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Structural Analysis Of The Central Ibex Hills, Death Valley, California

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STRUCTURAL ANALYSIS OF THE CENTRAL IBEX HILLS, DEATH VALLEY, CALIFORNIA

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STRUCTURAL ANALYSIS OF THE CENTRAL IBEX HILLS, DEATH VALLEY, CALIFORNIA

by

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THESIS

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ABSTRACT

The Ibex Hills, in southern Death Valley, California, are composed mainly of Late Proterozoic sedimentary rocks overlying middle Proterozoic basement that are complexly deformed by Mesozoic contractional structures overprinted by Neogene extensional/transtensional structures. Detail mapping of the Ibex Hills reveals evidence of several deformational events. Brittle deformation of both extensional and strike-slip origin are recognized throughout the mapped area, but the main structure identified is a low angle fault at the base of the Noonday Dolomite, Sentinel Peak member, herein called the Noonday Fault. This low angle fault is dipping toward the east-northeast and has a curved geometry that resembles a previously mapped fault ~4 km west of the study area. The Noonday Fault accounts for missing section in the upper Crystal Springs Formation, Becks Springs Formation, and the Kingston Peak Formation. The Noonday Fault contact places the Sentinel Peak member on the middle Crystal Springs Formation. This fault is the most continuous feature in the area until terminating into the eastern bounding fault of the area. This eastern bounding fault is observed as a steeper normal fault dipping to the east with a dextral slip component. These Neogene structures overprint a complex Mesozoic deformation that includes at least two generations of folds. Overprinting has led to a general noncylindrical geometry for these folds, but the associated cleavages are also refolded complexly suggesting at least three phases of fold systems, sheath fold development or both.
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INTRODUCTION

The pre-Cenozoic geologic history of Death Valley (Figure 1) provides a framework for understanding Cenozoic and later deformation and tectonics. Several models exist to explain the Cenozoic deformation in Death Valley. One family of models (e.g. Topping, 1993; Snow and Wernicke, 2000; Norton, 2010) suggests detachment faulting in which extreme extension is the dominant tectonic regime in the region. Alternatively, others emphasize a transtensional environment in which extensive and transtensive shear from a northwest moving Pacific plate controls the Cenozoic deformation (e.g. Wright et. al., 1991; Serpa and Pavlis, 1996). To evaluate these alternative models, we need to establish better piercing points in order to recreate the paleogeography before the Cenozoic deformation structures (Figure 2). Pre-Cenozoic structures that are apparent throughout the Basin and Range, including Death Valley are convergent type structures (Figure 3) such as thrust systems and related folds (Snow et. al. 2000).

In this study, the Noonday Formation’s Radcliff member, as defined by Petterson et.al (2011), preserves the later structures that can be used to quantify earlier deformational events.

This study evaluates the evolution from a contractional system to a transtensional system using cross cutting relationships in the Ibex Hills. Compilations by Jennings et. al (1962) had suggested a thrust fault in this region placed the Mesoproterozoic Crystal Springs Formation on basement; this is a younger-on older relationship that seems unlikely for a thrust system. However, more recent mapping by Toppings (1993) showed the same fault as a low angle normal fault with an east dip direction. In this study, I describe the results of a new, detailed geologic mapping in the Ibex Hills, focused on resolving the basic structural succession in Mesoproterozoic to Neoproterozoic strata and underlying basement. This mapping reveals a distinctive structural history from compressional, extensional, and extensional.
Figure 1: Location of regional area in Death Valley. BM- Black Mountains, NR- Nopah Range, WP- Winter Pass Hills, IH-Ibex Hills. This study is located in the Ibex Hills region seen here in the southern edge of the Death Valley. (Corsetti, 2005)
Figure 2: Cenozoic tectonic structures of the regional Basin and Range. Bold star denotes study area. (Modified from Snow and Wernicke, 2000)
Figure 3: Pre Cenozoic structures in the regional Death Valley area. Bold star represents study area location. (Modified from Snow and Wernicke, 2000)
Figure 4: Explanation for maps generated in the study area
Figure 5: Geology map for the study area. Explanation is found on Figure 4.
Figure 6: Cross sectional interpretation of the study area. Explanation is found in Figure 4.

Figure 7: Station location map.
GEOLOGIC BACKGROUND

The Ibex Hills are located in southern Death Valley at the southern end of the Black Mountains (Figure 1). The hills expose rocks ranging in age from Mesoproterozoic crystalline basement to Meso-Neo Proterozoic sedimentary cover that have collectively been subjected to Cordilleran Mesozoic contractional tectonics and Neogene extension. Before being able to analyze the structure, the stratigraphy had to be better understood. Therefore I describe the stratigraphy of the rocks exposed in the study area first.

