UNIVERSITY OF CALGARY

Bedrock Expression of the Eastern California Shear Zone: southern Stateline Fault, California/ Nevada

by

Ann Hislop

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOSCIENCE

CALGARY, ALBERTA

JANUARY, 2012

ABSTRACT

The Stateline Fault follows the California/Nevada state line and forms the eastern boundary of the Eastern California Shear Zone. The southern segment of this 200 km long fault system has ~ 30 km of documented dextral offset. The abrupt southern termination of the Stateline Fault within 30 km of its documented 30 km dextral offset presents a space problem.

Geologic mapping was conducted southwest of the south end of the Stateline Fault in order to resolve the space problem. Geologic mapping indicates that at least part of the displacement on Stateline Fault is absorbed by a sub-parallel dextral strike-slip fault southwest of the main fault trace. This is an important interpretation because it potentially resolves the fault termination problem and allows for the possibility that there are unmapped seismogenic faults in the region. Understanding the spatial and temporal evolution of the Stateline Fault is important for seismic hazard assessment in the region and models for the development of the Eastern California Shear Zone.

ACKNOWLEDGEMENTS

I would like to acknowledge my supervisor Dr. Bernard Guest for allowing me the opportunity to map in the beautiful eastern Mojave Desert of California. My mapping was based on an unpublished map by Dr. Gary Axen.

I would like to thank Pat of the Gallagher Library and Dr. Len Hills for all of their help. Thank you to Sarah and Michele and Julie-Anne for all your encouragement and support over the years. And thank you so much to my two awesome field assistants, Colt and Jak.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

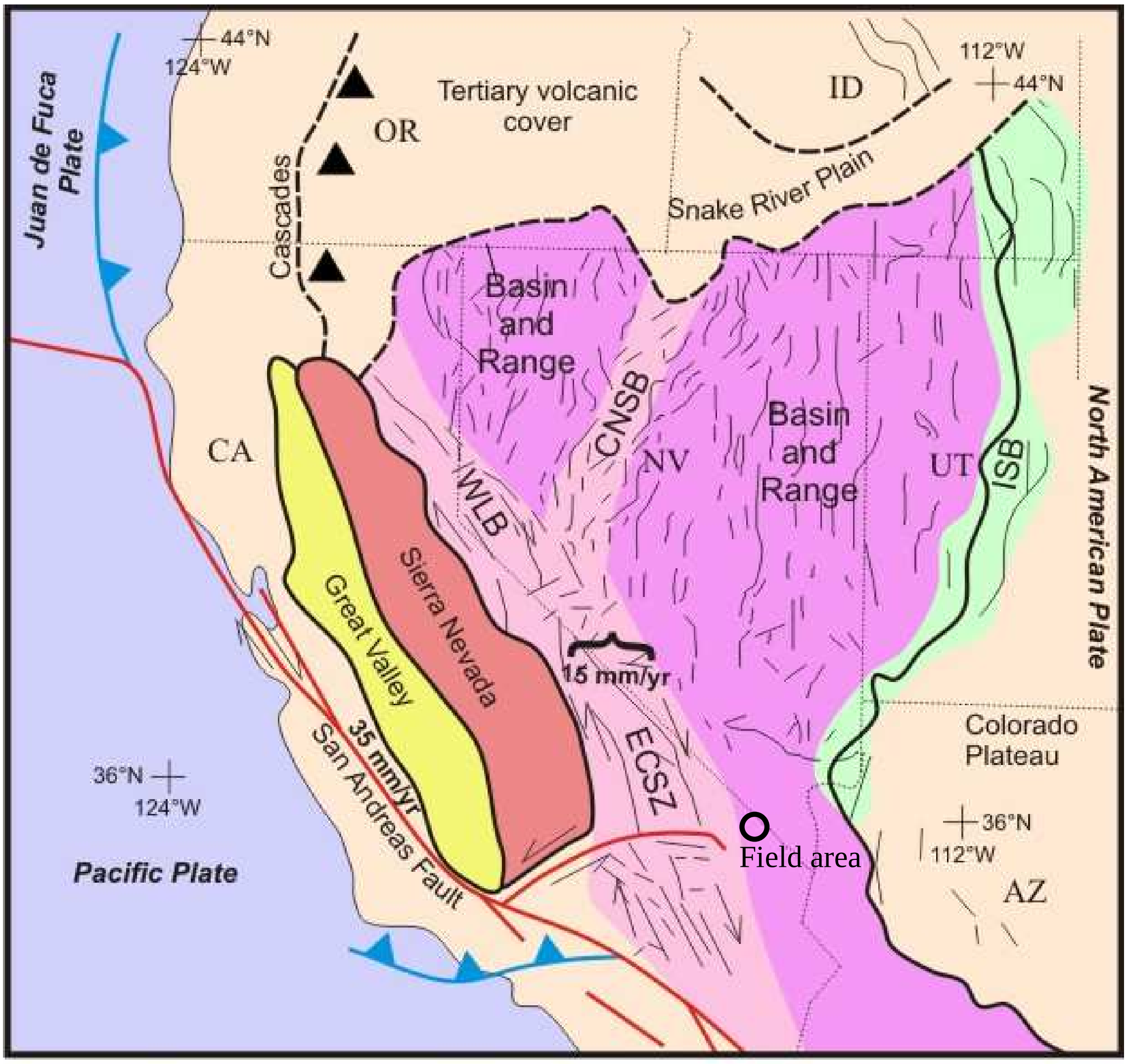
1. INTRODUCTION

The purpose of this thesis is to determine if there are dextral shear faults in the northeast Clark Mountains west of the southern termination of Stateline Fault. Documenting the extent of dextral faults and their offset is important because Stateline Fault forms the eastern boundary of the active right lateral Eastern California Shear Zone, the world's most studied diffuse plate boundary. It is also relevant for seismic hazard assessment in the region. The Stateline Fault is an important active fault located within 40 km of Las Vegas, runs through the town of Pahrump, Nevada and terminates just northwest of a major interstate highway (I-15), a large solar array currently being installed on the Ivanpah Valley fan, and new developments including a planned high speed mono rail and a planned international airport. Understanding the spatial and temporal evolution of the Stateline Fault is important for models of the development of the Eastern California Shear Zone, the world's most studied diffuse plate boundary.

The Eastern California Shear Zone (ECSZ) is a broad zone of dextral shear faults related to the San Andreas Fault system but located far inland (Fig. 1). It is 125 km wide and ~ 900 km long and it extends from north of the Salton Sea where it merges with the San Andreas Fault along the eastern side of the Sierra Nevada and terminates at the southern end of the Cascade Arc. The ECSZ accounts for about 28 % or ~ 13-14mm/year (Miller et al., 2001) and the San Andreas Fault accounts for ~ 35 mm/year of the relative motion between the Pacific and North American plates. The San Andreas Fault has ~ 50 mm/year dextral offset to the south after it merges with the ECSZ. Therefore the ECSZ distributes a substantial amount of plate motion that would otherwise be focused along the San Andreas Fault as it is to the south.

Stateline Fault is a 200 km long fault system that trends northwest to southeast along the state line between California and Nevada (Fig. 2). The Stateline Fault is an active right lateral fault with significant post-mid-Miocene displacement (Mahan et al., 2009) which forms the eastern boundary of the ECSZ (Guest et al., 2007). Recent geologic mapping has documented ~ 30 km of dextral offset along the southern Stateline Fault between Devil Peak in the southern Spring Mountains and Black Butte on the southwest side of the fault (Fig. 3) since ~13 Ma (Guest et al., 2007). This work moved the eastern boundary of the ECSZ ~ 50 km to the northeast from Death Valley to Stateline Fault (Guest et al., 2007). Stateline Fault is covered by alluvial fan sediments immediately south of Stateline Pass and dextral shear is not observed in the northern New York Mountains ~ 30 km southeast of Stateline Pass (Mahan et al., 2009). The abrupt southern termination of dextral shear on Stateline Fault within ~ 30 km of the point of maximum offset (Guest et al., 2007) presents a space problem.

Geologic mapping was conducted near the south end of the Stateline Fault (Fig.2) in order to resolve the space problem presented by its abrupt southern termination. Mechanically, the lateral motion has to be taken up by other structures in the area. The displacement may be taken up along a parallel array of dextral faults in the field area. Another hypothesis is that the displacement is accommodated by northwest directed extension along normal faults bounding the northern New York Mountains and the southwest Lucy Grey Mountains (Fig. 2) and sinistral slip on the Nipton Fault in southern Ivanpah Valley (Mahan et al., 2009).



WLB - Walker Lane Belt; ECSZ - Eastern California Shear Zone;
CNSN - Central Nevada Seismic Belt; ISB - Intermountain Seismic Belt

Figure 1: General Tectonic Map of Western United States showing the Eastern California Shear Zone (modified from Lee et al., 2006).

Mapping data indicates that there is a sub parallel dextral strike slip fault in the field area and it may absorb at least part of the displacement on the Stateline Fault. This is important because it helps to distinguish between these hypotheses and potentially resolves the fault termination problem. It provides geologic constraints for understanding the evolution of the ECSZ also allows for the possibility that there are unmapped seismogenic faults in the region.

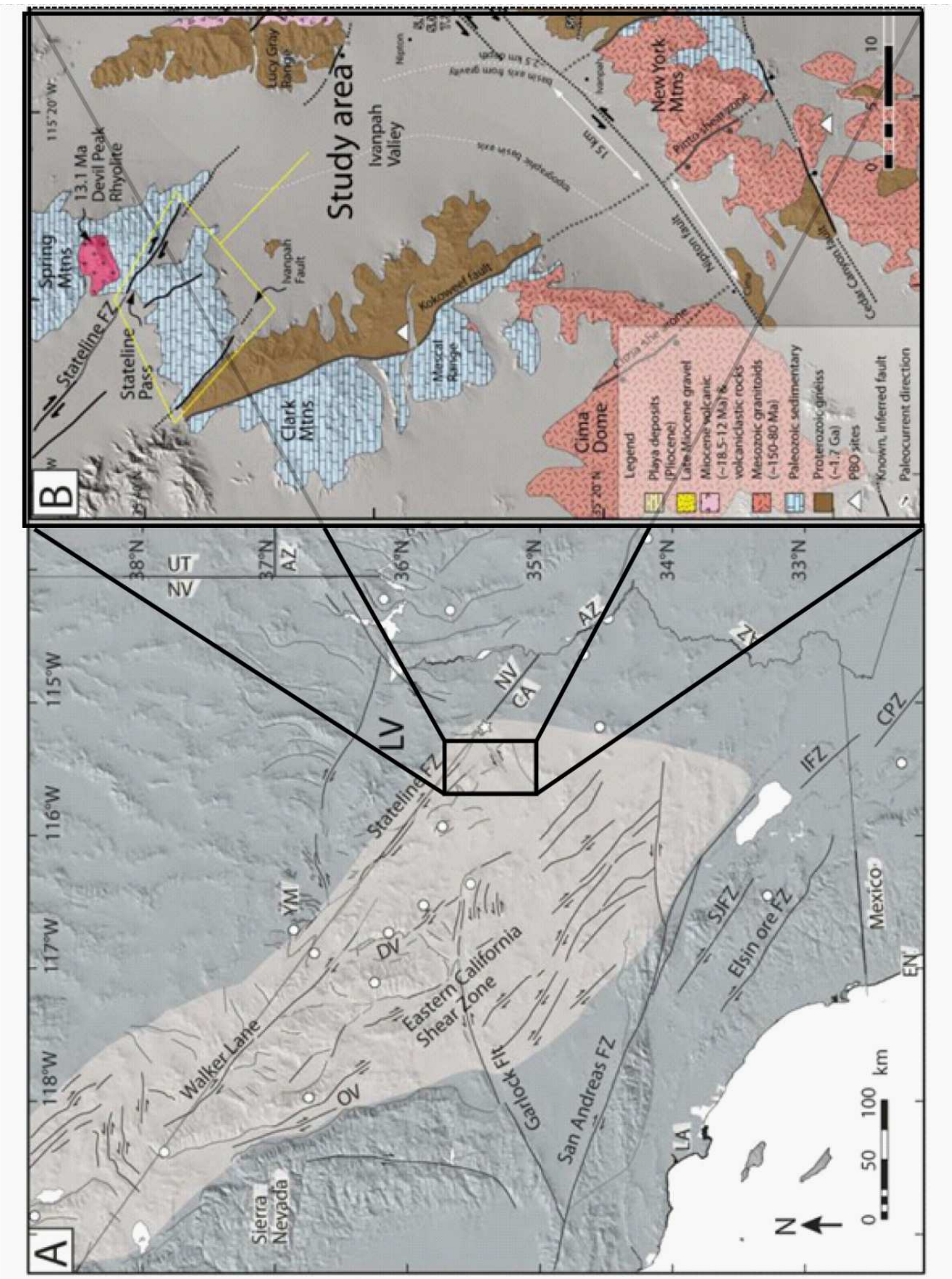


Figure 2: Stateline Fault System California/Nevada (modified from Mahan et al., 2009) A-Regional location of Stateline Fault. B-Major Features of the Study Area.

2. LOCATION AND ACCESSIBILITY

The study area is located at the eastern terminus of the 24 km (15-mile) long Clark Mountain Range in eastern California west of Primm, NV on the California/Nevada border (Fig. 3). The Stateline fault to the northeast separates the Clark Mountains from the southern Spring Mountains. Access to the field area is from the I-15 highway at Primm, NV, onto the road to Stateline Wilderness area and west along the Powerline road (Plate 1).

From the Powerline road there is a rough road through Stateline Pass on the eastern edge of the field area, and also into the alluvial fan leading to Umberci Mine and the next fan west of Umberci, but the other field areas are only accessible by walking in from the Powerline road. It is possible to access the northern parts of the field area via Sandy Valley on four wheel drive roads.

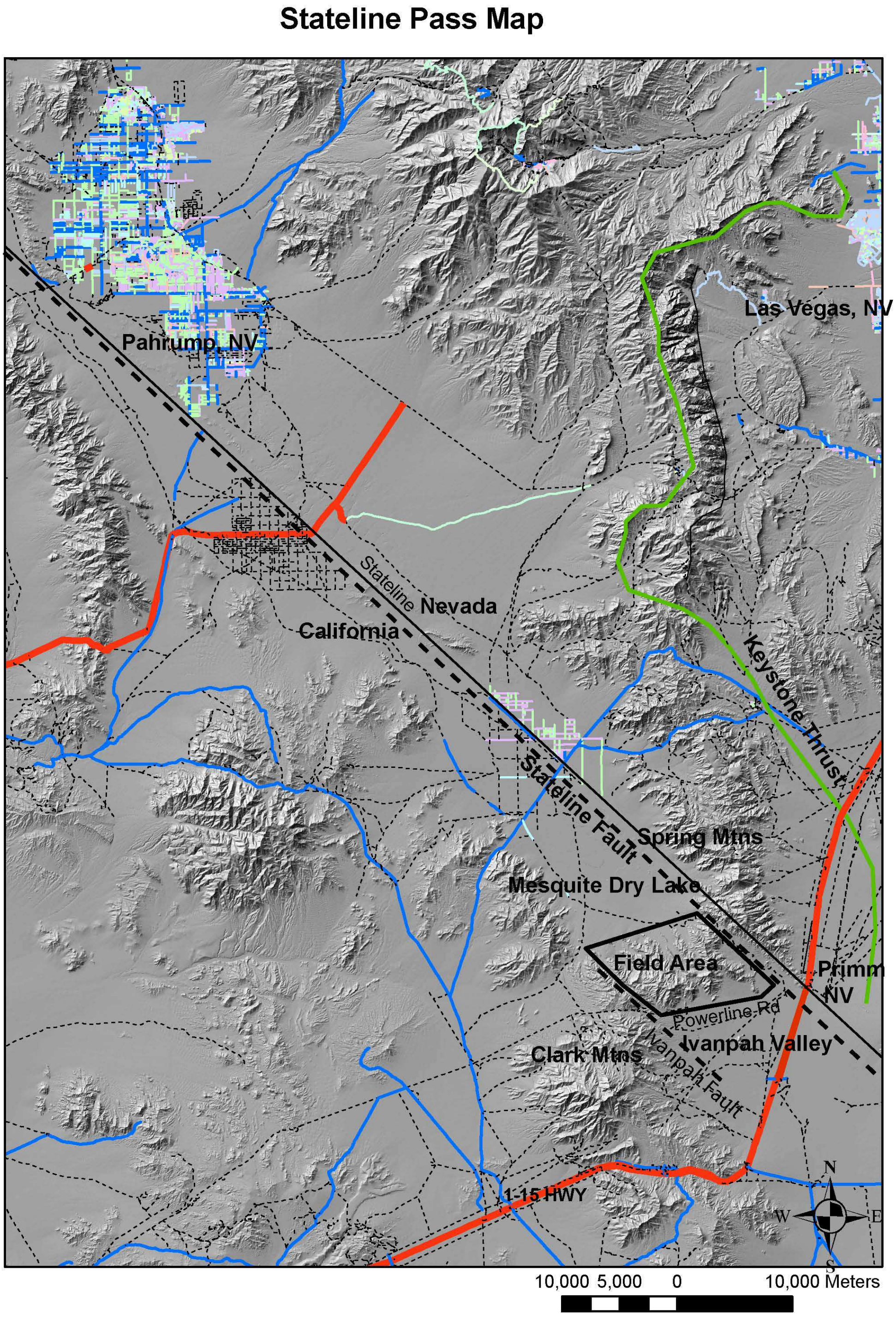


Figure 3: Stateline Pass Map showing Field Area (Digital Elevation Model Map from USGS Data Distribution Server G Topo 30)

3. METHODS

Geologic field mapping was the dominant data collection method, with some additional mapping done using satellite imagery. After initial reconnaissance mapping, traverses were selected along major faults and kinematic data was collected. The main focus was on sense of movement indicators including reidel shears, dominant fracture orientations, any discernable striations and the orientation of the major faults. The maps are in a digital format.

4. REGIONAL GEOLOGY AND TECTONIC HISTORY

4.1. Stratigraphy

In the northeastern Clark Mountains the rock units range in age from Proterozoic to Early Triassic and the basins are filled with Quaternary alluvial fan sediments. The Cambrian to Mississippian strata are dominantly carbonate rocks and the Pennsylvanian to Triassic strata are carbonate and clastic terrigenous units (Fig. 4).

Protereozoic basement is exposed on the southwestern side of Ivanpah Fault on the field area boundary. The Middle Cambrian - Ordovician carbonate rocks were deposited in a shallow to marginal marine environment such as an epieric sea (Gans, 1970). The dominantly dolomitized carbonates are interrupted by two thin clastic units; the silty unit that forms the base of the Bonanza King Formation, Banded Mountain Member and the Dunderburg Shale which is beneath the Nopah Formation. Both of these units are key marker beds in this region and were important for this structural mapping project.

The total thickness of bedrock from the lowest exposure of Bonanza King Formation, Papoose Lake Member (Middle Cambrian) to the highest exposure of Moenkopi Formation, Conglomerate unit (Early Triassic) is about 2995 m. The total thickness is a minimum value because the base of the Bonanza King Formation, Papoose Lake Member (Middle Cambrian) is not exposed. The upper contact of the Moenkopi Formation, Conglomerate unit (Early Triassic) is fault bounded and therefore also not exposed.

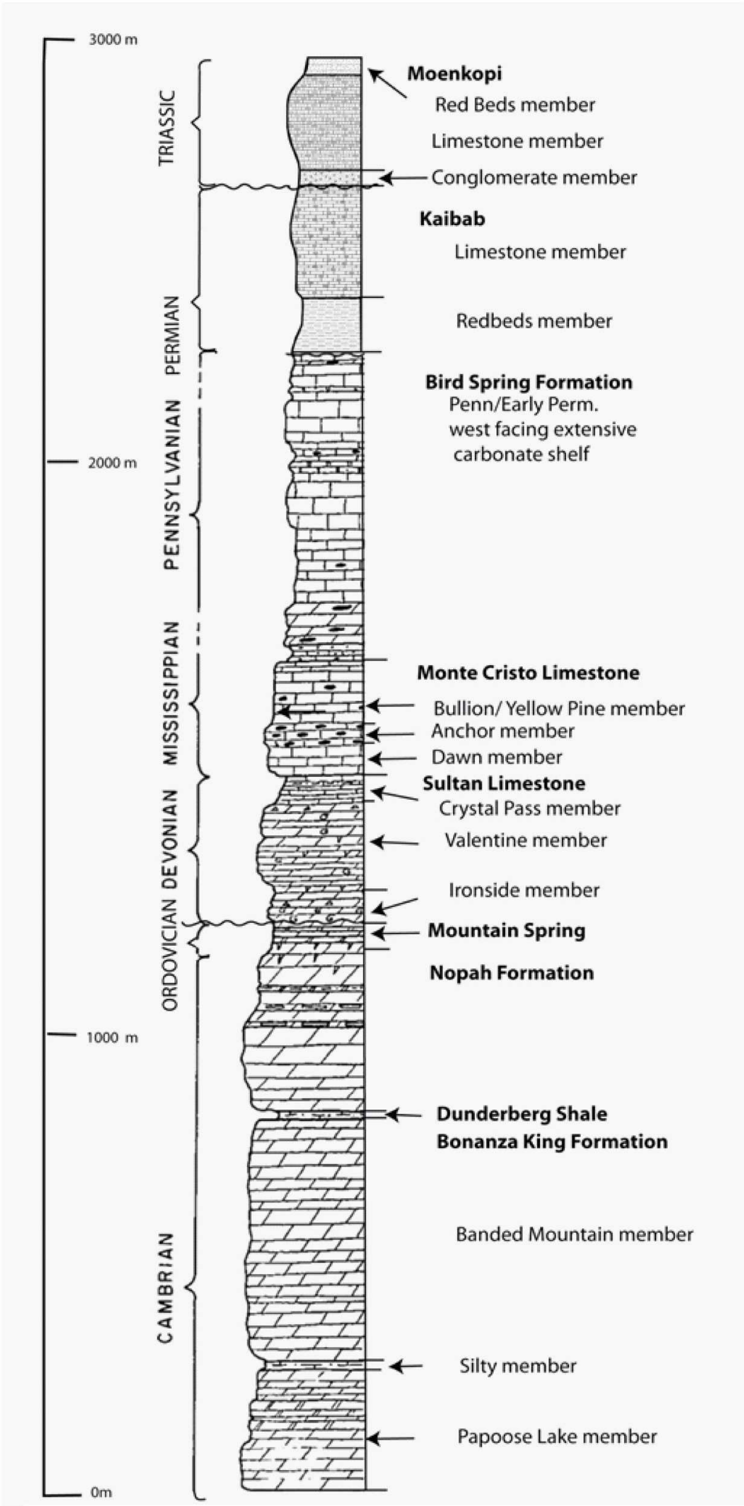


Figure 4: Clark Mountain Stratigraphy (modified from Burchfiel and Davis, 1977).

