigraphic order but have highly discordant contacts. The slip direction and amount of offset on these faults is best constrained by the stratigraphic throw and the bedding to fault cutoff angles. The gentle west dips of the normal faults and 35-45 degree eastward tilts of bedding in this domain are compatible with a domino-style fault block rotation kinematic model for the deformation in the hanging wall of the SPD(Fig11). Using the geometric relationship implicit in this type of model (e.g. Gans and Miller, 1983; Wernicke and Burchfiel, 1982) indicates the hanging wall normal faults initiated as steep (~60^o) west-dipping antithetic normal faults and that this portion of the hanging wall has been extended by a β ($\beta = l_f/l_0$) factor of ~2.

The southern portion of the SPD's hanging wall (Domain 5) is composed of the Notch Peak Fm. and Pogonip Group that is faulted by high- and low-angle, east-directed normal faults that repeat the hanging wall units multiple times. Low-angle faults in the hanging wall are difficult to recognize and map due to the monotonously thick Notch

Peak Fm. and dense vegetation. The best constrained low-angle faults juxtapose Pogonip Group in the hanging wall against the Notch Peak Fm. in the footwall. These fault dips west at ~ 10-25 degrees, and cut down section to the east. A particularly well-exposed fault in this system is located along the western extent of the Bastian Creek promontory where it dips east at ~20 degrees and places the upper Notch Peak Fm. and overlying Pogonip Group against the lowest part of the Notch Peak Fm. (Plate 1, 2)Another noteworthy low-angle fault is exposed within the Notch Peak Fm. cliffs at the head waters of Bastian Creek (Fig 9A). This fault dips 10^{o} to the north, places Notch Peak Fm. and Pogonip Group in the hanging wall on Notch Peak Fm. and has well-developed cataclasite and fault breccia along the surface. Slickenline data suggest slip to the north-northeast. A younger generation of high angle faults cut the system of low-angle faults but also root into the SPD within Domain 5 repeating the Notch Peak Fm. several times across the study area. This younger set of normal faults, strike NS, dip 45-60 to the east, and are spaced at ~300 meters.

The amount of westward tilting that is associated with extensional faults in the southern portion of the SPD hanging wall is ~15-25^{o} assuming horizontal bedding at the inception of faulting. The amount of extension in the southern portion of the SPD hanging wall is estimated to be stretched by a β factor of 1.35 to 1.5 based on offsets on faults and amount of tilting. This is surprisingly low compared to the northern portion of the hanging wall, and supports the interpretation that displacement on the SPD and hanging wall splays dies out to the south, as displacement increases on the structurally higher MPD.

5.5 Transfer Fault in the Schell Peak Detachments Hanging Wall

Within the hanging wall of the SPD (Domains 4 and 5) there are three transfer faults that help to accommodate flips in tilt polarity and along strike changes in the magnitude of extension from north to south. These fault are described from north to south, starting with the largest transfer fault located 2 km south of Cleve Creek Baldy. This fault can be traced for ~2 km in an ENE-WSW direction and separates the middle to upper Cambrian stratigraphy in the footwall form the Cambrian to Devonian stratigraphy in the hanging wall (plate 1). The fault is best exposed at the crest of the range where it dips 65 degrees to the southeast. Elsewhere, the fault is covered by colluvium and vegetation. The fault displaces the Notch Peak Fm. nearly 2 km in an oblique left lateral normal sense and separates a highly east-tilted section in the south from a less tilted section to the north. The fault terminates into the SPD where there is an increase of 2 km of stratagraphic omition on the south side of the SPD.

The 2nd transfer fault is located in the west central portion of the study area and accommodates the flip in tilt polarity in the hanging wall of the SPD, from east tilted to west tilted. The fault can be traced for ~2 km, trends NW-SW and dips SW at 35^{o} with east plunging (34^{o}) slickenlines that indicate oblique left-lateral normal slip. The faults trace becomes obscured in the Pogonip Group near the crest of the range but, it appears to steepen significantly based on the map pattern of the fault. The total amount of slip along the fault is unclear, but it offsets the low-angle fault at the base of the Pogonip Group by ~ 400 meters.

