2018-01-01

Mapping Complex Fold-Thrust Systems in an Inverted Rift Basin: Indio Mountains, West Texas

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MAPPING COMPLEX FOLD-THRUST SYSTEMS IN AN INVERTED RIFT BASIN: INDIO MOUNTAINS, WEST TEXAS

by

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Geological Sciences

THE UNIVERSITY OF TEXAS AT EL PASO

May 2018

Acknowledgements

I was first introduced to the beautiful Indio Mountains as an undergrad. I'll never forget that first drive out there, the winding dirt road, followed by the rough terrain through the mountain; which I would eventually love to drive. I remember the project we did for the structure class, unknowing that my own project would be located just to the south.

I would not have been able to accomplish this work without Dr. Terry Pavlis, who took me as student, despite my fear of heights. Although terrified at times, I never let that get in the way of reaching the top of the mountains. Terrys patience and encouragement provided me with the support needed to accomplish this project and for that I am extremely grateful to have had him as my advisor.

I thank Dr. Richard Langford for teaching me the proper techniques of measuring stratigraphic sections. Additional thanks to Dr. Jerry Johnson for not only allowing me the used of the Indio Mountains Research Headquarters, but also for the use of the ATVs. I would also like to express my appreciation to Dr. Gail Arnold and Dr. Annette Veilleux for their guidance and support these last few years.

I am grateful to Myra Guerrero for the days the she took the time to spend as my field assistant and for all the input she had in my project, especially during the hot, humid days spent measuring the upper Yucca.

I also thank Jim Rutkofske for giving me that initial push to apply to graduate school and for his assistance and advice both in the field and in the lab. Lastly, I would also like to thank Mark Torres for all the support and love he provided throughout my journey.

I am truly grateful for you all.

Abstract

This study reports on new geologic mapping in the southern Indio Mountains of west Texas, where minimal research has been done since development of modern fold-thrust belt concepts. This study integrated an analysis of structure and the stratigraphy of the region. A stratigraphic column of the middle Cretaceous upper Yucca Formation was measured to 1) compare the lithology to that of the section previously measured in the hanging wall of the Squaw Peak thrust in the footwall of the Indio normal fault, 2) create informal members in the formation to aid mapping; and 3) identify previously unmapped structures in the southern Indio Mountains through better division of the stratigraphic assemblage.

The mapping shows out-of-sequence thrust systems and complex thrust stacking that is not typical of conventional fold-thrust belt systems. Significant structures recognized include a flat-on-flat and ramp-flat thrust structures localized in the Yucca Formation at the basal part of the section. Both structures are apparently out-of-sequence thrusts because they show clear evidence of faults cutting off footwall folds. A previously unmapped half window with lower Yucca Formation emplaced atop middle Cretaceous Bluff Mesa Formation was identified in the central part of the mapped area. The thrust that bounds the window is correlated to a major thrust exposed at the northern edge of the mapped area, and this structure is referred to here as the Purple Sage thrust. Lithology similarities of the measured sections of the upper Yucca on the footwall and hanging-wall of the Indio normal fault, suggest that the Purple Sage thrust is part of the Squaw Peak thrust system dropped down during the extension that formed the Indio normal fault. A cross section reconstruction of the Purple Sage thrust system was generated using Midland Valley Move software, with the interpretation of the Squaw Peak thrust underlaying the mapped area.

Table of Contents

List of Figures

Introduction

The generalization that thrust systems propagate from hinterland to foreland has been accepted as far back to the mid 1960's. Foreland propagation is generally thought to originate from the systematic growth of orogenic wedges through frontal accretion and underplating via duplex formation (Mitra, 1997; Morley, 1988). However, recent studies show clear evidence of out-of-sequence thrusting. For example, the Kvitova Thrust sheet in southern Norway, the Numidian Thrust Sheet in northern Africa, and St. Elias orogen of southern Alaska have recently been shown to contain extensive out-of-sequence thrust systems (Morley, 1988; Pavlis, et al., 2012). Multiple hypothesis have been presented including, but not limited to, maintaining the orogenic wedge at its critical taper, and/or in order to help the in-sequence thrust when the main thrust is unable to continue propagation (Mitra, 1997; Morley, 1988).

The Indio Mountain range, located south-southwest of Van Horn, Texas, is a site where out-of-sequence thrusting is likely. This mountain range has exposed marine sedimentary rocks deposited in an Early Cretaceous rift basin, the Chihuahua trough. These sedimentary rocks were later subjected to the Late Cretaceous-Paleogene contraction generating complex thrust systems. Research by Page (2011) shows a duplex system located in the central part of the mountain range, and structural details on the western side of the area suggest possible out-of-sequence thrusting.

The published geologic map of the Eagle Mountains and their surrounded area, which includes the Indio Mountains, dates to 50+ years back (Underwood, 1963), predating most modern concepts of fold-thrust tectonics. This project was done with the following goals in mind; (1) create a detailed stratigraphic section of the Upper Yucca Formation which is a major unit within the study area; (2) create a new geologic map of the southern region of the Indio Mountains using

modern concepts of thrust belt evolution to provide new information on the structural process of this system, and; (3) create models to reconstruct the possible kinematic geometries in order to better understand the structural processes of the region. Specifically, in this project was done to test the hypothesis that out-of-sequence thrusting had played a major role in the structural evolution of the system.

Tectonic Setting

The Indio Mountains and its neighboring ranges are part of an inverted basin system, which includes multiple sub-basins, extending from California to the Gulf of Mexico along the U.S. Mexico border (Figure 1). Trending NNW, the Indio Mountains lie on the northeast margin of the Chihuahua trough: a depositional basin covering southern New Mexico, southwest Texas, northern Sonora, and northeastern Chihuahua (Figure 2) (Haenggi, 2002; Page, 2011). The development of the region began with the Ouachita-Marathon orogeny forming a Paleozoic fold-thrust belt to the south and the ancestral Rocky Mountains to the north in the Late Carboniferous (Kluth & Coney, 1981). The collision between the North American and South American-African plate started in the Early Pennsylvanian and remained south of the Ouachita region until the middle Pennsylvanian which then allowed for collision in the Marathon region (Kluth & Coney, 1981). During this time the foreland reached the peak of deformation, creating the ancestral Rocky Mountains, and by the Late Pennsylvanian in to the early Permian the collision slowed south of the Ouachita region, yet continued in the southern Marathon region (Kluth & Coney, 1981). This caused the growth of the ancestral Rocky Mountains in modern day Colorado, New Mexico, Texas, and Oklahoma (Kluth & Coney, 1981). The suturing caused by the Ouachita-Marathon orogeny ended in the Early Permian (Kluth & Coney, 1981). The area was later affected during the Jurassic by sinistral oblique motion of the North American plate, relative to the Eurasia plate.

The main events of the study area started with the formation of the Chihuahua trough in the Late Jurassic. During the Oxfordian the North America plate had begun to pull away from Eurasia in what is generally recognized as a left-lateral system based on plate motion and the geology of Mexico (Dickinson & Lawton, 2001; Anderson & Silver, 2005), but a dextral pull-apart model has also been proposed (Haenggi, 2002; Haenggi & Muehlberger, 2005). Throughout

Tithonian and Neocomian times the Chihuahua trough underwent a regressive event, resulting in evaporite deposition on the eastern side of the basin (Haenggi, 2002). Extension renewed in the Aptian-Albian with the deposition of coarse clastic rocks and syn-depositional normal faulting documented in the northern Chihuahua trough (Page 2011; Budhathoki, 2013; Li, 2014). The area became a carbonate depocenter by the middle Albian as shallow waters were left mostly undisturbed until the inversion of the Chihuahua trough formed the Chihuahua tectonic belt during the Laramide orogeny, lasting from the Late Cretaceous to the middle Eocene (Haenggi, 2002). Haenggi (2002) inferred left-lateral transpression tectonics and fault reactivation within the eastern region of the evaporates, as the driver for inversion of the rift system. Most studies, however, consider the contraction as a general, regional effect of Laramide contraction (Dickinson & Lawton, 2001). Post Laramide orogeny, evaporatite and gravity tectonism continued as well as igneous intrusion and some volcanism, along with Neogene extension creating the topography seen at present day, (Haenggi, 2002).

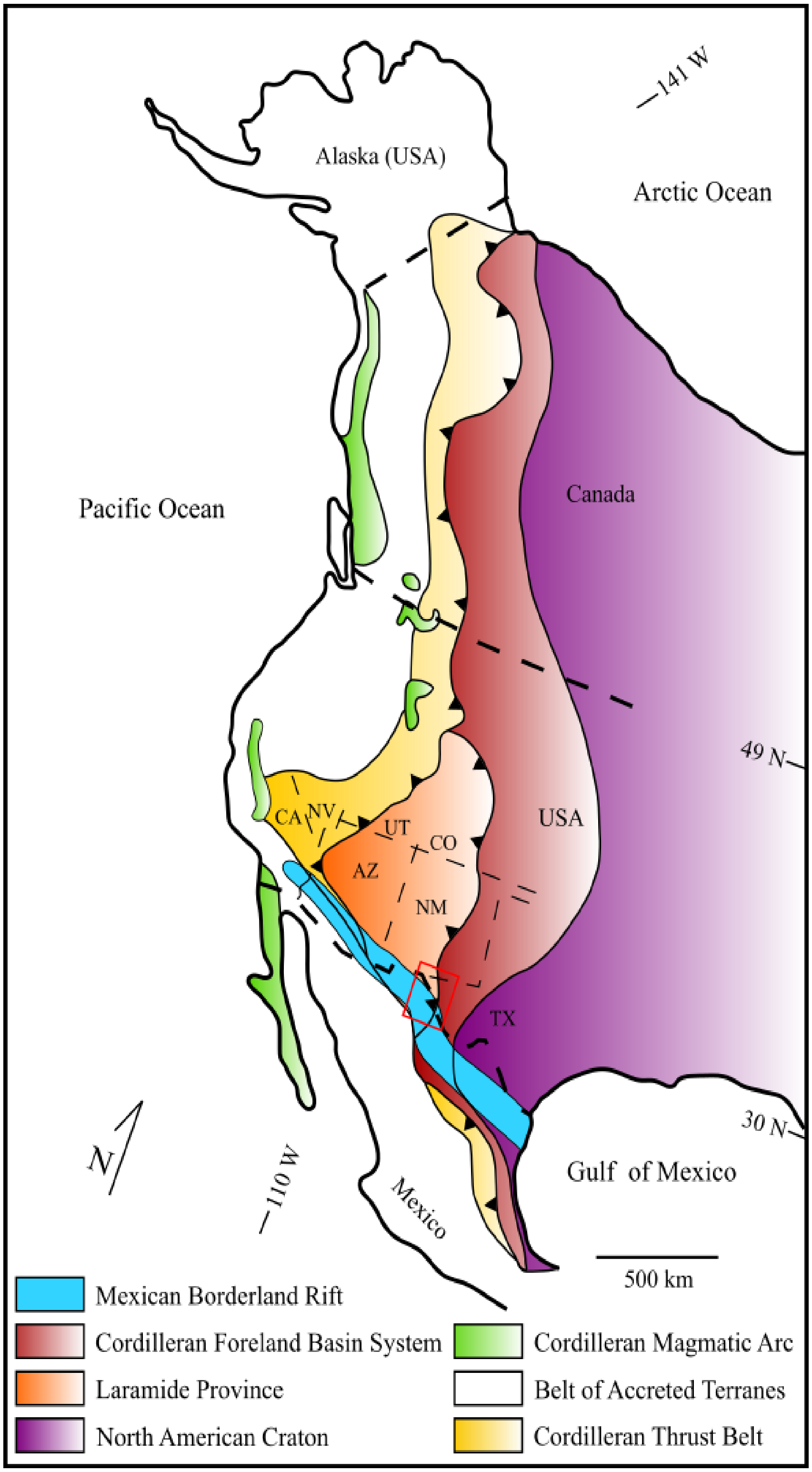


Figure 1: Map of western North America, showing location of Chihuahua trough and major tectonic zones. Red box represents figure 2. Modified from DeCelles (2004) and Lawton and McMillan (1999).