Stratigraphic Record

In the central Ibex Hills in Death Valley California, two distinct sedimentary assemblages can be observed and can be correlated to two major tectonic transitions that affected the evolution of the North American continental margin. Early rifting in the super continent of Rodinia begins the early evolution of the Cordillera margin in eastern California (Fedó, 2001). In association with this extensional period, the Precambrian, Pahrump Group, now exposed in the central Ibex Hills were deposited in a trough feature which trends west-northwest and known as the Amargosa Aulacogen (Figure 8) (Wright et. al. 1976). The Pahrump Group consists of the Crystal Springs Formation, Beck Springs Dolomite, and Kingston Peak Formation (Figure 9). The Pahrump Group is ~3-4 km thick, and unconformably overlies crystalline metamorphic basement rock. Further basin development, warmer climate conditions, and continuing fragmentation of the super continent are visible through the deposition and stratigraphy of the Noonday Dolomite and the overlying Johnnie Formation, with continued deposition of strata on the ancient passive margin continuing through the Paleozoic.
Figure 8: Depositional setting of the Pahrump Group in the Amargosa Aulacogen. (From Wright et. al., 1974)
Figure 9: Stratigraphic column for the exposed rocks in the study area. (From Corsetti et. al., 2003)
Crystal Springs Formation

The Crystal Springs Formation is intruded by diabase sills and consists of shallow marine to fluvial siliciclastic and carbonate facies (Heaman et. al 1992). These units represent a period of erosion the Nopah upland and sedimentation into the trough (Wright et. al. 1976). Cross-bedding, ripple marks, and mud cracks are present in the Crystal Springs clastic strata. Mafic intrusions are restricted to the lower and middle Crystal Springs Formation and can be up to 450 m thick and were emplaced between 1087-1069 Ma (Heaman, et. al. 1992). The intrusions are typically medium to coarse grained diabases, and the intrusive contact has developed talc deposits (Figure 10). In the study area the Crystal Springs covers nearly half of the mapped area, and crops out throughout the southern part of the study area. Above the intrusion contact, the Crystal Springs progresses from purple shale/mud layers (Figure 11) into a more clastic carbonate where the talc deposits are exposed. Given the abundance of plutonic rock throughout the mapped area and the abundance of talc mineralization associated with the intrusions, lower and middle Crystal Springs are present in the study area because the intrusions do not extend into the upper Crystal Springs, which is now known to be a distinctly younger Neoproterozoic unit (Mahon, 2012).
Figure 10: Talc mine in the Crystal Springs Formation located in Station 1.
Becks Springs Formation

The Becks Springs Formation and Crystal Springs contact have a transitional sequence of laminated carbonates of the Beck Springs Dolomite recording a flooding event (Corsetti, 2003). Whether the contact is conformable or disconformable throughout the region remains a topic of discussion. However in the study area, the entire lower section and upper section are absent. In the study area, a structural klippe of the upper middle member consisting of cherty grainstone with localized brecciation (Figure 12) is faulted upon the middle Crystal Springs. Deposition of
the Beck Springs Dolomite was in a shallow platform environment (Wright et. al. 1976). The presence of paleokarst within the dolomitic units gives evidence for subaerial exposure during part of the unit’s history.

During the Neo-Proterozoic era, the Earth’s climate was under a period of extreme changes both climatologically and tectonically as interpreted through sedimentary deposition. The upper Pahrump Group (Becks Spring Dolomite and Kingston Peak Formation), deposited during the late Pre-Cambrian shows an environmental transformation of a warm tidal environment (Becks Springs) to a colder and glacial environment (Kingston Peak) (Corsetti et. al. 2005).
Kingston Peak Formation

The Kingston Peak Formation lies depositionally on the Beck Springs Formation over large parts of the Death Valley region. Within the Kingston Peak Formation, depositional environments swing from glacial to a warmer climate as seen through the existence of diamictites and limestone members (Clapham, 2005). Two distinctive glaciation events are observed in the Kingston Peak Formation which are associated to ‘snowball earth’ (Corsetti, et. al. 2005). The
earliest event is referred to as Sturtian, and is associated to the Surprise Member of Kingston Peak Formation. Sturtian is dated globally between 750 Ma and 700 Ma (Corsetti, et al 2005). The second ‘snowball earth’ episode is found in the Wildrose Member in the uppermost Kingston Peak Formation, and it is referred to as Marinoan which is estimated to have taken place between 635 Ma and 600 Ma (Corsetti, et. al. 2005). Both diamictites are thought to have been deposited during times of active rifting in the Death Valley area. In the study area, only the Wildrose Member crops out (Figure 13).

