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Fold-Thrust System Overprinting Syn-Rift Structures On The Margin Of An Inverted Rift Basin: Indio Mountains, West Texas

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FOLD-THRUST SYSTEM OVERPRINTING SYN-RIFT STRUCTURES ON
THE MARGIN OF AN INVERTED RIFT BASIN: INDIO MOUNTAINS,
WEST TEXAS

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THE MARGIN OF AN INVERTED RIFT BASIN: INDIO MOUNTAINS,
WEST TEXAS

By

SETH J. PAGE, B.S

THESIS

Presented to the Faculty of the Graduate School of

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Abstract

Detailed mapping in the central Indio Mountains in west Texas, reveal a complex stacking of thrust sheets that record inversion of the Mesozoic Chihuahuan Trough rift basin. Important newly recognized structural complexities include both folding of older thrust sheets and development of younger, out-of-sequence thrusts that cut across older folds; detachment fold horizons within thrust sheets; and a regional anticlinorium that exposes the Squaw thrust in a structural half-window bounded on the west by the Neogene Indio normal fault. The Chihuahuan trough originated as part of the late Mesozoic border rift system and was inverted during Laramide thrusting. Remnants of Mesozoic rifting are preserved in Cretaceous strata as facies and stratigraphic thickness variations between different thrust sheets. Stratigraphic thickness variations are particularly prominent in the Yucca Formation. A well exposed transgression divides the upper yucca into a fluvial lower interval and a coastal upper interval. The Upper Yucca is 650m thick in the hanging wall of the Squaw thrust and 280 m in the structurally lowest footwall of the thrust system. Reported klippe-fenster relationships indicate a minimum displacement of 7-10km for the structurally highest thrust (Squaw thrust). However, after evaluating the newly identified duplex and incorporating a lower decollement, balanced cross-section reconstructions give a new minimum displacement of 17.3 km. Section reconstruction also indicates that a cryptic basin margin normal fault is carried in the hanging wall of the Squaw Peak thrust to account for both stratigraphic variations and hanging-wall cutoff relationships. Similarities between the structures and models of the Atlas Mountains to those presented in this study suggest the Atlas Mountains and its continuous deformation could be a modern analog for the Indio Mountains.

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1. Introduction

The goal of this study was to better understand inverted basins and their deformational mechanisms and structural geometries by using the Indio Mountains as a case study. The Indio Mountains provide an excellent location to study inverted basins because of the very good exposures of an oblique view of Laramide thrust systems produced by a poorly understood combination of thrust-related folding and extensional tilting. It is known that inversion structures and their geometries are highly dependent on the orientation and geometries of the original syn-rift structures with regards to the principle compression axis (Lowell, 1995, Beauchamp et al., 1999, Mattioni et al., 2007), however an in-depth study of these geometries have not been completed in the Indio Mountains.

In hydrocarbon exploration, inverted basins provide additional complications in structural analysis of prospects, and if not interpreted correctly could cost millions of dollars. For example, depending on the amount of shortening due to inversion, hydrocarbon traps formed during the rifting phase may maintain their integrity or be destroyed causing hydrocarbon migration out of the system or to newly formed traps in the footwalls of thrusts (Beauchamp et al. 1997). The Laramide structures in the Indio Mountains serve as an analog to offshore inverted basins that could prove very valuable in making correct interpretations of oil prospects.

In addition to applications to exploration, this study also bears on tectonic problems related to the origin of the Chihuahua trough. The Chihuahua trough is part of the much more extensive Jura-Cretaceous “border rift system” (Dickinson and Lawton, 2001) but the Chihuahua trough remains the most poorly understood part of this system. Specifically, the tectonic setting as well as the effects of Laramide deformation in this region is poorly known relative to adjacent regions and basic questions of magnitudes and thrust transport direction remain poorly resolved.

Studies of the Indio Mountains also serve as deeply exhumed analogs for more current inverted basins such as the Atlas Mountains of Morocco, North Africa.