4.1.1 Proterozoic Basement

The basement is an orthogneiss in the New York Mountains to the south (Mahan, et al., 2009). It is exposed on the southwest side of Ivanpah Fault on the boundary of the field area.

4.1.2 Bonanza King Formation (Middle to Late Cambrian)

The Bonanza King Formation was named and described by Hazzard and Mason, (1936) from a type section in the Providence Mountains of California. This formation was deposited on a broad nearly flat Cordilleran passive margin after the breakup of a late Proterozoic supercontinent around 600-550Ma (Stewart and Suczek, 1977). During deposition of this unit, the continental margin was oriented roughly east-west and located near the equator at 10-15^0 N latitude (Scotese and McKerrow, 1990). From the craton margin hinge line west of Frenchman Mountain near Las Vegas to the base of continental slope facies at Last Chance Ridge north of Death Valley is a palinspastically restored estimated distance of 250-300 km with a relief of only 5-15 m (Montanez and Osleger, 1993). It thickens westward from 400 in the eastern Mojave to 1300 m at shelf edge and base of slope facies at Last Chance Ridge (Montanez and Osleger, 1993).

It is divided into two members, the lower Papoose Lake and upper Banded Mountain (Barnes and Palmer, 1961). A distinctive orange-brown recessive silty interval at the base of the Banded Mountain Member is a regional marker bed. Both members have ubiquitous mottling in which both the matrix and the mottles are dolomitized (Gans, 1970).

Bonanza King Formation has a total thickness of approximately 871 m, with the base of the Papoose Lake Member not seen.

4.1.3 Papoose Lake Member (Middle Cambrian)

The Papoose Lake Member is approximately 437 m thick with its base not exposed. In autochthonous sections this member is ~ 460 m thick but its thickness varies along the Keystone Thrust where large portions have been cut out (Gans, 1970). It is a finely bedded to laminated dolomitic limestone cliff- former. The upper cliffs are non-silty with some zebra banding and sucrosic layers. Weathered layers have an orange and brown mottled appearance.

Mottling is the most distinguishing feature of the Member (Gans, 1970) and indicate the presence of burrowing organisms in a low intertidal environment over the entire deposition of this member. The mottles weather out, by solution and have a rusty orange colour due to concentration of ferrous oxide (Gans, 1970).

4.1.4 Banded Mountain Member (Middle to Late Cambrian)

The Banded Mountain Member includes the Silty unit, at its base which will be described separately. Banded Mountain Member is a dark grey dolomite and limestone unit approximately 407 m thick in the field area (Gans, 1970 and this study). It is micritic at the base with chert nodules and an oolitic grainstone layer 30 m up from base. It is a cliff-former with cm-scale banding within larger scale (0.5 m) alternating dark and medium grey bands in some layers. There are also layers with chert , mottling and abundant vugs. Characteristic banding is mostly composed of meter scale peritidal parasequences with dark subtidal limestone bands alternating with light dolomitized laminate caps (Montanez and Osleger, 1993).

Silty Unit

The Silty unit is a yellowish tan siltstone which forms the basal unit in the Banded Mountain Member (Gans, 1970). It is approximately 27 m thick. The lower part is a finely laminated light yellow to tan siltstone and the upper part has half meter thick beds of pale grey micritic dolostone interbedded with orange/brown silty layers. The silty unit is recessive. Both the silty unit and the Dunderberg Shale are thin terrigenous recessive units and key marker beds in the dominantly carbonate rocks in this area. Both the Silty unit and the Dunderberg Shale were mapped separately.

4.1.5 Dunderberg Shale Formation (Late Cambrian)

The Dunderberg Shale has been mapped both as a separate formation (Burchfiel, 1964) and assigned to the Nopah Formation as its basal member (Gans, 1970). It is mapped as a separate formation in this work. A thin terrigenous unit, it is a key marker bed in the dominantly carbonate rocks of the Paleozoic in this area. The Dunderberg Shale is about 30 m thick and consists of basal greenish shale and an upper bioturbated tan siltstone in 2-8 half-meter beds and discontinuous carbonate layers with crinoids. It is a quartz rich unit with silt, shale and carbonate present. It is fossiliferous and contains the Dunderbergia trilobite fauna which defines its upper Cambrian age (Gans, 1970).

4.1.6 Nopah Formation (Late Cambrian)

The Nopah Formation is a 200 m thick pale grey cliff-forming dolomite. The Nopah is more highly recrystallized than the Bonanza King Formation which is attributed to deposition in quiet shallower supratidal waters (Gans, 1970). The base of this unit was placed at the first grainstone cliff above the Dunderberg Shale. The lower part of the unit is pockmarked from algal balls eroding out. The upper part of the Nopah Formation is a lighter grey coarsely crystalline sucrosic dolomite in massive beds that commonly forms ridges of large jointed boulders (Gans, 1970). The Nopah weathers roughly into a light grey-golden tan colour. The Nopah contains many brecciated zones without mappable faults.

Post-Upper Cambrian to pre-Upper Orodvician Disconformity

The lower Ordovician Pogonip Group which is present to the north of the field area in Red Rock Canyon, west of Las Vegas, is absent and may have been eroded regionally to the south (Gans, 1970). Lower and Middle Ordovician rocks are not present in the field area. This puts Upper Cambrian Nopah Formation in contact with the overlying Upper Ordovician to Middle Devonian Mountain Spring Formation This disconformity is indicated by the presence of the Receptaculites oweni fossils (Upper Ordovician) in the base of the Mountain Springs Formation (Gans, 1970) overlying the Nopah Formation.

4.1.7 Mountain Springs Formation (Upper Orodvician to Middle Devonian)

The Mountain Springs Formation was named by W. Gans (1970) and described as disconformably overlying the Upper Cambrian Nopah Formation and conformably below the Ironside Member of the Sultan Formation (Middle to Upper Devonian). The Mountain Springs Formation is dark grey banded dolomite about 55 m thick in the field area. At its type section near the hamlet of Mountain Springs, Nevada, it is 117m thick (Gans, 1970). It is massive near the base contrasting with the underlying thinly bedded pale grey upper Nopah, and it is poorly bedded about 5m above base. It is locally vuggy, sucrosic and brecciated about 10m above base. Possibly recrystallized grainstone tempestites with chert present and silicified corals poorly preserved occur near the top. The upper contact was drawn below the first chert bed of the overlying Ironside Member of the Sultan Formation (Devonian).

Post-Upper Ordovician – pre-Middle Devonian disconformity

Mountain Spring Formation has Upper Ordovician fossils in its basal section and is in conformable contact with Middle Devonian rocks in the upper part of the formation. Silurian to Lower Devonian strata are missing suggesting a post-Upper Ordovician – pre-Middle Devonian disconformity within the upper units of the Mountain Springs Formation (Gans, 1970). In the southern Spring Mountains, the disconformity is estimates to be about 10-40 feet below base of the Sultan Limestone (Gans, 1970). There was no discernable field evidence for this disconformity (Gans, 1970).

4.1.8 Sultan Limestone Formation (Middle to Upper Devonian)

The Sultan Limestone Formation is a carbonate inner shelf sequence (Harrington, 1987) that is 186 m thick. It was defined by Hewett (1931) and divided into three Members: in ascending order the Ironside, Valentine and Crystal Pass. It is considered a transgressive sequence from supratidal to wave base occurring from the deposition of the Ironside Member to the deeper depositional environment of the Valentine Member (Harrington, 1987).

4.1.9 Ironside Member

This member is a dark grey dolomite ~47 m thick with a vuggy, stromatoporoid boundstone 20m above base. Some stromatoporoids are silicified . Branching corals are present. The lower to middle section of this Member has a distinctive dark grey to chocolate brown colour with white to cream coloured mottled patches aligned with bedding. The Ironside is a resistant cliff-former.

4.1.10 Valentine Member

The Valentine Member is a tan to light grey dolomitic limestone with less resistant thinly bedded light grey units alternating with darker grey thicker beds. It has calcite filled vugs, and abundant chert especially in the middle part and blue-grey upper sections. It is about 59m thick and weathers in a shelf-step pattern. It is fossiliferous with stromatoporoids and tabulate and rugose corals, brachiopods and gastropods in the lower half (Harrington, 1987).

4.1.11 Crystal Pass Member

The Crystal Pass Member is a pale grey limestone to calcitic dolostone about 80 m thick and a strong cliff-former. The base is brecciated. It weathers orange-brown, is locally vuggy with caves and has wavy cross-bedding with no known macrofossils fossils or chert.

4.1.12 Monte Cristo Limestone Formation (Lower Mississippian)

This formation was deposited along the proto-North American continental shelf in environments ranging from supra- to sub tidal (Dolbier et al., 2009). It is 209 m thick abd is comprised of the Dawn, Anchor, Bullion, and Yellowpine members in ascending order. Regionally there is often a fifth Member called the Arrowhead, but it was not identified in the field area. The Bullion and Yellowpine members can be indistinguishable. They are both are grey carbonates with chert and fossils in some layers and form caves.

It typically has abundant chert especially in the Anchor Member. The chert is interpreted to be of non-biogenic origin, based on geochemical analysis (Dolbier et al., 2009). It formed in a marine setting possibly during dolomitization (Dolbier et al., 2009) and may have resulted from the input of volvanic ash and siliceous sediments sourced from the Antler Orogeny to the west (Dolbier et al., 2009).

4.1.13 Dawn Member

The Dawn is a dark grey dolomitic limestone 50 m thick . Fossils are abundant especially near the base including calcitic corals, crinoids, brachiopods and rare nautilus. It weathers tan-brown often in vertical streaks.

4.1.14 Anchor Member

This member is a 51 m thick light to medium grey limestone, with abundant bedded and planar chert throughout. Wavy stromatolitic bedding is present in some sections.

4.1.15 Bullion Member

It is a grainy calcitic dolomite about 49 m thick with crinoids and other fossils fragments. It is pale grey with vugs and caves. There is much less chert in the Bullion compared to the Anchor Member.

4.1.16 Yellowpine Member

This member is a dark grey limestone about 59 m thick which is brecciated at the base. Coral and crinoid fossils are present. A fetid smell when samples containing shell fragments are broken indicates sulphur is present. Small chert nodules and large caves occur in this unit. Beds range from 15 cm to 0.5 meters in thickness. It is a weak cliff-former with an apparently erosional top.

Middle Mississippian to Pennslyvanian Disconformity

4.1.17 Birdspring Formation (Pennsylvanian to Early Permian)

The Birdspring Formation was named by Hewitt (1931) from a type area in the southern Spring Mountains and defined as all strata above the Monte Cristo Limestone (Mississippian) and below the Supai Formation. The Birdspring Formation represents a broad continental shelf deposit that extended from southern California to southern Idaho and was located just north of the paleoequator at the time of deposition (Stevens and Stone, 2007). Only Pennsylvanian fossils have been reported in the Clark Mountains (Stevens and Stone, 2007). The Birdspring is ~750 m thick in the type area and about 780 m thick in the field area. It is a variable unit with thickly bedded limestone interbedded with chert rich layers especially in the lower parts, sandy and silty cream coloured or weathered orange-brown beds and blue-grey silty limestone. Some limestone beds are medium grey with a speckled appearance due to the presence of abundant calcite filled fractures. Silty units weather into orange-brown blocky layers. Fusulinid fossils date this unit as Early Pennsylvanian to Late Permian. Colonial corals are often present (Stevens and Stone, 2007). The Birdspring Formation unconformably overlies the Monte Cristo Limestone (Middle Mississippian) in the field area.

Midde Permian to Early Triassic disconformity

4.1.18 Red Beds Formation (Early Permian)

This red sandstone is 172 m thick. It may be equivalent to the Queantoweap Sandstone which is a pink and grey cliff-forming cross bedded sandstone located in the Virgin Mountains of Nevada and northern Arizona (McNair, 1951).In the Queantoweap Sandstone the dominant dip direction of cross-bedding is to the south and southeast, indicating a source area to the north (McNair, 1951).

4.1.19 Kaibab Formation (Middle Permian)

The Kaibab Limestone is about 46 m thick. Kaibab was divided by McKee (1938) into the lower Torroweap Formation and the upper Kaibab Formation (Longwell et al., 1965). The Torroweap Formation is comprised of a basal shale, sandstone and gypsum sequence with a middle cherty limestone and an upper red sandstone and shale with gypsum although in some areas the upper unit is entirely gypsum (Stanka and Hess, 1998). It is a cliff former composed mainly of cherty limestone. The Harrisburg Gypsiferous Member which forms the uppermost 30 m of the Kaibab Formation contains nearly pure gypsum in some areas. Gypsum was mined from this member in nearby Blue Diamond, Nevada and other sites near Las Vegas (Longwell et al., 1965).

4.1.20 Moenkopi Formation (Early Triassic)

The Moenkopi Formation unconformably overlies the Middle Permian Kaibab Formation (Brady et al., 2000). The Moenkopi is interpreted to have been deposited in a shallow sloping deltaic environment similar to the Yellow River Delta in China (Stewart et al., 1972). The Moenkopi thickens westward from a thin edge in the eastern Colorado Plateau to ~ 600 m in the western Colorado Plateau province (Stewart et al., 1972). It is 447 m in the field area and is divided into three Members; a basal conglomerate, Shnabkaib and upper Red Beds. The Shnabkaib Member grades from a red siltstone and white gypsum in Utah to the east and gray limestone and dolomite in the west (Stewart et al., 1972).

About 80 % of the Moenkopi Formation is horizontally laminated to thick bedded siltstone, claystone, limestone dolomite and gypsum near Las Vegas, Nevada (Stewart et al., 1972). Thicknesses in the southern Spring Mountains are very thin and patchy with only 2 m of Triassic Moenkopi present above the Kaibab Limestone (Stewart et al., 1972).

4.1.21 Conglomerate Member

This unit is a reddish brown pebble conglomerate 22 m thick. The base is pebble conglomerate and the upper parts are thinly bedded carbonate.

4.1.22 Shnabkaib Member

Dominantly limestone100-250m thick.

4.1.23 Upper Red Member

This unit has a red sandstone base and sandstone to shale upper parts. It is about 340 m thick although the top contact is not seen. It is a recessive unit.

4.2 Tectonic History of the Region.

The region has experienced three major structural deformation events. These are ; Mesozoic contraction during the Cordilleran Orogeny, Eocene extension during the formation of the Basin and Range province and Miocene transtension during the formation of the San Andreas Fault and the related Eastern California Shear Zone. (Fig. 5)

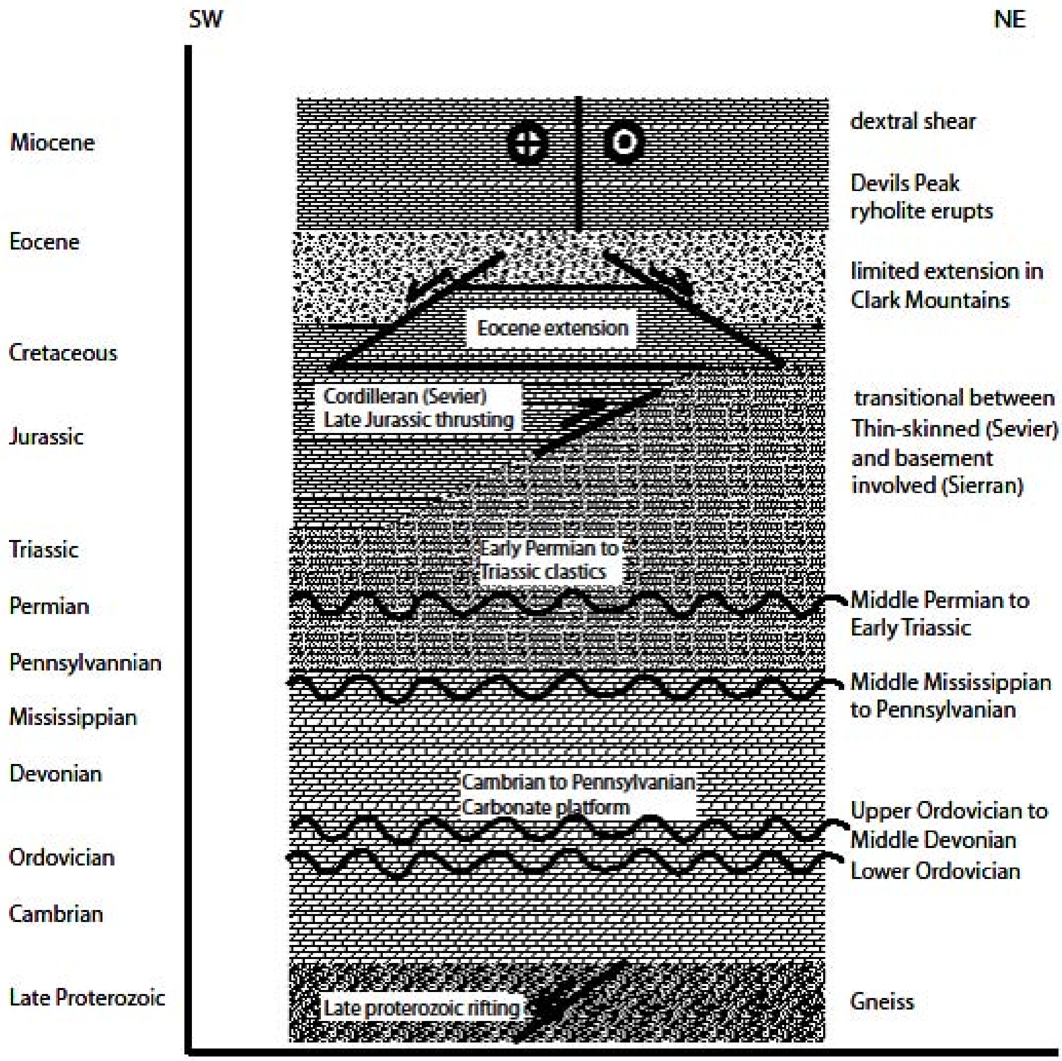


Figure 5: Tectonic History of Clark Mountains.

The broad Cordilleran passive margin developed during the Late Proterozoic (600-550 Ma) break up of a supercontinent (Stewart and Suczek, 1977). The dominantly carbonate lower Paleozoic rocks were deposited near the paleoequator (Scotese and McKerrow, 1990). The carbonate platform was essentially flat, with a slope to the northwest of less than one degree (Gans, 1970). Subsidence of the platform was very slow, with 100 feet (30.5 m) of Bonanza King Formation deposited per million years (Gans, 1970).

During the Paleozioc there were four regional disconformities; the post Upper Cambrian to pre-Upper Ordovician, the post-Upper Ordovician to pre-Middle Devonian, the Middle Mississippian to Pennsylvanian and the Middle Permian to the Early Triassic. The Antler Orogeny (Devonian to lower Mississippian) was the major tectonic event during the Paleozoic. From Middle Cambrian to Ordivocian deposition was continuous in clear, clastic – free epieric seas occurred with only minor fluctuations in sea level in a tectonically stable environment (Gans, 1970).

The Mesozoic to Early Tertiary contraction led to the east vergent thrust system of the Cordilleran Orogeny. The Cordilleran foreland fold and thrust belt extends from northern Canada to the New York Mountains approximately 50 km south of the study area (Burchfiel and Davis, 1977). The frontal segment of the Cordilleran fold and thrust belt is called the Sevier orogeny (DeCelles and Coogan, 2006). East-west shortening occurred within the west thickening passive margin sequence deposited during the Paleozoic (Snow and Wernicke, 2000). The Clark Mountain thrust complex forms the eastern boundary of the Cordilleran orogen (Walker et al., 1995).