A climatic warming trend ensued following the Kingston Peak deposition. This recognized as the Noonday Dolomite which rest above the Kingston Peak. The nature of the contact is controversial. In some areas, an angular uncomformity is inferred between the two units in which the Noonday Dolomite was deposited above a deeply eroded Parhump group (Wright et. al. 1984). However, Miller (1987) argues that sedimentation was more continuous than otherwise believed. Miller recognizes that angular contacts observed but that angular contacts are only localized.
Figure 13: Wildrose member of the Kingston Peak Formation exposed in Station 4. Black arrows point towards Becks Springs clasts.
**Noonday Dolomite Formation**

The Noonday Dolomite can be divided into three units (Petterson et al. 2011). The lowermost member, the Sentinel Peak Member (Figure 14), is a sub wave base algal member, but can have breccias and conglomerate beds. The Sentinel Peak Member is commonly interpreted as a cap carbonate deposited above the upper glacial deposit of the Kinston Peak Formation (Prave, 1999). The middle member, Radcliff Member, is 100 m to 200 m in thickness and can be further subdivided into 3 units (Petterson et al, 2011). The lower unit of the Radcliff member is mostly an arkosic sandstone (Figure 15) to feldspathic wacke with some siltstones, shales, and limestones. The middle unit has thin bedded limestones, intraformational breccias, and shales. The upper unit is dolomitic sandstone with an overlying siltstone with gravity flow textures. The upper member of the Noonday Dolomite is the Mahogany Flats Member (Figure 16) which is dolomite/sandy dolomite which possesses current related sedimentary structures in the upper member (Corsetti, 2005, Petterson et al, 2011).

In the Ibex Hills, the Noonday Formation was long separated as a separate lithostratigraphic unit, the Ibex Formation, to distinguish it from the characteristic Sentinel Peak member that typically dominates exposure of the unit (Wright and Troxel, 1984). The Ibex Formation was always recognized as a basinal facies equivalent of the Noonday and that it thickens to the west (while the Noonday thins) (Corsetti, 2005). The Ibex Formation was defined by Wright and Troxel (1984), and is subdivided into 6 members. However, a reevaluation of the nomenclature and stratigraphy has integrated the Ibex Formation into the Noonday Dolomite (Petterson et al, 2011). This revision reduces redundancy and is a better representation of the carbonate platform (Noonday) and basinal facies (Ibex) depositional environment. This combined stratigraphy is used for this investigation (Figure 17).
Figure 14: Sentinel Peak member of the Noonday Formation at Station 5.
Figure 15: Arkose section of the Radcliff member in the type locality in the Southern Ibex Hills.
Figure 16: Laminated limestone section in the Mahogany Flats member of the Noonday Formation. Black arrows point to "teepee structures" described by Corsetti (2005). This photo was taken at Station 8.
Figure 17: Revised stratigraphic column for the Noonday Formation. (Petterson, 2011)
**Johnnie Formation**

The Noonday Formation is overlain by the Johnnie Formation which is a mixture of siliciclastic-carbonate lithofacies with multiple sequence boundaries (Clapham, 2005). The Johnnie Formation was deposited in a shallow marine environment, however some fluvial processes are observed especially in the lower half. The younger Johnnie Formation has thicker coarse sand sequences and fines to a silty sandstone with time. A carbonate member is compromises the bulk of the upper part of the section. The Johnnie Formation is found in the northeastern part of the study area.

**Stirling Formation**

The Johnnie Formation is unconformably overlain by a thick siliciclastic section comprised of four lithostratigraphic units which include, from oldest to youngest: The Stirling Quartzite, the Wood Canyon formation, the Zabriski Quartzite, and the Carrera Formation. The youngest pre-Cenozoic rocks in the study area are Stirling Quartzite and Wood Canyon formation. The Stirling Quartzite is typically routinely divided into 3 members (e.g. Wright and Troxel, 1984): a lower white to maroon quartzite member, a middle mixed shale-quartzite member, and an upper white quartzite member. The Wood Canyon formation is also routinely divided into 3 members: a lower mixed siliciclastic and brown dolomite member, a middle siliciclastic member with distinctive coarse maroon conglomerates, and an upper mixed siliciclastic, brown, sandy-dolomite member with distinctive cross bedded sandy dolomite beds.
Regional Tectonics

Rodinia and Neoproterozoic

All pre-Cenozoic units were deposited in the trough during and after the breakup of the supercontinent Rodinia along the passive margin that developed in western North America during Neoproterozoic time. All rock units below the Johnnie Formation show complex facies variations indicating syn-extensional deposition in the Neoproterozoic, but the Johnnie Formation was deposited in the structural lows of the pre-extensional landscape and forms a blanket deposit similar in facies across the region. The unconformity between the Noonday and the underlying Pahrump sequences cuts out progressively older Pahrump units and is interpreted as a continuation of extensional tectonics during Noonday time. In its upper member, deep incised valleys could be indication of a reactivation of extensional faulting or a third glacial episode. Following deposition of the Johnnie Formation is a classic syn-rift succession of siliciclastic rocks (Stirling-Wood Canyon-Zabriski) overlain by classic Cambrian transgressive sequence of western North America (Carrera-Bonanza King-Nopah sequence) and associated passive margin rocks that record thermal subsidence following Neoproterozoic rifting. (Wright, 1984)