The 3rd transfer fault is located just north of Cave Mountain near the crest of the range. The fault is easily seen on air photos where it truncates resistant units within the Pogonip Group and offsets the faulted contact between the Pogonip Group and Notch Peak Formation. The fault trends east-west and dips steeply to the southeast. The total amount of offset is not clear, but a minimum southeast-directed separation of 1 km of inferred based on the offset of the Pogonip Group and Notch Peak Fm. contact (Plate 1).

5.6 Footwall Structure of the Schell Peak Detachment

Faulting in the footwall of the SPD is largely limited to the younger generation of high-angle and isolated low-angle faults. Two noteworthy low-angle faults were identified in the footwall of the SPD. South of Cleve Creek, a fault contact between the Pole Canyon Limestone and Lincoln Peak Formation is expressed as a meter thick interval of silicified limestone with discordant bedding. There is little stratagraphic omission across the fault, so the total amount of offset is likely small. To the northeast the discordant bedding and silicification disappears and the contact looks depositional or becomes a bedding parallel faults. The second low-angle fault is located north of Cooper Canyon and places Lincoln Peak Fm. in the hanging wall on Pole Canyon Fm. in the footwall. The fault can only be traced for a few 100 meters and is locally beautifully exposed as a flat polished 10 m by 8 m ledge (Fig 9). Bedding in the hanging wall dips ~45 degrees to the east and is truncated by the fault.

5.7 Majors Place Detachment

The MPD was first described by Drewes (1967), who called it the "Schell Creek Thrust". It first appears 1 km south of Majors Place along the eastern range front and can be traced continuously for 20-25 km to the NNW where it breaks up into several splays in the vicinity of Cave Creek and Steptoe Creek (Drewes, 1967). The fault consistently dips 20-25 degrees to the west and southwest and is interpreted to have top-to-the-west, normal displacement based on: 1) imbricate west-directed normal faults and east-tilts in the hanging wall; 2) normal sense drag of both hanging wall and footwall strata adjacent to the fault and; 3) growth fault relations within Tertiary sedimentary and volcanic sections in the hanging wall of the fault. The fault is mostly covered by colluvium and vegetation, but where exposed it is a sharp polished plane with a well-developed cataclasite. The precise direction and total amount of slip on the MPD is poorly constrained. The tilt direction of hanging wall Paleozoic and Tertiary strata suggest slip to the west or WNW. A minimum amount of offset is provided by the stratigraphic omission of > 3 km of Upper Cambrian to Devonian strata across the fault, but is likely much more because of the low footwall cutoff angle. At Cooper Summit (10 km north of Majors Place), a thick (> 1 km) succession of conglomerate interstratified with Eocene ignimbrites in the hanging wall of the MPD and is tilted and truncated by the fault, indicating that at least some of the slip must be Eocene or younger. Indeed, the fanning of tilts within this Eocene section and the local accumulation of >500 m of coarse cobble and boulder conglomerate suggests that the MPD was likely the basin bounding fault during accumulation of this section. The ignimbrites occur near the top of the basin fill section and have been dated by $^{40}Ar/^{39}Ar$ at 36 to 37 Ma, constraining timing of movement on the MPD (P. Gans, pers. Comm.).

5.8 Schell Creek Range Fault

The range-bounding fault along the eastern flank of the SCR was first described by Young (1960) who called it the Schell Creek Range Fault. The fault strike north-south along the eastern flank of the range and its sharp linear trace can be followed for nearly 90 km from the northern tip of the SCR to the vicinity of Cleve Creek. A high resolution seismic reflection profile across Spring Valley has shown this fault dips between 45-50 degrees and has nearly 10 km of top to the east displacement (Gans et al, 1985). As the fault approaches the study area it breaks up into multiple splays. The splays in the Cleve Creek area dip between 45-65 degrees to the east with approximately 100 meters of offset on each fault. The total amount of tilting associated with the SCRF is estimated to be 10-25 degrees based on the amount of rotation required to restore the SCRF to 60 degrees. The largest of the splays is located at the mouth of Cleve Creek where it places Pennsylvanian and Mississippian units on the Cambrian Prospect Mountain Quartzite, a stratigraphic omission of 5-6 km. A likely interpretation for the large stratigraphic omission at this locality is that the fault juxtaposes the hanging wall of the SPD, against the footwall Prospect Mountain Quartzite.