The Keystone thrust is the easternmost major thrust of the Sevier belt (Burchfiel et al., 1974) at this lattidtude. It emplaces Bonanza King Formation (Middle Cambrian) in its hanging wall against Aztec Sandstone Formation (Jurassic) rocks in its footwall with a minimum displacement of 12 to 23 km (Burchfiel et al., 1974). Displacement could easily be double the minimum (Snow and Wernicke, 2000). The thrust is exposed for over 70 miles (113 km) in length running through the eastern Spring Mountains and Clark Mountains (Burchfiel and Davis, 1969). The Keystone thrust lies in the boundary between the Papoose Lake and Banded Mountain Members of the Bonanza King Formation for much of its exposure which suggests that it is stratigraphically controlled (Burchfiel and Davis, 1974). It follows the basin margin between the Paleozoic miogeocline and the craton (Snow and Wernicke, 2000).

The Keystone has a minimum shortening of 20 km, which means the original length was probably over 250 km (Snow and Wernicke, 2000), using the usual 10 or 15:1 relationship between thrust faultlength and displacement. The Keystone fault trace extends northward from the southern Spring Mountains ~ 170 km into southeastern Utah (Snow and Wernicke, 2000) where it is covered by Tertiary material for another 200 km. Its southern termination has been located in the southern Spring Mountains passing on displacement to the Keaney Pass thrust (Snow and Wernicke, 2000), or continuing through to the Clark Mountains southwest of the study area (Burchfiel and Davis, 1969).

Using U-Pb zircon dating the timing of thrust faulting is well constrained to about 144 Ma (Latest Jurassic) in the southern Clark Mountains (Walker et al., 1995). The Pachalka thrust located ~ 20 km southwest of the field area carries Late Jurassic aged granites in its hanging wall dated at 146 +/- 2Ma and is cut by the Pachalka pluton which is dated at 142 +/- 7Ma (Walker et al., 1995). This is late in the ductile, basement involved Sierran thrust system (major movement 165-140 Ma) and early in the Sevier thin-skinned thrust and fold belt (150-93 Ma) (Dunne, 1986).

The Clark Mountain thrusts contain both ductile basement involved faults characteristic of the Eastern Sierran thrust belt to the southwest and thin-skinned thrusts typical of Sevier Cordilleran deformation to the north (Walker et al., 1995). The Pachalka thrust is a ductile thrust carrying plutonic rocks of the magmatic arc in its hanging wall in the west-central part of the Clark Mountain complex and the correlative Winters Pass thrust which is roughly 20 km northwest of the field area is a basement involved thin-skinned thrust (Walker et al., 1995). Pachalka and Winters Pass thrusts have characteristics of both Sierran and Sevier thrust styles and are therefore transitional in structural style as well as age (Walker et al., 1995). Stratigraphic control on the geometry of thrusting in the Sevier belt is weakened in the southern Clark Mountains and to the south by the effects of the nearby magmatic arc which increases the ductility of the basement (Walker et al., 1995).

Extension began in the last ~30 Ma as the margin of western North America evolved from a convergent to a transform margin (Faulds et al., 2005). The transition from a convergent to a transform margin is reflected in the Clark Mountain thrust complex in Mesozoic ENE directed thrust faults and Tertiary aged high angle faults and folds related to extension (Walker et al., 1995). At ~ 20 Ma (Early Miocene) the last of the subducting Farallon Plate began to fragment, sea floor ridge spreading and subduction slowed because the young buoyant ridge material wasn't dense enough to subduct. The Farallon fragment was partially subducted when subduction stopped (Nicolson et al., 1994) and it became attached to the Pacific plate and began moving northwest. This caused the oblique gently dipping subduction zone interface along the California margin to change into a transtensional vertical fault with dextral motion initiating the San Andreas Fault system (Nicolson et al., 1994). This transition also caused strike-slip motion to jump well inland in early Miocene time (Nicolson et al., 1994) and oblique extension to the southwest began in what is now the Mojave area (Dokka, 1989).

Early extension from 20 Ma to 10 Ma was oriented WSW-ENE based on preferentially oriented dyke swarms and fault slip vectors (Zoback et al., 1981). The extension direction was roughly parallel to the continental margin of the time (Zoeback et al., 1981). Early extension occurred during Pacific seafloor subduction in a convergent plate regime (Hamilton, 2002). The field area of this study is in the southern Basin and Range near the boundary between the two sub provinces (Zoback et al., 1981). Typical basin and range block faulting occurred in the southern Basin and Range from ~ 13 Ma-10 Ma (Zoback et al., 1981).

Basin and Range block faulting results in parallel elongate ranges oriented ~ north to northwest with Tertiary to Quaternary basin fill between the ranges (Zoback et al., 1981).

Crest spacing of the range blocks is 25-35 km and the basins average ~ 10-20 km wide (Zoback et al., 1981). This basin width is also about the thickness of the brittle crust (Eaton, 1980). Northern Basin and Range block faulting occurred later (10 Ma-present) than in the southern Basin and Range, has a least principle stress direction of WNW-ESE and is rotated ~ 45° clockwise from earlier extension (Zoback et al., 1981).

Regionally the extension was significant, the Basin and Range doubled in width since 34 Ma (Hamilton, 2002) and the Sierra Nevada block moved ~250-300 km west away from the Colorado Plateau (Snow and Wernicke, 2000). The westward motion occurred primarily between 16-5 Ma at 2 cm/year and slowing to 1 or 1.5 cm/year in the last 5 Ma (Snow and Wernicke, 2000). This motion is accommodated by vertical crust thinning normal faulting and conjugate shear faulting (Snow and Wernicke, 2000). The Spring, Mesquite and Clark Mountains remained a coherent block during extension (Axen, 1984) and are relatively unextended internally and unrotated (Wernicke et al., 1983;Burchfiel and Davis, 1987).

The transition from extension to dextral transtension between the Pacific and North American plates began after 12 Ma with 20-25 km right lateral shear (Oskin and Stock, 2003). The vast majority of dextral shear (>90% or 260 km) has occurred in the last ~ 6 Ma (Oskin and Stock, 2003) based on correlated ignimbrites near the Gulf of California. Rifting in the Gulf of California (12-14 Ma) (Stock and Hodges, 1989) rotated Baja California and moved it ~ 400 km northward along the coast (Atwater, 1998). After 5 Ma, Baja California joined the Pacific Plate and obliquely collided with southern California (Atwater, 1998). The San Andreas Fault elongated and dextral shear was partitioned between the San Andreas Fault and the developing Eastern California Shear Zone (ECSZ) which probably started ~10 Ma to 6 Ma (Dokka and Travis, 1990b). The San Andreas Fault accounts for ~ 35 mm/year of the 48 mm/year relative plate motion between the Pacific Plate and the North American Plate with the ECSZ accounting for ~ 9-23 % or 6-12 mm/year (Dokka and Travis, 1990b).

The ECSZ was named by Dokka and Travis (1990b) for the regional right shear zone along which heterogeneous strain has been accommodated during post-middle Miocene time, in contrast to the homogeneous strain or simple shear which was assumed by previous models. Walker Lane in northern Nevada and the ECSZ form the northern and southern parts respectively of a system of dextral faults that accommodates a significant portion of the motion between the Pacific and North American plates (Thatcher et al., 1999). The ECSZ and northern Walker Lane merge into the San Andreas Fault in the south near the Salton Sea and terminate to the north near the southern end of the Cascade Arc (Faulds et al., 2005).

Miocene transtension (~12 Ma to present) is reflected in the field area by the Stateline Fault. The Stateline Fault forms the eastern boundary of the ECSZ which moves the boundary ~ 50 km to the east-northeast from the previous boundary along the Death Valley Fault system (Guest et al., 2007). This 200 km long fault system closely follows the state line between California and Nevada. Recent geologic mapping has documented ~ 30 km of dextral offset along the southern Mesquite segment of the fault since ~13 Ma, which translates to a minimum long-term geologic slip rate of ~ 2.5 mm/year (Guest et al., 2007).

Given that the estimates of ECSZ initiation ranges from 10 to 6 Ma (Dokka and Travis, 1990b) the slip rate may be higher (~5-6mm/year) if the ECSZ started in the last 6 Ma.

Stateline Fault terminates abruptly to the south. There is no evidence of dextral offset in the New York Mountains which are located south of Ivanpah Dry Lake ~ 30 km south of the field area and the documented 30 km dextral offset of Stateline Fault. Determining if there is dextral shear in the field area is a main focus of this study. It is important to document the offset and establish if the faults are connected to Stateline Fault and therefore splays absorbing offset or unconnected to Stateline Fault and adding to the total fault motion. Recent work along the Stateline Fault supports a model where the dextral strike-slip motion of the main fault is linked to the extension occurring near the termination point and possibly to the sinistral strike-slip faults in Ivanpah Valley to the south (Mahan et al., 2009). This could indicate a wedge of rock southwest of the Stateline Fault is being moved to the northwest allowing the abrupt southern termination of dextral motion on the fault.

5. DATA

The principle work of this thesis is a map of the Northeast Clark Mountains (Plate 1). Fourteen areas of this map are discussed in detail in the following subsections, each divided into an observation and an interpretation part. Portions of the field area map with stereonets are used for these discussions. The kinematic data appearing in the stereonets are found in appendix A. Figure 6 shows the locations of the detailed maps of the field area shown in Figures 7-20.

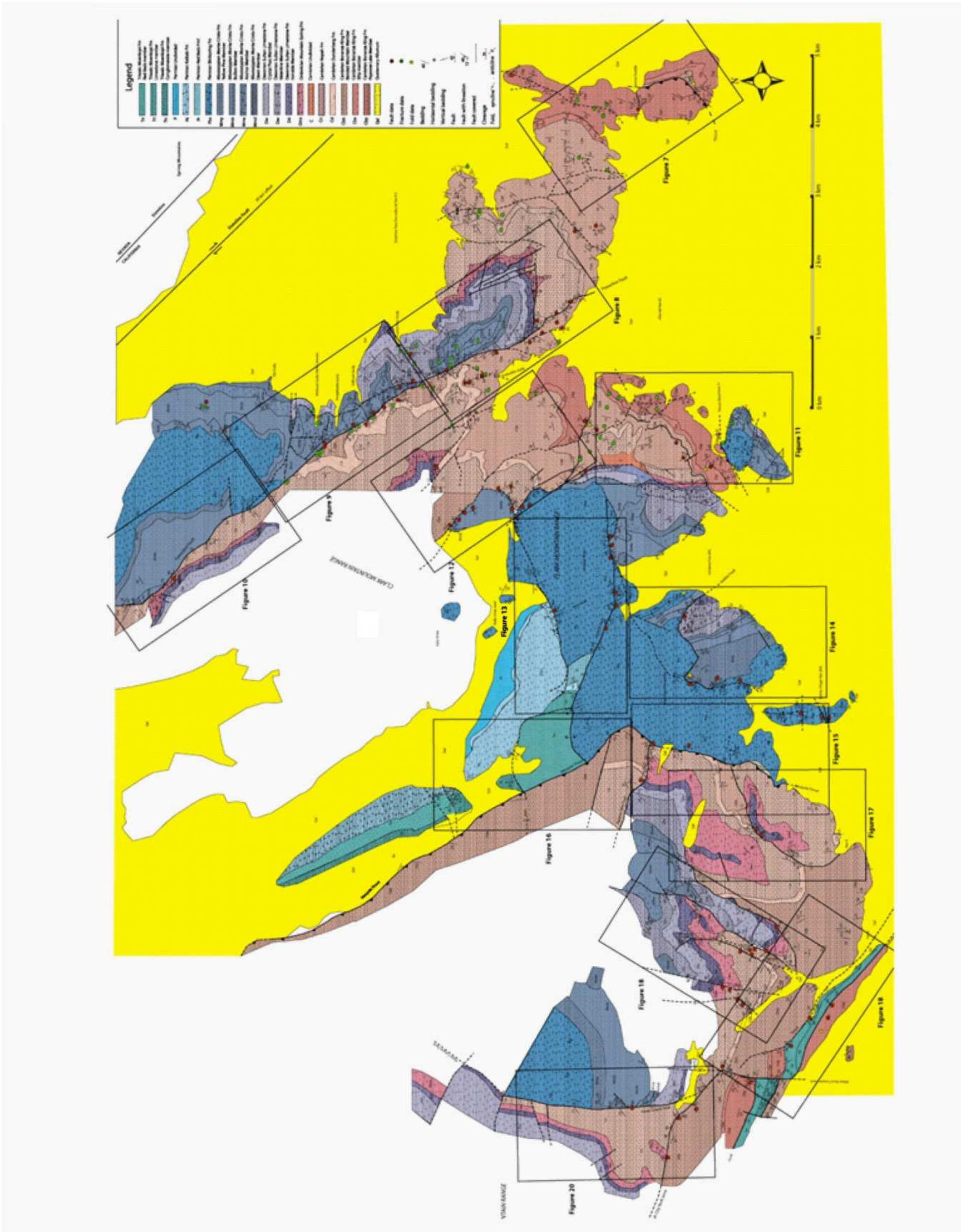


Figure 6: Locations of the detailed maps of the field area shown in Figures 7-20

5.1 Geologic map of southeastern part of study area

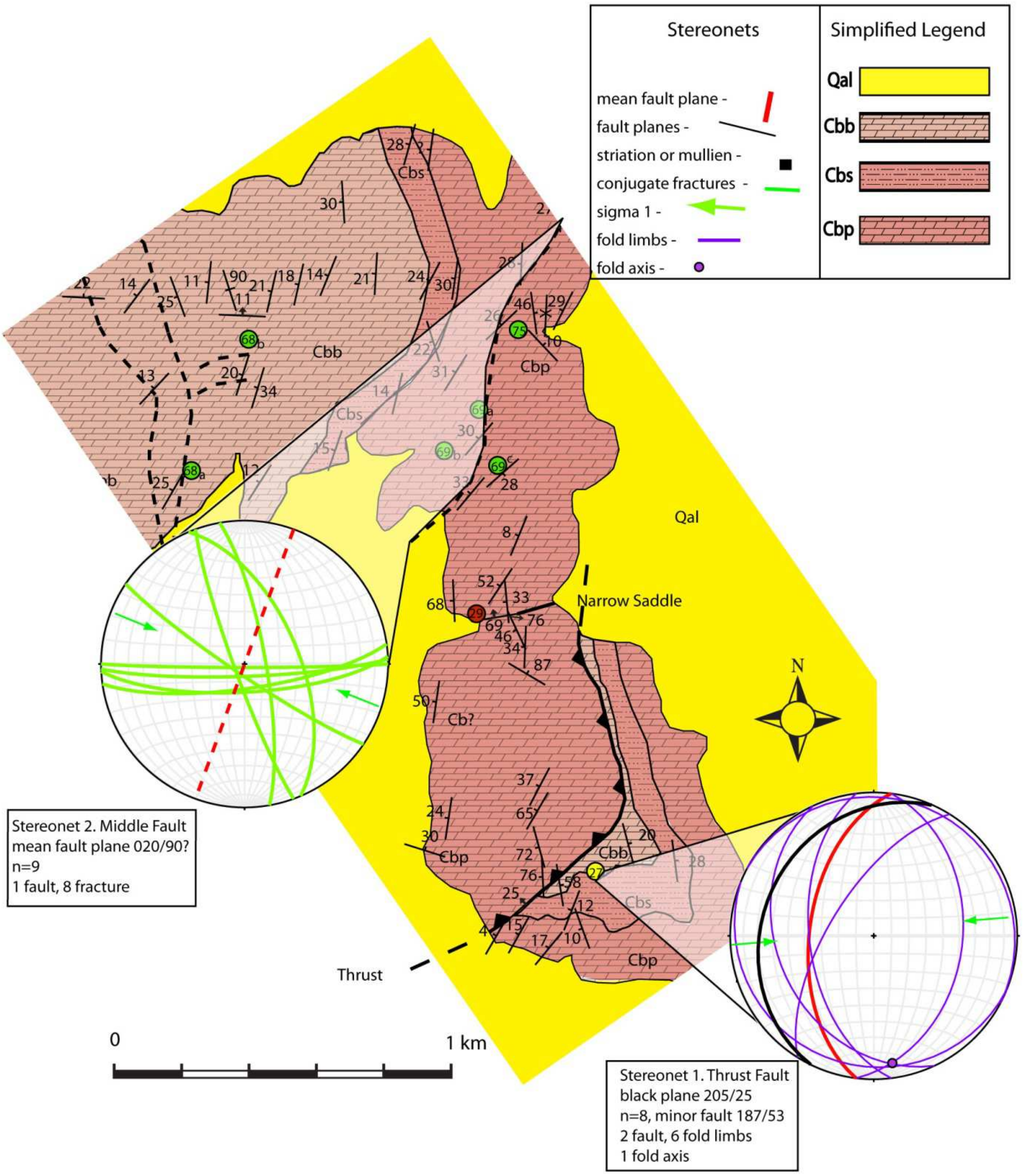


Figure 7: Map showing a portion of the southeast zone. Stereonet plots of structural data are tied to the faults where data was collected.

Observations:

Stereonet 1. Figure 7. The thrust fault is shown in black, it has a dip of 25° to the northwest and moderate stratigraphic offset of ~ 460 m, repeating the lower Papoose Lake Member and the base of the Banded Mountain Member of the Bonanza King Formation. The purple planes show a set of folds with a nearly horizontal fold axis located at yellow fold symbol 27 on the map. The folds are associated with a minor fault shown in red, which is oriented sub parallel to the thrust. The fold orientation gives a sigma 1 direction (maximum compressive stress) roughly east-west and perpendicular to the minor fault and the thrust which are both strike roughly north-south. The fault in the narrow saddle is high angle with steep striations (slip vectors) and no apparent stratigraphic offset.

Stereonet 2. Figure 7.The NNE fault north of the narrow saddle is oriented ~ 020°/? (unknown dip). The conjugate fractures give a sigma one maximum compressive stress direction perpendicular to the fault.

Interpretation:

The southeast thrust (Figure 7) that repeats the lower Papoose Lake Member of the Bonanza King Fm has been interpreted as being the Keystone Thrust (Walker et al., 1995). As discussed in section 4.2., the Keystone Thrust is the easternmost major thrust in the Sevier fold and thrust belt (Burchfiel and Davis, 1974). It is exposed for 112 km (70 miles) along the eastern Spring Mountains to the Stateline Fault area and dominantly juxtaposes Bonanza King Formation (Middle to Late Cambrian) with the Aztec Formation (Jurassic) of the Birdspring allochthon. Both the Keystone and this fault lie in the Bonanza King Formation between the Papoose Lake and Banded Mountain Members. However, this fault has significantly less stratigraphic offset than the Keystone Fault has to the north; less than 500 m compared with ~ 2 km.

The Keystone allochthon is juxtaposed against the Birdspring allochthon with ~ 1km of dextral offset across the Stateline Fault in Figure 2 (Walker et al., 1995). Northwest of Stateline Fault the Keystone Thrust is mapped covered to the south in Ivanpah Valley, before it is cut by Stateline Fault. Recent geologic mapping has documented ~ 30 km of dextral offset along the southern part of the Stateline Fault system of the fault since ~13 Ma (Guest et al., 2007). A 1 km dextral offset (Walker et al., 1995) is not compatible with the 30 km offset documented along Stateline Fault at Devils Peak a few kilometers to the north. This thrust is not interpreted as the Keystone based on the abrupt change in geometry required to cut down stratigraphically ~ 1.5 km to Cambrian rocks in the footwall from Jurassic and lose ~ almost 30 km dextral offset over a distance of 1.9 km. Unpublished mapping (Axen) identified the NNE fault as the Keystone. NNE fault doesn’t have comparable stratigraphic offset or dextral shear across Stateline Fault as the Keystone and is not interpreted here to be the Keystone Thrust based on the abrupt change in fault geometry required.