Mesozoic

Throughout the Great Basin, there is extensive evidence of Mesozoic contractional tectonics. The change from a passive to an active margin resulted in the thrust faulting and folding in the miogeoclinal strata of the Death Valley region and associated plutonism to the west associated with the Cordilleran convergent plate margin. In the study area, no Mesozoic units have been identified, but it is well known that the region experienced major Mesozoic contraction.
Immediately to the east, in the Nopah and Resting Springs ranges, at least three major thrust sheets have been mapped (Burchfiel et al., 1983). Major questions remain on the correlation of these thrust systems, but recent work by Guerrero (2008) suggests that two distinct generations of thrust faulting are present in the Death Valley region: an older, NE trending thrust system related to regional “Sevier” thrusts seen throughout southern Nevada and a younger generation of NW trending thrust systems recognized from Mexico through the US-Mexico border, into southern California (Burchfield et al., 1993).

_Cenozoic_

In the Cenozoic Basin and Range tectonics shaped the region, producing some of the most complex extensional structures seen anywhere (Wright and Troxel, 1984). An important issue in the Death Valley region has been the role of strike-slip motion in the development of the extensional structures. One of the major strike-slip zones, the Southern Death Valley Fault zone, runs just a few kilometers west of the study area. Crustal transtension has produced the normal faults and strike-slip faults cross cutting into Quaternary units exemplifying the tectonic setting. This deformation is associated with northwest movement of the Pacific plate along the transform boundary just west of the Death Valley, and is part of the eastern-California shear zone/Walker Lane belt of transtensional deformation. This regime is responsible for shaping the area’s landscape and geomorphology to its present state.

Although the Death Valley region today is clearly transtensional (Figure 18), it is not clear if transtension was the driver for the main extensional deformation within the region. The most intense extensional episode in the region occurred in the latest Miocene when areas just to the north of the study area, in the central Black Mountains, were stripped of their cover by extension,
exhuming mid-crustal levels beneath the Amargosa detachment systems and associated structures that comprise the Death Valley turtlebacks (Holm et al., 1992; Miller and Pavlis, 2008). The study area lies within a critical up-dip position of the Death Valley detachment systems. As such, it has been variably interpreted as either a part of the Amargosa detachment complex (Holm et al., 1992) or a relatively intact crustal block that lies in the footwall of these detachments (Wright et al., 1991; Serpa and Pavlis, 1997).
Figure 18: Regional geologic map of the Cenozoic structures. Study area is within the red box.

Arrow points to the Crystal Springs Fault depicted here as a low angle normal fault (Modified from Topping, 1993).
METHODOLOGY

The work area is located in the central Ibex Hills. Fellow graduate student, Sarah Cervera and the author mapped the area using various handheld computers using ArcPad software, GeoClinos (recording compass –inclinometer), and Brunton compasses. Along with the mapping of structures in the area, mapping the poorly understood Ibex Formation was needed to better understand its deformation. After the subdivision of the Ibex Formation into the Sentinel member, the Radcliff member and Mahogany member by the terminology of Petterson et. al. (2011) the mapping was improved greatly by clarification of the stratigraphic order.

After completion of the field work, the field data were exported to ArcMap. Contacts were adjusted using high resolution imagery, and this software was used to construct polygons for lithologic units and draped onto a digital terrain model for 3D control. The final geologic map was exported to Abope Illustrator where it was annotated for final presentation. Shapefiles and DEM data were then exported to MOVE. A cross section was then constructed in MOVE 2D. The cross section was also annotated in Illustrator to produce the final figures. Also, a stereo net analysis was constructed from the field data in MOVE 2D to better evaluate the structures’ orientations. The orientation data were also analyzed using the program GeoOrient.
FIELD ANALYSIS

Field Observations

The Central Ibex Hills study area exposes the Crystal Springs Formation (and its mafic intrusion), Becks Springs Formation, Noonday Formation, Johnnie Formation, and the Stirling Formation. West of the study area, previous work mapped a low angle fault that has a curved geometry. Jennings (1962) compilation of this mapping showed this fault as a thrust fault (white arrow, Figure 19). However, Topping (1993) showed this same fault as a low angle normal fault (Figure 18) with an eastern dip. Aside from these two references, there are no published data about the study area.

Figure 18 and Figure 19 have generalized the study area’s stratigraphy and structure. Previous structural interpretations have simplified the deformation history to an extreme extension event (Toppings et. al. 1993, Wright personal communication, 2010). Ductile deformation in the study area had also gone unmentioned. Petterson’s (2011) detailed stratigraphic work of the Noonday Formation has facilitated this study’s mapping project. Previous work had mapped most of the stratigraphy as uncertain as seen on Figure 19 (Jennings, et. al. 1962).