Conjugate to the SCRF are a set of NW trending high angle normal faults. The faults dip steeply (60^{o} and 90^{o}) to the west and have top-to-the-west displacement. These faults have offsets of only a few 100s of meters, but repeating the Prospect Mountain

Quartzite and clearly cut the SPD in the headwater of Cleve Creek.

5.9 Other young faults

Several high-angle normal faults that do not appear to be related to the SCRF occur locally throughout the area. Two of these faults are noteworthy: the Kolcheck Basin Fault in the northwest portion of the study area and the Bastian Creek fault in the central portion of the study area (Plate 1, 2). The Kolcheck Basin Fault dips 80-90^{o} and has oblique ENE-trending, 70^{o} plunging slickenlines. The fault is best exposed along Kolcheck Creek where a 5-m-long polished fault surface with slickenlines is preserved. The fault offsets the SPD 500-700 meters and places Lincoln Peak and Notch Peak Fm. in the hanging wall against Prospect Mountain Quartzite in the footwall. The mismatch in the footwall stratigraphy of the SPD on either side of the Kolcheck Basin fault has left the footwall units with more apparent offset than the SPD itself. One possible resolution is that there was an earlier (pre-SPD) episode of slip, followed by slip on the SPD and then a late episode of slip (or reactivation) that also offset the SPD by 700 meters.

The Bastian Creek Fault is another large fault that offsets the SPD near the promontory near Bastian Creek. The fault dips to the east and can be traced for approximately 5 km before it breaks up into a series of splays to the north or is buried by Quaternary alluvium to the south. The fault dips to the east at ~65 degrees and has offset the SPD by ~500 meters in a normal sense (Plate 2).

5.10 Summary of faults

Detailed mapping in the SCR has revealed at least three distinct generations of normal faults.

The earliest faults are a NE-trending, SE-dipping fault in Kolcheck Basin that places Lincoln Peak Fm. against Prospect Mountain Quartzite. The next episode of faulting is recorded by low-angle "detachment faults" (SPD and MPD) with abundant imbricate splays in their hanging wall. These faults are associated with major east-west extension and record both top-to-the-east and top-to-the-west slip. The youngest generation of faults is recorded by the SCRF and other high angle faults. These normal faults clearly cut the older low-angle faults and are associated with the development of the modern topography.

6 Discussion

The data presented here yield insight into the evolution of the central SCR. I present a three-stage model that accounts for multiple tectonic events from the Mesozoic to Present.

1. Mesozoic age contractonal structures produce large scale folds including the Butte and Confusion Range Synclinorium (Hose and Blake, 1976).
2. Early Eocene extensional structures cut previously folded strata leading to the formation of extensional detachment faults with footwall units locally parallel to the faults
3. Mid-Miocene to present high-angle normal faults cut the previous structures and carve out the modern Basin and Range topography.

The discussion below elaborates on this tectonic framework and addresses some of the key structural complexities in more detail

6.1 Schell Peak Detachment Initial Dip and Reconstruction:

A fundamental question is the original dip of the SPD? Two possibilities are: 1) the fault initiated and slipped at low-angles (<25^o) or; 2) The fault initiated at moderate to high angles fault (25^o to 60^o). Regional evidence described below suggest that the fault was likely a steeply dipping fault that slipped at an angle between 25^o to 60^o. East of the SCR in the northern Snake Range the correlative footwall units to the SPD have been buried to deeps of 20-30 km (Miller et. al. 1999; Cooper et. al. 2010) whereas the same units in the SCR have been buried to depths no greater than 8-10 km or deeper than their original stratigraphic depths (Miller et. al, 1989). This suggest the units had an eastward dip prior to extension. Undoing the extension caused by the modern range bounding faults; the lateral distance separating the units in the SCR from the same units in the northern Snake Range would be ~20 km suggesting that the footwall stratigraphy and SPD dips at ~45^oor more.