5.2 Geologic map of southern part of Powerline Fault

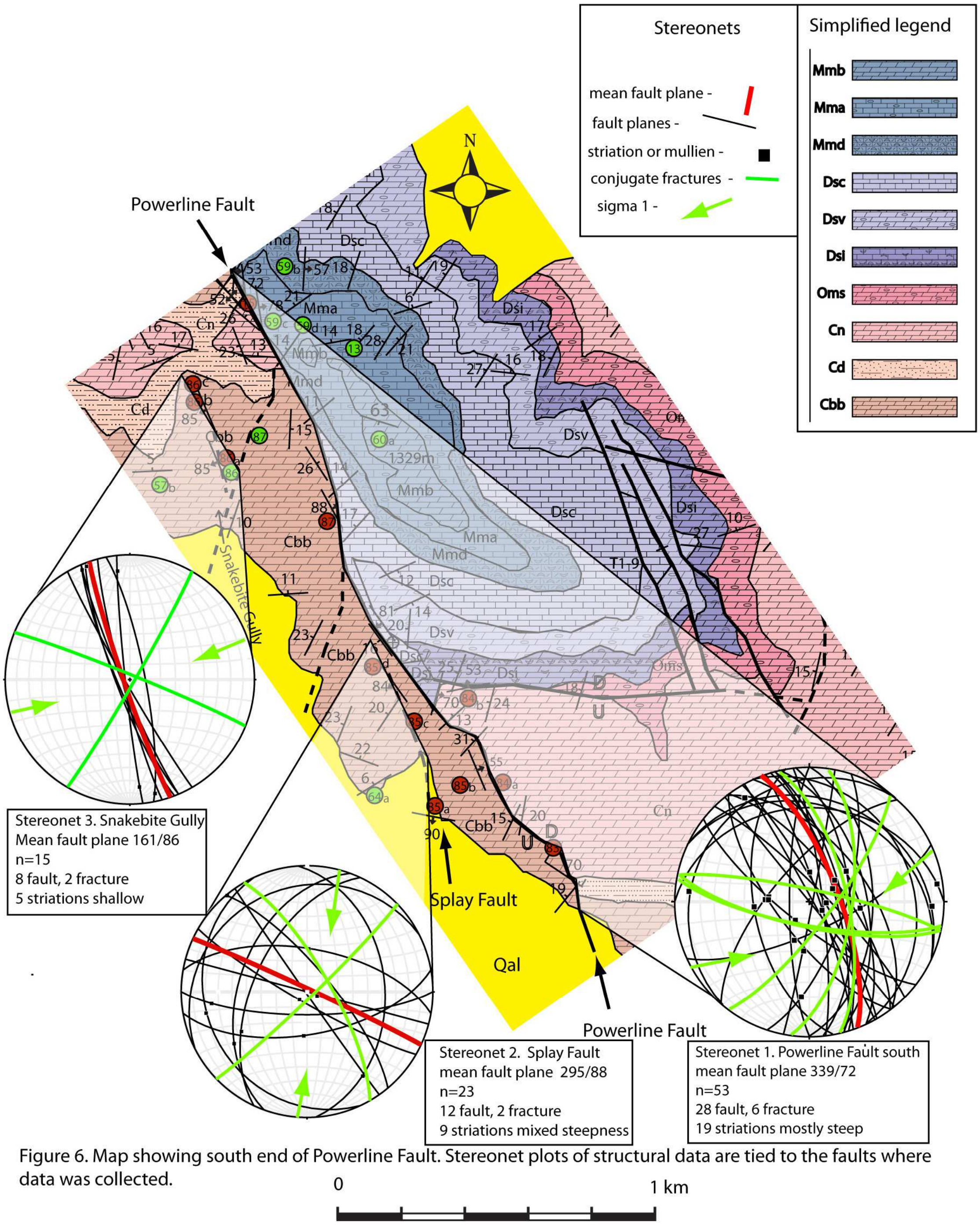


Figure 8: Geologic map showing the southern part of Powerline Fault. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 8. The average orientation of the southern Powerline Fault is 339°/72°, close to the orientation of the Stateline Fault (310°/90°) which lies 2.7 km to the east. There are several shallow fault planes ~ 300°/30°. The striations are mostly steep, unlike the shallow striations observed on the rest of this fault. The fractures show a sigma 1 direction perpendicular to the fault.

Stereonet 2. Figure 8. The average orientation of the southern Powerline Splay Fault is 295°/88° with striations of varied steepness. Almost half the fault planes are perpendicular to the average orientation, so the data is scattered. The limited fracture data indicates sigma one is perpendicular to the mean fault plane.

Stereonet 3. The average orientation of the Snakebite Gully fault is 161°/86° or roughly 341°/90° with shallow striations. The fractures have a sigma one direction of the fracture planes perpendicular to the mean fault plane.

Interpretation:

Most of the data for the southern Powerline Fault was gathered at fault data station 83 (Fig.8). Station 83 lies at convex to the west compressional bend in the poweline fault. I interpret the steep striations as indicating dip slip motion along this section of the fault. The conjugate fractures indicate a sigma one direction of (070° - 250°) roughly perpendicular to the mean fault plane. This non-Andersonian geometry is consistent with stress orientation along the San Andreas Fault (Zobach et al., 1981) and where it is attributed to the weak shear strength of the strike-slip fault and the slightly convergent relative motion between the Pacific and North American plates.

5.3 Geologic map of the central part of Powerline Fault

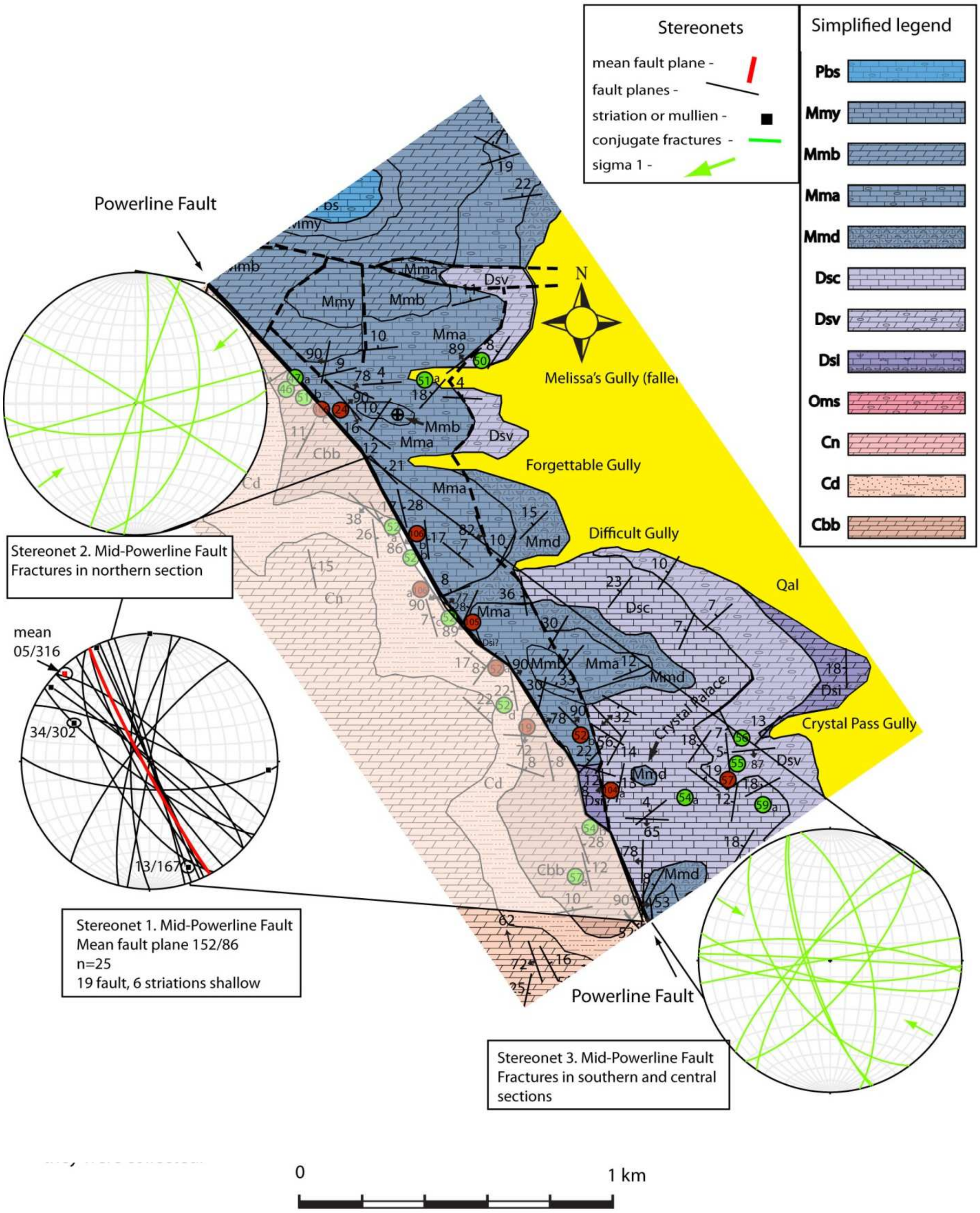


Figure 9: Map showing the central portion of Powerline Fault. Stereonets of structural data are tied to locations where they were collected

Observations:

Stereonet 1. Figure 9. Mid-Powerline Fault has an average fault plane orientation of 152°/86° and 6 shallow striations. The plunges of the striations range from 34°/302° to 13°/167° with an average value of 05°/316°. The striations end members and average give a range of possible slip vector orientations and are circled on stereonet 1 (Figure 9) and plotted on Plate 2 and in Figure 21.

Stereonet 2. Figure 9. Fracture data north of Forgettable Gully had a sigma one direction oriented northeast- southwest (050°-230°) roughly perpendicular to Powerline Fault. The fracture data are shown in two separate stereonets because the sigma one direction of the fractures varied from north to south. The fault has a gentle curve concave to the southwest in this central section.

Stereonet 3. Figure 9. The south and central portion of Mid-Powerline Fault has a sigma one direction oriented northwest-southeast (120°-300°). Maximum compression is not orthogonal to the fault in this section, but is rotated approximately 20°-25° counterclockwise from the fault plane.

Interpretations:

Mid-Powerline Fault (Fig. 9) has a vertical dip (~332°/90°), close to the orientation of Stateline Fault (~315°/90°) and shallow striations. These orientations are consistent with a strike-slip fault. Fracture data in the northern part of mid-Powerline Fault shows sigma 1 almost perpendicular to the fault plane, with a slightly dextral orientation. Fracture data in the south and central portion of mid-Powerline Fault indicates left-lateral or sinistral motion. This is contrary to the dextral motion indicated by stratigraphic offset and stereonets from other parts of this fault.

5.4 Geologic map of the northern part of Powerline Fault

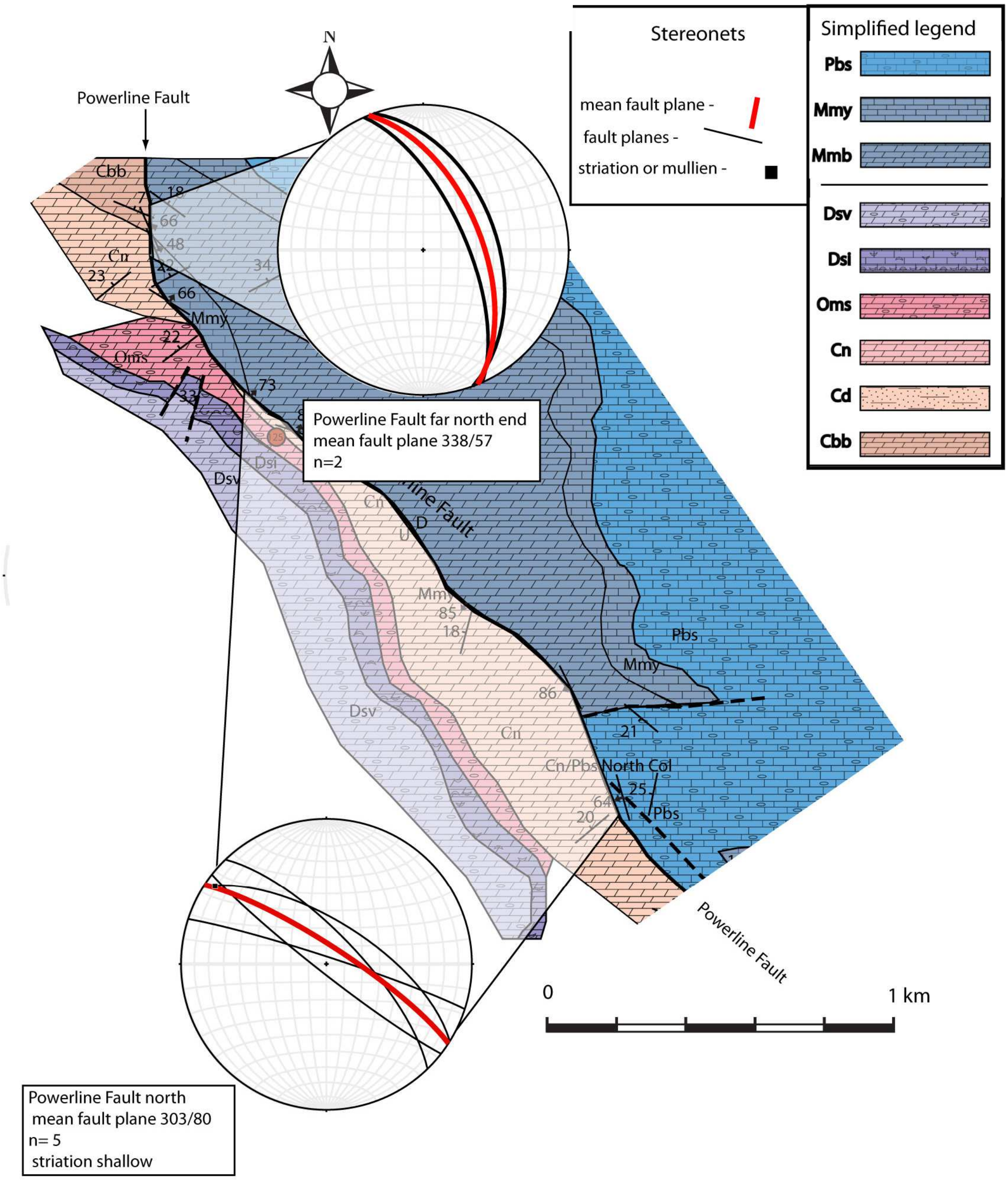


Figure 10: Map showing northern portion of Powerline Fault. Stereonets of structural data are tied to locations where they were collected.

Observations:

Stereonet 1. Figure 10. Northern Powerline Fault has an average orientation of 303°/80° close to the orientation of Stateline Fault (310°/90°) and has a shallow striation.

Stereonet 2. Figure 10. Powerline Fault far north has an average orientation of 338°/57°. This fault dips moderately to the northwest and its strike has rotated about 40° clockwise from the average (303°/80°).

Interpretations:

Northern Powerline Fault (Figure 10) continues to have a steep, relatively straight fault trace with a shallow striation all of which are consistent with strike-slip faults. At the far northern end where Powerline Fault almost reaches the Sandy Valley or Mesquite dry lake, the fault takes a turn to the north and its dip shallows from near vertical to ~ 60°. If Powerline Fault is a splay off of Stateline Fault, the change in strike direction could be pointing to where Powerline Fault joins the Stateline Fault.

5.5 Geologic map of the southwest side of Alluvial Fan #2

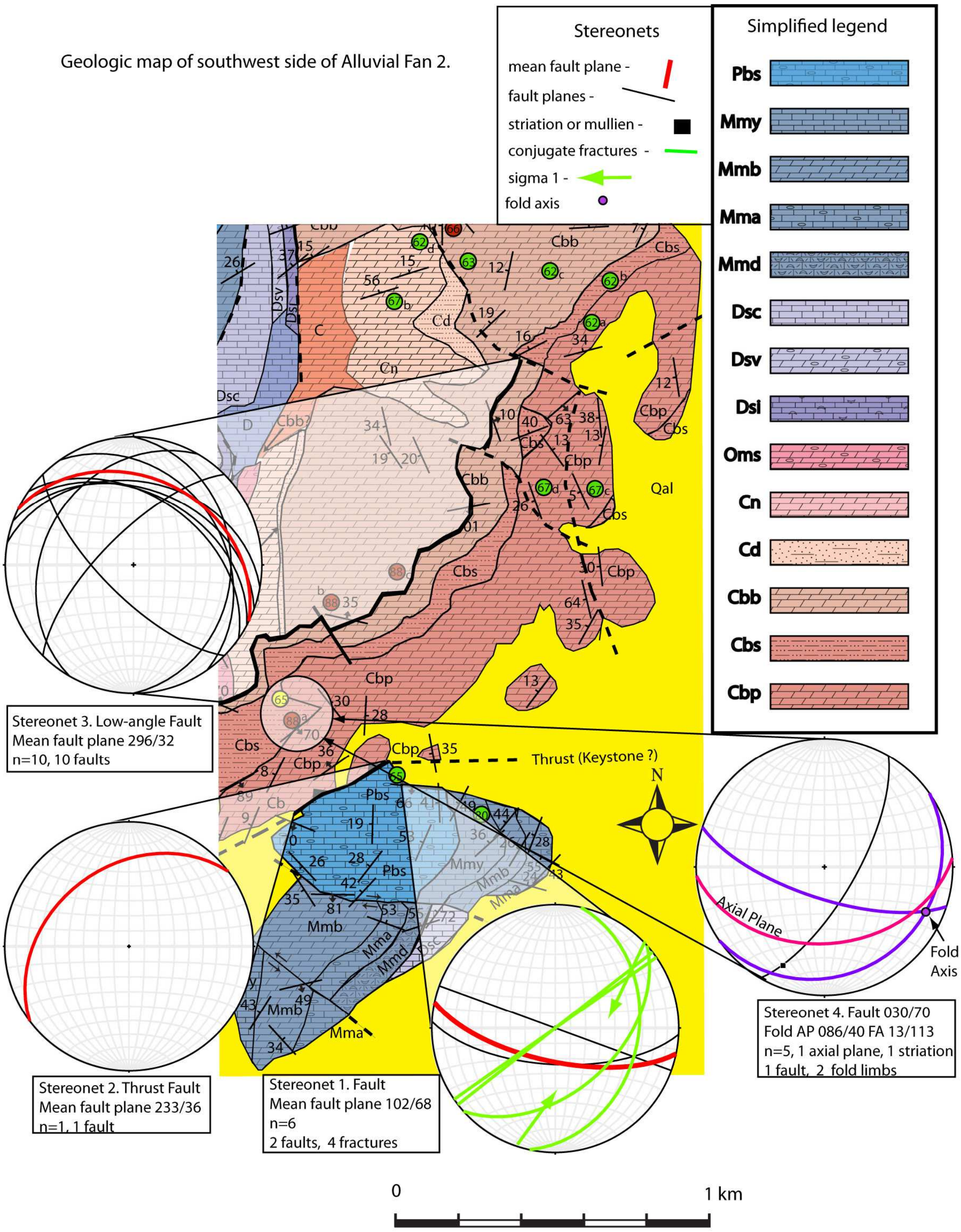


Figure 11: Geologic map showing the southwest side of Alluvial Fan #2. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 11. The two exposed fault planes are in the Birdspring Fm. rocks just south of a covered gully. They have an average orientation of 102°/68°. They are located ~ 50 m south of the major thrust and the fractures give a sigma 1 direction roughly perpendicular to the fault.

Stereonet 2. Figure 11. The Keystone (?) thrust has an average orientation of 202°/36°. It juxtaposes Bonanza King Formation, Papoose Member (Middle Cambrian) against the base of the Birdspring Formation (Pennsylvanian).

Stereonet 3. Figure 11. The low-angle fault (~300°/32°) has normal offset and dips shallowly to the northeast. This fault drops Nopah and overlying units up to Monte Cristo Formation Anchor Member against the base of Bonanza King Fm Banded Mountain Member. It truncates the younger strata at a high angle to the underlying Bonanza King bedding and unit contacts.

Stereonet 4. Figure 11. This fault is steep with a shallow striation and may be very minor as there is no apparent offset.

Interpretations:

There is a fault required between the Birdspring Formation (stereonet 1; Figure 11), and the Bonanza King Fm., Papoose Member across the gully to the north, but it is not exposed. The major thrust 30 m to the north is exposed and verges southeast placing Bonanza King Fm., Papoose Member against Birdspring Fm. Based on its geometry and orientation, the major thrust may be part of the Late Jurassic Sevier Belt. This thrust is shown projected onto the southern Powerline Fault in Fault Plane Diagram (Plate 2).

The next fault to the north is a steep fault within the Bonanza King Fm.

The last fault to the north is a low angle normal fault which is oriented ~ 296°/32° and drops Nopah Formation down against basal Bonanza King Formation, Banded Mountain Member in an angular unconformity. This fault may have had a typical normal fault dip of~ 60° and then been rotated to a lower angle dip of 32° on an underlying decollment normal fault during Basin and Range extension. The strike orientation of the fault (296°) is roughly orthogonal to the southern Basin and Range extension direction of WSW-ENE (Zoback et al., 1981) and it may be part of that Miocene extension.