The major structural feature mapped in this project is a fault that shares a similar geometry to the structure shown by the Jennings (1962) and Toppings (1993) map. This feature is a normal fault which strikes nearly east-west in the eastern part of the study area but curves towards the northwest and becomes ~ NS striking in the western part of the mapped area (Noonday Fault, Figure 21). The general dip direction of this fault is east to north-east. Aerial imagery north of the study area suggests the fault also curves to northeast strikes just north of the study area. On
Figure 19: Regional geology map of the central Ibex Hills. Study area is in the box. Arrow points to the Crystal Springs Fault. (after Jennings et. al. 1967)
the west side of the study area, the normal fault is observed to be a low angle, east dipping structure and increases inclination towards the east.

The stratigraphic sequence suggests there is approximately 2km of the upper Pahrump Group between the Sentinel Peak Member of the Noonday Formation, and the middle Crystal Springs Formation. Because the base of the Noonday Formation is an unconformity that cuts out the underlying Pahrump Group section regionally this contact could easily be interpreted as an unconformity, yet several observations indicate the contact is a fault: 1) both the Beck Springs Formation and Kingston Peak Formation are present in the study area and should be absent if the basal Noonday unconformity had removed these units; 2) the Kingston Peak’s Wildrose member is seen locally below the Sentinel member of the Noonday as lenses in one location of the study area (Along the Noonday Fault, north of the Eclipse Mine in Station 4 and field view in Figure 13). Admittedly, similar contact relationships are observed below the Noonday in the Nopah Range, but in those localities Beck Springs Formation is also removed; 3.) Finally, in the western part of the mapped area, the contact is demonstrably a fault, suggesting the remainder of the contact is also a fault. Figures 20 and 21 show this contact relationship of the Noonday Dolomite faulted onto the Becks Springs Dolomite which is in turn faulted on top of the middle Crystals Springs formation.
Figure 20: Unedited photograph showing the Sentinel Peak member of the Noonday Formation faulted on the Becks Springs Formation and Crystal Springs Formation.
Figure 21: Annotated photograph showing the Noonday Fault. View is from Station 4 looking west to Station 9.

A cross sectional interpretation (Figure 6) of the study area shows an open synclinorium cross-cut by faults dipping to the west-southwest. This synform structure has a general inferred fold axis plunging toward the northeast. The core of the synform consists mainly of the Radcliff member of the Noonday Dolomite. The Radcliff member is also seen thrust over (Figure 22 and 23) the Mahogany Flats member near the west side of the study area. The Radcliff member also has numerous mesoscopic folds.
Figure 22: Thrust fault on the western side of the Study area looking North to Station 14.

Radcliff Member is Znr and Mahogany Flats member is Znmf.
Figure 23: Folds along the thrust of Radcliff member looking south at Station 14 and Station 15. Note the detachment fold in the hanging wall developed in shaley rocks of the Radcliff member.

**Folds and Cleavage**

The composition of the Radcliff beds and their primary rheological properties allowed for greater ductile deformation in relation to the more rigid overlying Mahogany Flats member and underlying Sentinel Peak member. This mechanical instability in the Radcliff member has produced macroscopic folding within the unit. Ductile deformation within the Radcliff member exhibits at least two episodes of compression as seen by superposed folding. Along with folding,
a prominent slatey cleavage is observed in the Radcliff member as well as in the overlying Mahogany Flats member. Cleavage refraction is apparent from a more competent bed to less competent bed within the Radcliff sequence. In the Mahogany Flats member, this cleavage is less pronounced presumably due to its more massive and competent rheology. Where folds and cleavage were observed, the cleavage planes are sub-parallel to the fold axial planes.

In the western part of the study area (Figure 24), the Radcliff member has parallel folds and stereonet analysis of the bedding planes suggest a larger scale fold plunging to the northeast (Figure 26). In the eastern part of the study area (Figure 25), deformation is complex and informally referred here as the “Ductile Corridor” (Station 11). In this area, the red/pink beds have more pronounced folding than the purer carbonate beds. The red/pink beds are shaley limestone. Fold axis orientations on the eastern side of the study area vary from trending southeasterly (140) with a moderate plunge (42) to steeper (62) plunging folds trending in the opposite direction (northwest, 304). There are also folds with orientations that lie perpendicular to the NW-SE trend (Figure 27).