A palinspastic reconstruction of cross-sections across the SPD is challenging, due to a flip in tilt and fault polarity of the hanging wall and the near parallelism of the footwall stratigraphy to the fault. As discussed above, the fault is inferred to have top-to-the-east displacement and consistently omits section. Although cross-sections A-D of plate 2 do not look easily restorable, two models that assume the presence of pre-existing folds can help to explain the observed geometric relations (Fig 10). Two alternatives are considered. In the first model (fig. 10A), an east dipping normal fault (the SPD) cuts and decapitates an older system of west-dipping normal faults that were developed mainly to the west of the study area, and carried the upper portions of these fault blocks eastward. The parallelism of the SPD to the footwall stratigraphy is attributed to the SPD cutting obliquely across an older anticline and following the east-dipping limb. The second model (Fig. 10B) is broadly similar to the first, with the exception that in this case the west-directed imbricate normal faults (and eastward tilts) in the hanging wall of the SPD are attributed to coeval antithetic normal faulting in some portions of the hanging wall, resulting in eastward tilts despite the overall top-to-the-east displacement on the underlying fault. The parallelism of the footwall stratigraphy is once again attributed to a pre-existing east dip of that part of the footwall due to earlier folding.

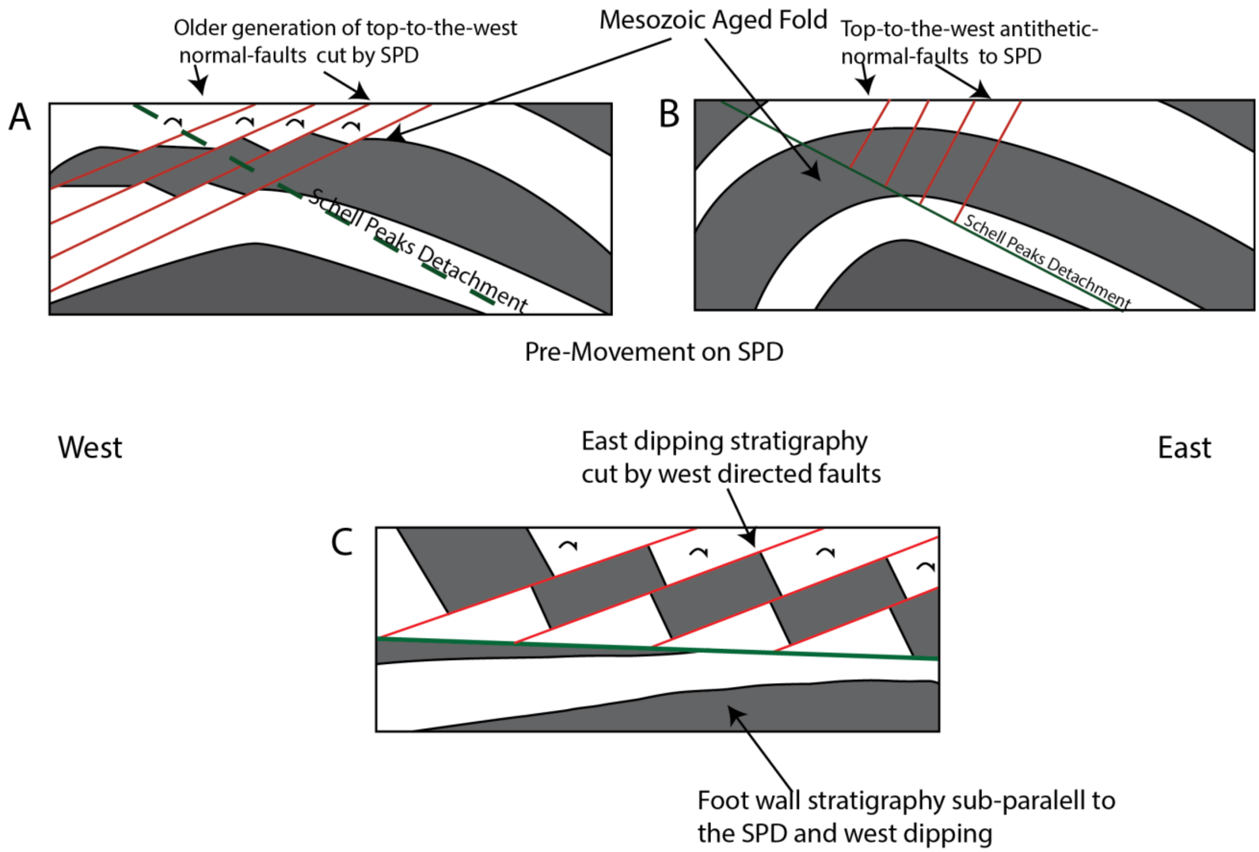


Fig 10. Schematic drawing demonstrating two possible geometric relationships pre-slip on the SPD. A) In this cartoon, a Mesozoic fold is cut by and imbricate set of closely spaced, top-to-the-west normal faults (red) with the location of the SPD (green). B) A Mesozoic fold is cut by the SPD (green) and antithetic top-to-the-west normal faults (red). C) Post slip sketch of the current geometries seen in the northern SPD. Both models account for the east dipping stratigraphy in the hanging wall and sub-parallel, west dipping, stratighraphy in the footwall.

6.2 Accommodation zones

Extensional tilt domains in the Basin and Range Province are commonly segmented by accommodation zones where the polarity of tilting and faulting is opposite on either side of the zone. Thought the Basin and Range there are accommodation zones that are both orthogonal and parallel to the extension direction .The location of accommodation zones in extensional terrains has been often attributed to previous structures (Faulds and Varga, 1998). but a fundamental question remains - what controls the dip direction of normal-fault systems on either side of an accommodation zone?

Accommodation zones exist at multiple scales in the SCR and surrounding region. Transecting the Egan, Schell Creek, and Snake Range is a 100's of km scale accommodation zone where the older generation of low-angle fault within the ranges and younger high-angle range bounding faults of opposing polarity interact, forming an east-west trending accommodation zone. Within the larger regional accommodation zone are smaller scale accommodation zones, in the hanging wall of the SPD (Plate 1). Here synthetic and antithetic splays of the SPD interact. The location and dip-direction of this regional extensional accommodation zone appears to be controlled in part by previous shortening structures (i.e. folds). The SPD and MPD low-bedding to fault cutoff angle can be explained by the faults exploiting the limbs of folds (Fig 10). In the north, the east-directed SPD exploited the east-dipping limb of a north-west trending antiform. In the south, the west-directed MPD exploited the west-dipping limb of the same antiform.