In this paper we outline the results of new geologic mapping of the central Indio Mountains and the implications of previously unmapped structures on the presence of duplexes, cross-section reconstruction and shortening. We demonstrate the existence of a major syn-rift fault and a duplex stack and propose this process as a major deformation mechanism. We summarize two possible thrust systems and provide cross sections that would produce the current map geometries. Reconstruction of these cross-sections suggests up to 33 km of Laramide contraction within the Indio Mountains.

2. Geologic Setting

The Indio Mountains are located along the Rio Grande River, approximately 200 km SE of El Paso. The range trends north-northwest and extends from the Eagle Mountains in the North, to the Rio Grande in the South. Tectonically the range lies on the eastern margin of the Chihuahua trough (fig. 1 and 2) just inside the frontal thrust of the Chihuahua tectonic belt about 50 km south of Van Horn, TX (fig. 2). The Chihuahua trough is a depositional basin that covers northeastern Chihuahua, southwestern Texas, southern New Mexico and northeastern Sonora. The Chihuahua trough began to form in the Late Jurassic as an extensional basin, either as a pull-apart basin extended from the opening of the Gulf of Mexico (Haenggi, 2002) or a back-arc spreading system due to slab roll back of the Mezcalera plate (Dickinson and Lawton, 2001). Upper Jurassic rocks in the Chihuahua trough indicate it was part of a larger Jurassic marine basin known as the Mexican Borderland rift system (Haenggi, 2002; fig. 1).

The stratigraphy of the Chihuahua trough varies laterally, but in general consists of upper Jurassic evaporites at the base deposited during a regressive period, followed by an overall transgressive sequence recognized as interbedded conglomerate, sandstone, siltstone and limestone with a maximum thickness of 4,700 m (Haenggi, 2002). The bulk of the basin fill is early to early-late Cretaceous in age (Haenggi, 2002).

Following the deposition of the Cretaceous rocks the Chihuahua trough was inverted during the Laramide orogeny (84-43 Ma) producing the Chihuahua tectonic belt (Deford, 1958). Tectonism of the Laramide orogeny advanced from the west toward the east as the Farallon plate subducted under the North American plate. The timing of onset of Laramide deformation affecting the Chihuahua trough range from 78-84 Ma and come from dated rocks from Sierra Samalayuca (Denison et al., 1970), and east of Big Hatchet Mountains (Lopez-Ramos, 1988),