5.6 Geological map of the west side of Alluvial Fan #2

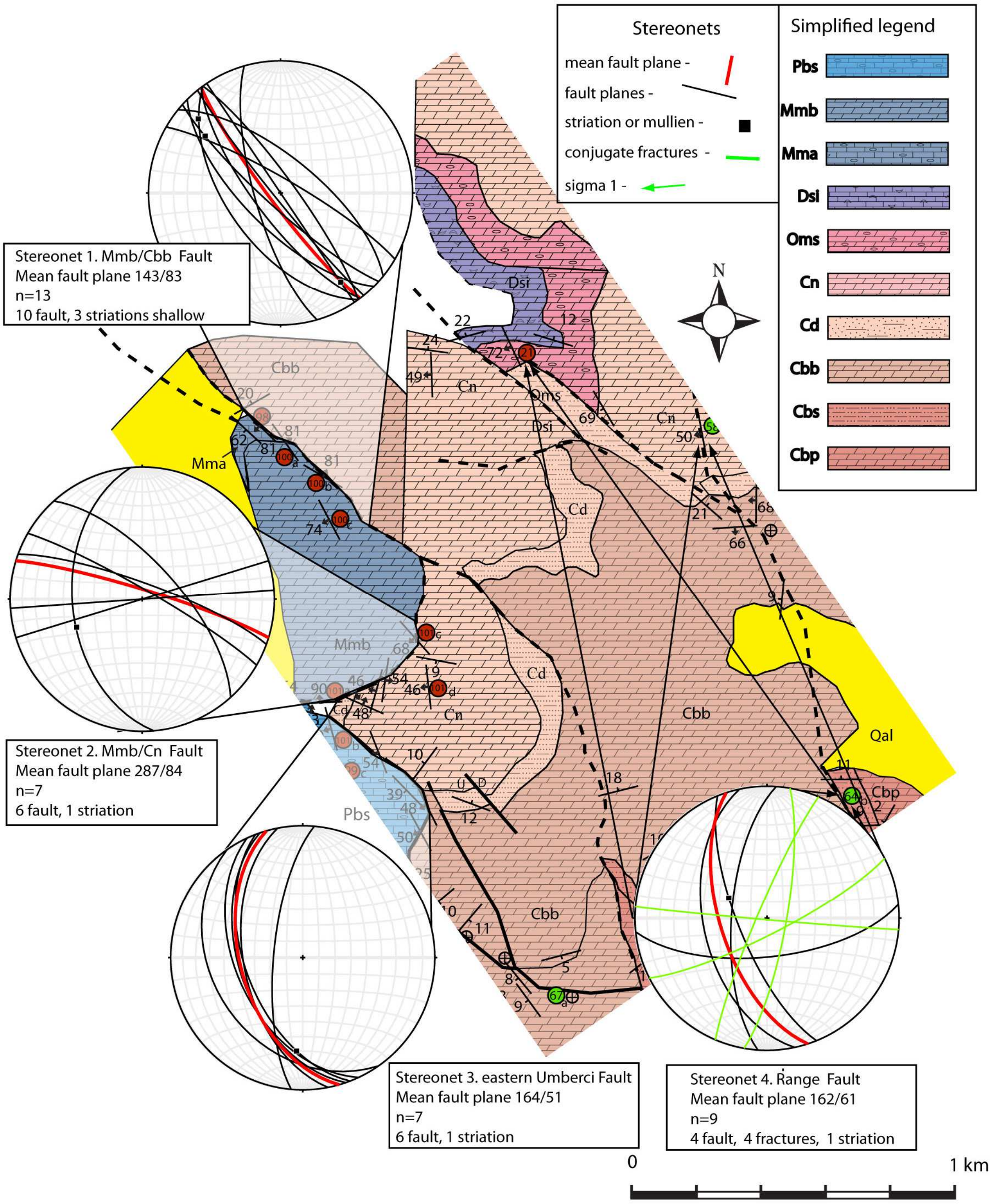


Figure 12: West side of Alluvial Fan #2. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 12. The northern Bullion/ Banded Mountain fault has an average orientation of 143°/83° and has shallow striations. The fault juxtaposes Monte Cristo Formation (Lower Mississippian) against Bonanza King Formation, Banded Mountain Member (Middle to Late Cambrian).

Stereonet 2. Figure 12. The Bullion/ Banded Mountain fault average orientation changes to 287°/84° from (143°/83°) in its northern part (stereonet 1) with similar stratigraphic offset of Mississippian and Cambrian Rocks. It has a moderately steep striation with a plunge of ~ 45°.

Stereonet 3. Figure 12. Eastern Umberci Fault has an average orientation of 164°/51° with a shallow striation. It juxtaposes Birdspring Formation (Pennsylvanian-Early Permian) against Nopah and Dunderburg formations to the east.

Stereonet 4. Figure 12. Faults through Range Mountain have an average orientation of 162°/61° and places Dunderburg Formation against Mountain Spring Formation.

Interpretations:

The northern Bullion/Banded Mountain fault (Figure 12) has shallow striations and nearly vertical dip (143°/83° or ~ 323°/90°) which is close to the orientation of Stateline Fault (310°/90°). This geometry suggests a fault with strike slip motion. However, after the fault bends to the south it has an average orientation of 287°/84° and has a steeper striation indicating oblique slip motion. It has apparent normal fault motion and juxtaposes Monte Cristo Formation, Bullion Member (Lower Mississippian) against Nopah Formation (Late Cambrian).

The Eastern Umberci Fault to the south is a normal fault with a moderate dip to the west. It is connected with the Umberci Mine Fault and the northern Umberci Fault which both offset younger Permian and Triassic strata suggesting this fault is younger than Early Triassic. Umberci Fault cuts the Bullion/Banded Mountain fault to the north. Range Faults have a moderate stratigraphic offset (Cambrian/Ordovician) and show offsets suggesting oblique fault motion with reverse and dextral components.

5.7 Geological map of the Umberci Fault

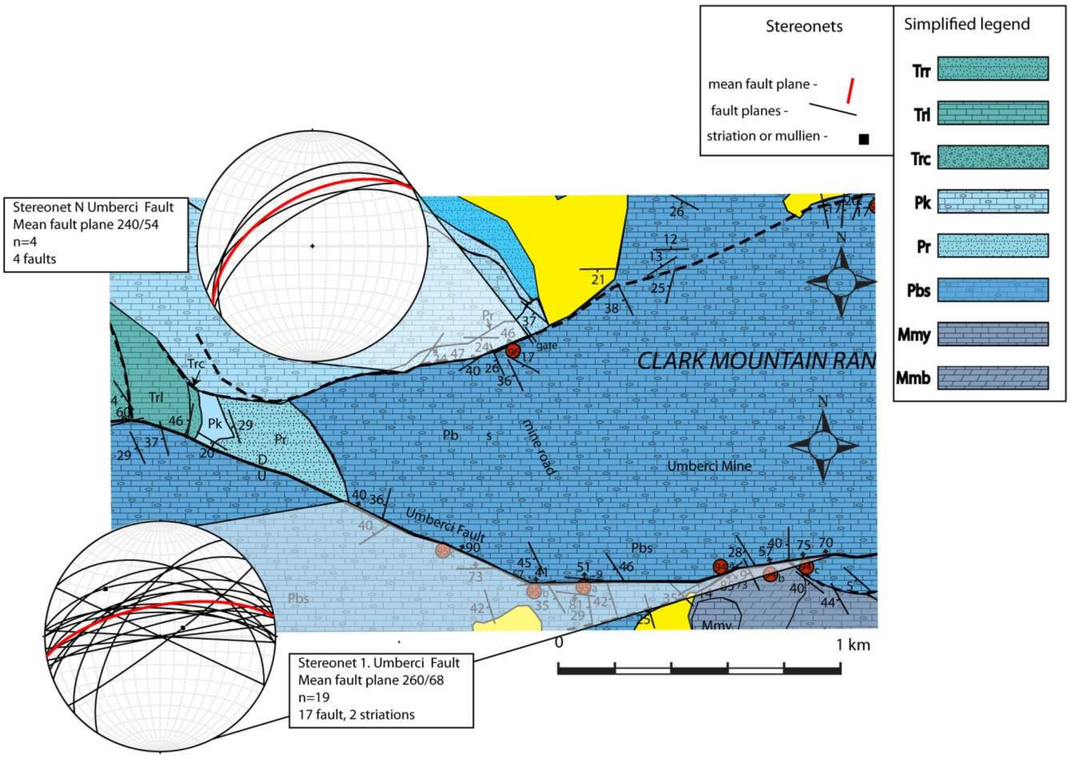


Figure 13: Umberci Fault. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 13. Umberci Fault has an average orientation of 260°/68° and its trace runs roughly east- west and is at a high angle to the Stateline Fault, Powerline Fault and Mesquite Pass Thrust. The Umberci Fault juxtaposes Permian and Triassic strata in its hanging wall with Mississippian and Pennsylvanian strata in its footwall. It has two striations indicating steep and moderately steep slip vectors.

Stereonet 2. Figure 13. Northern Umberci Fault has an average orientation of 240°/54° and is sub parallel to Umberci Fault to the south. It juxtaposes Birdspring Formation (Pennsylvanian-Early Permian) against Permian and Early Triassic Strata. Birdspring has a thickness of 780 m, it can have significant offset within the formation.

Interpretations:

Umberci and northern Umberci Faults(Figure 13) are both east-west striking normal faults, except for the western end of northern Umberci Fault. The limited striation data indicates dip slip on moderately dipping fault planes. This fault is younger than Early Triassic because it cuts strata of that age and both Umberci and northern Umberci Faults are cut by the Mesquite Pass Thrust so they are older than the Mesquite Thrust. Assuming the Mesquite Thrust is part of the Late Jurassic Sevier fold and thrust belt, that puts the age of both Umberci Faults between Early Triassic and Late Jurassic.

5.8 Geological map of Monument Mountain Faults

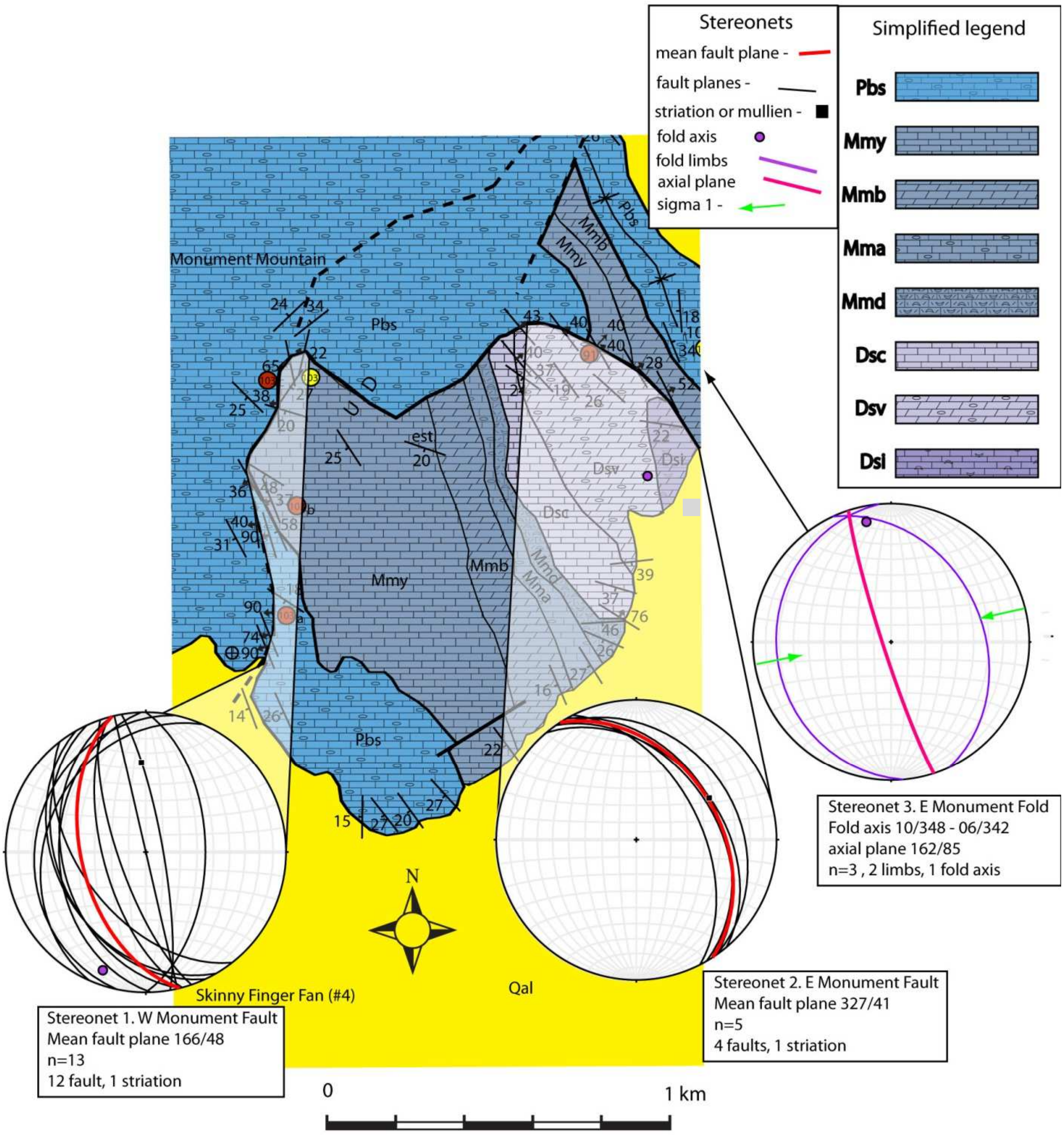


Figure 14: Monument Mountain Faults. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 14. Western Monument Mountain Fault has an average orientation of 166°/48° with one striation with a plunge of 36° and a small fold with a fold axis of 12°/200°.

Stereonet 2. Figure 14. Eastern Monument Fault has an average orientation of 327°/41° and one low angle striation. It juxtaposes Birdspring Formation to Monte Cristo Formation (Lower Mississippian) against the Sultan Formation (Middle to Upper Devonian) There is a fold in the Birdspring Formation which is parallel to contacts and both Itzalier Fault and eastern Monument Fault.

Interpretations:

Western Monument Fault (Figure 14) is a normal fault that dips moderately to the west. This fault juxtaposes middle Birdspring in its hanging wall against basal Birdspring in its footwall, and has an offset of ~ 450 m down to the west. Eastern Monument Fault is a normal fault that dips moderately to the northeast and has stratigraphic offset of ~ 380 m. Monument Mountain is a horst or uplifted block. Itzalier fault has an unknown dip, but based on stratigraphic relations, it appears to be another normal fault which drops Birdspring Formation down to the northeast against Monte Cristo Formation.

5.9 Geological map of Mesquite Thrust

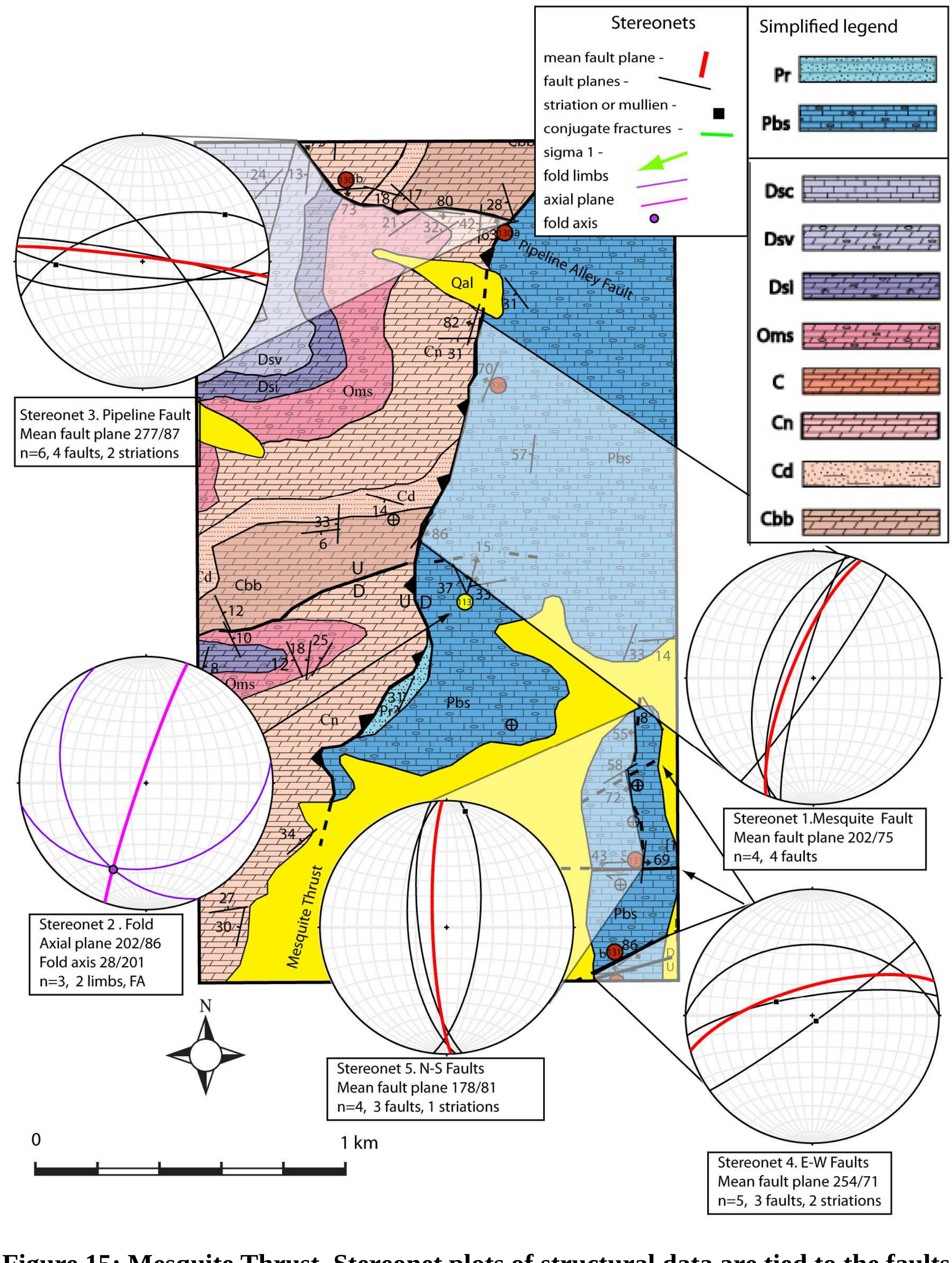


Figure 15: Mesquite Thrust. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 15. Mesquite Thrust trends NNE in this section with an average orientation of 202°/ 75°. It juxtaposes Cambrian strata to the west against uppermost Birdspring Formation (Pennsylvanian) and Permian Red Beds to the east.

Stereonet 2. Figure 15. This fold is within the Birdspring Formation and is oriented nearly horizontal with an axial plane striking 202°/86°.

Stereonet 3.Figure 15. Pipeline Alley Fault has an average orientation of 277°/87° or roughly east-west with a steep dip and two fairly shallow striations.

Stereonet 4. Figure 15. Shows east-west oriented faults in Skinny Finger (Birdspring Formation) located in the middle of Alluvial Fan #4. These faults have an average orientation of 254°/71° and steep striations.

Stereonet 5. Figure 15. The north-south oriented faults on Skinny Finger have an average orientation of 178°/81° from limited data and one shallow striation.

Interpretations:

Mesquite Pass Thrust (Figure 15) is a major fault with large stratigraphic offset placing Bonanza King Formation Banded Mountain Member (Middle to Late Cambrian) against Permian Red Beds and uppermost Birdspring (Pennsylvanian). Mesquite Thrust trends NNE in this section. It dips quite steeply to the west. The fold is parallel with Mesquite Thrust and is a fault related fold.

Pipeline Alley Fault truncates the Nopah to Monte Cristo section to the south and has Upper Cambrian on the north side of the fault, all of which have parallel bedding. It has a steep dip and has shallow striations which indicate a strike-slip fault. Using the offset of the upper Nopah contact, that suggests a sinistral minimum offset of ~700 m. The faults in Skinny Finger Fan do not show stratigraphic offset, however it is possible that the faults may connect with East Monument Fault or the small dextral fault that runs along the base of Monument Mountain.

5.10 Geological map of northern portion of Mesquite Thrust

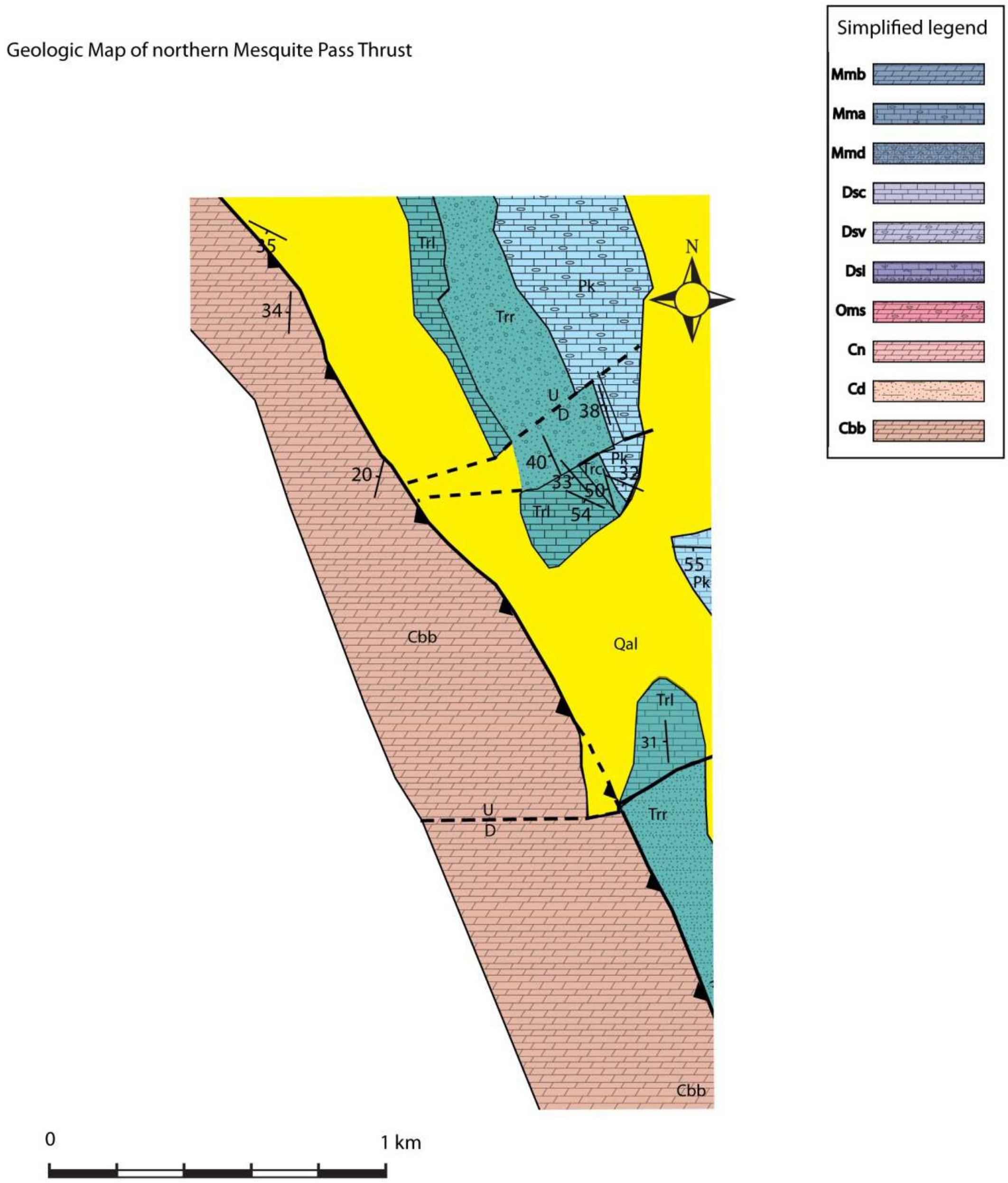


Figure 14. Map showing the northern portion of Mesquite Thrust.