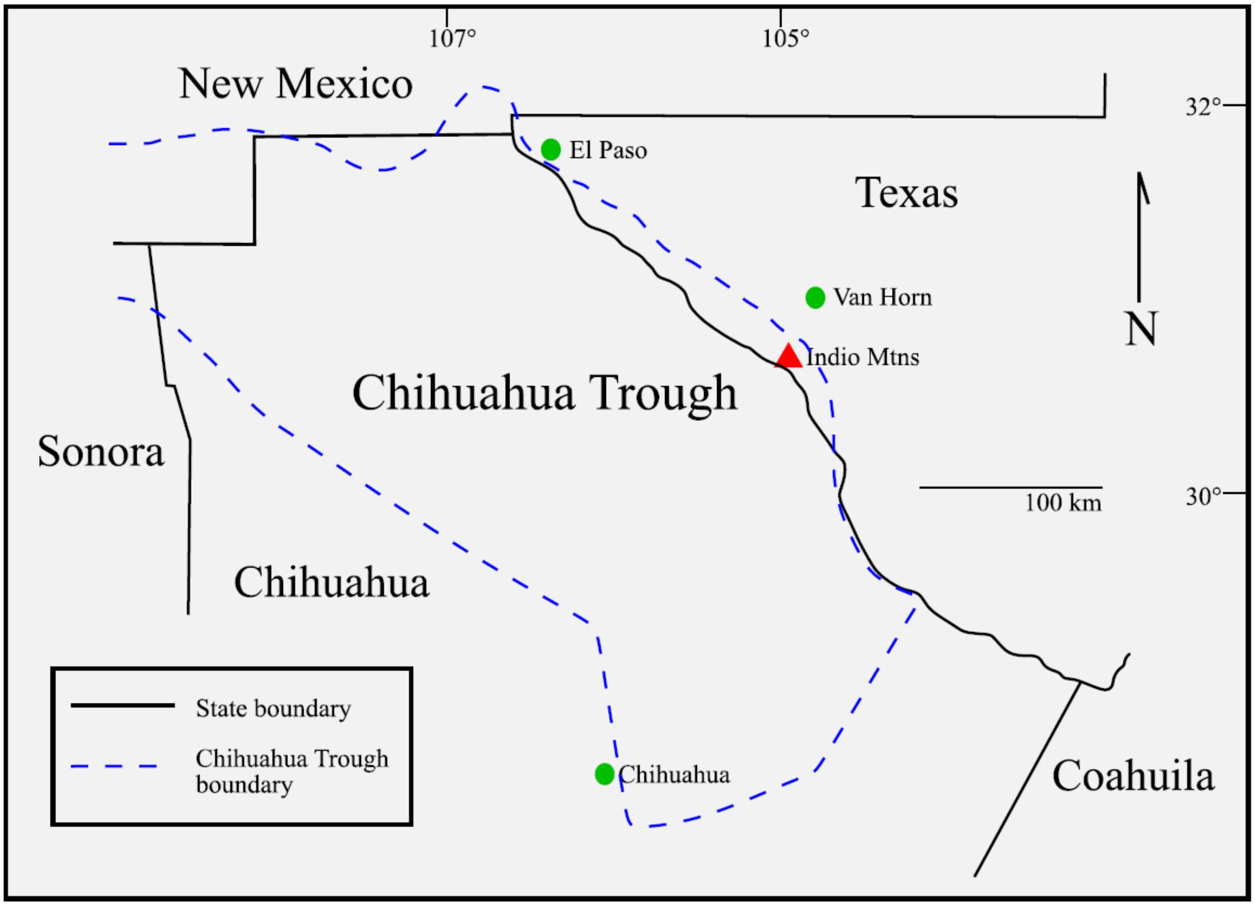


Figure 2: Map showing extent of Chihuahua trough. Modified from Haenggi (2007).

Study Area

The study area is within the Indio Mountains Research Station (IMRS) located in the Indio Mountains in southeastern Hudspeth County, Texas, south of Van Horn near the U.S. Mexico border (Figure 3). The Indio Mountains are underlain by predominantly Cretaceous rift-fill sedimentary rocks deposited unconformably on older Paleozoic rocks (Underwood, 1980; Haenggi, 2002; Page, 2011). The oldest rift-fill unit in the study area is the Yucca Formation, which may be as old as Late Jurassic (Oxfordian), but is predominately, or entirely, of middle Cretaceous, late Aptian to early Albian age (Figure 4), (Haenggi, 2002). The Yucca Formation is a thick unit, with a lower conglomeratic member and an upper heterogeneous member composed of interbedded conglomerate, sandstone, shale, and limestone (Page, 2011; Li, 2014). The lower Yucca Formation is entirely non-marine as evidence by sedimentary structure and scattered terrestrial fossils shows (Underwood, 1980). This is not the case for the upper Yucca Formation, which is more complex. Although Underwood (1980) interpreted the upper Yucca Formation as marginal marine strata, Li (2014) and Fox (2016) presented evidence that these rocks are non-marine fluvial and lacustrine strata, with marine depositions limited to the uppermost part of the formation. However, Anderson (2017) observed that the entire upper Yucca Formation is non-marine, with the transgression occurring at the base of the overlaying Bluff Mesa Formation. The boundary between the lower and upper Yucca is gradational but is defined by an abrupt fining-upward sandstone sequence (Page, 2011). The sequence then transitions into sandstone and siltstone interbedded with limestone (Li, 2014) in the upper Yucca Formation.

By the mid-Albian a marine transgression crossed the area and deposited the Bluff Mesa Formation, (Haenggi, 2002). Like the upper Yucca Formation, the Bluff Formation is lithologically heterogeneous but characterized by a prominent limestone sequence within the

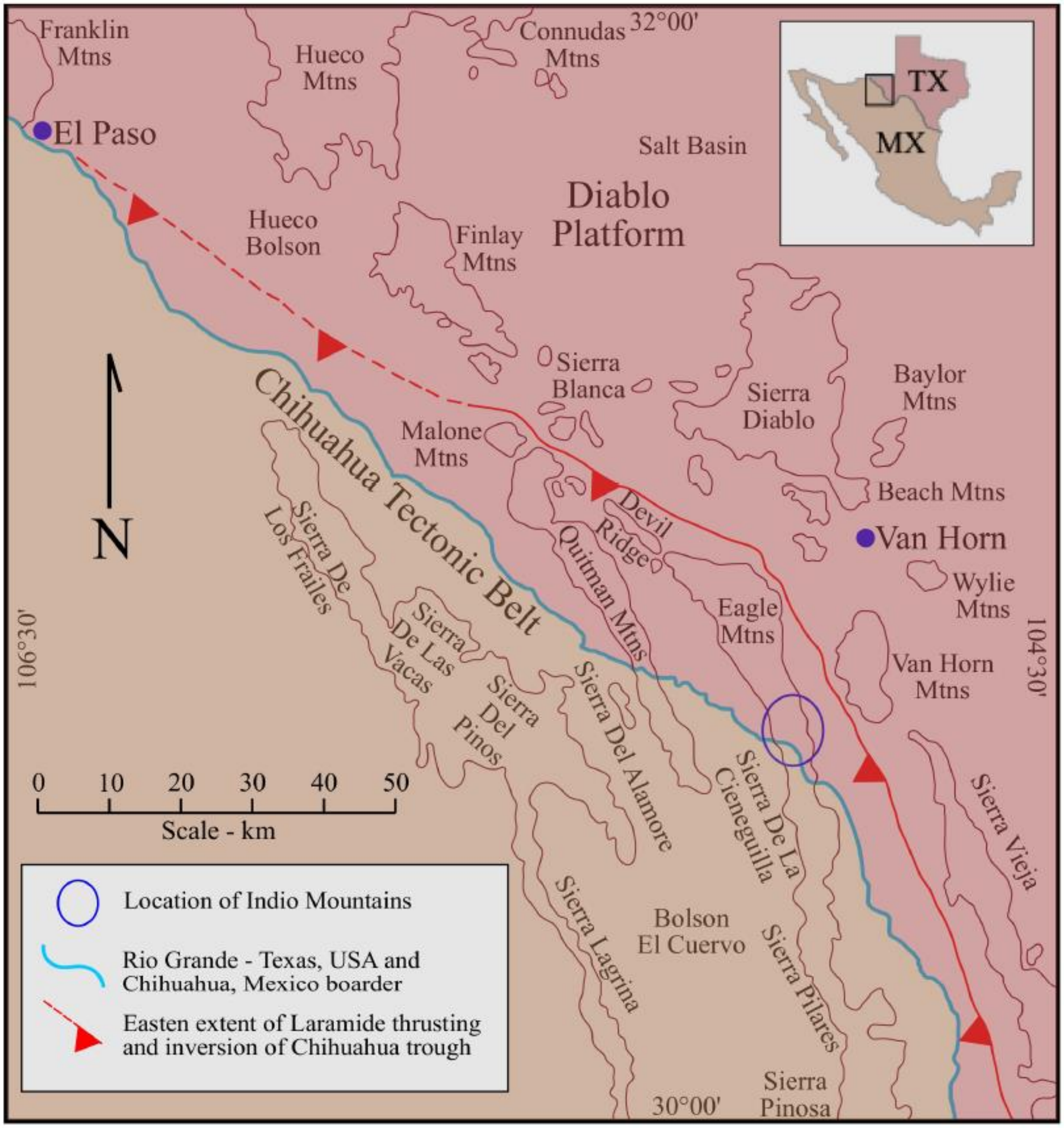
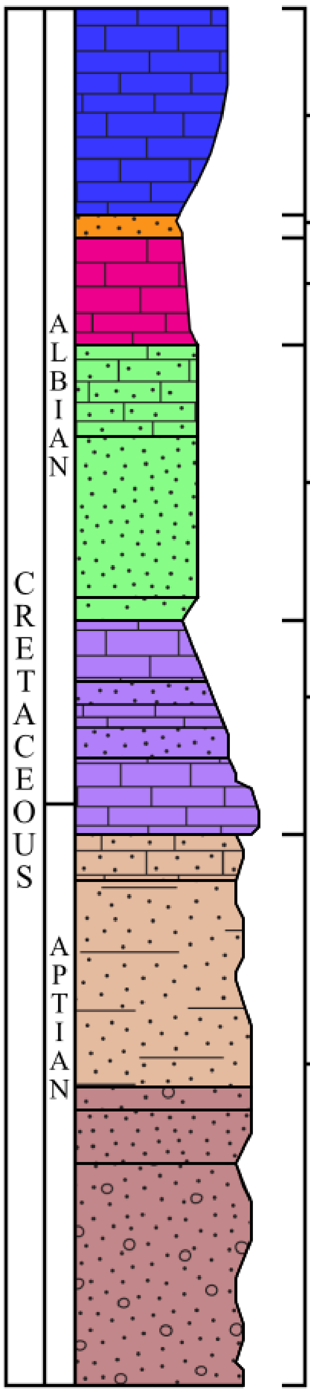


Figure 3: Eastern section of the Chihuahua trough, showing regional mountain belts and location of Indio Mountains. Modified from Underwood (1962), Rohrbaugh (2001), and Page (2011).



Espy Limestone

The Espy Limestone is composed predominantly of medium to dark grey limestone. The lower section is characterized by shale with interbedded nodular limestone and marl. Fossils are predominantly bivalves with a small frequency of gastropods. Fossils are abundant in the lower section and diminish in the meter scale beds of the upper section.

Benevides Formation

Visible outcrops of the Benevides are usually limited to the orange-brown sandstone in the upper unit. The lower section is a non-resistant, shaley siltstone. The upper exposed portion is characterized by its cross-bedding and intersecting fossilized burrows.

Finlay Formation

The Finlay formation is a fine-crystalline, grey limestone cossting of massive beds 1 to 3 meters thick. The Finlay formation is composed of dense fossil hash and identifiable gastropods and bivalves. Abundant silicified pelecypod shells on the jagged weathered exposures are a common feature of the Finlay formation.

Cox Sandstone

The Cox Sandstone is a cross-bedded, fine to medium, quartz-arenite cemented by quartz. The sandstone is fairly resistant to weathering and is a ridge former. Pale yellow to white sandstone mixed with iron-oxide stained grains is characteristic of the Cox. Several lenses of conglomerate-sandstone composed of rounded quartz, chert and limestone exist but are not pervasive. Shale units (often dark red) exist in the lower column. In the upper Cox a 3 meter thick, light grey, fossiliferous limestone.

Bluff Mesa Formation

The Bluff Mesa is a fossiliferous, fine-grained to crystalline, grey limestone interbedded with quartz-arenite sandstone. A forminifera index fossil call Orbitolina in only present in the Bluff Mesa and is used for identification of this unit. The Orbitolina is located in the and uppermost parts of the Bluff Mesa. Oolitic limestone beds are also common within the Bluff Mesa.

The Bluff Mesa is divided into three units; an upper, middle, and lower unit. The lower section contains massive beds (up to 3 m) of fossiliferous limestone. oolitic rich beds are most abundant in this lower unit. The middle section consists of limestone beds 2 meters or less in thickness. The limestone beds are interbedded by layers of quartz-arenite sandstone of half meter or less in thickness and closely resemble the overlaying Cox formation, but not as indurated. The upper section consists of a fossiliferous, nodular, micritic limestone and is typically a valley former.

Yucca Formation

The Yucca formation can be divided into distinct upper and lower units. The lower unit is a conglomerate with clasts compsed of grey limestone and black, pink, and white chert cemented by a fine-grained, maroon sandstone matrix. The clast range from a few millimeters to approximately 20 centimeters in diameter.

A sudden fining upward sequence of sandstone in the Yucca defines the base of the upper unit, which consists of sandstone, shale, siltstone, and limestone. The maroon shale layers are easily eroded and define slope with an average thickness of one to two meters. The siltstone is typically dark brown with an average thickness less than a meter. Two limestone layers reside in the upper portion of the Yucca column. The lower limestone layers reside in the upper portion of the Yucca column. The lower limestone bed average 3 meters in thickness and the upper bed marks the Yucca Bluff Mesa contact.

Figure 4: Stratigraphic column and description of rocks found at Indio Mountains. Modified from Underwood (1962), Rohrbaugh (2001), and Page (2011).

formation. Previous work by Page (2011) and UTEP geology field classes indicate that the Bluff Mesa Formation can be readily dived into three units. However, a recent study by Anderson (2017) identified four units in this formation.

Other rock formations of the Indio Mountains are not found in the area of this study and are all Albian in age (Underwood, 1980), including the Cox Sandstone; described as cross bedded, fine to medium grained quartz-arenite, containing conglomerates, shales units, and some fossiliferous limestone towards the top of the formation. The Finlay Formation; consists of massive grey limestone beds; it is micritic, and very fossiliferous containing gastropods and bivalves. The Benevides Formation; is comprised of two main units, the lower unit is a shaley siltstone, while the upper unit is an orange/brown sandstone; it contains burrows and is cross bedded. The final formation identified in the Indio Mountains is the Espy Limestone; it is mostly grey limestone ranging from medium to dark grey, the lower sections are shaley and interbedded nodular and marls, it is also fossiliferous but diminish towards the top of the section. Detailed descriptions of these formations can be found in Underwood 1980.