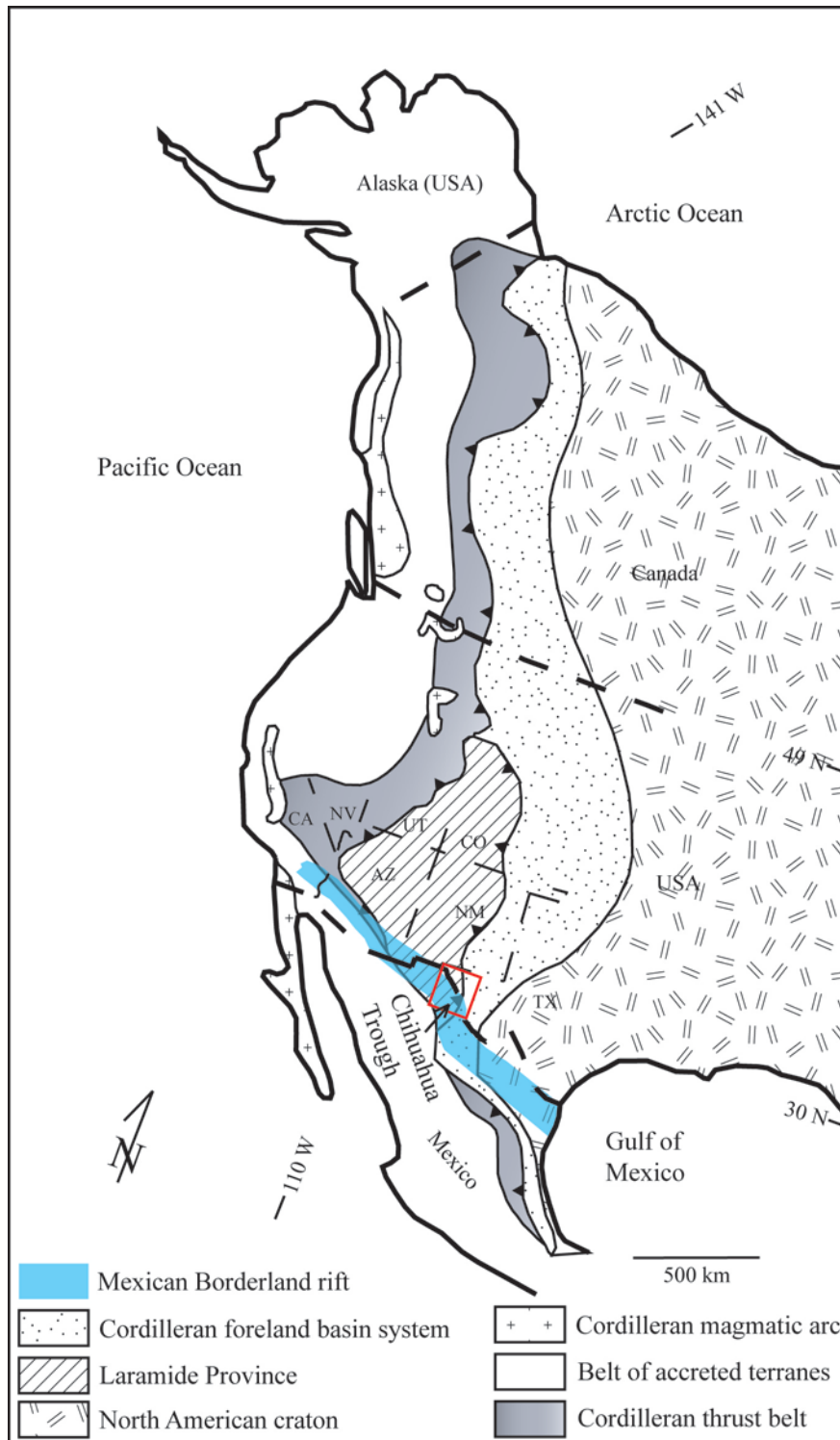


Figure 1: Generalized map of western North America showing approximate locations of the Chihuahua Trough and major tectonic zones. Red box is blown up in figure 2. Modified from DeCelles (2004) and Lawton and McMillan (1999).

which have been interpreted as Laramide's earliest igneous activity. Lehman (1991) documented two major phases of tectonism at 70 and 61 Ma from the sedimentary history of the Laramide foreland basin (Tornillo basin) east of the Chihuahua trough. The youngest Laramide deformation recorded in the Chihuahua trough is Paleocene - Eocene in age (68-44 Ma) acquired from dating deformed igneous and volcanic rocks (McDowell and Maugher, 1994; Reyes-Cortes and Goodell, 2000).

Currently there are two hypotheses that are used to explain the driving mechanisms of the Laramide orogeny that caused inversion in Mexico and the border region. The first, orthogonal compression, whose proponents conclude that a northeast transport direction formed the northwest trending thrust faults and folds (Underwood, 1962; Reaser, 1982), while the second hypothesis suggests sinistral transpression for observed northeast-southwest trending folds (Dickerson, 1985; Drewes, 1988; Rohrbaugh, 2001).