Not all the younger range bounding faults have previous structures controlling their location and orientation yet they still terminate in the same location as the older low-angle faults. The SCRF, for example, cuts bedding at a high angle and is part of an east-dipping normal-fault system, north of the accommodation zone. One possibility that explains termination of the SCRF in the same region as the older fault is that the oldest fault in the fault system could control the orientation of the rest of the faults in the system. An example of this relationship includes the Miocene slip surface of the NSRD which exploited an Eocene, east-dipping shear zone (Miller et al, 1999, Gans, 2000; Gans et al, 2012). The SCRF is younger than the NSRD and might have oriented with the same dip direction as the Miocene NSRD because it is more energy conserving to have a sequence of faults of the same tilt polarity. The small scale accommodations zones in the hanging wall of the SPD appears to be a random intersection of two opposing tilt domains with no obvious structures controlling it location or tilt polarity.

7. Summary of Tectonic History

The following tectonic history for the SCR is proposed based on the structural relationships observed in the field area and regionally. Folds such as the Butte and Confusion Synclinoria (Hose and Blake, 1976) and a recumbent fold in the Northern Snake Range Lee et al (1999) are clear evidence that there must have been large scale crustal shortening and folding in the region prior to the inception of extension. Lower and Middle Cambrian units in the northern Snake Range were buried to depths of 25-30 km and metamorphosed to amphibolite grade during the latest Cretaceous (Miller et al, 1989;

Cooper et al, 2010) while the same units in the SCR were never buried much deeper than their original stratigraphic depths of 6-9 km (Gans and Miller, 1983). This implies that at the end of the Cretaceous thickening event the units that are now in the footwall of the SPD in the northern part of the study area dipped moderately to steeply eastward on the eastern limb of a broad antiformal structure. Southward, the depth of burial of Cambrian rocks in the southern Snake Range, is less than the Schell Creek Range exposures near Majors Place. This demonstrats the southern portion of the range had likely cross this pre-existing antiformal culmination, such that Cambrian rocks in the footwall of the MPD are interpreted to lie on the west-dipping limb. Obviously, many uncertainties remain regarding the exact geometry and location of these pre-extensional structures, but the evidence suggests that such structures played an important role in controlling the geometry of the subsequent extensional fault systems.