Figure 16: Northern portion of the Mesquite Thrust.

Observations:

The Mesquite thrust (Figure 16) trends NNW, verges eastward and juxtaposes Bonanza King Formation (Middle to Late Cambrian) with Moenkopi Formation (Early Triassic). The fault carries three east-west faults in its hanging wall including one north of the Pipeline Alley Fault (Fig. 15). The fault north of Pipeline Fault is parallel to Pipeline and also shows an apparent shear movement. Mesquite thrust cuts the Umberci and northern Umberci Faults.

Interpretations:

The Mesquite Pass Thrust (Figure 16) is an east verging post- Early Triassic fault and is likely part of the Sevier Thrust Belt which is ~ 144 Ma of Late Jurassic age. If the Stateline Fault has 30 km dextral shear since ~ 13.1 Ma (Guest et al., 2007), then the Keystone Thrust of Late Jurassic age would need to be offset from where it hits the alluvial fan south of the Spring Mountains by 30 km. The Mesquite Thrust has similar stratigraphic throw (Middle Cambrian against Early Triassic) as the Keystone Thrust (Middle Cambrian against Jurassic). The Mesquite Thrust is in the base of the Bonanza King Banded Mountain Member as is the Keystone Thrust. If the 202°/75° orientation of the southern Mesquite Thrust is assumed to be planar and projected to the north, it intersects the Stateline Fault near the town of Sandy Valley. That is under the cover of Mesquite dry lake which leaves it fairly unconstrained. That gives a minimum distance of ~13 km of dextral shear from the intersection point to the southernmost Spring Mountains which is the nearest point the Keystone Thrust could intersect the Stateline Fault from the northeast side without being exposed in the southern Spring Mountains. In the south it is covered by Ivanpah Valley dry lake.

5.11 Geological map of Faults west of the Mesquite Thrust

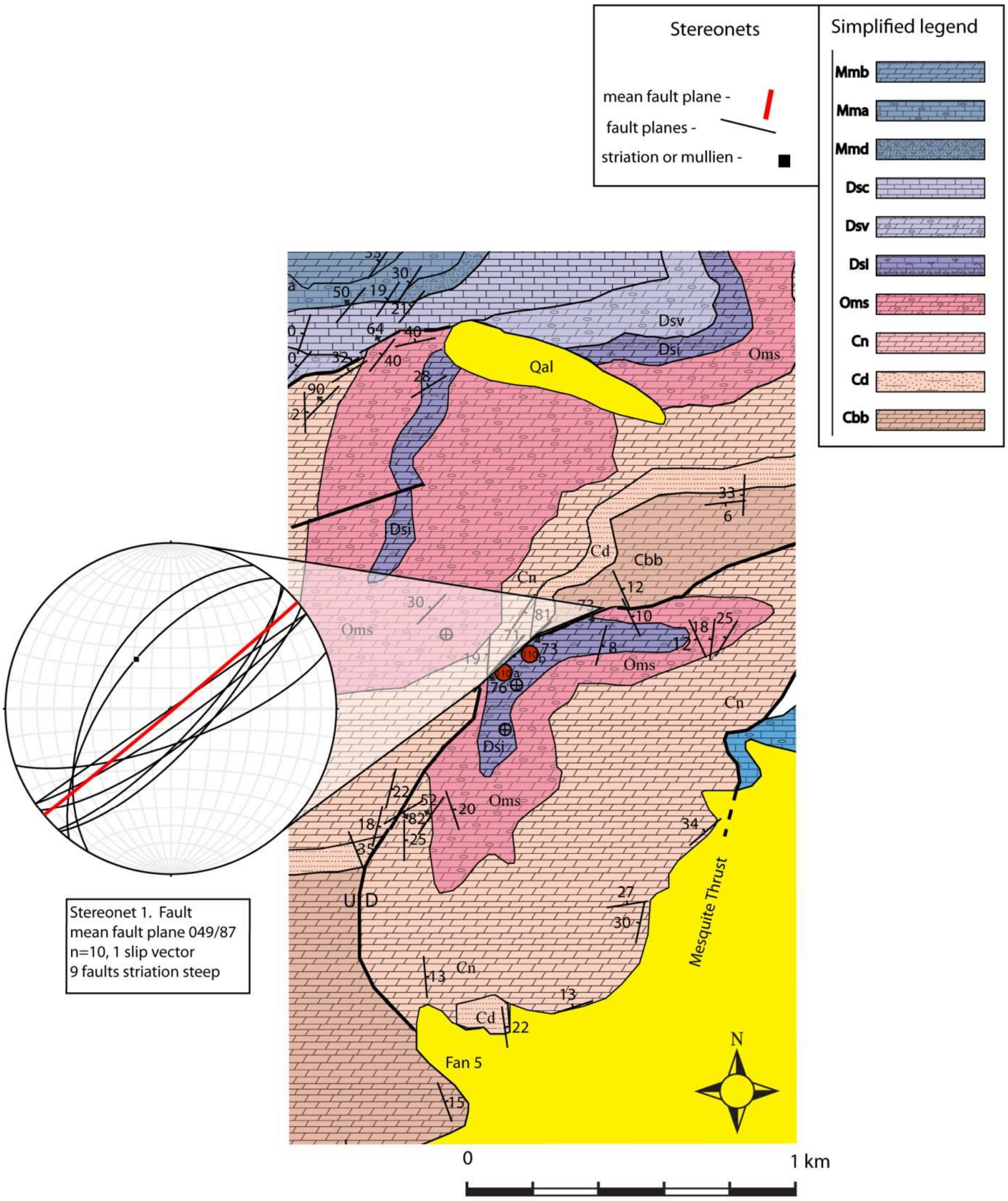


Figure 17: Faults west of Mesquite Thrust. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1 Figure 17. The fault west of Mesquite Thrust has an average orientation of 049°/87° and intersects and ends at the Mesquite Thrust to the northeast. It has a steep striation and the fault places Bonanza King Formation, Banded Mountain Member (Upper Cambrian) against Sultan Formation (Middle Devonian).

Interpretations:

This fault (figure 17) repeats the Cambrian to Devonian sequence and has a nearly vertical dip with normal fault displacement. Given that it is in the hanging wall of the Mesquite Thrust and within 500 m of the Mesquite Fault trace, this fault may have been a thrust originally and was subsequently rotated to a steeper dip angle as the Mesquite Fault moved. It joins the Mesquite Thrust at its northeast end and is covered at its southern end where it is within ~ 300 m of the Mesquite Thrust. This fault may be a splay off of the Mesquite Thrust. The Mesquite Thrust itself is over steepened for a thrust fault and therefore both faults may have been rotated subsequently perhaps by Basin and Range extensional faulting.

5.12 Geological map further west of Mesquite Thrust

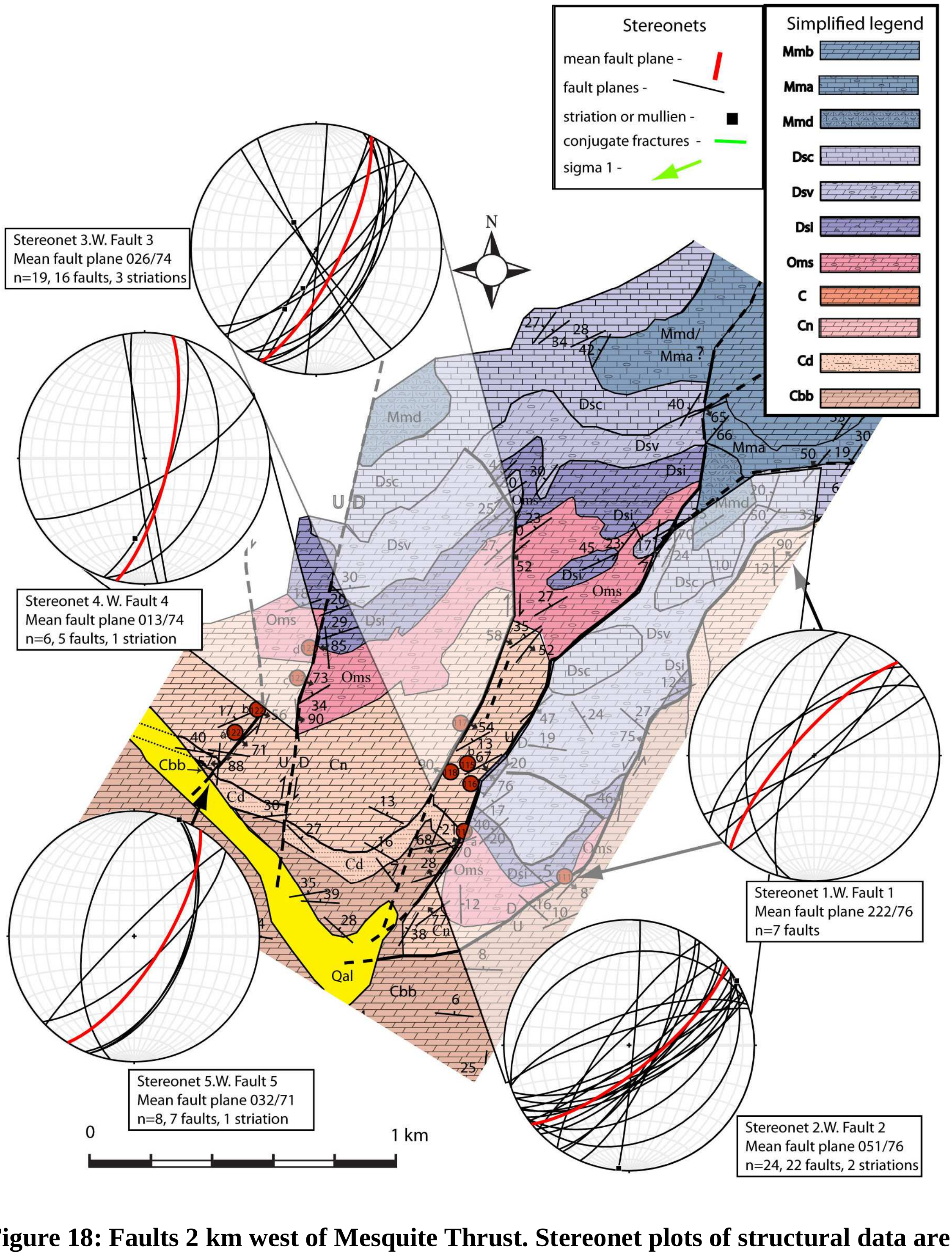


Figure 18: Faults 2 km west of Mesquite Thrust. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Faults are numbered 1 through 5 from east to west as shown in Figure 18.

Stereonet 1. Figure 18. Fault 1 has an average orientation of 222°/76°. It is the easternmost of five sub parallel faults in the hanging wall of the underlying Mesquite Thrust. Fault 1 juxtaposes Cambrian in its hanging wall with Devonian units in its footwall with an apparent normal displacement.

Stereonet 2. Figure 18. Fault 2 has an average orientation of 051°/76° and juxtaposes Cambrian and Devonian strata, but it has Devonian in its hanging wall against Nopah in its foot wall. There are two near horizontal striations.

Stereonet 3. Figure 18. Fault 3 has an average orientation of 026°/74 and steep striations. Dip slip movement suggests this is a reverse fault with at most a small strike slip component.

Sterenets 4, Figure 18. Fault 4 has an average orientation of 013°/74° and fairly minor stratigraphic throw, offsetting Cambrian strata by ~ 30 m. Its striation is shallow indicating strike slip motion.

Stereonet 5. Figure 18. Fault 5 has an average orientation of 032°/71°and fairly minor stratigraphic throw, offsetting Cambrian strata by ~ 30 m. Its striation is horizontal indicating pure strike slip motion.

Interpretations:

Fault 1 (Figure 18) is apparently a normal fault, although no striations were observed which would give direct evidence of the sense of motion of this fault. Fault 2 has nearly horizontal striations indicating pure shear movement which is calculated to be ~ 745 m dextral shear. Fault 3 has steep striations indicating dip slip motion and is a reverse fault. Fault 4 has shallow striations and ~ 94 m of dextral shear. Fault 5 has a nearly horizontal striation indicating pure shear and it has a minimum of 100m dextral shear. The total lateral movement summed across these 5 faults is ~ 930 m of dextral shear.

5.13 Geological map of Ivanpah and Nameless faults

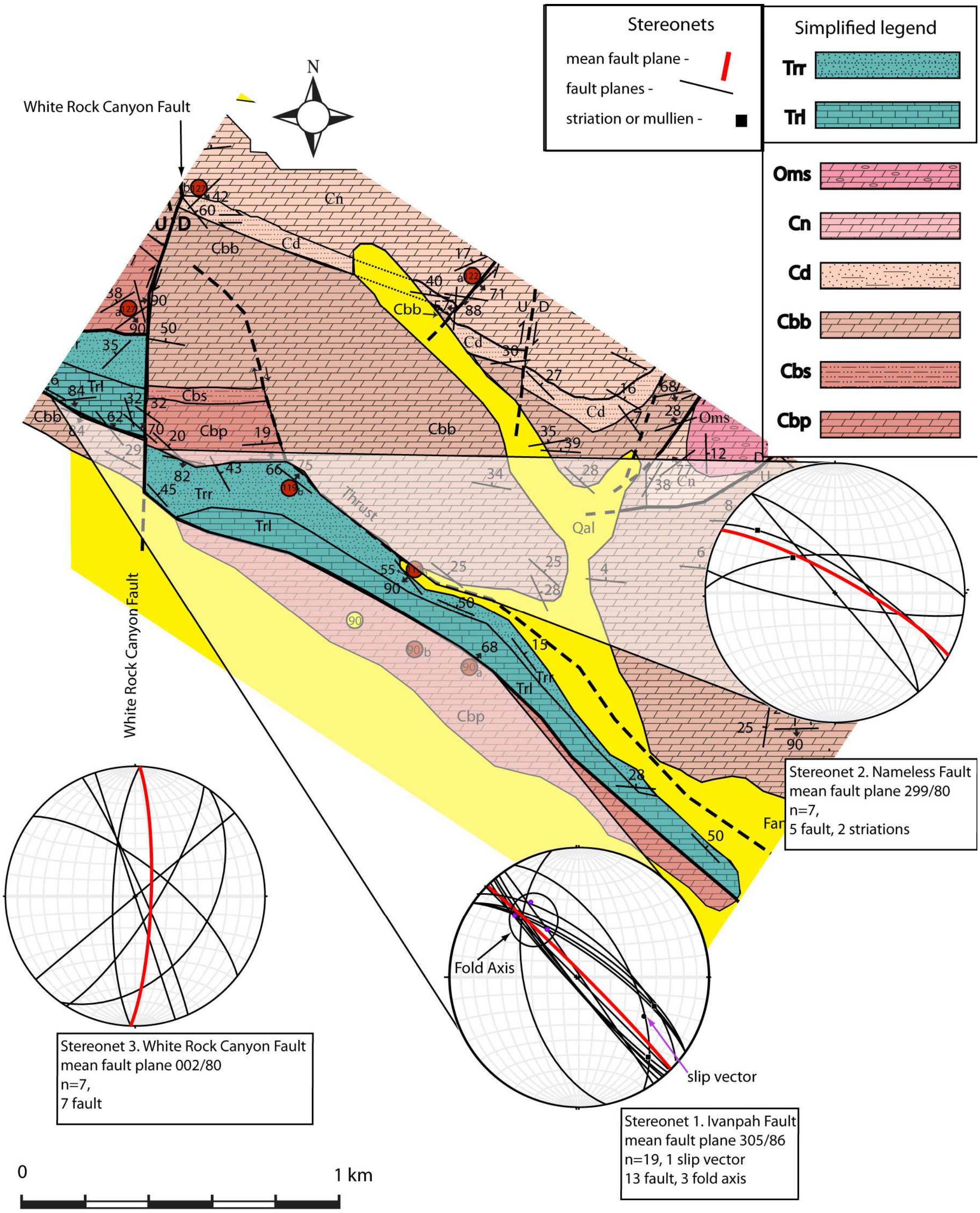


Figure 19: Ivanpah and Nameless faults. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 19. Ivanpah Fault has an average orientation of 305°/86°. It trends northwest and dips nearly vertically. It juxtaposes Bonanza King Formation, Papoose Lake Member (Middle Cambrian) with Moenkopi Formation Limestone unit (Early Triassic).

Stereonet 2. Figure 19. Nameless Fault has an average orientation of 299°/80°. It trends northwest and dips steeply to the northeast. It juxtaposes Bonanza King Formation, Papoose Lake Member with Moenkopi Red Beds (Early Triassic).

Stereonet 3. Figure 19. White Rock Canyon Fault has an average orientation of 002°/80°. The fault shows variable orientations and may not be planar. It trends north and offsets both Ivanpah and Nameless faults by ~ 130-245 m of dextral shear.

Interpretations:

More data is needed on the Ivanpah Fault(Figure19). Nameless Thrust has moderately shallow striations and a steep dip to the northeast. It has significant stratigraphic throw. White Rock Canyon fault trace is oriented north-south and is younger than both Ivanpah and Nameless faults. White Rock Canyon fault appears to splay to the north. One strand that continues north-south and may die out to the north, the middle strand branches north and forms the Pirate Canyon Fault, and the last strand trends to the west and forms the Fault City Fault Zone.

5.14 Geological map of Pirate Canyon and Fault City Faults

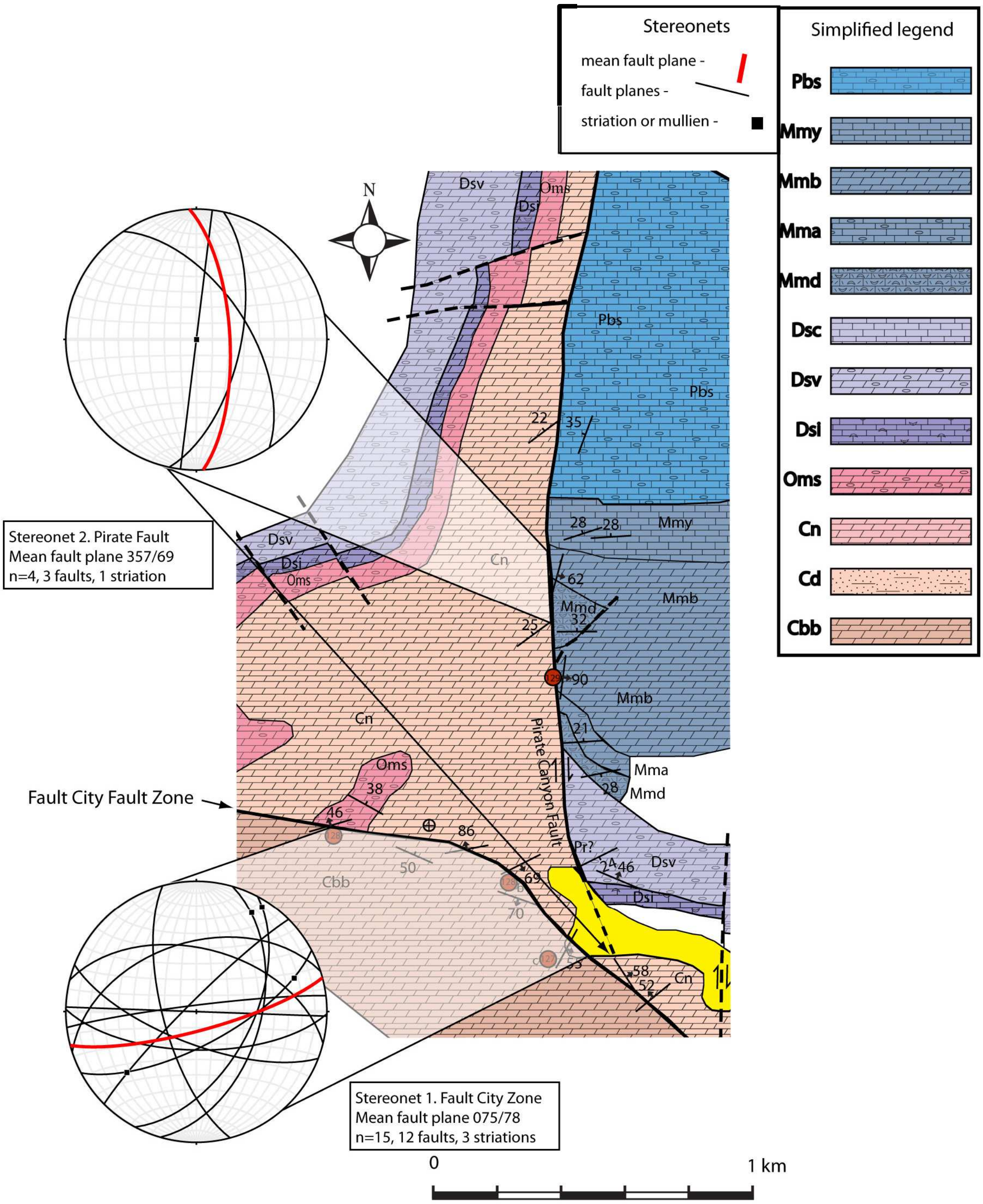


Figure 20: Pirate Canyon and Fault City Faults. Stereonet plots of structural data are tied to the faults where they were measured.