Haenggi (2002) reviewed three hypotheses regarding the structural development of the Chihuahua tectonic belt. First, the Cretaceous section above the evaporites was folded and thrust faulted as the section moved eastward until buttressing against the Diablo Platform (fig. 2). Additional faulting due to diapiric injection of the evaporites followed (Haenggi and Gries, 1970). Second, the Chihuahua tectonic belt is characterized by symmetrical upright and asymmetrical folds as a continuation of the Cordilleran fold and thrust belt (Drewes, 1978 and Hennings, 1994). Third, deformation resulted from left-lateral Laramide transpressional tectonics (Dickerson, 1985). In all cases, the Jurassic evaporates would have played a major role in the deformation providing a decollement for detachment folds and subsequent diapirism (Haenggi, 2002). Haenggi (2002) suggested the following events as a time progression of deformation: 1) reactivation of the bounding basin normal faults to left-lateral reverse faults

with the development of all folding, 2) amplification of folds due to salt mobilization, and 3) development of thrusts along the margin of the basin where salt is absent.

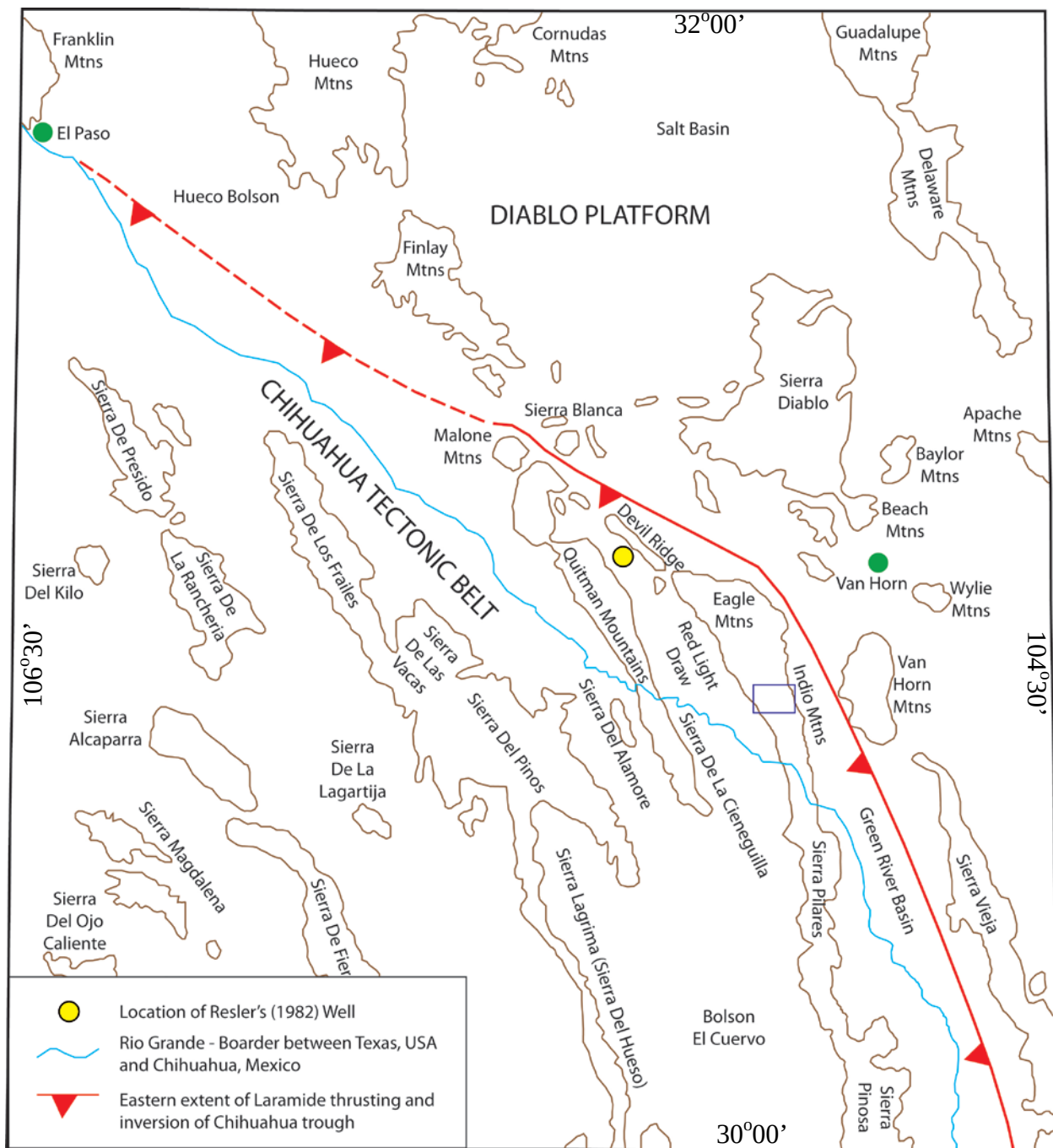


Figure 2: Eastern portion of the Chihuahua Trough showing names of mountain belts. The location of the Indio Mountains is south west of Van Horn. Box is shown in figure 4. Modified after Underwood (1980) and Rohrbaugh (2001).

A study by Hennings (1994) found total Laramide displacement across the Chihuahua trough, southeast of the Indio Mountains, between Ojinaga, TX, and Aldama, Chihuahua, Mexico to be 20 km with the eastern portion of the trough accounting for only 6 km. A previous study by Hennings (1991) showed three additional sections within the eastern Chihuahua trough to the north to have 7 km of displacement in the Finlay Mountains, 18.5 km of displacement in the northern Quitman Mountains and Devil Ridge, and 27.5 km of displacement in the southern Quitman Mountains and Eagle Mountains. He used a transport direction of 078 degrees and explained the increase in displacement due to the deformation front encountering basin bounding faults in the north before the south. Haenggi (2002) estimated similar displacements to those of Hennings (1991, 1994); however, Reaser (1982) estimated a minimum of 48 km of displacement along the northeastern portion of the Trough with a transport direction of 058 degrees. Structures consist of open, tight and overturned folds with geometries suggesting fault-bend and fault-propagation folding (Underwood, 1962; Reaser, 1982; Hennings, 1991, 1994; Rohrbaugh, 2001; Haenggi, 2002).