Three Tertiary volcanic rocks have also been identified in the Indio Mountains; Hogeye Tuff; Pantera Trachyte; and the Garren Group (Sahin, 2015). The Hogeye Tuff is composed of three units, the lower and upper unit is a tuff and the middle are a trachyte, with a thickness of 96 meters. The Pantera Trachyte is a grey to red/light brown trachyte, ranging from 30 to 90 meters thick. The Garren Group is undivided and consist of crystal tuff, trachyte, tuff, aphanitic basal, porphyritic basalt, tuff with sandstone and conglomerate, and andesite, creating a total thickness of 244 meters.

Methods

This project was created with two general goals: to create an updated map of the southern region of the Indio Mountains and to reconstruct the geologic structure of the area. Construction of the geologic map began with identification of rocks, mapping the structures, and collection of orientation data. This work was done by using the digital field mapping based on the techniques outlined by Pavlis et al. (2010). Field mapping and data collection were accomplished utilizing a tablet computer connected to a handheld GPS via Bluetooth and equipped with the open source GIS program QGIS Essen. High resolution orthophotos (0.5 m) and Google satellite images aided in locating structures and projecting line work. Most orientation measurements were taken using a Brunton compass, but some were collected using a geoclino; an automated GPS equipped compass inclinometer that allows fast digital recording of strike and dip, trend and plunge, or both.

Because the research area consisted of mostly the Yucca Formation, creating a stratigraphic column of the upper Yucca was important in order to understand the structures in the region. A secondary result of creating the column was to be able to compare the upper Yucca Formation from the down-thrown block of the Indio normal fault to the up-thrown block stratigraphic column created by Page (2011). The upper Yucca section was measured in the southeast section of the study area. Here, the formation was generally homoclinal allowing for easy measurement of the section. The section was measured with a 1.5-meter Jacob's stick and a Brunton compass, detailed descriptions were taken throughout measurement. Finding and mapping the base of the upper Yucca was aided by the aerial photography. The top of the section was assumed due to a large-scale fold that complicating completing the section.

After completing field work, map data were imported into the software package Move 2016, 2017, 2018 by Midland Valley Ltd, where the data were projected onto a DEM of the study

area. This allowed for a 3D structural visualization and analysis of the southern Indio Mountains. Topographic profiles were constructed from the DEM in order to create cross sections and restorations. Stereonets were analyzed using both the Midland Valley Move software and the open source Stereonet software, (Allmendinger, 2018).

Results

General Structures of the Study Area

The Indio Mountains can be divided into two blocks separated by the Indio normal fault creating an offset unconformity (Figure 5), with a displacement of ~1550 meters (Page, 2011). In the footwall located on the east side of the Indio normal fault, are the Squaw Peak and Bennett thrust faults. Traces of these thrust faults are sub-parallel in the northern part of Page's map (Figure 6), but merge together to the south. Page (2011) interpreted the Bennett thrust as the upper horse of a duplex which developed under the Squaw Peak thrust. On the hanging-wall side of the Indio normal fault, Page (2011) mapped a thrust which underlines the IMRS headquarters and interpreted this thrust as part of the Squaw Peak thrust displaced by the Indio normal fault, making this section a half-klippe (Figure 6), (Page 2011).

The research area of the study presented herein is to the south of the area Page (2011) mapped, with the Indio normal fault located to the east. The mapped area contains exposures of the Cenozoic basin that developed in the hanging-wall of the Indio normal fault. The basin initiated in the Paleogene (Sahin, 2015) as a composite sedimentary and volcanic assemblage deposited above an angular unconformity but evolved into a Neogene extensional basin during motion of the Indio normal fault. To the west of the exposed unconformity is a vast area of the Yucca Formation with notable fold systems, two major normal faults, and complex cross-cutting relationships, which characterizes the mapped area. By separating the lower and upper Yucca, as well as subdividing the upper Yucca, new structures have been identified in the region. Thus, I begin with a description of the stratigraphic section in the mapped area and continue with a description of the structures.

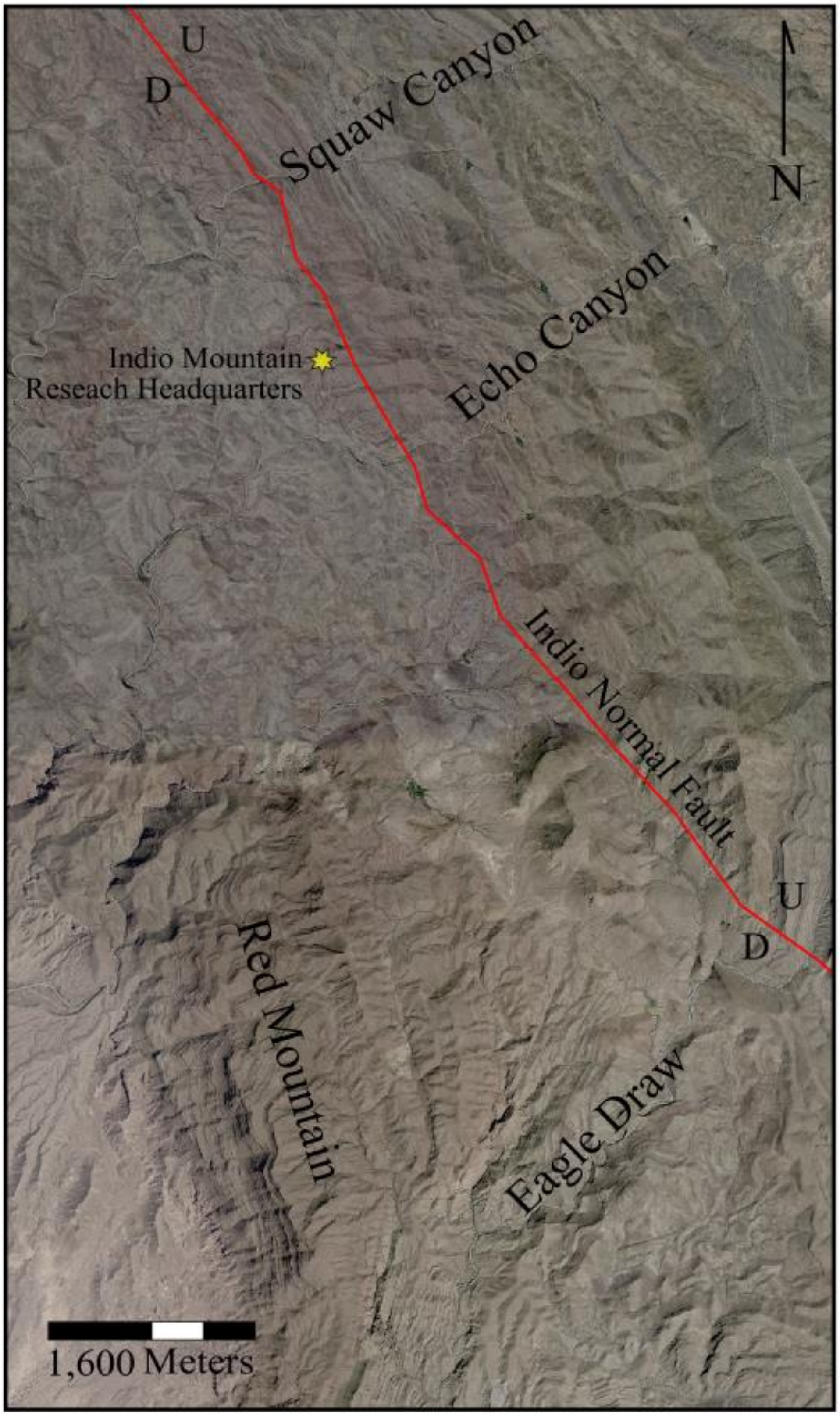


Figure 5: Orthophoto of the Indio Mountains, the IMRS is located on the northern half of the image, the research area is located to the south around Red Mountain.

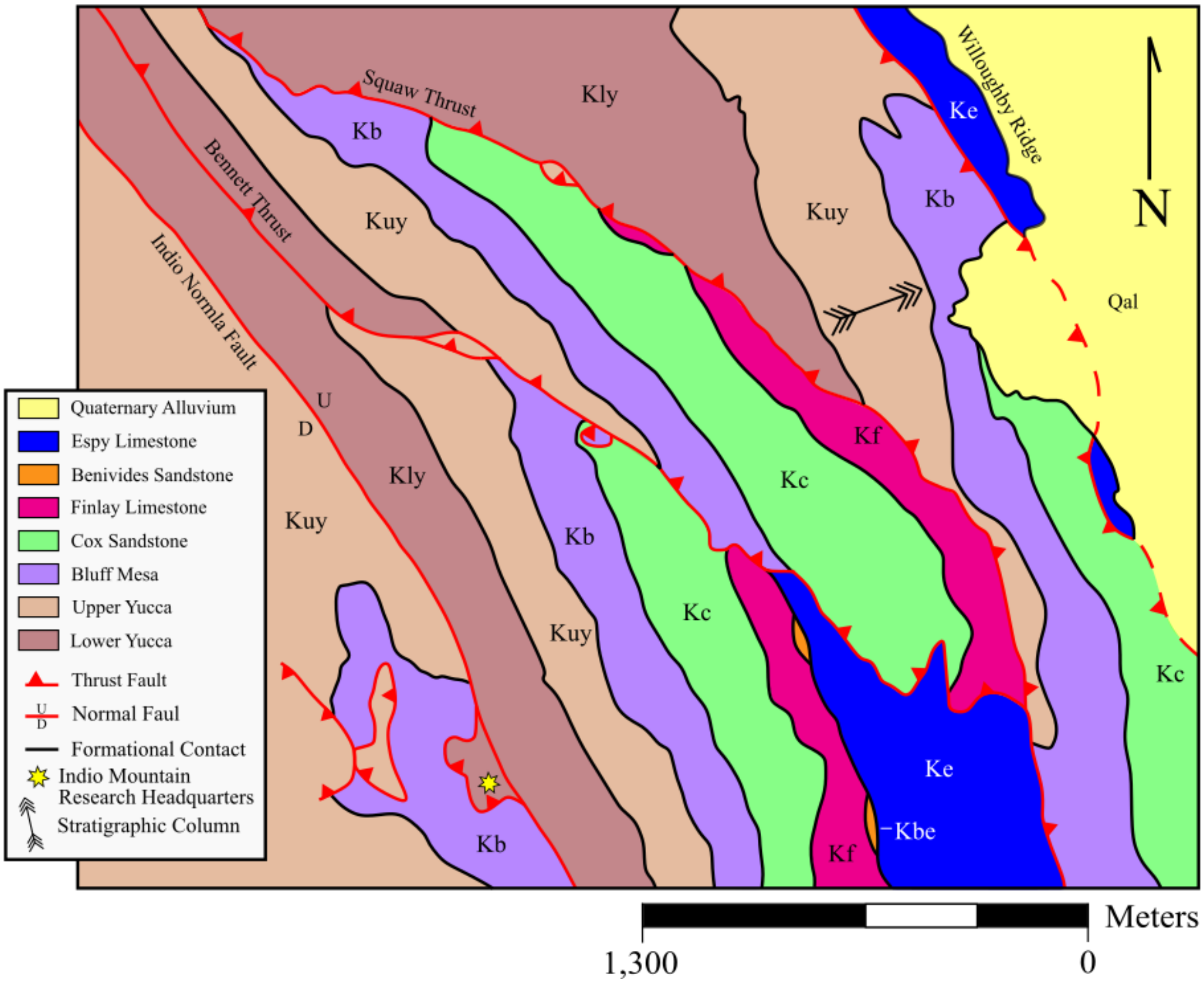


Figure 6: Geologic map of central Indio Mountains, showing major faults in the area. Modified from Page (2011).

STRATIGRAPHY

The upper Yucca section measured 587 meters in thickness. The measured section is located towards the southeast corner of the mapped region (Figure 7). Based on the measured section, I separated three informal lithostratigraphic members: units 1 through 3. The contact with the lower Yucca, which is itself an informal division recognized in this section by change in lithology from conglomerates to sandstones and mudstones.

Unit 1 of the upper Yucca is 88 meters thick; its contact with unit 2 covered in the measured section (Figure 8.1). Unit 1 is a lithologic transition unit from the coarse conglomerates of the lower Yucca Formation to the finer grained mudstones and sandstones of the upper Yucca Formation. This unit is composed of 3 fining upward cycles that begin with conglomeratic horizons and end with sandstone units. The unit is readily mappable by a prominent marker bed of red mudstone with carbonate nodules; informally called "potato beds" at the base. The top is defined by the uppermost thick conglomerate-sandstone cycle below coarse sandstones interbedded with shales in unit 2.

Unit 1 is characterized by fine grained, well rounded, well sorted, red to maroon and grey sandy mudstone. The mudstones are massive, however at the base they are poorly exposed. "Potato beds", 10-30 cm in diameter, are also present at the base; they have a rough texture and are commonly grey or brown in color. The conglomerates are composed of a sandstone matrix; medium to coarse grained, rounded, and well sorted, and ranging in color from white, pink, orange, grey, brown, and yellow. There are two types of clasts within in the conglomerate, the first is a dolostone, with clasts ranging up to 12 cm in diameter, usually subangular, and grey, with a rough texture. The second are multicolored (white, red, grey, purple, black) chert pebbles, ~6 cm in diameter, which are always well rounded. Conglomerates are usually massive and moderately

sorted, however there are some graded conglomerates present in this section interbedded with sandstone layers. Sandstones range from being coarse to medium to fine grained as the cycles progress. They are rounded to well-rounded, and moderately sorted and range in color from white, pink, orange, purple, and grey, mostly cross stratified if not laminated or massive.