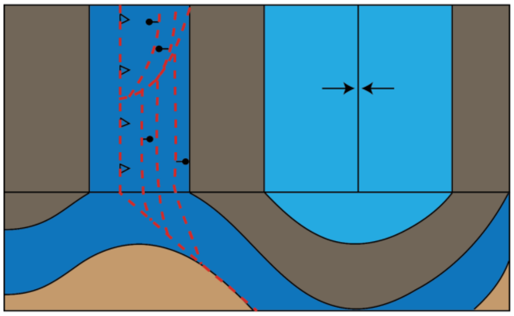
The dominant Eocene structures are the SPD and MPD along with their synthetic and antithetic hanging wall splays. These two faults are interpreted to have produced at least 5-10 km of ~ E-W extension and accommodated the majority of crustal thinning of the upper Cambrian-Permian stratigraphy. The steeply-dipping bedding in the hanging wall and the gentile dips of faults suggest that there have been large amounts of tilting, of both bedding and faults, during this extensional event. One of the uncertainties with this older generation of faults is the magnitude of the tilting that was associated with this event as well as the original orientation of the presently low-angle faults. Their current orientations makes them problematic given our general understanding of fault mechanics (Anderson, 1951) where normal faults cannot overcome the static friction and cannot slip once they dip less than 20^{o}, many of the Eocene aged faults are currently dipping <20^{o}. By undoing tilting caused by the Miocene-Holocene faults some of the older faults steepen but not enough to be in a suitable orientation to slip and some restore to even lower angles prior to Miocene tilts. One hypothesis is that many of the large low-angle faults in the Schell Creek Range, Egan Range, and Snake Range all passively rotated "domino-style" or at nearly the same time causing these faults to tilt to their present low-angle orientation (Gans and Miller, 1983). In the Egan Range the older low-angle faults cut bedding at high angles and are compatible with this interpretation. However, in the SCR, this model is more difficult to apply because a number of faults have very low bedding to fault cutoff angles. In particular the SPD and MPD are not easy to explain by simple domino-style block rotation because they have hanging wall strata that are highly discordant to the fault and footwall strata that parallel the faults. One way to explain this relationship is to discount the assumption that the stratigraphy was sub-horizontal prior to extensional faulting. If there was significant pre-extensional folding, there might still have been high-angle normal faulting and block rotation but a wide range of bedding-to-fault cutoff angles. In the vicinity of the Egan Range bedding could have been flat-lying and faults would have to cut bedding at high angles. In the Schell Creek Range, bedding may not have been flat-lying and the bedding parallel "detachments" may have exploited limbs of large folds (Fig. 11). These same detachment faults may have surfaced close to the hinges of these folds, where bedding would have been more gently dipping. This could explain why bedding in the hanging walls is commonly discordant (Fig. 11)

Large high-angle normal faults including the SCRF, Kolcheck Basin Fault and

Bastian Creek Fault (Plate 1, Plate 2) as well as other smaller steeply dipping faults dominate the younger (Miocene-present) extensional history. The SCRF is the largest of this younger generation of faults and has accommodated the largest amount of offset and tilting within the northern part of the range. By restoring the15-20 degrees of tilting cause by the SCRF, and other range front faults, the footwall units of the SCR rotate back to be flat lying to gently west dipping. The older SPD would rotate to a flat lying or gently east tilted fault, more appropriate for its top to the east displacement.

There is some ambiguity as to when some of the other Miocene-Holocene faults were active relative to the SCRF including the Kolcheck Basin Fault and Bastian Creek Fault. Both of these faults cut the older Eocene-age faults and may have originated as early as the Oligocene and continued until most of the extension was being accommodated by the SCRF in the Miocene.