Henry et al. (1991) reported the regional stress field changed from compressional to extensional around 31 Ma. Haenggi (2002) suggests initial extensional tectonics following the Laramide was due to resettling of blocks from continued salt mobilization and gravity collapse of over steepened anticlines. Most recently, Basin and Range and Rio Grande Rift associated extension has affected the Chihuahua trough with basin bounding normal faults striking north-south (Haenggi, 2002). While extensional stress regimes and minor tectonics may have commenced earlier, work by Langford et al. (1999) just to the north, suggests that the modern mountains and basins began to form 12 Mya. This is supported by Cather et al. (1994) in the

Socorro Basin, 200 km to the North and (May and Russell 1994) in the Albuquerque Basin who also indicate that the modern Rio Grande rift basins began to subside between 12 and 15 Mya.

3. Geology of Indio Mountains

3.1. Stratigraphy

The stratigraphy of the Indio Mountains has been described in detail by Underwood (1962), therefore only a brief description is given below of the formations in the study area. The Indio Mountains are devoid of Jurassic evaporites, presumably due to their position at the eastern edge of the Chihuahua trough. All rock units are Cretaceous (Aptian through Cenomanian) in age and consist of, from the base, the Yucca formation, Bluff Mesa formation, Cox Sandstone, Finlay Limestone, Benevides formation, and Espy Limestone (fig. 3).

The units have been interpreted to broadly define a transgressive coastal and shelf sequence (Underwood, 1962). Initial deposition of the Yucca formation occurred in a nonmarine to marginal marine rift basin. Relative sea level began to rise during the Albian producing a marine environment depositing the Cretaceous transgressive sequence (Haenggi, 2002). Active faulting in the study area continued at least up through the deposition of the Cox sandstone (communication with Dr. Richard Langford and Pawan Budhathoki, 2010). However, basin subsidence and possibly regional tectonism continued throughout deposition of all the units in the study area as all but the Cox and Finlay are absent, 30 km north on the Diablo Plateau.