Figure 26 is an equal area stereonet which plots all of the bedding data collected in the study area. This shot gun pattern supports the field observation that the folds are noncylindrical as a result of refolding. Plotting the fold axis measurements in Figure 27 also show similar scatter, consistent with more than one folding generation in the study area. On the western side of the study area, the bedding plane data are scattered but show a nonrandom pattern (Figure 28) suggesting a shallow to moderately NE plunging fold system consistent with larger scale mapped structures.
Figure 24: Folds in the western side of the study area show a more harmonic pattern at Station 10.
Figure 25: Photograph shows a more complex fold pattern as a result of superposed folding at Station 11, the Ductile Corridor.
Figure 26: Equal area stereographic projection of bedding planes in the study area. Shot gun pattern suggest multiple folding events.
Figure 27: Equal area stereographic projection showing fold axis orientations in the study area showing the scatter of fold axes from predominantly NE to SE plunging folds.
Figure 28: Equal area stereographic projection plot of bedding planes on the western side of the area where folding is less complex. Although scattered, these data suggest a NE plunging fold system consistent with a macroscopic syncline mapped in this region.
Figure 29: Equal area stereographic projection showing bedding planes in the eastern side of the area in the “ductile corridor”. This plot is consistent with field observations of curved fold axes and highly variable fold axis orientations among folds, supporting evidence for multiple generations of folding.
The folds within the Radcliff member are closely associated with a prominent spaced cleavage (Figures 30-34). This cleavage is most pronounced in the eastern side of the study area. In carbonate rich lithologies, the cleavage domains are prominent in the field with spacing ranging from a few mm (Figure 30) to a ~1 cm (Figure 33). Whereas in more shaley horizons, the cleavage spacing is penetrative at hand specimen scale (Figure 31, 32). Although the cleavage has not been extensively examined in thin section, this cleavage is clearly a pressure solution cleavage. The parting surfaces (Figure 30-34) typically display bands of insoluble residues, particularly in the carbonate rocks, consistent with a pressure solution mechanism.

The cleavage ranges from nearly perpendicular to bedding (Figure 30) to lower angle intersections (Figures 32,33), presumably marking changes from fold hinges zones (near perpendicular intersections) to fold limbs. However, due to the complexity of the folding, these variations occur at smaller scales and did not allow routine mapping of larger scale folds. The cleavage and bedding relationships in Figure 32 suggests an east vergent folding. However, Figure 33 suggests the folding is west vergent.
Figure 30: Closely spaced cleavage nearly perpendicular to bedding just above the Ductile Corridor, Station 11.
Figure 31: Cleavage face in the arkose section of the Radcliff member showing prominent bedding-cleavage intersection with strike and dip of bedding annotated on the figure. Location is just east of Station 8 (See Figure 7 for location).
Figure 32: View of the same area as Figure 31 viewing along the bedding-cleavage intersection, illustrating, cleavage intersection bedding with cleavage dipping more steeply than bedding. This relationship indicates a larger scale fold is to the east.
Figure 33: Spaced cleavage of a sandy limestone bed in the Radcliff member at Station 8 (Figure 7). Note the wider spacing of the cleavage relative to Figure 30 and moderate intersection angle suggesting upright beds on the upper limb of a nearly recumbent anticline with a vergence to the west.
Faults

In the study area, strike-slip faulting, thrust faulting, and normal faulting are observed. These series of brittle structures can be better clarified by understanding their cross cutting relationships. A reverse fault (Radcliff Fault) can be observed in Figure 22 and Figure 23 on the western side of the study area. This fault thrusts the Radcliff member on the Mahogany Flats member of the Noonday Formation. Folding is seen above this fault in Figure 23. This fault strikes approximately north-south and dips towards the east. This geometry is similar to that of the large Crystal Springs/Basement fault to the west of the study area illustrated by Jennings (1967) and Topping (1991) in Figures 19 and 18 respectively, but the Ratcliff fault places older rocks on younger rocks consistent with a thrust system. However, the low angle normal Noonday Fault (Figure 5) also has similar strike in this locality as the Radcliff Fault.

There are a series of faults that are antithetic to the easterly dipping Noonday fault. Figure 34 shows a fault offsetting the Radcliff member. This fault is striking near north-south and is dipping towards the west. This fault displaces approximately 250 m of section based on the marker bed capping the exposed Radcliff member. The fault on Figure 34 is the most westerly fault of this fault system. The faults in this system also change strike to the east, with faults becoming more northwest striking to the east. These faults are not observed east or south of the wash, mapped in this study as Quaternary alluvium (Qal). The wash itself appears to be following a minor right-lateral fault.
The most significant fault in the mapped area is the Noonday Fault. At the western end of its exposed trace, the fault is relatively low angle. Towards the southeast, it increases in dip, (Figure 35). This fault is dipping approximately 20 degrees to the northeast while the Crystal Springs beds are nearly horizontal. As the fault is traced to the east, the dip on the fault increases to 70 degrees (Figure 34). The fault overall cuts out about 2 km of the stratigraphic section which includes the Kingston Peak and Becks Springs in their entirety and the half of the Crystal Springs. The fault below the Becks Springs Formation is also cut by the Noonday Fault. The map
Figure 35: Noonday Fault represented in dashed red line. The Noonday Fault is the contact between the Sentinel Peak member (Znsp) and the middle Crystal Springs Formation (Ycpu).