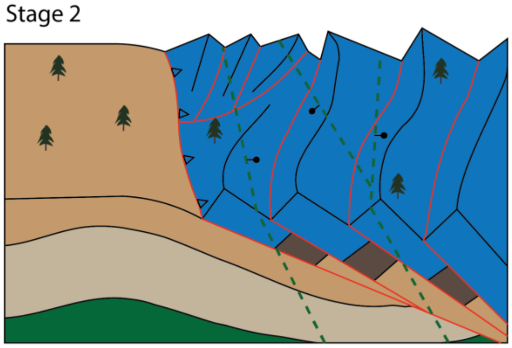
Stage 1



Createaceous

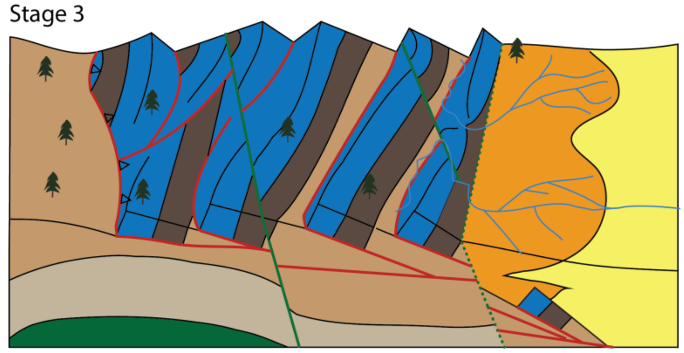
Fig (11)Three stage model for the evolution of the central SCR from Cretaceous though Holocene time. Stage 1: Cretaceous shortening forms large-scale anticline, synclines and domes. Stage 2: extensional structures and large detachment faults exploit planes of weakness between rheologicaly different units with synthetic and antithetic splays rooting into detachment fault attenuating and tilting the hanging wall. Stage 3: Basin and Range style normal faulting cut previous structures and forming north south trending ranges.

Stage 2



Early Eocene ? - Early Miocene

Stage 3



Miocene -Holocene

8. Conclusions:

Detailed mapping in the central SCR identifies six individual tilt domains, the location and stratigraphic offsets of several generations of normal faults, and the location and scale of several different extensional accommodation zones that transect the range. Bedding orientations within the range vary dramatically, but discrete domains of internally coherent bedding exist. Two large low-angle faults (SPD and MPD) dominate the early structural evolution of the range and act to separate different tilt domains and thin the crust to a fraction of its original thickness. The older faults systems within the range cut bedding at a range of orientations from very steep to near parallel. The low-bedding to fault intersection angle can be interpreted in two ways: 1) bedding was nearly flat lying and these large faults formed at a range of orientations from steep to flat. 2) Bedding was folded and most faults formed at nearly the same orientation and have variably rotated to their current orientation. The second interpretation is considered more likely because it is easier to reconcile with our understanding of rock mechanics and is supported by the observation that nearly all modern range bounding faults appear to have originated at steep angles and have rotated to their current orientation. Furthermore, the along strike variability in fault to bedding cutoff angles for a single consistently-oriented fault suggests that bedding was not uniform over large areas; rather I argue that it was likely to have been highly variable prior to the inception of faulting. The location of accommodation zones bisecting the range appears to be controlled by the location of pre-existing Cretaceous structures related to shortening (i.e. folds). The east-directed SPD in the north appears to have exploited the east-dipping limb of a large scale Mesozoic fold while the west-directed MPD in the south appears to have exploited the west-dipping limb of the same fold, resulting in low-bedding-to-fault cutoff angles in the footwalls for both faults. The origin of small scale accommodation zones in the hanging wall of the SPD are unclear but, are inferred to be due to the random intersection of two discreet tilt domains with no previous structures controlling its location. The total magnitude of extension across the SCR is very high (factor of 3-4) whereas average Basin and Range estimates are by a factor of ~1.5. More than half the extension in the SCR is estimated to pre-date the Miocene to recent faulting associated with the development of the modern basins and range topography.

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