Unit 2 of the upper Yucca is 305.5 meters in thickness (Figure 8.1-8.4). Lithologically, the majority of the rocks are similar to unit 1, but in this unit the sandstones are conspicuously burrowed and interbedded with shales. The base of unit 2 is marked by a massive sandstone with burrows and interbedded shales. A thick bed of cross stratified sandstone marks the top of unit 2, it is below mudstones interbedded with limestones of unit 3.

Unit 2 is identified by coarse-grained rounded, well sorted, grey, massive sandstone interbedded with very fine grained, grey/brown shale beds usually measured 1 meter each. Burrows are evident and sparse “potato beds”, 10-30 cm in diameter, are present. Sandstones are massive or cross bedded and coarsen upward to very coarse. The sandstones are rounded, well sorted, and interbedded with conglomerates and cross laminated shales, burrows are also present. The top 125 meters of unit 2 experienced a fining upward to a fine grained, dark red, massive mudstone with burrows present. This sequence coarsen to a rounded, grey sandstone with laminated shales which then fine upward into a mudstone with trough cross stratification and interbedded conglomerates. This patter is repeated for the remainder of the unit, however the sandstones become cross laminated and “potato beds” become more evident. The top of the unit is identified with a section of fine grained, brown/maroon mudstone with “potato beds”, coarsening upward to a thick coarse, rounded, grey, cross stratified sandstone.

Unit 3 is 183 meters thick and is distinguished from unit 2 by the lack of burrows and shales in the sandstones (Figure 8.4-8.6). The difference between unit 3 and unit 1 are the layers

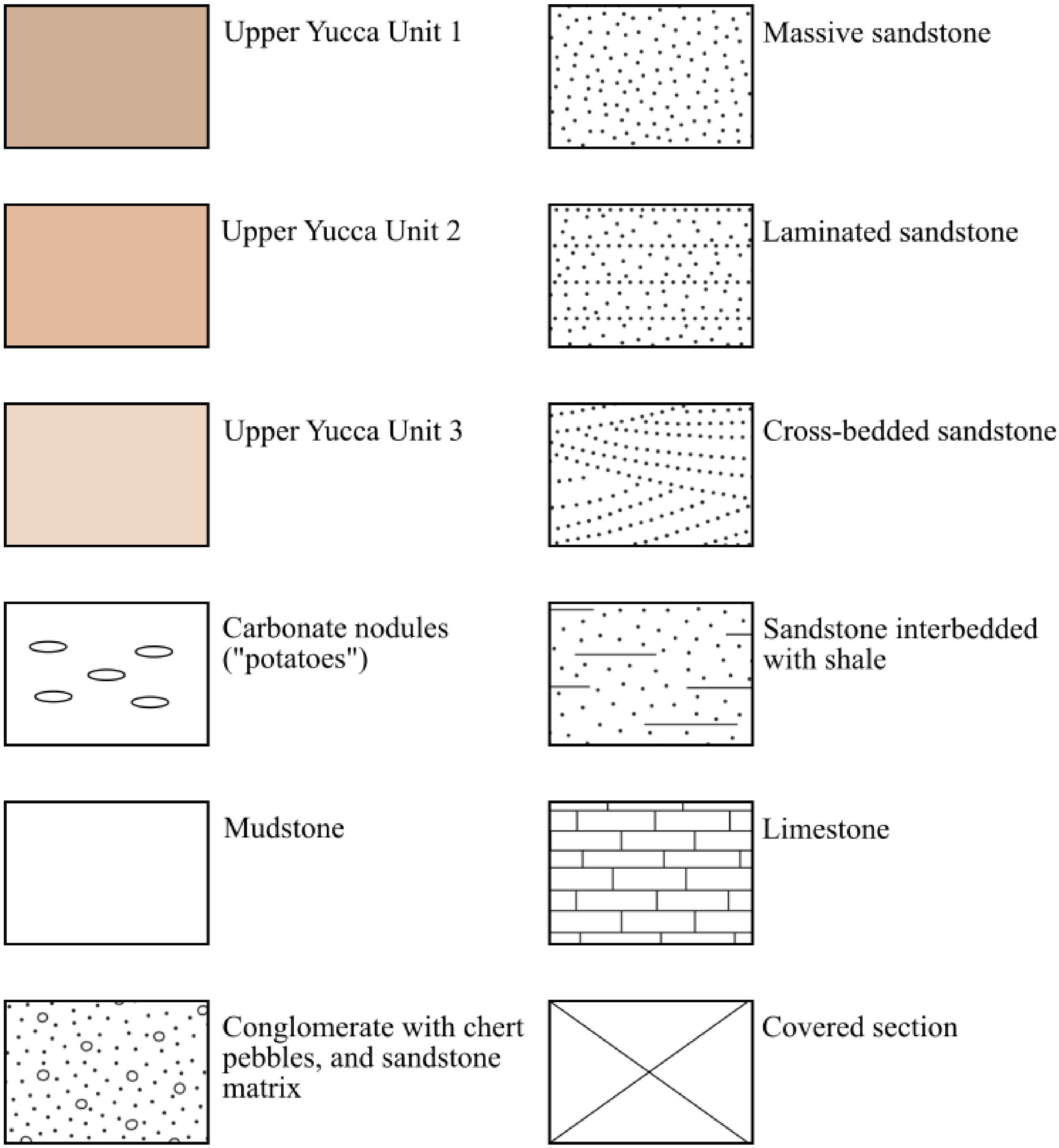


Figure 8: Key of stratigraphic column

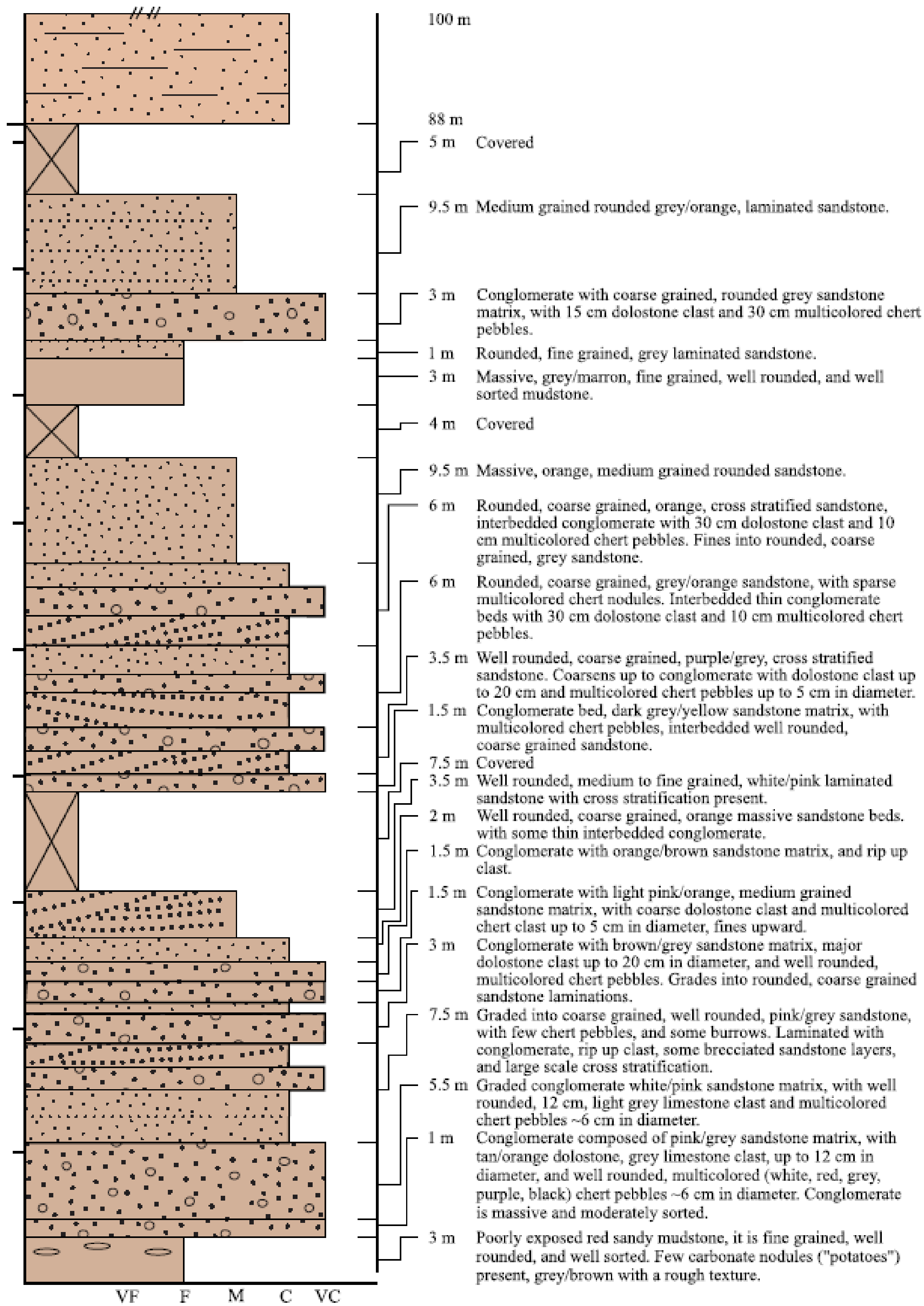


Figure 8.1: Stratigraphic column of upper Yucca, here is the base measured up to the first 100 meters.

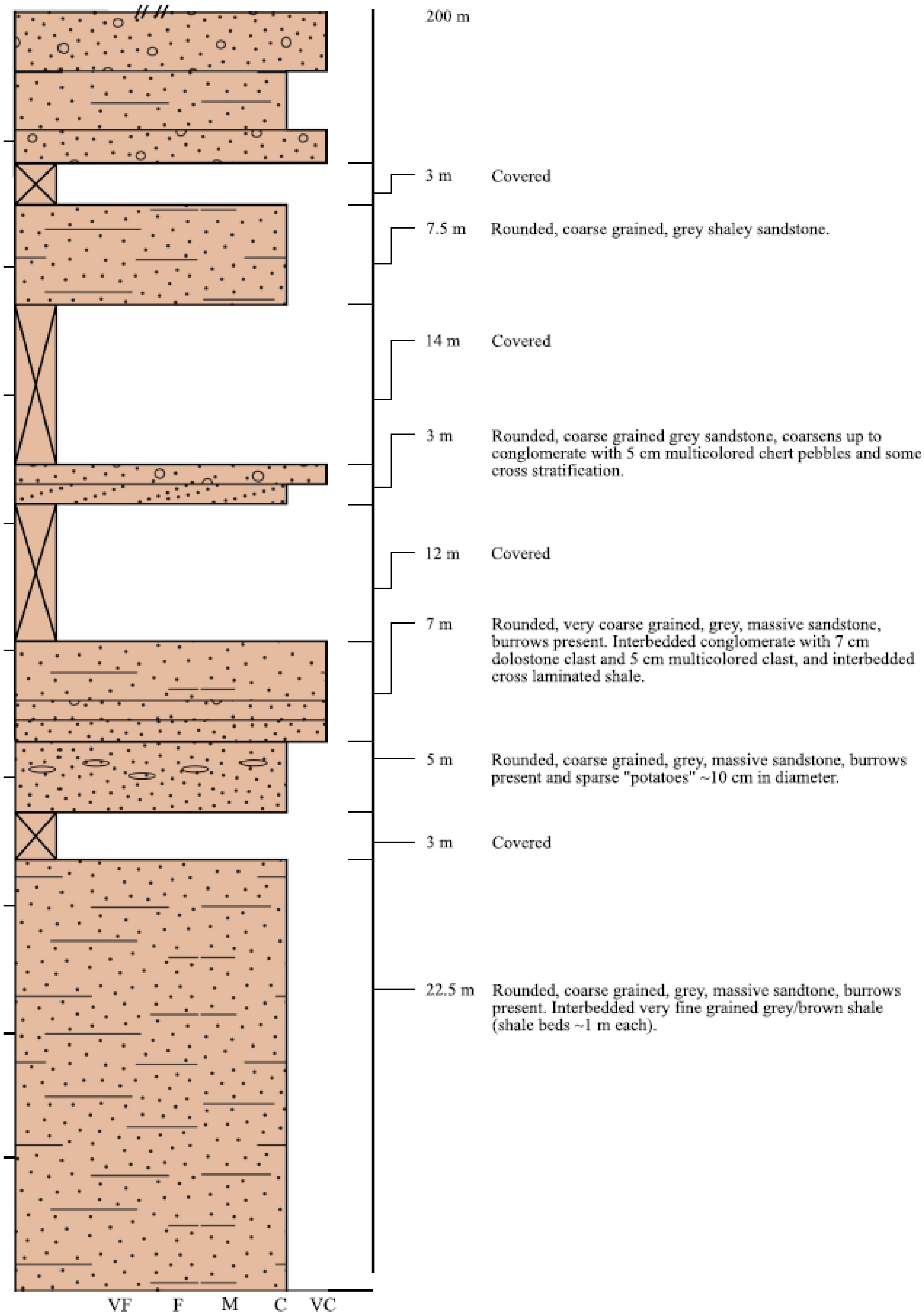


Figure 8.2: Stratigraphic column of upper Yucca, here is the continued measurement from 100 meters to 200 meters.