The Yucca formation is the oldest unit and covers a significant portion of the Indio Mountains (fig. 4 and 5). Underwood (1962) measured a 610 m section of the Yucca formation in the footwall of the Indio fault. This measurement is a minimum however because the base of the Yucca formation is not exposed and in fact, is not exposed anywhere in the Indio Mountains. Well data northeast of the Indio Mountains between the Quitman Mountains and Devil Ridge (fig. 2) from Reaser (1982) shows 2160 meters of Yucca formation unconformably overlying Permian carbonate rocks in that area.

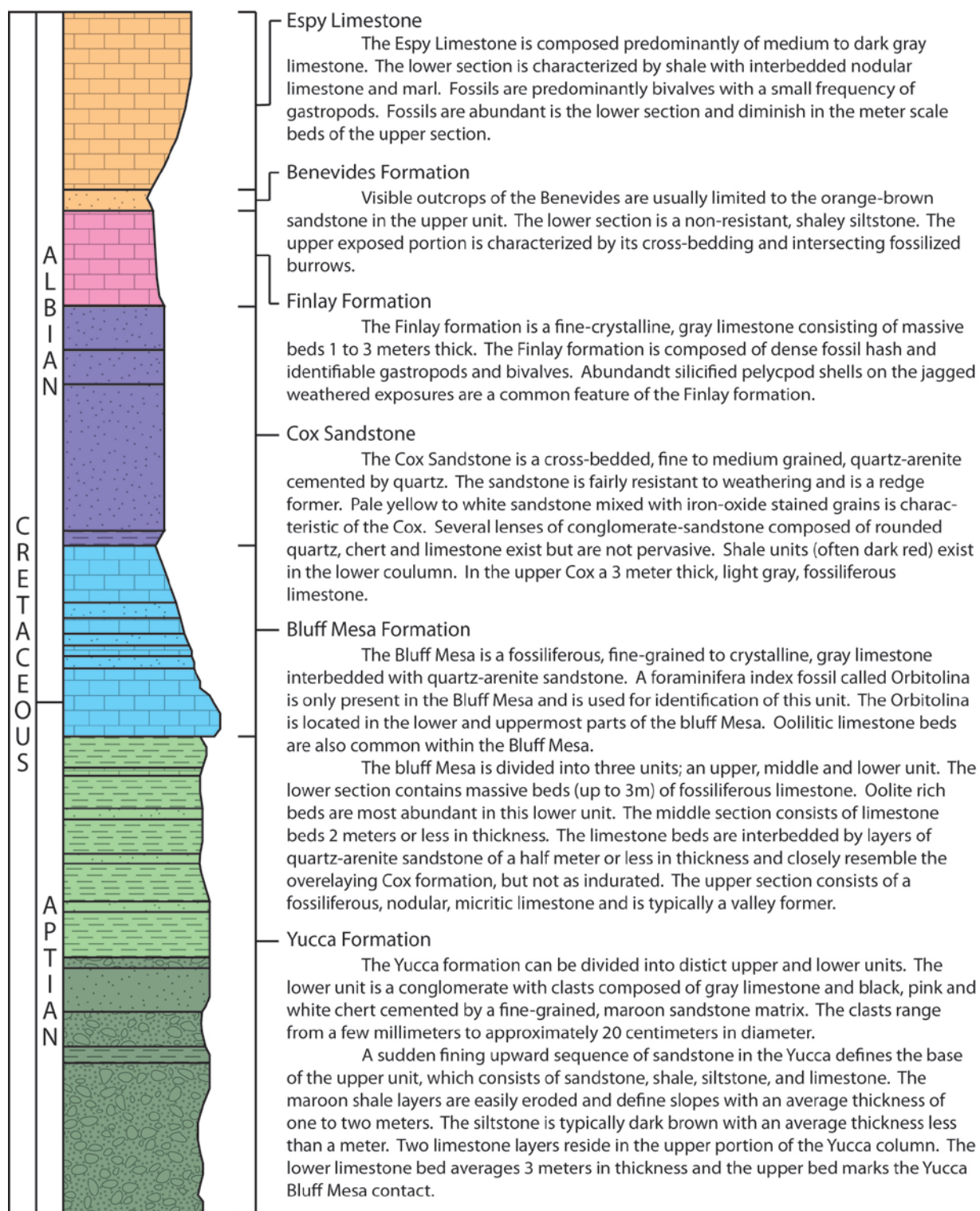


Figure 3: General stratigraphic column and description of rock units found in the Indio Mountains; modified from Underwood (1962) and Rohrbach (2001). Color of units coincides with those on the map in figure 5 and in cross-sections (fig. 14-15).