View is from Station 16 looking northwest to Section 18.
Figure 36: The Noonday Fault from Station 18 looking east toward Station 4. Here Sentinel Peak member is faulted on top of the Becks Springs Formation (Ybs).
view geometry of the fault is similar to the map view geometry of the fault mapped by Jennings (1967) and Topping (1993), although the Noonday fault has a more strongly curved trace.

**Cross-Section**

Stratigraphic thickness used in the cross section in Figure 6 is based on Petterson’s interpretation (2011) and field observations. Table 4 represents the thickness of each formation present in the study area. The Noonday Dolomite has been divided into its three individual members (Sentinel Peak, Radcliff, and Mahogany Flats). The cross section (Figure 6) shows a minor synclinorium above the Noonday Fault. Map views of this syncline feature (Figure 5) are consistent with the NE trend shown by stereonet analysis (Figure 28). This bedding geometry mirrors the Noonday Fault which displays the same curvature as bedding consistent with an approximately bedding parallel geometry in the hanging-wall of the Noonday Fault. On the west end of the cross section, is the low-angle Crystal Springs Fault shown by Jennings (1962)/Toppings (1991) that places the Crystal Springs on top of basement. In this context, the Noonday Fault appears as a synthetic fault to the larger scale fault to the west. The antithetic faults dipping towards the west terminate at the Noonday Fault. On the eastern side of the cross section, a series of faults in the Johnnie Formation cross-cut the Noonday Fault. Field observations suggest that this eastern bounding fault cross-cuts all structures. This fault (Stirling Fault) is dipping east, and it also has a right lateral shift in which the younger units (Mahogany Flats, Johnnie Formation and Stirling Formation) are displaced to the south.
Figure 37: Annotated photograph looking northwest from Station 3.
DISCUSSION AND CONCLUSION

The study area was chosen because it is situated in an area where the Mesozoic structures potentially could be used for reconstructing the extension. Deciphering the stratigraphy is a primary task to be tackled before the structural geometry of the area can be addressed. In this context, the revised stratigraphy of the Noonday Formation by Petterson et. al. (2011) was critical. The Radcliff member is particularly important as an observable marker. In the western part of the study area, a harmonic folding pattern is developed but to the east this pattern is complicated by what I infer is at least 2 generations of folding showing fold overprinting. Both domains (West and East) are bounded by two major normal faults which dip, generally to the east. The placement of the Noonday Dolomite above the middle Crystal Springs is the result of a fault with approximately 2km of stratigraphic throw-the Noonday Fault (NDF). The NDF cuts out two formations: Kingston Peak Formation and the Becks Springs Dolomite. The eastern Stirling Fault also dips towards east but has a right-lateral shift. This slip is inferred from an apparent drag of the Noonday Formation along the fault contact. This right lateral slip places the Stirling Formation against the Noonday Dolomite and the Crystal Springs, truncating the Noonday Fault.

The dip direction of the beds (East) is in the same direction as the fault, but variably steeper. Thus, the beds show a hanging-wall cut off relationships suggesting the fault initially dipped westward, assuming the beds were relatively low-angle before the formation of the fault. This attitude would have to predate the brittle deformation of the Noonday Fault, and the Noonday Fault must have a low angle and sub planar surface. For example, assuming that the Noonday Fault originated as a high-angle fault, a significant rotation would be seen on the hanging wall. But even if the beds were near their current dip, a high-angle normal fault would rotate the beds.

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back to near horizontal. This slight rotation would have the Noonday Dolomite beds dipping towards the west; again assuming that the beds were sub-horizontal prior to faulting. Alternatively, however, if the beds were already steeply dipping this inference would not necessarily be correct. Instead, if steeply east dipping beds were cut by a lower-angle, east dipping fault, the observed hanging wall cutoff would be produced. Given the complexity of the Mesozoic structures, including thrust and intense folding in this area, the latter hypothesis seems mostly likely.

One element of the structure in the mapped area appears to be a significant thrust system with associated folds. This deformational event was not recognized in previous work in the area. However, extensive fold patterns in the study area support complex compressive deformation with at least two kinematically distinct events. The idea of a thrust fault with a dip to the east had been proposed by Jennings (1962) map. This fault geometry would account not only for the easterly dipping formations, but also some of the folding seen in the Radcliff member. The western harmonic folds could be associated with this thrust fault or even a smaller thrust within the study area. The thrust fault seen on Figure 22 could be remnant of a thrust system associated with the observed folding in the study area.