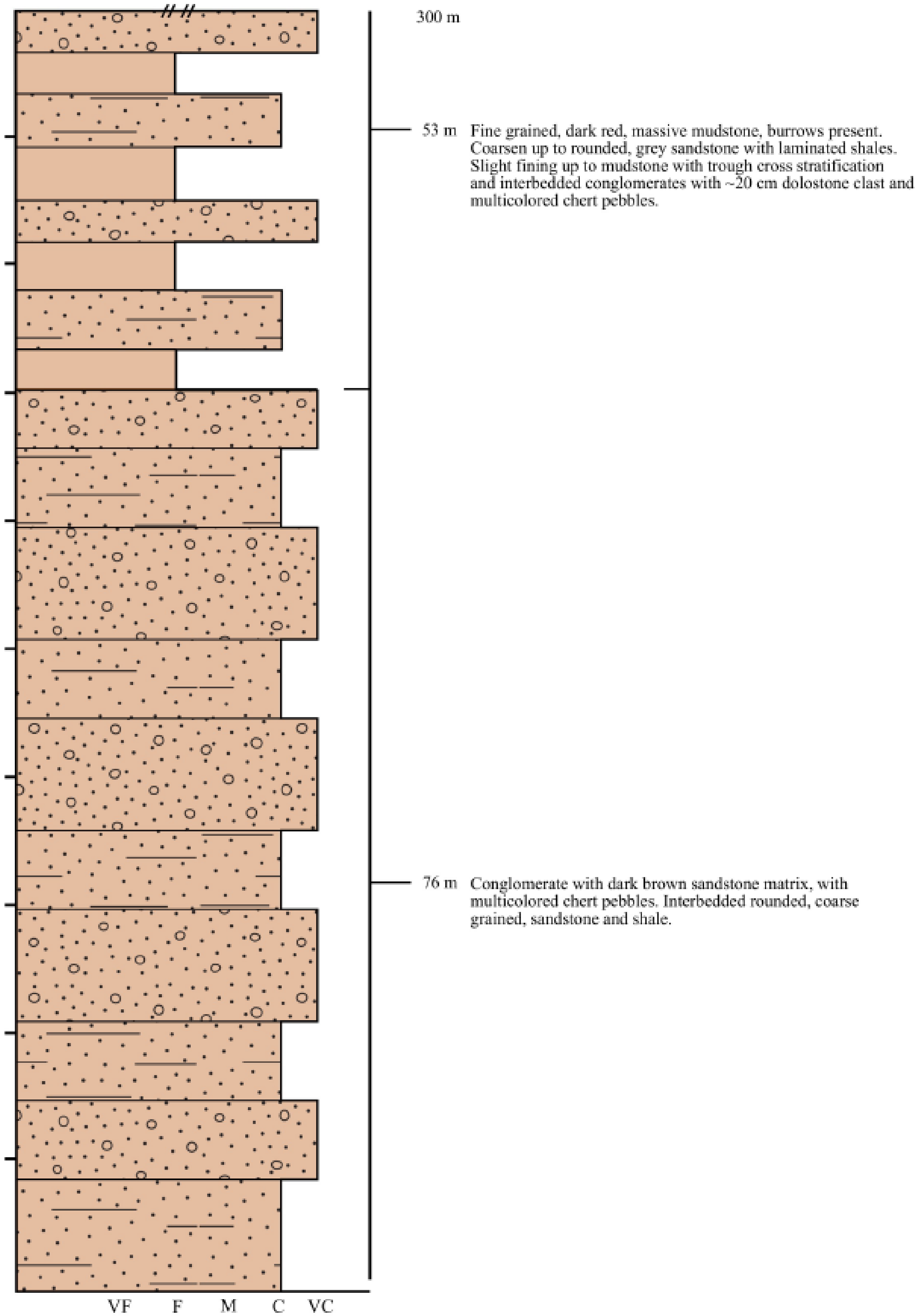


Figure 8.3: Stratigraphic column of upper Yucca, here is the continued measurement from 200 meters to 300 meters.

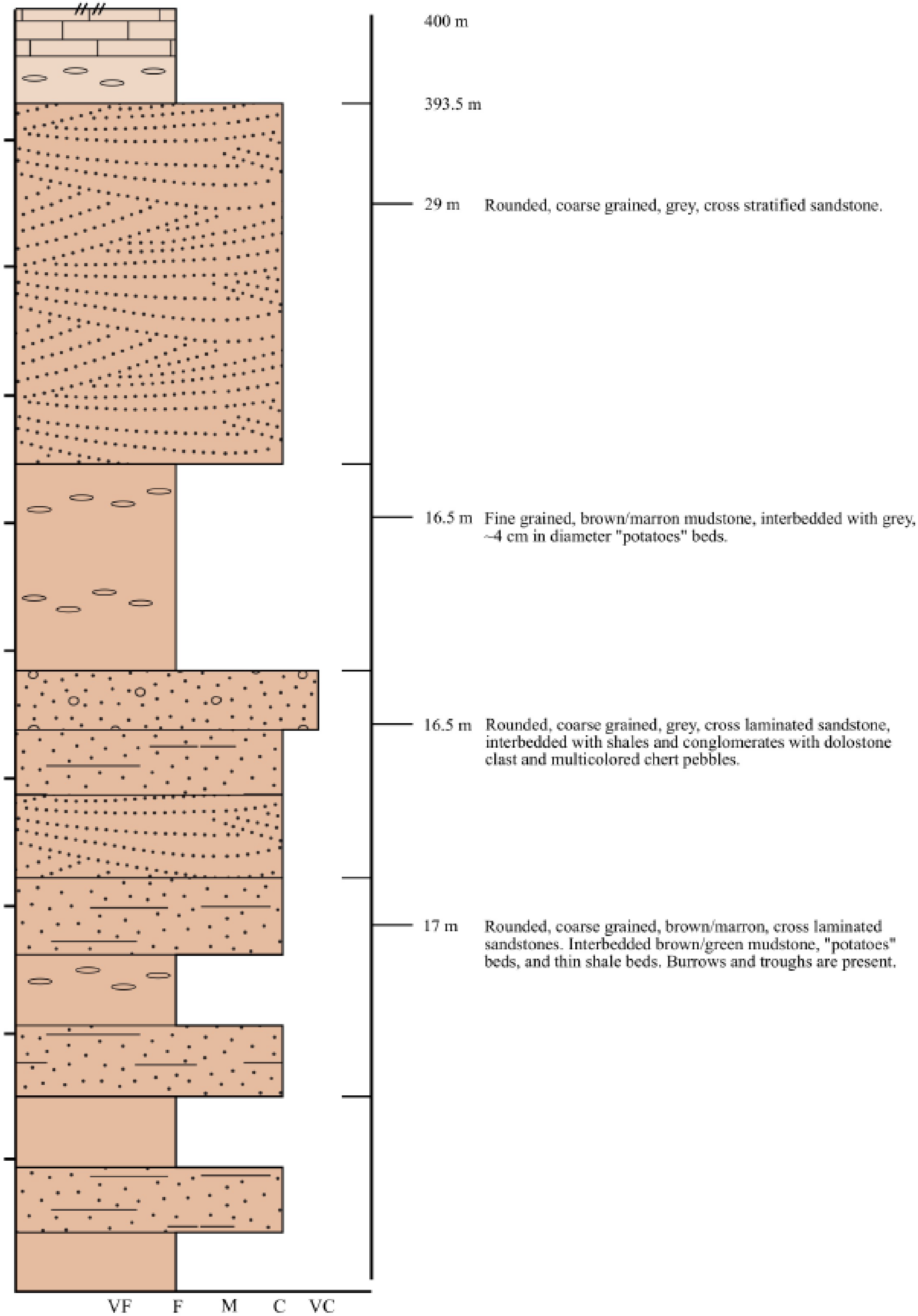


Figure 8.4: Stratigraphic column of upper Yucca, here is the continued measurement from 300 meters to 400 meters.

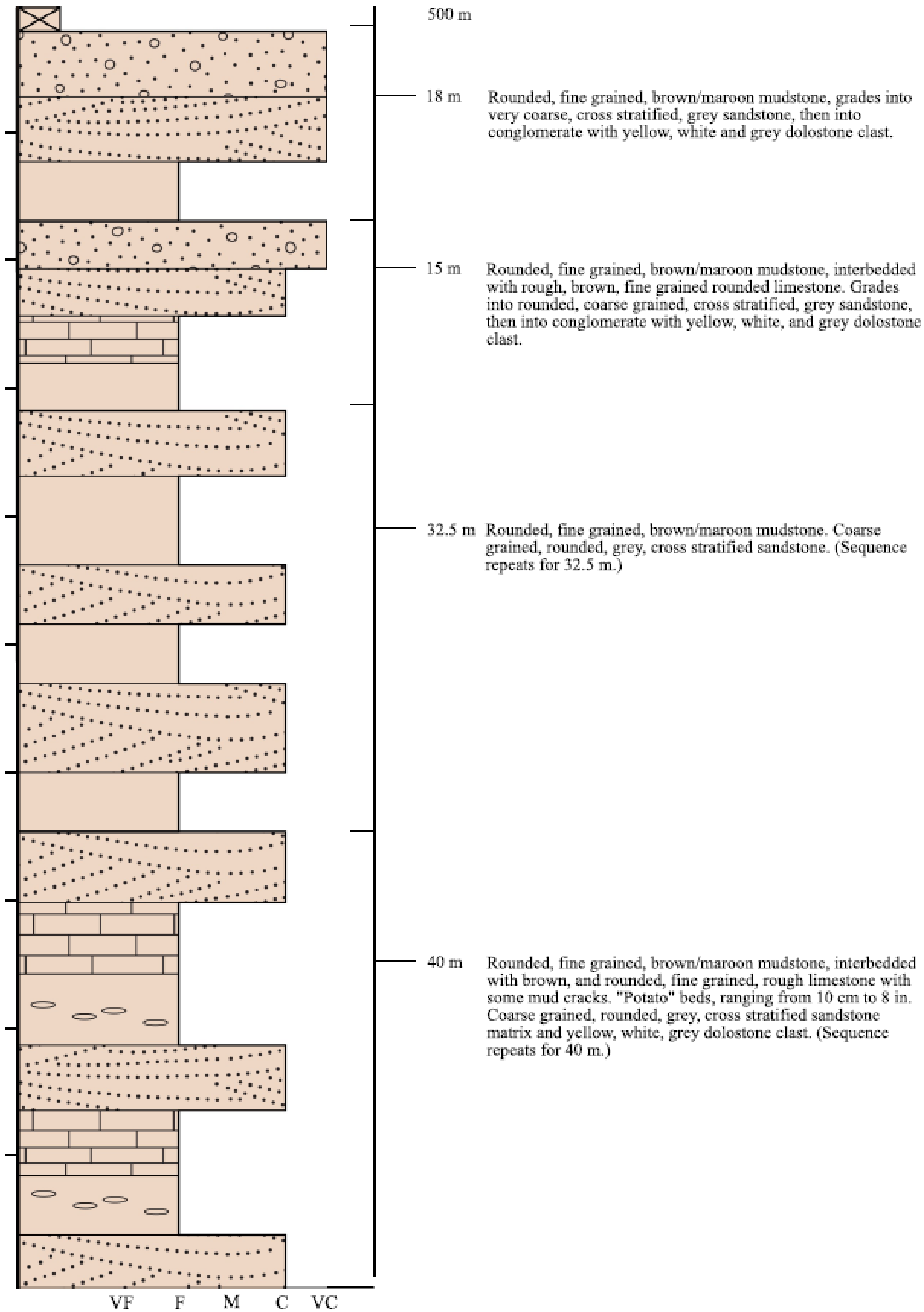


Figure 8.5: Stratigraphic column of upper Yucca, here is the continued measurement from 400 meters to 500 meters.

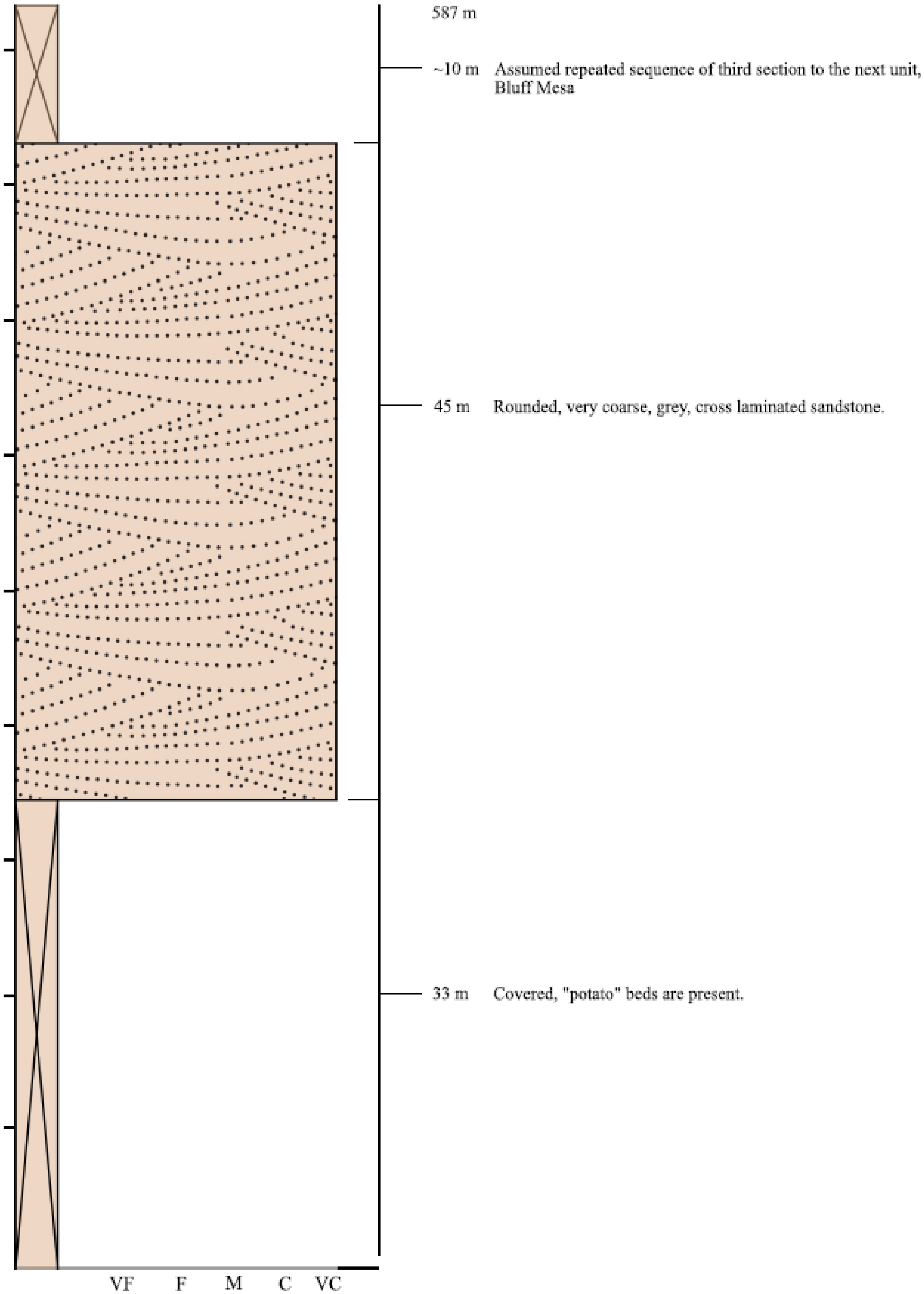


Figure 8.6: Stratigraphic column of upper Yucca, here is the continued measurement from 500 meters to 587 meters.

of limestone in the sequence. This unit is 5 distinctive sequences that follow a coarsening upward pattern. The base of unit 3 is marked by brown/maroon mudstones interbedded with rough limestone beds and the last sequence of the unit measured is a thick cross laminated sandstone.