As described by Underwood (1962), the Yucca formation can be divided into an upper and lower unit. The lower unit is a cobble and pebble conglomerate composed of gray limestone and black, pink and white chert clasts deposited during a predominately fluvial environment. The clasts are cemented by a medium sandstone matrix that can be maroon or grayish-white in color, however, the maroon is most characteristic and dominant. These large conglomerate beds are interbedded with smaller beds of sandstone and even smaller beds of shale.

The upper Yucca formation unit represents a change from fluvial to predominately coastal marine environment shown by a fining upward sequence of interbedded sandstone, siltstone, shale and limestone. The shales are predominately maroon in color while the sandstone and siltstone are mostly grayish-white and reddish-brown. Limestone is present in the upper Yucca unit as three distinct facies: as limestone nodules found within the maroon shale sections, as two fossiliferous limestone beds found in the uppermost 60 meters, and as small 15-20 cm thick limestone clast conglomerates (Underwood, 1962).

The Bluff Mesa formation conformably overlies the Yucca formation. The Bluff Mesa formation is a fossiliferous gray limestone interbedded with quartz sandstone. Underwood (1962) measured a thickness of 242 meters in the footwall of the Indio fault, while Reaser's (1982) well data shows a thickening to 2,042 meters to the west. Underwood (1962) also divided the Bluff Mesa formation into three units. The lower unit contains massive fossiliferous limestone beds; the middle unit is interbedded limestone and quartz sandstone, and the upper section a blue-gray fossiliferous limestone marl with abundant occurrences of the index fossil *Orbitalina* (Underwood, 1962). Although Underwood (1962) described the divisions within the Yucca and Bluff Mesa formations they were not shown on published maps.

The Cox Sandstone is predominately a well-cemented quartz sandstone interbedded with red shale at the base of the unit. Sporadic pebble conglomerate lenses are also found in the unit. The uppermost Cox also contains one to two thin beds of fossiliferous limestone that are lithologically equivalent to the overlying Finlay formation (Underwood, 1962). Underwood's (1962) section shows a thickness of 365 meters for Cox Sandstone in the footwall of the Indio fault while Reaser's (1982) well data has a thickness of 1540 meters.

The Finlay is composed of a gray, fine-crystalline limestone with beds up to 3 meters thick. Dense fossil hash with identifiable gastropods and bivalves is characteristic of the Finlay (Underwood, 1962). The Finlay measures 244 meters at the Indio Mountains (Underwood, 1962) and thickens to 1450 meters to the northwest in the Red Light Draw well (Reaser, 1982).

The Benevides formation is orange-brown sandstone and a non-resistant, shaley siltstone 30 meters thick. The sandstone is usually the only exposed section and contains fossilized burrows (Underwood, 1962).

The Espy Limestone is predominately a medium to dark gray limestone but contains a lower section which consists of interbedded shale and marl. Fossils, bivalves and gastropods, are abundant in the lower section and become scarce in the upper section (Underwood, 1962).

3.2. Structures

At map scale (fig. 4 and 5) the Indio Mountains are dominated physiographically by an arcuate, convex-eastward shaped range formed by bedding traces that range from northeast trending structures in the south to northwest trending structures in the north (Rohrbaugh, 2001, Carciamaru, 2006). This large-scale structure is the consequence of large-scale structural domains within the Indio Mountains: an eastern domain characterized by a fold thrust stack that came from the basin to the west, complicated by a large-scale antiformal arching, and a western

domain dominated by complexly deformed Yucca formation. The boundary between these two domains is a major normal fault, the Indio fault (Underwood, 1962).