Observations:

Stereonet 1. Figure 20. Like the connected White Rock Canyon Fault, the Fault City Faults also show a lot of scatter on the stereonet plot. Fault City Faults have an average orientation of ~ 075°/78° and it has shallow striations. This fault juxtaposes Bonanza King Formation, Banded Mountain Member (Middle to Upper Cambrian) with Nopah and Mountain Spring Formations (Upper Cambrian, and Ordovician to Middle Devonian respectively).

Stereonet 2. Figure 20. Pirate Canyon Fault has an average orientation of 357°/69° and one steep striation. It juxtaposes Cambrian strata with Devonian to Pennsylvanian strata.

Interpretations:

Fault City Faults (Figure 20) have shallow striations indicating mostly strike slip motion. It may have oblique normal and dextral motion. Pirate Canyon Fault trace runs mostly north-south. It truncates the Devonian and Mississippian strata in its hanging wall. It has a single steep striation which suggests that it has dip slip motion. It puts Nopah Formation (Upper Cambrian) against Monte Cristo Formation (Lower Mississippian) and Birdspring Formation (Pennsylvanian to Early Permian).

SUMMARY OF FIGURES 7-20

Figure 7-Thrust is interpreted not to be the Keystone Thrust based on stratigraphic offset and 30 km dextral shear on Stateline Fault.

Figures 8,9,10-Powerline Fault is a vertical fault with shallow striations and a relatively straight trace across topography, which are characteristics of strike slip faults. Striations circled in Fig. 8 were used for Fault Plane Diagram.

Figure 11-Low angle normal fault oriented 300°/32° in accord with WSW-ENE southern Basin and Range extension direction. Thrust has 1.5 km stratigraphic offset, is oriented 202°/36°, verges east and lies in the Bonanza King near the silty unit. Interpreted to be a Sevier Belt thrust. Projected onto Fault Plane Diagram

Figures 12,13,14-Normal faults with a spoon shape.

Figure 15,16- Mesquite Thrust strikes north verges east and has significant stratigraphic offset and is interpreted as the Keystone Thrust.

Figures 17,18-Faults in the Hanging wall of Mesquite Thrust. May be rotated by Mesquite slip.

Figures 19,20-Need more data. Ivanpah is a candidate for further study. It is also sub parallel to Stateline and Powerline Faults, has a relatively straight trace across topography and significant stratigraphic offset.

6. FAULT PLANE DIAGRAM ANALYSIS

Fault plane diagrams were constructed for Powerline Fault to determine fault type and offset. Powerline Fault was selected because it is the closest sub parallel fault in the field area 2 km southwest of Stateline Fault and with a similar orientation. Powerline Fault has an average orientation of 324°/90° and Stateline Fault is oriented 315°/90°. The trace of Powerline Fault is nearly straight despite rugged topography and is exposed for over 5 km from its northwest end near Mesquite dry lake to its southeast end on the north side of alluvial fan # 2 (Plate 1). This fault is has the characteristics of a strike slip fault which have steep dips, shallow striations and a straight trace across topography.

Striations from the middle and north of Powerline Fault are mostly shallow. Many steep striations along with striations of moderate steepness were measured at fault station #83 in the southern segment of the fault (Figure 8). Steep striations are an indication of dip slip motion, which is contrary to the strike slip characteristics of Powerline Fault. The steep to moderate striations were all from one location and are attributed to a local bend in the fault causing dip slip movement. These striations were not used in the fault plane diagram as they are interpreted to be unusual and not representative of the overall fault motion.

Two fault plane diagrams Plate 2 and Figure 21 were constructed to determine the offset and fault type. The fault plane diagram of Powerline Fault (Plate 2) shows three segments reflecting the slightly different orientations of southern, middle and northern sections of

Powerline Fault. Strike and dip measurements of the rock units and their contacts were plotted along the fault exposure. The units on the northeast side of the fault are shown in green and those on the southwest side are shown in red. The dips of the rock units were projected onto the fault plane diagram as apparent dips and similar values were grouped together into dip domains. The dip domains are bounded by axial planar surfaces which are oriented at the bisecting angle between the dip domains and allow the units to keep consistent thicknesses along the fault plane. Faults that intersect the Powerline Fault were also projected into the fault plane using apparent dips.

The fault plane was extended past its exposure to the south to show the relative positions of the rock units and major structures on either side of the projected fault plane where the Powerline Fault is covered in alluvium. The projection from the southwest across alluvial fan #2 shows the relative position of the thrust labeled Keystone (?) (Figure 9) to the rock units on the southeast side of the fan. The Keystone (?) has Birdspring Formation in its footwall, which is not exposed in the rocks across Powerline Fault on the southeast side of the fan. The distance along the fault plane from the projection of the Keystone (?) fault to the southernmost exposure of Bonanza King gives a minimum dextral offset of 2.7 km to the most northerly possible position of the thrust where it is cut by Powerline Fault (Plate 2).

Whether the thrust is the Keystone or not, it is a major east verging thrust probably part of the Late Jurassic Sevier Thrust system. It juxtaposes Middle Cambrian rocks in its hanging wall with Pennsylvanian to Early Permian rocks in its footwall which is a significant stratigraphic offset or throw of ~ 1.0 km, and suggests a minimum displacement of ~ 1.7 km. These thrusts are commonly hundreds of kilometers in length in a ratio of 10-15:1 relative to their displacement. This fault likely had an original strike length of at least ~ 20-25 km and continued into the southern Spring Mountains.

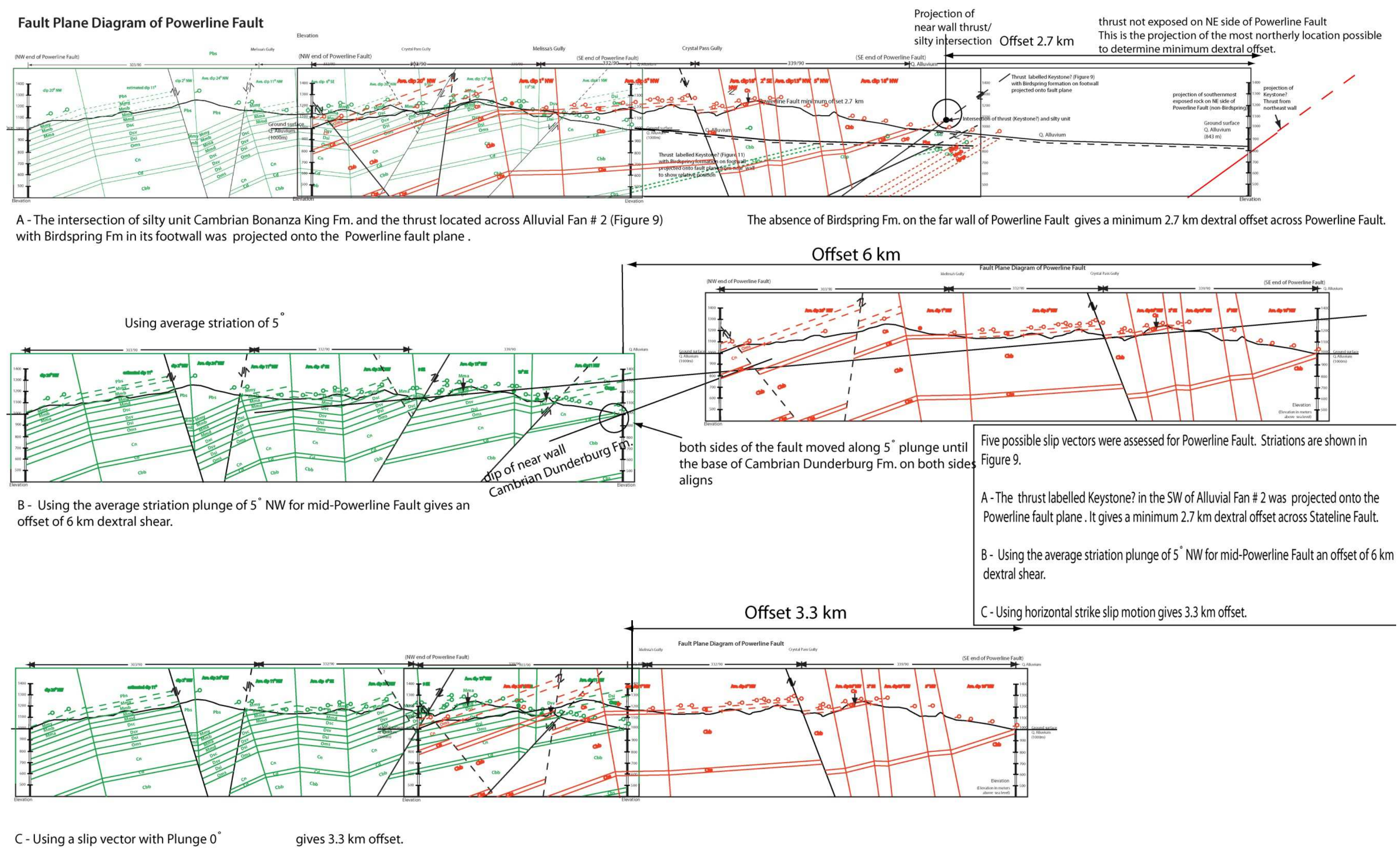
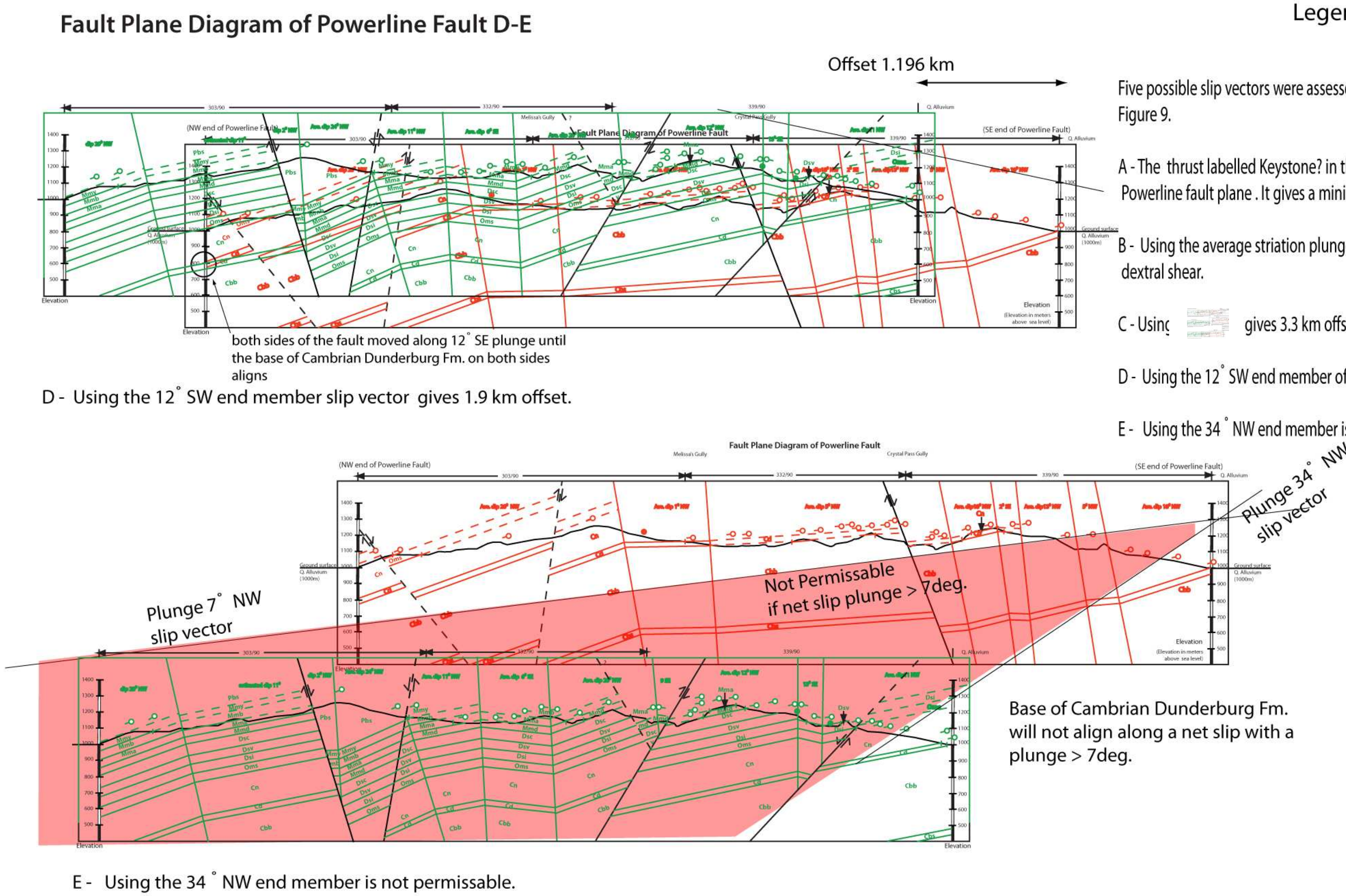


Figure 21. Powerline Fault Net slip Diagram Part A-C.



Legend

Five possible slip vectors were assessed for Powerline Fault. Striations are shown in Figure 9.

A - The thrust labelled Keystone? in the SW of Alluvial Fan # 2 was projected onto the Powerline fault plane . It gives a minimum 2.7 km dextral offset across Stateline Fault.

B - Using the average striation plunge of 5˚ NW for mid-Powerline Fault an offset of 6 km dextral shear.

C - Using gives 3.3 km offset.

D - Using the 12˚ SW end member of the range of striations gives 1.9 km offset.

E - Using the 34 ˚ NW end member is not permissable.

Figure 22: Powerline Fault Net Slip Diagram Part D-E and Legend.

The second fault plane diagram shows five possible net slip vectors with the aim of determining net slip on Powerline Fault (Figure 21). In the top fault plane diagram, (A) the major thrust in the southwest corner of alluvial fan #2 is projected onto Powerline fault. As outlined in Plate 2, the thrust has Birdspring Formation in its footwall. Birdspring Formation is absent in the southeast corner of the field area. This thrust is offset by the Powerline Fault at least the distance along the fault from the southeastern corner of exposed rocks in the field area to the projected intersection which gives a possible minimum dextral shear of 2.7 km. This is the smallest offset required for the fault cross Powerline Fault without any footwall Birdspring Formation being exposed. This diagram shows the units, such as the Dunderburg Formation, at the northwest end of the fault plane are not aligned, but are offset by about 300 m vertically which indicates that horizontal dextral shear of 2.7 km is not a good fit with the data.

For the next four net slip diagrams, striations measured on the fault plane gave a range of possible net slip vectors. Both sides of the fault plane can be offset relative to the other along a slip vector plunge until units from either side of the fault line up and a possible offsets is determined.

In part B, the fault planes are shown offset along the average striation plunge of 5° to the northwest. The Dunderburg Formation and other rock units are aligned with 6 km of dextral offset and would be aligned with greater offset, but it is unconstrained. The dip of the rock units are not the same on either side of the fault. The overlying Devonian to Pennsylvanian strata are not present on the southwest side of the fault.

In part C, the fault planes are offset by horizontal strike slip. When the base of the Dunderburg Formation is aligned on both sides of the fault, all the rock units align. The dip of the Dunderburg Formation is similar on both sides of the fault. Horizontal shear gives an offset of 3.3 km.

In part D the slip vector plunging 12° SE is used to offset the fault planes. This gives an offset of 1.2 km to align the base of the Dunderburg Formation. The dip of the units on either side of the fault plane do not align well.

In part E the striation plunging 34° to the northwest is tested and does not give a permissible solution. The units such as the Dunderburg Formation will not align if a slip plunge steeper than ~ 7° is used.

The five net slip diagrams evaluated five possible slip vectors with a range of resultant offsets. The projection of the thrust from the southwest side of fan #2 (A) gave a minimum dextral offset of 2.7 km, but the units did not align well. In B (Figure 21) plunge from average striation of 5° to the northwest gave a minimum offset of 6 km dextral shear and the Dunderburg Formation lined up well, but the dips were not the same. In C (Figure 21) with strike slip motion along a horizontal slip vector (0° plunge) the offset was 3.3 km, the units aligned well and the dip angles of the beds were similar. In D (Figure 21) the steepest plunge to the southeast gave an offset of 1.196 km and poor alignment of units. And in E- the steepest plunge of the striations to the northwest was not permissible as the units would not coincide. The favoured solutions are B and C with 6 and 3.3 km of dextral shear respectively and C had the best alignment of units.

7. DISCUSSION

A purpose of this study was to document the extent of dextral shear in the northeast Clark Mountains which is important to evaluate geohazards, constrain the slip rate on Stateline Fault and potentially to resolve the space problem presented by the abrupt southern termination of the Stateline Fault. Establishing the offset and slip along the faults in the study area will also help improve the understanding of the Eastern California Shear Zone the world's best studied diffuse plate boundary.

Powerline Fault is interpreted as a dextral strike slip fault based on detailed geologic mapping at 1:10 000. Kinematic data was collected along the faults in the field area and used to construct fault plane diagrams which gave an offset on Powerline Fault of between 1.9 and 6 km (Figure 21 and Plate 2) with ~ 3.3 km being the favoured solution. This suggests that the off fault distribution of shear on southern Stateline Fault may be partially taken up by dextral faults in the field area if Powerline Fault is a splay of Stateline Fault.

Powerline Fault has the characteristics of a strike slip fault; it is a vertical fault, with a nearly straight trace across topography and shallow striations indicating strike slip motion along the fault. The steeply plunging striations in the southern segment of the fault are attributed to the local bend in the fault causing dip slip motion and have not been included in the calculation of average striation plunges. There were limited striations and they were generally poorly preserved in the dominantly carbonate strata. Good striations were limited to fault planes with chert present, which sometimes resulted in excellent, well preserved striations.

It is not known if Powerline Fault is a splay of Stateline Fault. Powerline Fault strikes more northerly than Stateline Fault so the distance between them decreases from 2.7 km at the southernmost exposure of Powerline Fault to 1.8 km at the northern end of the fault. If it splays from Stateline Fault, the intersection is covered by the sediments of Mesquite Dry Lake. If they don't intersect and Powerline Fault is not a splay and not directly connected with Stateline Fault then the slip on Powerline could add to the dextral shear in the region and not just absorb some of the right lateral offset on Stateline Fault.

Keystone Fault is exposed for 113 km (70 miles) along the eastern Spring Mountains (Fig. 3) and then is covered by alluvial fan sediments to the south before it intersects Stateline Fault. As discussed in section 4.2., the Keystone Thrust is the easternmost major thrust in the Sevier fold and thrust belt (Burchfiel and Davis, 1974) which extends from northwest Canada about 3000 km to its southern termination in the Clark Mountains. It mainly juxtaposes Bonanza King Formation (Middle to Late Cambrian) with the Aztec Formation (Jurassic).

The thrust in the southeast corner of the field area (Figure 7) is identified as the Keystone Thrust in Walker et al's 1995 paper (Fig. 2 in Walker et al., 1995) where it is shown with ~ 1-3 km of dextral offset across the Stateline Fault. Dextral shear of a few km is not compatible with the 30 km offset documented along Stateline Fault at Devils Peak which is located ~ 5 km to the north of the southeast corner of the field area. The southeast thrust is not the Keystone based on the abrupt change in geometry required to cut down ~ 2 km to Cambrian rocks from Jurassic and dissipate ~ 27-29 km lateral offset over a distance of <3 km between southeast thrust and Stateline Fault. Both the Keystone and the southeast fault lie in the Bonanza King Formation (Middle to Late Cambrian) above the Papoose Lake Member in the silty unit at the base of the Banded Mountain Member. However, southeast fault has significantly less stratigraphic offset than the Keystone Fault has to the north. Southeast thrust repeats only the Papoose Lake Member of the Bonanza King Formation with less than 500 m stratigraphic offset compared with Keystone Fault to the north which has ~ 2.5 km of throw.

Mesquite Thrust in the central part of the field area (Figures 15 and 16) is proposed as a candidate for the Keystone Thrust. Mesquite Thrust has an average orientation of 202°/75°, it juxtaposes Nopah Formation and Bonanza King Formation, Banded Mountain Member (Late Cambrian) in its hanging wall and Moenkopi Formation Red Beds and Limestone units (Early Triassic) in its footwall. Mesquite and Keystone Thrusts both lie in between the Banded Mountain and Papoose Lake Member of the Bonanza King Formation. Mesquite Thrust has similar stratigraphic offset as the Keystone Thrust juxtaposing Late Cambrian and Triassic versus Late Cambrian and Jurassic. The Mesquite Thrust cuts Early Triassic strata so it is younger that Early Triassic in age and likely part of the Late Jurassic Sevier Fold and Thrust Belt of the Cordilleran Orogeny based on the north striking, east verging, major stratigraphic offset typical of the Sevier Thrusts in this area.