The base of unit 3 is a fine grained, rounded, brown/marron mudstone, which is interbedded with fine grained, rounded, brown textured limestone, with mud cracks. "Potato beds" are present and range from 10 to 20 cm in diameter. The sequence coarsens upward to a coarse grained, rounded, well sorted, and grey cross stratified sandstone. Sandstone contains dolostone clast ranging in color from white, yellow, and grey. This cycle repeats until reaching the next sequence; a fine grained, rounded, brown/maroon mudstone, which coarsens upward to a coarse grained, rounded, well sorted, grey, cross stratified sandstone. The following sequence consist of the same pattern as the first, however the limestones do not have mud cracks, and the sandstone coarsens upward to a very coarse conglomerate with clast of dolostone instead of chert. The fourth sequence is similar to the third but lacks the interbedded limestones. The final sequence is a thick, very coarse, rounded, well sorted, and grey cross laminated sandstone.

STRUCTURES OF THE MAPPED AREA

Although previous studies by Underwood (1963) recognized a number of faults in the mapped area, the more detailed division of the stratigraphy and the large-scale mapping presented herein revealed complex fold-thrust relationships cut by a pair of normal faults. Previously unmapped features include thrust faults that are clearly cut by the normal faults to the north and west; folds that are decapitated in the west by thrust faults (Figures 7, 9); and a large-scale fold to the south.

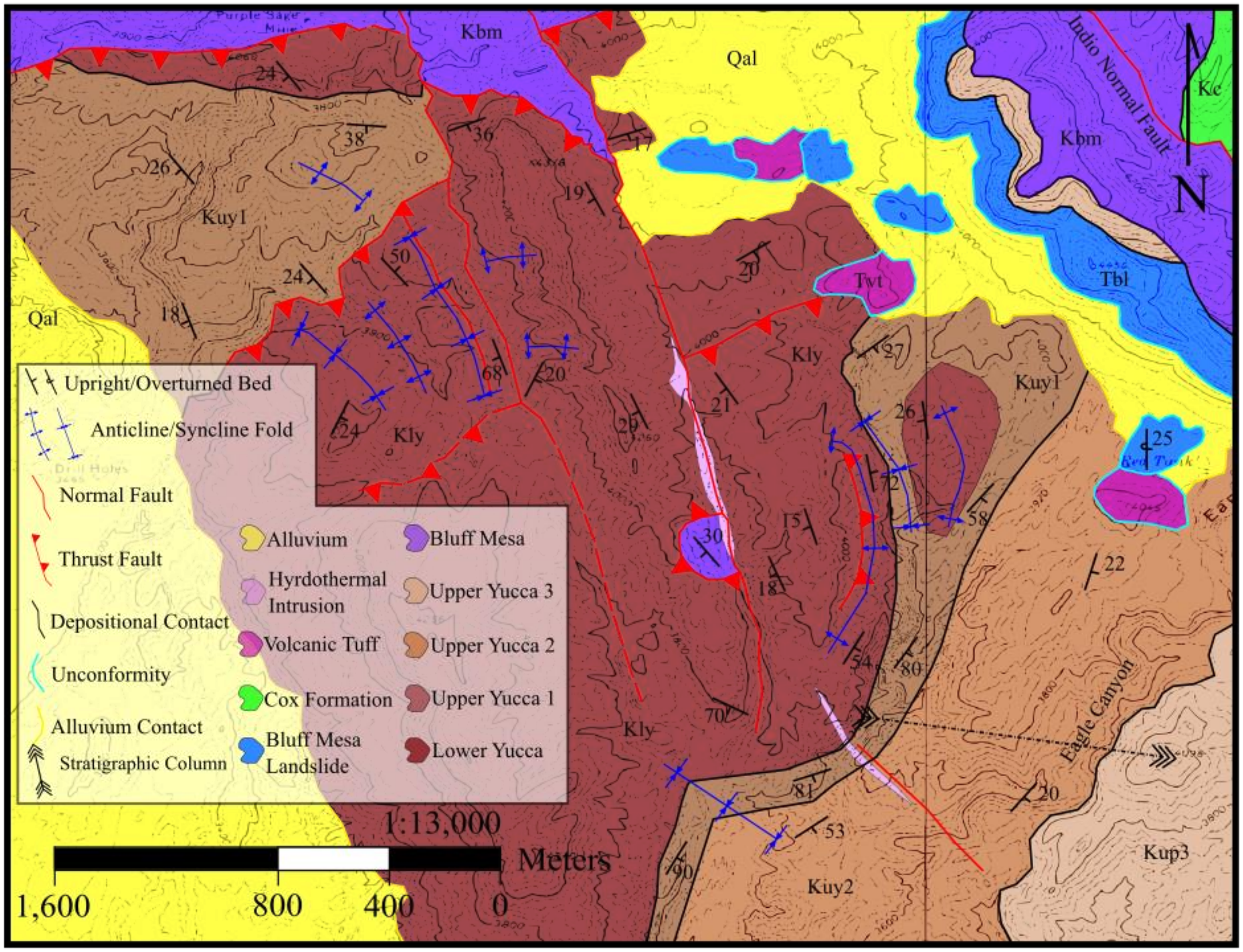


Figure 7: Geologic map of the southern Indio Mountains showing the sectioned Yucca Formation and previously unmapped structures.

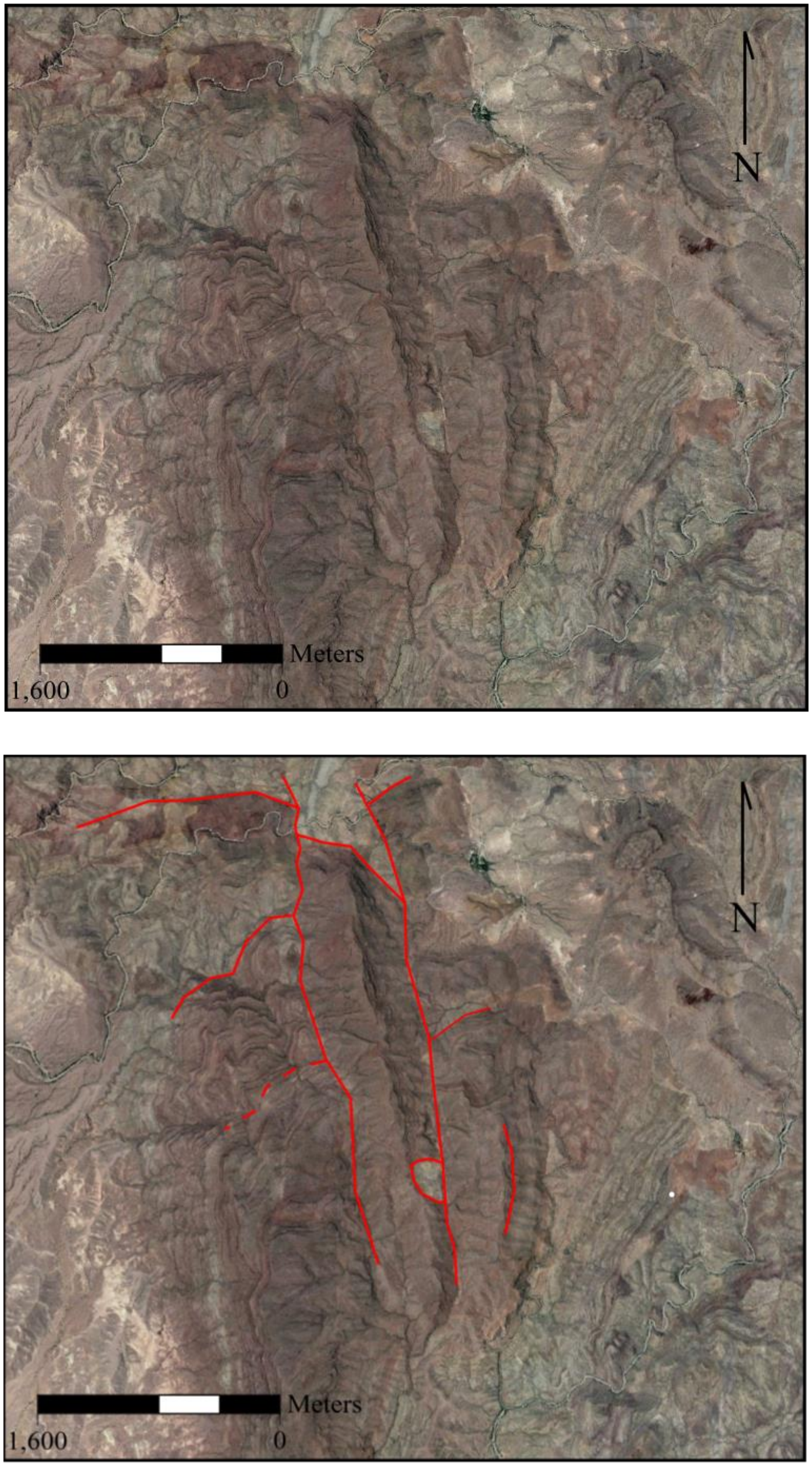


Figure 9: Google Earth images showing research area, with and without major faults in the region.

Neogene Structures

The normal faults are the youngest and cut all older structures consistent with their origins as part of the Neogene normal system that formed the Indio normal fault. Specifically, a pair of antithetic normal faults to the east and west of Red Mountain forming a horst block centered on Red Mountain (Figure 7). The western normal fault in the study area has been referred to the Borrega fault and the eastern fault the Red Mountain fault (Underwood, 1963). Both faults are well exposed locally, with steep dips of 50 to 60 degrees, and well-developed fault rocks from 0.5-2 meters thick. The Red Mountain fault is also marked by conspicuous travertine deposits that form a broad zone of veins up to 5 meters across. The travertine typically occurs as vein fillings along vertical fissures that are consistent with extension fractures formed contemporaneously with the Red Mountain fault's motion and hydrothermal fluids circulating along the fault during its motion. Another travertine vein measuring one-meter wide is located on the southeastern portion of the map, where a smaller scale normal fault cuts through the upper Yucca in a NW-SE trend.

An unusual feature of the Red Mountain fault is apparent near the northern end of its region in the study area (Figure 7). In this area the fault places older rocks over younger rocks, a stratigraphic juxtaposition typically seen only in thrust systems. In this case, however, the juxtaposition is brought on by normal slip exhuming the footwall of an older thrust fault in the footwall of the fault, producing the older on younger relationship.

Laramide Contraction Structures

The normal faults cut at least two major thrust faults produced during Laramide contractions. The angular unconformity on the east side of the mapped area provides a minimum

age for the Laramide structures of 38.02 ± 0.99 Ma based on U/Pb dating of zircons on one of the oldest volcanic units in this succession (Sahin, 2015).

The most conspicuous thrust is recognized on the northern end of Red Mountain (Figure 7) and is referred to here as the Purple Sage thrust. This northern thrust places lower Yucca Formation atop Bluff Mesa Formation and is cut by both the Borrega and Red Mountain faults (Figure 7). Along the Red Mountain fault, the trace of the Purple Sage thrust is shifted in a sinistral sense, consistent with west side down offset on the Red Mountain fault. This same thrust is also seen just south along the western flank of Red Mountain, located in the central part on the map. Here, the thrust creates a half window: a hole within the hanging-wall of the thrust that has been removed by erosion (McClay, 1992). In this case the lower Yucca Formation is atop the Bluff Mesa Formation, but the trace is cut by the Red Mountain fault.