The Topping (1991) interpretation of the larger scale fault feature west of the study area could also be correct. Topping (1991) suggested that this feature is part of the Amaragosa detachment. If this detachment surface was driving extension to the east, the Noonday Fault could have coupled with the deeper fault. The Noonday Fault does have a curvature similar to larger features, and the Crystal Springs follows the synclinal geometry around the Noonday Dolomite (Figure 37). Both features, the Noonday Fault and the Crystal Springs fault, would then be contemporaneous and part of the same detachment system.
In contrast, the Stirling Fault to the east is probably not directly linked to the Noonday Fault or the underlying fault system. Instead this fault system is a younger structure. The relatively steep dip of this structure, together with its orientation and associated shifts in rock units suggest this fault could be a dextral strike slip fault, but more work is needed to clarify the fault’s kinematics. That is, the rock unit shifts could also originate by east–side down normal faulting.

The Proterozoic sedimentary rocks of the Ibex Hills display deformation structures that range from compressional to extensional to transtensional. Also, the West and East domains of the study area show a difference in the intensity of the deformation. Folds on the west side of the study have a more harmonic style as opposed to the noncylindrical superposed folding which occurs to the East. Thrust faults on the west side of the study area were also observed with a dip direction to the East. Associated deformation is more pronounced within the Noonday Radcliff member which is folded and also thrust upon the overlying Noonday Mahogany Flats member. This ductile deformation is recognized as tight folding and refolding which is not correlated to surrounding areas or in other formations. The mechanical properties of the stratigraphy affect the spatial patterns of the deformation at the outcrop scale. For example, the Radcliff member is a thinly-bedded argillaceous limestone that is less competent than its overlying and underlying massive members. Field mapping shows a westerly trending thrust fault along the base of the Radcliff member which is cross cut by a more recent extensional fault which dips to the northeast.

The Noonday Fault has a throw of approximately 2 km and cuts out the Kingston Peak and Becks Springs Dolomite. The Noonday Dolomite with localized lenses of Kingston Peak Formation lies above the middle Crystal Springs Formation in the study area. This fault is observed to be low angle and has a tight curvature suggesting a folded fault or a primary scoop
shape to the fault. This fault is interpreted to be a detachment fault with associated antithetic faults. This fault is cut by the Stirling Fault, which is interpreted as a tranpressional structure. The Stirling Fault strikes approximately north-south and has an east dip and a right lateral slip.

The current tectonic regime of the study area is transtensional, as well as for the Death Valley region. However, the Noonday Fault could be a detachment surface that previously accommodated significant extension. This fault surface could have a greater tectonic significant than the faults that place the Crystal Springs Formation on basement. Reconstructions of the regional deformation history must account for the study area’s deformation and can serve as piercing point to better develop the structure geology of this transitional tectonic setting.
Table 1: The two tables below list all the bedding data collected in the study area.

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<tr>
<th>Bedding Type</th>
<th>Quantity</th>
<th>Region</th>
<th>Temperature</th>
<th>Humidity</th>
<th>Moisture</th>
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<tbody>
<tr>
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<td>32°C</td>
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<tr>
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<tr>
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<td>28°C</td>
<td>50%</td>
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</tr>
<tr>
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<td>30</td>
<td>West</td>
<td>30°C</td>
<td>55%</td>
<td>30%</td>
</tr>
</tbody>
</table>

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<tr>
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<td>West</td>
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<td>55%</td>
<td>30%</td>
</tr>
</tbody>
</table>
Table 2: The table below lists all bedding data from the east side of the study area.

| No | X | Y | Z | Bedding Type | Orientation | Strike | Dip | Strike Error | Dip Error | bedding data from the east side of the study area. |
Table 3: The table below lists all bedding data from the west side of the study area.

Table 4: The table below lists approximate formation thicknesses of the units exposed in the study area.

<table>
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<tr>
<th>Study Area's Observed Formations</th>
<th>Approximate Formation Thickness (m)</th>
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<tr>
<td>Johnny</td>
<td>900</td>
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<tr>
<td>Noonday</td>
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</tr>
<tr>
<td>Member</td>
<td>Height</td>
</tr>
<tr>
<td>---------------</td>
<td>----------</td>
</tr>
<tr>
<td>Mahogany Flats</td>
<td>100</td>
</tr>
<tr>
<td>Radcliff</td>
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<tr>
<td>Sentinel Peak</td>
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<tr>
<td>Beck Springs</td>
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</tr>
<tr>
<td>Crystal Springs</td>
<td>800</td>
</tr>
</tbody>
</table>

REFERENCES


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CURRICULUM VITA

Oscar Esparza Jr. was born in El Paso, Texas and grew up in El Segundo Barrio. The son of Oscar Esparza and Blanca Estela Esparza Rochel, he graduated from Bowie High School in 1997. He received his Bachelors of Science degree in geology in 2005 from UTEP where he received the 2005 Eugene M. Thomas Award for Outstanding Geological Sciences Student. He
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