8. CONCLUSION

The purpose of this study was to determine if there is significant dextral shear in the field area southwest of the southern segment of the Stateline Fault. This was one of the three hypotheses put forward to resolve the space problem which is caused by the abrupt southern termination of the Stateline Fault ~ 30 km south of a documented 30 km dextral offset (Guest et al., 2007; Mahan et al., 2009).

I found dextral shear in the field area on Powerline Fault. The fault offset is 3.3 -6 km which is 10 – 20% of the dextral shear on Stateline Fault. If Powerline Fault is a splay of Stateline Fault then it absorbs 10-20% of the offset on Stateline Fault. If it is not directly connected to Stateline Fault, then it adds 10-20% to the offset on Stateline Fault. The 6 km solution was unconstrained and could be more than 6 km, but the 3.3 km offset had the best alignment of units and dip angles of the rock unit and is the best estimate of offset on Powerline Fault based on the data from this study.

The thrust fault on the eastern side of alluvial fan #2(Fig. 7) is not interpreted as the Keystone Thrust. Both faults lie in the same horizon between the Papoose Lake and Banded Mountain Members of the Bonanza King Formation (Middle to Late Cambrian). However, this fault (Fig. 7) has significantly less stratigraphic offset than the Keystone Fault has to the north. It repeats the lower Papoose Lake Member of the Bonanza King Fm (throw < 500 m) compared with the Keystone Fault which dominantly juxtaposes Bonanza King Formation with the Jurassic Aztec Formation (throw ~ 2 km) .

The Mesquite Thrust is suggested as a candidate for being the Keystone Thrust based on stratigraphic offset, and dextral offset along the Stateline Fault. Further work along Powerline Fault and Ivanpah Fault to the west focusing on kinematic data would help determine the total shear across the field area. Ivanpah Fault is another possible sub parallel shear fault that may link back to Stateline Fault. It is vertical, has a relatively straight trace across topography and major stratigraphic offset. Further work possibly using seismic across Mesquite Dry Lake may be able to trace Mesquite and Powerline Faults to the north and determine if and where they intersect Stateline Fault.

9. REFERENCES

Atwater, T. 1970. Implications of Plate Tectonics for the Cenozoic Tectonic Evolution of western North America. *G.S.A. Bulletin, v. 74, p. 3513-3536.*

Barnes, H. and Palmer, A.R., 1961. Revision of Stratigraphic Nomenclature of Cambrian Rocks, Nevada Test Site and Vicinity, Nevada: ***U.S**. G.S.A. Prof. Paper 424-C, p. C100-C103.*

Brady, R., Wernicke, B. and Fryxell, J., 2000. Kinematic evolution of a Large-Offset Normal Fault System, South Virgin Mountains, Nevada. *G.S.A. Bulletin, v. 112, no. 9, p. 1375-1397.*

Burchfiel, B.C., 1964. PreCambrian and Paleozoic Stratigraphy of the Specter Range Quadrangle, Nye County, Nevada: *A.A.P.G. Bulletin, v. 48, p. 30-56*

Burchfiel, B.C. and Davis, G.A., 1977. Geology of the Sagamore Canyon-Slaughterhouse Spring area, New York Mountains, California. *G.S.A. Bulletin, v. 88, p. 1623-1640.*

DeCelles, P. G., and Coogan, J.C., 2006. Regional Structure and Kinematic History of the Sevier fold – and - thrust belt, central Utah. *G.S.A. Bulletin, v. 118, p. 841-864*.

Dixon, T.H., Robaudo, S., Lee, J. and Reheis, M.C. 1995. Constraints on present-day Basin and Range deformation from space geodesy *Tectonics v. 14, No. 4, pages 755-772*

Dokka, R.K. and Travis, C.J., 1990a. Late Cenozoic strike-slip faulting in the Mohave desert, California, *Tectonics,v.9, 311-340.*

Dokka, R.K. and Travis, C.J., 1990b. Role of the Eastern California Shear Zone in Accommodating Pacific-North American Plate Motion *Geophysical Research Letters v.17, No.9, p. 1323-1326.*

Dolbier, R.A., Anderson, T., and Temple, R.N., 2009. Origin of Chert in Mississippian Monte Cristo Formation, southern Nevada, and its Relationship to the Antler Orogeny. *Search and Discovery Article #50238. Adapted from a poster presented at AAPG Convention, Danver, Colorado, 2009.*

Faulds, J.E., Henry, C.D. and Hinz, N.H., 2005. Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific- North American Plate Boundary *Geology, v. 33, n0. 6, p. 505-508.*

Gans, W. T., 1970, The Detailed Stratigraphy of the Goodsprings Dolomite, southeastern Nevada-California *[Ph.D. thesis]: Houston, Texas, Rice Univ., 174 p.*

Guest, B., Niemi, N., and Wernicke, B., 2007, Stateline Fault System: A New Component of the Miocene-Quaternary Eastern California shear zone: *G.S.A. Bulletin, v. 119, p. 1337-1346*

Hamilton, W., 2002. Crustal Extension on the Basin and Range Province, southwestern United States *The Geological Society, London, Special Publications 28, 155-176.*

Hazzard, J.C. and Mason, J.F., 1936. Middle Cambrian formations of the Providence and Marble Mountains, California. *G.S.A. Bulletin, 1936, v.47,no.2, p.229-240.*

Harrington, R.J., 1987. Lithofacies and Biofacies of the Middle to Upper Devonian Sultan Formation at Mountain Springs, Clark County, Nevada: Implications for Stromatoporoid Paleoecology. *J. Paleontology, v. 61, No. 4, P. 649-662.*

Hewitt, D.F., 1931, Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada: *U.S. Geol. Survey, Prof. Paper 162, p. 172.*

Lee et al., 2006 http://geology.csupomona.edu

Longwell, C.R., Pampeyan, E.H., Bowyer, B. and Roberts, R. J., 1965: Geology and Mineral Deposits of Clark County, Nevada.- *Nevada Bureau of Mines and Geology, Bulletin 62, Mackay School of Mines University of Nevada-Reno, Prepared cooperatively by the U. S. Geol. Survey, 218 pp and 16 plates.*

Mahan, K., Guest, B., Wernicke, B. and Neimi, N.A., 2009. Low- temperature thermochronologic constraints on the kinematic history and spatial extent of the Eastern California shear zone *Geosphere, v. 5, no.6, p. 483-495.*

McKee, E.D., 1938. Original Structures in Colorado River Flood Deposits of the Grand Canyon: *J. Sed. Petrology, v. 8, no 3, p. 77-83.*

McNair, A., 1951. Paleozoic Stratigraphy of Part of northwestern Arizona. A.A.P.G. *Bulletin, v. 25, no 3, p. 503-515.*

Miller, M., Johnson, D., Dixon, T., and Dokka, R., 2001. Refined Kinimatics of the Eastern California shear zone from GPS observations, 1993-1998*. J. of Geophysical Research, v. 106, No. B2, p. 2245-2263.*

Montanez, I., and Osleger, D., 1993. Parasequence Stacking Patterns, Third Order Accommodation Events, and Sequence Stratigraphy of Middle to Upper Cambrian Platform Carbonates, Bonanza King Formation, Southern Great Basin. Chpt 12 *in* R. Loucks, and F. Sarg, Eds*, Carbonate Sequence Stratigraphy: Recent Developments and Applications AAPG Memoir 57.*

Scotese, C.R. and McKerrow, W.S., 1990. Revised World Maps and Introduction *in* W.S. McKerrow and C. R. Scotese, Eds, *Palaeozoic Palaeogeography and Biogeography: Geol. Society of London, Memoir12, p.1-24.*

Snow, J.K. and Wernicke, B.P., 2000. Cenozoic Tectonism in the Central Basin and Range: Magnitude, Rate and Distribution of Upper Crustal Strain.*American J. Science, v. 300, p. 659-719.*

Stanka, S. and Hess, J., 1998. Geological Characteristics of Desert and Upper Desert Caves; NE Blue Diamond Hill, Nevada, USA. *Acta Carsologia Ljubljana, v. 27/2, no. 15, p. 265-283*.

Stevens, C.H. and Stone, P., 2007. The Pennsylvanian-Early Permian Bird Spring Carbonate Shelf, Southeastern California: Fusulinid Biostratigraphy, Paleogeographic Evolution, and Tectonic Implications. *U.S. Geol. Survey Special Paper 429.*

Stewart, J.H., Poole, F. G. and Wilson, R. F., 1972. Stratigraphy and Origin of the Triassic Moenkopi Formation and Related Strata in the Colorado Plateau Region *U.S.Geol. Survey Prof. Paper 691.*

Stewart, J.H. and Suczek, C.A., 1977. Cambrian and Latest Pre-Cambrian Paleogeography and Tectonics in the Western United States, *in* J.H. Stewart, C.A. Suczek, and A.E. Fritsche Eds., *Paleogeography of Western United States: SEPM Pacific Section, Pacific Coast Paleogeography Symposium*, p.1-18.

Thatcher, W., Foulgar, G.R., Julian, B.R., Svarc, J., Quilty, E. and Bawden, G.W. 1999. Present-day deformation across the basin and range province, western United States: *Science, v. 283, p. 1714-1718.*

Walker, J.D., Burchfiel, B.C. and. Davis, G.A., 1995. New Age Controls on Initiation and Timing of Foreland Belt Thrusting in the Clark Mountains, southern California *G.S.A. Bulletin, v. 107, no. 6, p. 742-750*

Zoeback, M.L., Anderson, R.E. and Thompson, G.A., 1981. Cainozoic Evolution of Stress and Style of Tectonism of the Basin and Range Province of the western United States. *Phil. Trans. R. Soc. London, A-300, p. 407-34.*

APPENDIX A

Kinematic Data from the Clark Mountain range. This data appears in the stereonets on figures 7-20. There are three tables of data; conjugate fracture data, fault data and fold data. The value that appears in the Page No. column corresponds to the number on the map, locating the measurement station.

Table 1: Conjugate Fracture data

Page No.	fracture	fracture	unit etc.
T1-[9]	090/75	085/80	joints ?
T1-[13]	044/65		not plotted
T1-[46]	255/90	200/90	
T1-[47a]	013/52	084/72	location uncert.
T1-[47b]	273/90	013/?	
T1-[49]	065/76	352/75	
	275/21	264/13	
T1-[50]	270/89	135/80	Mma
T1-51a]	018/85	311/75	Mma
T1-[51b]	302/88	005/85	Cbb
	161/75	260/89	Big Fault
T1-[52a]	214/76	162/77	Cd or Cn
T1-[52b]	092/77	226/76	Cn
T1-[52c]	143/59	273/89	Ed?

Page No.	fracture	fracture	unit etc.
T1-[52d]	040/72	102/78	Cn?
T1-[54a]	244/83	227/04	
T1-[54b]	275/78	347/66	Cb west of CP
T1-[55]	041/77	284/74	Dsv
T1-[56]	071/88	144/86	Dsv in Rf CP
	348/90	024/78	Dsv in Rf CP
	333/86	274/73	Dsv in Rf CP
T1-[57a]	154/90	104/90	Cbb cliff
T1-[57b]	079/73	128/60	Cbb plateau
T1-[58]	203/84	095/89	Cn
T1-[59a]	056/76	345/64	Dsc
T1-[59b]	020/66	141/75	Mmd
T1-[59c]	102/75	008/64	Mma
T1-[59d]	282/82	347/67	Mma
T1-[60]	037/77	100/76	Mmb
T1-[61a]	060/90	090/90	Cbb
T1-[61b]	039/54	285/86	Cd or Cn
T1-[61c]	357/88	094/78	Cbb
T1-[62a]	172/77	095/61	Cbp
T1-[62b]	241/16	016/73	Cbs
T1-[62c]	056/85	147/82	Cbb

Page No.	fracture	fracture	unit etc.
T1-[62d]	254/56	068/50	Cn
T1-[64a]	330/75	046/86	Cbp
T1-[64b]	063/80	010/78	Cbs
T1-[65]	048/48	235/90	
T1-[66]	135/70	118/77	Cbb?
T1-[67a]	262/89	015/83	Oms?
T1-[67b]	188/61	345/74	Oms?
T1-[67c]	282/70	253/72	Cbp?
T1-[67d]	297/53	269/66	Cbp
T1-[68a]	320/73	082/74	Cbb
T1-[68b]	255/72	188/70	Cbb
T1-[69a]	337/59	088/83	Cbp
T1-[69b]	087/74	160/84	Cbp
T1-[69c]	350/78	082/76	Cbp
T1-[75]	090/88	124/84	Cbp
T1-[79]	085/75	002/64	Cbb
T1-[80]	012/23	052/90	Mmy base
T1-[86]	030/87	292/87	Cbb
T1-[87]	091/86	214/54	Cbb

Table 2: Fault Data

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[5]	Normal 10cm breccia	93/44				
		137/76		127/67		21/135
				110/90		
T2-[15]/ T2-[104]	along big fault near lunch col	343/72	53/154 faint			
	also T2-[104]* data	165/65		335/52	347/90	
T2-[19]	perp. to big fault	097/72	08/094			
T2-[21]		158/72				62/345
T2-[24]	big fault	155/90	02/334 faint			
	minor fault	296/78				16/159
T2-[33a]		169/87				02/004
T2-[33b]	minor fault	059/75	064 trend only			85/052
T2-[49]	north part of Fan 1 near St. Pass	024/66				72/120
T2-[52a]	218/78	194/78	shears in fault z.			
T1-[52b]	313/73	344/88	shears			

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[57]	minor fault	210/85	07/039		137/87	
T2-[66]	000/70	310/63				
T2-[83]		353/82	80/095			
		335/62	59/100			
		000/51	65/295			
		347/55	72/049			
		143/70	65/030			
		323/70	10/325			
		221/68	63/265			
		011/88	60/180			
		330/82	81/225			
		018/68	30/202			
		128/76	76/218			
		341/84	72/018			
		065/72	65/205			
		295/25	10/084			
		335/24	??/093			
		295/30	??/083			
		270/31	05/082			
		354/65	64/050			
		170/56	56/265			

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
		345/74	74/060			
		220/15	10/275			
		321/90		342/90	084/76	
		345/70			085/80	
T2-[84a]	sm f. Cn near Pwrln F	322/55		355/33	055/65	
T2-[84b]	at Dsi/Cn contact	263/55	50/022			
T2-[85a]	small fault in Cbb	105/90	29/287	090/90	040/67	
		145/89	83/113			
		243/18				
		205/55	40/238			
		200/45	90/245			
T2-[85b]		280/62	62/002			
		155/20	19/258			
		120/83	83/225			
		080/62	70/186			
		090/75	30/270	317/85	023/75	
T2-[85c]		356/38	17/145	035/55		
			50/154	350/75		

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
			19/197	328/60		
			15/167			
			10/150			
T2-[85d]	sm f. 30m below o	320/75	00/320			
	normal (on saddle)					
			20/185	005/75		
			24/168	175/90		
				040/86		
				030/79		
			05/003	010/85		
				355/80		
T2-[86a]	snakebite gully	157/85				
		159/81	03/339			
T2-[86b]		157/85	03/335			
		150/87				
		157/82				
T2-[86c]		165/85	15/002	185/85		
		349/80	15/179			
		174/87	07/080			

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[87]	near Big F. All. Fan #2	315/81	72/039			
		331/88				
T2-[88a]		030/70	60/135			
		020/61	18/190			
T2-[88b]		280/35				
		305/45				
		298/43				
T2-[88c]		325/30		025/27	135/70	
		210/30				
T2-[90a]	Ivanpah Fault Zone Cbp/Trl	305/75				
		305/73	38/125			
		330/60	20/140			
		305/70		325/89	202/84	
				140/85		
				142/85		
				139/84		
T2-[90b]		330/60				
		075/72		168/55	144/49	
		145/59		137/84	226/84	

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[91]	curved fault btwn Dsc and Dsi	330/40	40/060			
		325/28				
		320/40				
		325/43				
T2-[94a]	btwn Pbs/Mmb	053/85	73/135			
T2-[94b]		248/57		084/89	213/63	
		255/81	90/239			
			76/200			
			72/073			
T2-[94c]	b/f gully forks	253/62		270/67		
	after gully forks	261/75				
		258/90				
T2-[94d]		273/70		273/90		
T2-[95a]	below rd near mine tailings	274/51		285/75		37/332
T2-[95b]		260/41		54/228		
T2-[95c]		295/90		270/73		
T2-[96]	30m fr Kally mine rd.	238/65		247/58		

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
		232/40		059/81		335/47
T2-[97]	Pbs/ Pk? Fault past gate	264/64		270/74		
T2-[98]		132/81	29/351	135/68		
				164/74		
		141/86		309/68		
T2-[99a]	up Pbs/Cb col, @triple junction	088/87		094/78		
T2-[99b]		128/68	18/119	114/58		
	striation on r1	100/54	12/145	137/59		
T2-[99c]		155/48		145/32		
		159/54	30/254			
T2-[100a]		324/81			185/78	
T2-[100b]	near col btwn Mmb/Cn	300/81				
		144/57				
	at col	146/90	20/150	150/81		
T2-[100c]	Mmb/Cbb/Pbs	143/74	17/312			
T2-[101a]	n side of Pbs/Cn col	086/90		073/90		
T2-[101b]		161/50		185/72	273/82	

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
		169/53				
T2-[101c]		318/68		300/84		
				290/80		
T2-[101d]	fault below col	175/46	45/212		075/58	
T2-[103a]		161/74	36/355	350/80		
		000/55				
T2-[103b]		155/37		142/52		
		150/36				
T2-[103c]		178/38		204/29		
T2-[104a]	big f. w of Xstal P. in Dsi?	180/78		190/90		
		152/81				
T2-[104b]	big f. just S. of Diff. gully inter.	307/88	04/303			
		125/78	34/302			
T2-[106a]	big f. 5m N Diff. gully /F inter.	341/90	13/167			
T2-[106b]	btwn Diff/Forget. Gullies	145/86				sub-horiz.

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[106c]	on fault pl. btwn Diff col/M gul.					sub-horiz.
T2-[110]	on Dsi col,F. w of Mesquite P.T.	043/76		050/89	285/85	
T2-[111]	Dsi/Cbb col e gully longfinger	30		041/82		
				191/46		
				197/75		
T2-[114a]	Cn/Dsi fault west of above f.	30		060/77		
				253/80		
				250/28		
				251/70		
			02/084	005/87		
				032/74		
				060/63		
T2-[115]	middle fault	059/67	00/069			
				215/76		
T2-[116]	fault west of above fault	50		205/75		
		065/79				

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
				045/69		
				015/58		
		034/71		045/69		
		023/72				
T2-[117]	fault west of above fault	30		225/72		
			63/214	047/76		
	small fault	028/54				
T2-[118]	fault west ~50m of above fault	32				
	main gully fault good exp	028/90	45/212	258/22		
	poor			119/87		
	"			143/86		
	"		67/338	152/85		
				005/89		
	main fault?	025/85				
	main fault?	035/65				
T2-[119a]		320/90	55/310			

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[119b]		302/75	24/310	320/72		
T2-[120]	Mesquite thrust	200/70		179/54		
T2-[122a]	western fault	047/71		191/57	114/88?	
		225/85		023/55		
T2-[122b]	western fault	021/56	24/000			
T2-[123a]	eastern fault	019/73	36/205			
T2-[123b]	eastern fault	018/44		061/72		
T2-[124]	Ivanpah fault z. west of WRCF	107/87				
		101/76				
			14/260	083/84		
		324/61	09/327			
T2-[125]	N. col f. Sandy Valley side	316/73		288/86		07/305
T2-[126]	Pbs/Cn N. col	155/86	20/339			
T2-[127a]	WRC fault	032/77		050/90		
		336/85				
		342/90				
T2-[127b]	WRC fault, N-S after bend	182/76		035/42		

page No.	description	Fault	striations	reidel 1	reidel 2	mulleins
T2-[127c]	WRC fault, NW-SE	310	06/048		028/55	
T2-[128a]	fault city fz, E-W	280	30/212	252/46	225/84	
T2-[128b]	fault city fz, NW	~295		092/90	062/69	22/072
T2-[129]	Pirate Canyon Fault N-end	355	90/095	007/90		
T2-[130a]	Pipeline Alley Fault	095/80	26/075	254/63		
T2-[130b]	Pipeline Alley Fault	315	32/267	084/73		
T2-[131a]	~E-W fault thru Skinny Finger	250		261/77		65/354
T2-[131b]	~E-W fault thru Skinny Finger	65		054/86		90/145 poor
T2-[131c]	~N-S fault thru Skinny Finger	006/69				08/009

Table 3: Fold Data

No.	Anticline limbs	Syncline limbs	anticline limbs	axial plane	fold axis	assoc. fault
T3-[27]	173/53 298/04	007/38 112/10	155/33 212/65			
T3-[65]	055/70 108/70			086/40		
T3-[90]					44/332	310/65
					65/334	
					45/315	
						135/90
T3-[99]					03/185	
T3-[100]		w-335/34 e-178/18			10/335	
T3-[103]					12/200	165/65