A second thrust was mapped to the west of the Borrega fault, with a trace just south of the trace of the Purple Sage thrust on Red Mountain (Figure 7). In this fault, the lower Yucca is thrust onto unit 1 of the upper Yucca. Although lithologically similar, unit 1 of the upper Yucca at this locality may be significantly thicker than the unit in the measured section. A series of ~N-S trending folds are seen in both the hanging-wall and footwall of this thrust system (Figures 7, 10.1). One of these folds is a conspicuous upright, tight syncline with a half wavelength of ~180-m that is limited to the hanging-wall of the thrust. This fold is unusual, however, because beds are abruptly cut off to the south (Figure 9), indicating that this fold has been decapitated by a structurally higher-lever thrust. Because the rocks are all lower Yucca, this structural subtlety is not obvious on the map but is significant because this structure is a clear indication of out-of-sequence thrusting. That is, the folds clearly formed prior to the development of the structurally

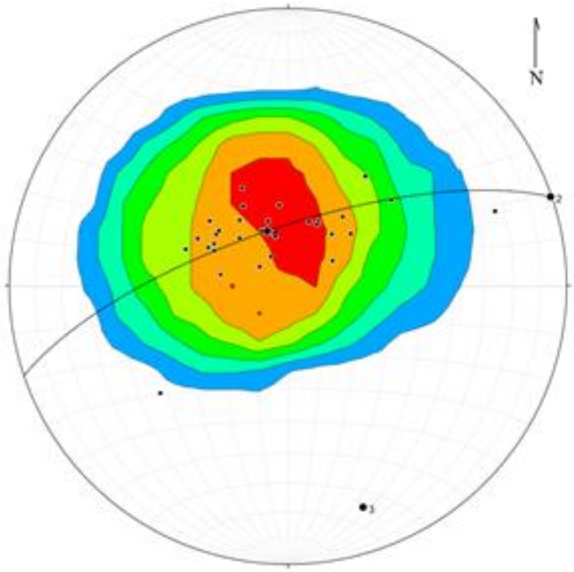


Figure 10.1: Stereonet showing poles bedding with measurements collected for the folds on the west side of the Borrega fault. These folds are located in both lower Yucca and unit 1 of upper Yucca on Red Mountain. Contours were added to see a better concentration of the poles.
Pi pole has a trend of 161 and plunge of 12.

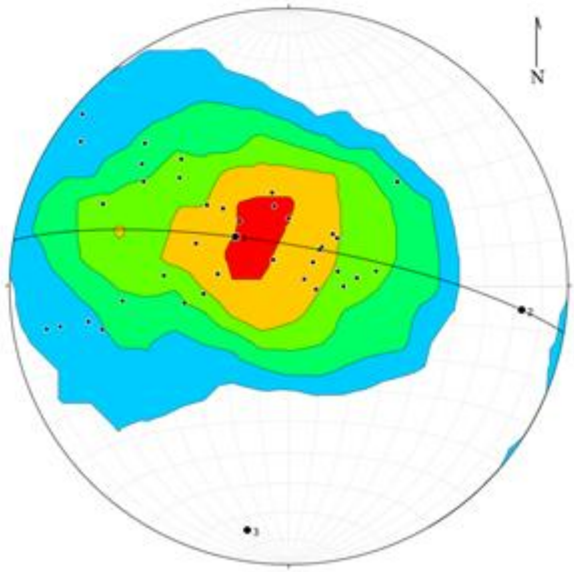


Figure 10.2: Stereonet showing poles of bedding with measurements for the folds on the east side of the Red Mountain fault caused by the back thrust. Contours were added to see a better concentration of the poles.
Pi pole has a trend of 190 and plunge of 12.

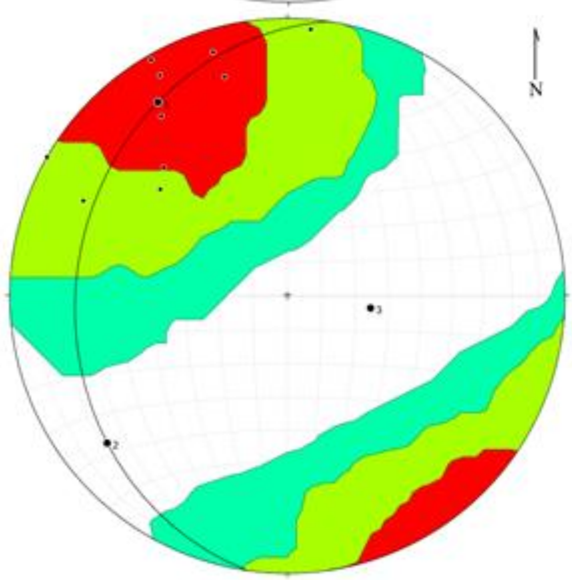


Figure 10.3: Stereonet showing poles bedding with measurements collected for the fold located south of the map. Contours were added to see a better concentration of the poles.
Pi pole has a trend of 98and plunge of 65.

higher-level fault, indicating the structurally higher fault is younger and of out-of-sequence. This same thrust can also be seen on the east side of the Red Mountain fault, where orientation data trends ~W-E in the footwall and ~N-S on the hanging wall (Figure 7).

A small back thrust, on the east side of the Red Mountain fault, is developed in the lower Yucca (Figure 7) in rocks that are part of the hanging-wall of the Purple Sage thrust. This back thrust, unlike the others in the region, has a ~N-S trend that adheres to the thrusts in the northern areas of the Indio Mountains (Figure 6). The back thrust creates a hanging-wall anticline with a gently-dipping limb to the west, and a steep limb to the east (Figures 7, 10.2). Also, to the east there is a syncline-anticline pair, extending into unit 1 of the upper Yucca, with the eastern most anticline exposing the lower Yucca.

The southern 1/3 of the mapped area exposes a distinctly different structure than the structures to the north. Specifically, this area exposes a large-scale syncline-anticline fold pair involving the entire Yucca section (Figures 7, 9). This fold system is clearly developed entirely in the hanging-wall of the Purple Sage thrust because the hanging-wall assemblage is continuous through the mapped area aside from the window. Unlike the other fold sets in the region, this fold pair shows a significantly different trend (Figure 10.3), which is presumably related to the structure at depth that produced it.

CROSS SECTIONS

Three cross sections were created for the mapped area, using contacts and orientation data collected in the field to model the deformation. Cross section A – A' (Figure 11) was constructed across strike in the center of the map, trending W-E, cutting through both normal faults, the window, and the back thrust. The section was constructed with the assumption that the window, along with the Purple Sage thrust, are part of the Squaw Peak thrust dropped down into the

subsurface during the extension that formed the Indio normal fault. The assumption was made as a result of the similarities in upper Yucca Formation on both sides of the Indio normal fault, discussed below. Because the Bennett thrust was developed beneath the Squaw Peak thrust (Page, 2011), the Bennett is also assumed to be at depth.

Section A – A' was partially validated by reconstruction using Move software. In step 1 the slip on the normal faults bounding Red Mountain were restored (Figure 11.2), then the units were unfolded using a simple flexural slip restoration. The second step restores the fold and folded thrust as indicated by the window in the Purple Sage thrust but makes no assumption on the process producing the fold. Given the thrust modeling by Page (2011), it is possible this fold originated via duplexing, but that interpretation is not used here due to insufficient data. Finally, note that this section could also be fully restored by restoration of the slip on the Purple Sage thrust, to restore the fault-bend fold inferred at the eastern end of the section (Figure 11).

Cross section B – B' is an along strike section and trends NNW-SSE (Figure 12), cutting through the Purple Sage thrust, including the window between the normal faults. In addition, towards the south end of the section the line crosses the Red Mountain fault and the large-scale fold. A key feature of this section is the illustration that the Purple Sage thrust lies at a shallow depth beneath Red Mountain, which is consistent with its outcrop trace and the occurrence of the window.

Cross section C – C' (Figure 13) is an across-strike section at the southern end of the mapped area, trending SW-NE. This section cuts through the fold pair in the area where the slip of the Borrega and Red Mountain faults have decreased and are no longer recognizable. This

section shows the location of back thrust, interpreted Squaw Peak, Bennett thrusts and an interpreted duplex at depth without the complications from normal fault deformation.

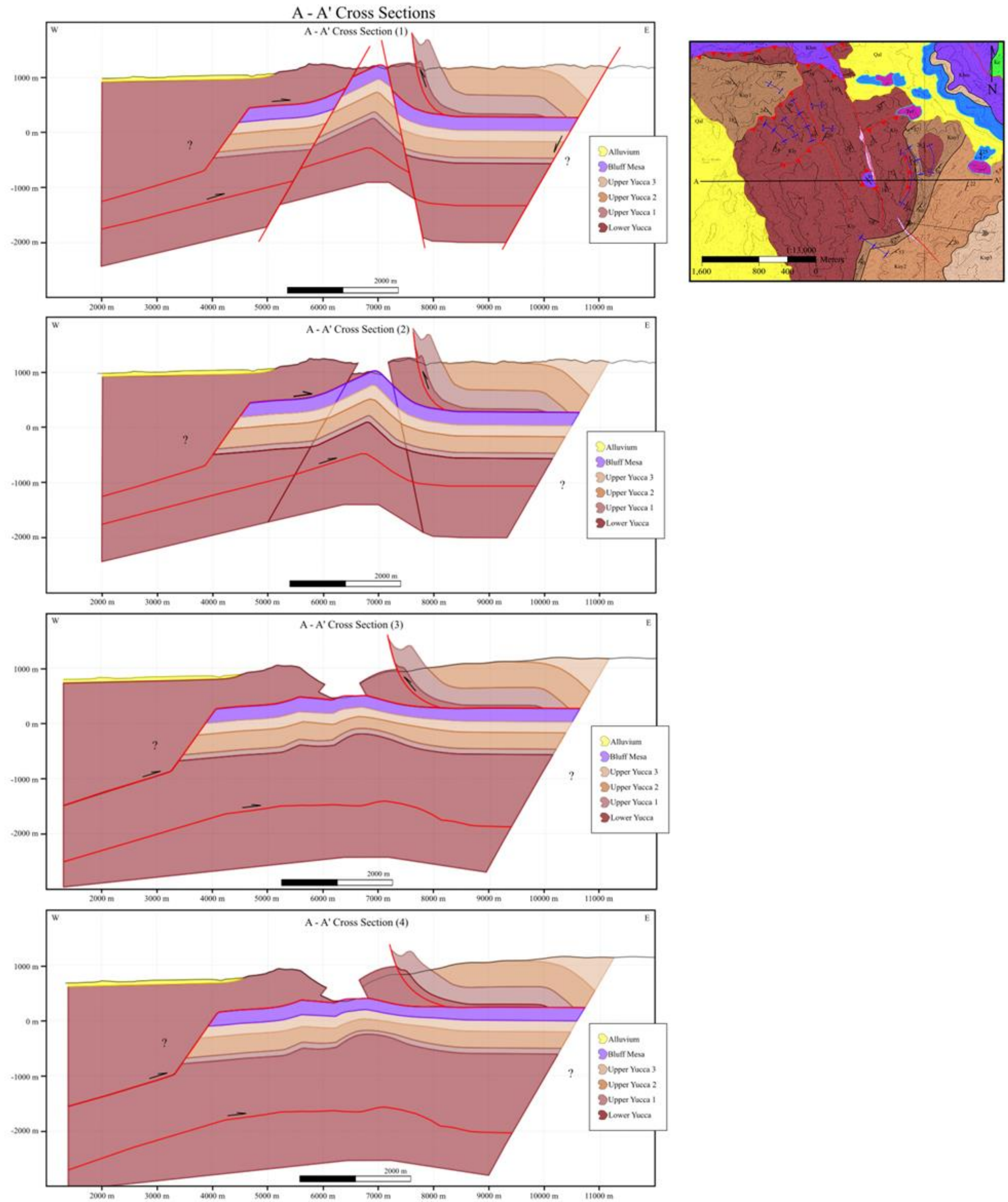
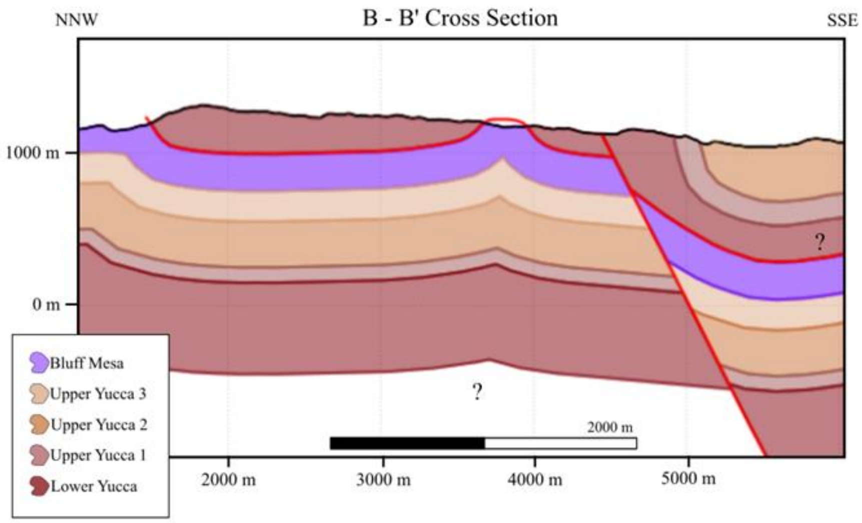


Figure 11: A – A’ Cross Section. 1: Deformed section. 2: Normal faults restored, dropping the block down, (all normal faults removed). 3: Unfolded strata and thrust faults in the subsurface. 4: Restored back thrust. Map to show location of cross section.



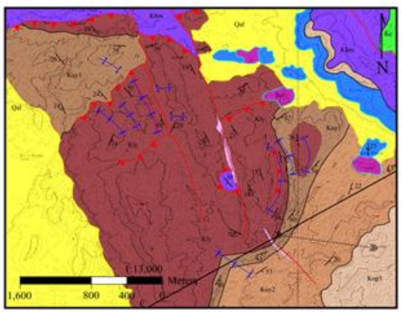
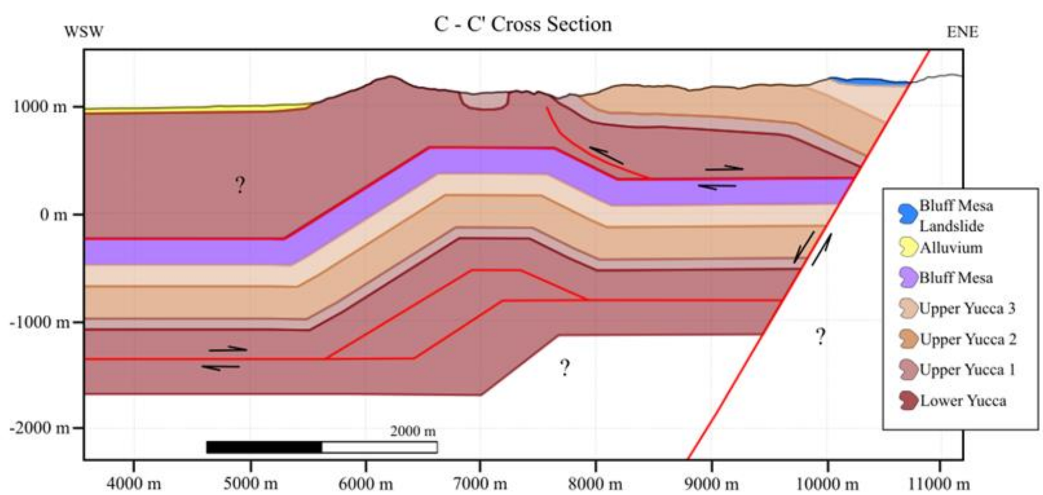


Figure 12: B – B' Cross Section. Map to show location of cross section.



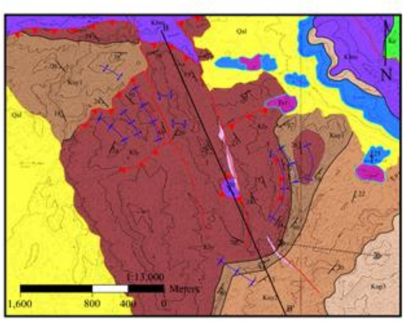


Figure 13: C – C' Cross Section. Map to show location of cross section.

Discussion

STRATIGRAPHY

The measured stratigraphic section of the upper Yucca Formation for this study was obtained from the hanging-wall of the Purple Sage thrust. Thus, if the Purple Sage thrust and Squaw Peak thrust are the same structure, the stratigraphic section in this study should be similar to the section measured by Page (2011) within the range of reasonable facies changes.

The column in this study measured 587 meters thick and was divided into three informal lithostratigraphic members with the key difference being shale beds and sparse burrows in unit 2 and limestone beds in unit 3, with neither being identified in unit 1. In the stratigraphic column measured by Page (2011) on the hanging-wall of the Squaw Peak thrust, the thickness of the upper Yucca Formation totaled 657 meters, slightly thicker than the measured section herein, but significantly thicker than section from the hanging-wall of the Bennett thrust which is 320 meters thick (Anderson, 2017). While Page (2011) did not divide the stratigraphic column into units, similar lithologies are present at equivalent stratigraphic levels (Figure 14). The differences in the stratigraphic columns of the unit, including the 70-meters difference in thickness, an increase of burrows and shale, and a decrease of conglomerate upsection (Page, 2011), can be attributed to regional facies differences. Therefore, the Purple Sage thrust along with the window in the center of the map, are interpreted to be part of the same thrust sheet with the Squaw Peak thrust system.

FOLD-THRUST SYSTEMS IN THE STUDY AREA

The reconstructed cross section A – A’ (Figure 11) provides a reasonable explanation for the window of Bluff Mesa in the center of the map, however it still presented other issues. Having

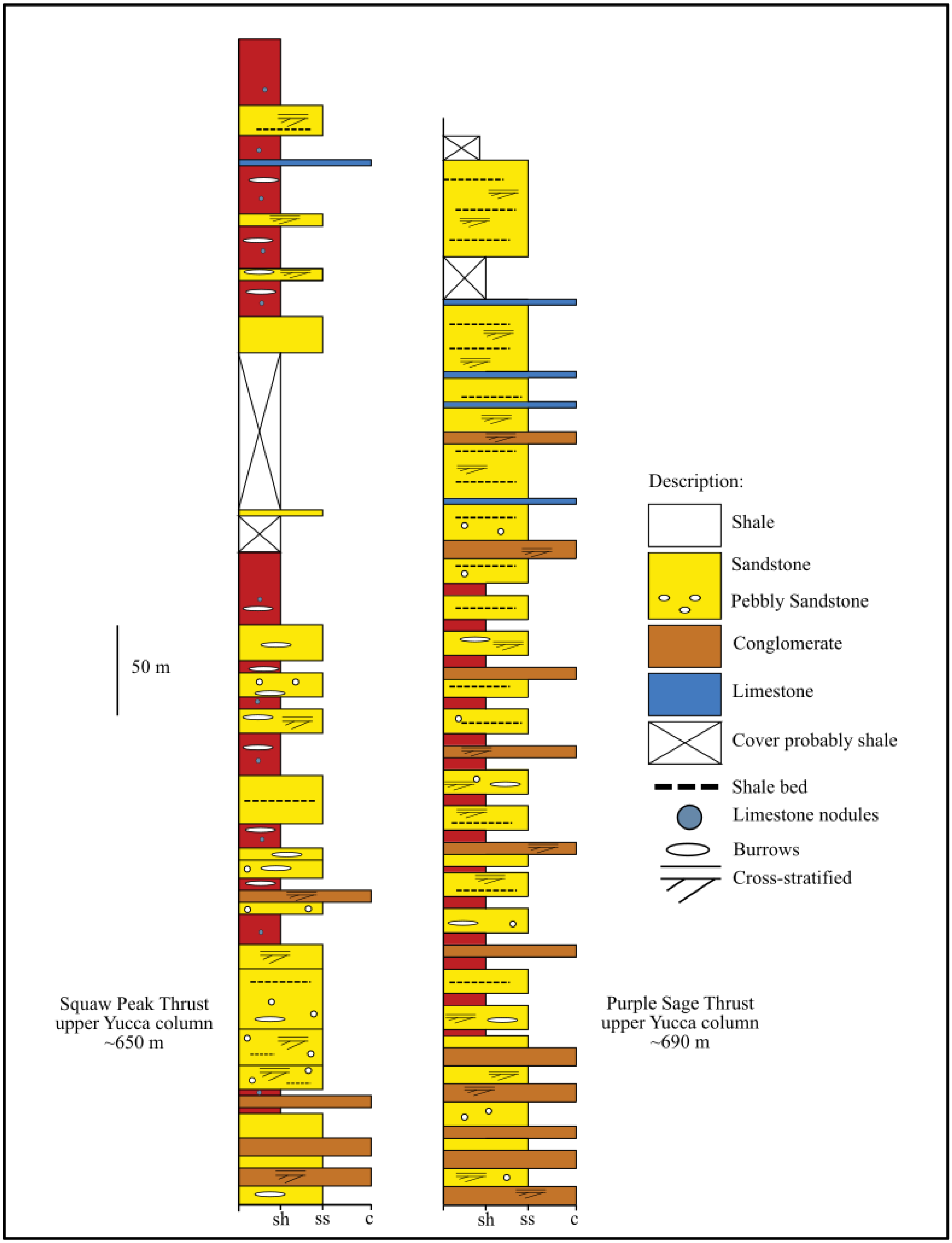


Figure 14: Simplified stratigraphic columns of the upper Yucca Formation. Right column measured on footwall of Indio normal fault, left column measured on the hanging-wall of the Indio normal fault.

interpreted the Purple Sage thrust as part of the Squaw Peak thrust leads to the hypothesis that the Bennett thrust is at depth in the cross section, yet, once the normal faults were restored (Figure 11.2), the question became; what caused the fold that warped the thrust that produced the window? The interpretation by Page (2011) of the decollement at depth below the inferred Bennett thrust provided the mechanisms for the fold in that section. However, Page (2011) suggested the upper Yucca Formation was a more likely decollement horizon where shale is present. A second option is that the fold developed above a duplex that would include the interpreted Bennett thrust as shown in figure 13. This duplex would create the system needed for the fold after the normal fault restoration (Figure 11.2). Note, however, that this inferred duplex could not be the same duplex modeled by Page (2011) because that structure lays well to the east of the study area.

The key feature of cross section B – B' (Figure 12) is to illustrate the shallow depth of the Purple Sage thrust beneath Red Mountain and its connection to the window; for simplicity the interpreted Bennett thrust is not shown. This section also shows a NNW-SSE view of the southern fold, where the beds have a steep dip that shallows as you head further south.

The southern cross-section is most problematic at depth. In map view this section clearly crosses an anticline syncline fold pair that plunges moderately to the SE (Figure 7). The stereonet data, however, (Figure 10.3) suggests a ~N-S compression with eastern plunging folds. This inconsistency with the map traces suggest the possibility of the folds having a curved axis at depth.

In cross section C – C' (Figure 13) this fold appears in isolation, above the inferred Purple Sage/Squaw Peak thrust system, but generally along trend from the back thrust system and associated folds recognized in the east-central part of the mapped area. This suggests two possible origins for this fold: 1) it is the lateral termination of the back thrust system, developing into a fold-pair along strike towards the tip of the thrust as it loses slip to the south, (Wilkerson, et. al.,

2002); or 2) the fold is a large-scale fold caused by a lateral ramp: a ramp that parallels the direction of transport of, in this system, the Squaw Peak thrust sheet, (McClay, 1992) forming a fold with its axis highly oblique to the other fold systems (Figures 10.1-10.3), presumably because the fold is a geometric response to the ramp geometry.

OUT-OF-SEQUENCE THRUST SYSTEMS

One of the objectives of this study was exploratory, to determine if out-of-sequence structures were present in this area because out-of-sequence thrust systems are common in other inverted basin systems. This objective was achieved in structures recognized along the western side of Red Mountain. In particular, the thrusts to the west of the Borrega fault show cross-cutting relationships clearly indicative of an out-of-sequence thrust system (Figure 7). That is, the two thrusts that lie structurally above the Purple Sage thrust violate the general geometry of fold-thrust systems typically seen in thrust belts with relatively planar fault surfaces cutting across folded strata (Figure 9). This geometry could only form if these rocks were first folded and faults then cut across the folded beds, a clear out-of-sequence feature. The structurally highest thrust located farther south, can be seen on the east side of the Red Mountain fault where the bedding trend shifts roughly 90 degrees. However, the lower-level thrust with unit 1 of the upper Yucca in the footwall was not revealed during field mapping, therefore it’s assumed to be either buried by alluvium or the two thrusts merged above what is now the eroded section above Red Mountain.

Finally, the general map patterns throughout the study area implies structures that are distinctly more complex than typical fold-thrust belt structures. In many thrust belts (Chapple, 1978) strata are imbricated into distinct panels plus or minus related folds, but these patterns produce a typical map trace of subparallel fault and fold traces over large areas. However, in the southern Indio Mountains, this pattern is not observed. Instead the units and associated faults show

major variations in strike across the mapped area, particularly from east to west, and none of the map traces follow the general trend seen throughout the Indio Mountains. Nonetheless, even though map traces are highly variable, most of the fold systems observed in the mapped area conform closely to the NNW to NW-SE trends of folds seen over a broader area (Figures 10.1, 10.2). Collectively, these observations suggest map patterns are the result of three-dimensional structures at depth, that warp the traces of structures at the surface. This geometric complexity is shown not only in the orientation data but also in stereonets where the plots lack a clean, simple great circle distribution which is indicative of simply folded rocks. Instead, the poles to beds scatter over large segments of the stereonet which suggest noncylindrical folding. These complexities probably represent unrecognized structure at depth, many presumably out-of-sequence.

Conclusion

An updated map of the southern Indio Mountains was developed with the aid of modern orthoimagery and a newly measured stratigraphic column of the upper Yucca Formation. The upper Yucca section assisted in identifying previously unmapped structures west of the Borrega fault, where out-of-sequence thrusts were identified. A window, previously unmapped by Underwood (1963), has been identified in the center of the study area which is correlated to the structure here referred to as the Purple Sage thrust, which is extensively exposed in the northern part of the study area. To the south a large-scale fold pair was identified and is interpreted as either a lateral termination to a small back thrust located within the central part of the mapped area, or to the presence of a lateral ramp at depth, with an oblique orientation to account for the unusual fold trend. Similarities in lithology of the measured section to that of the measured section by Page (2011) on the Squaw Peak thrust, and the similarity in structural geometry suggest that the Purple Sage thrust is part of the Squaw Peak thrust system, separated by offset on the Neogene Indio normal fault. Cross sections were constructed using this interpretation of the Squaw Peak and Bennett thrust being at depth, with the Squaw Peak thrust sheet brought to surface during normal faulting. In order to confirm these structure's geophysical data, such as a seismic reflection profile, would be required, but with the complex structures at depth, multiple profiles would be needed. However, due to the size of the mapped area and the large amount of relief, collecting geophysical data would be close to impossible for this area.

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Vita

Samantha Eve Ramirez was born in Phoenix, Arizona and moved to El Paso, Texas as a child. Here, she attended high school at Canutillo High where she graduated in the top 10% of her class in 2009. She enrolled at the University of Texas at El Paso to pursue a B.A. in Communications but changed her major to geology after taking intro geology classes. In the summer of 2015, she graduated with a B.S. in the Geological Sciences and continued on as a graduate student of the geological sciences with a focus on structural geology maintaining a perfect grade point average of 4.0. In the spring of 2018, she received her M.S. in the Geological Sciences and was honored as the banner bearer for the graduate school during the commencement ceremony.

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