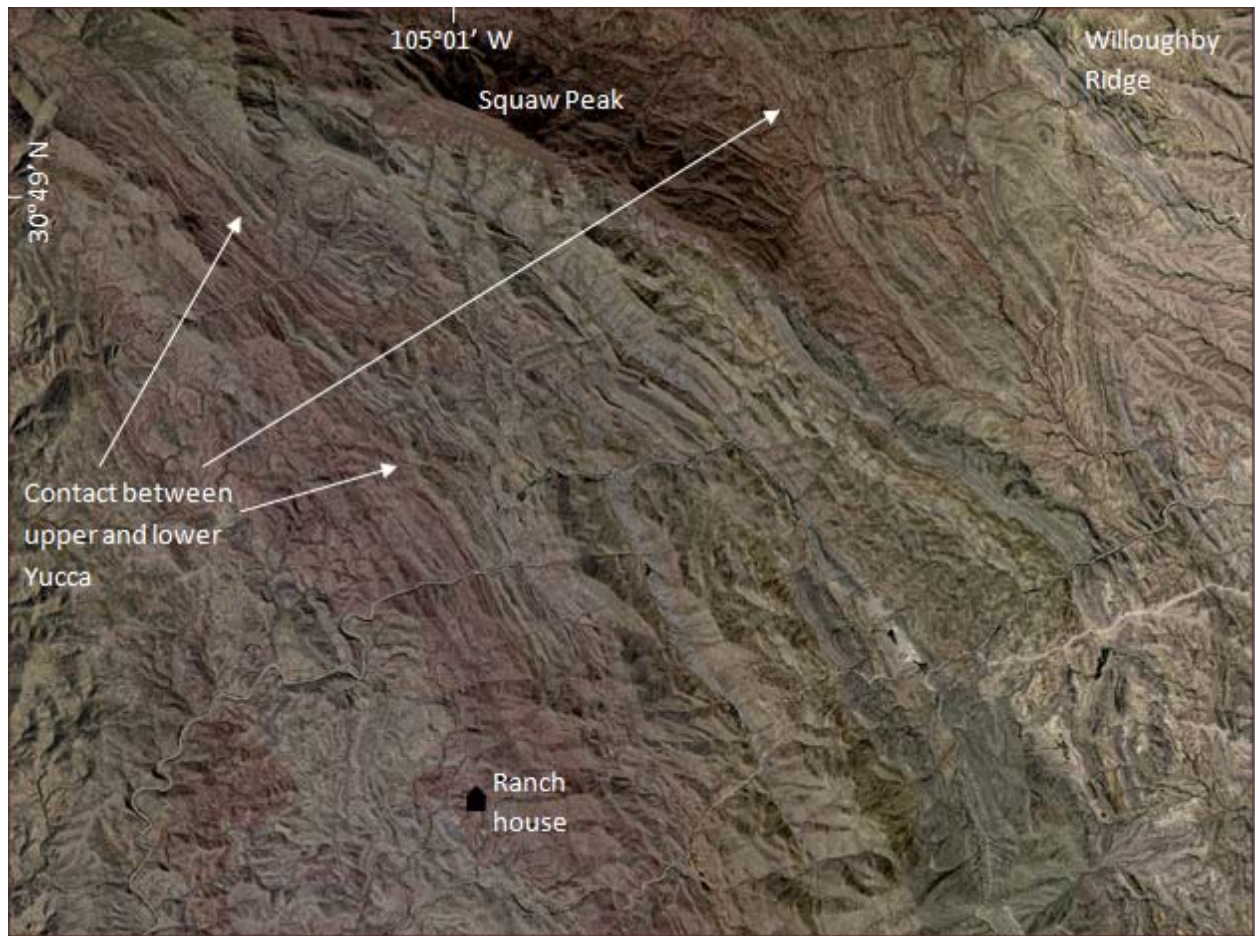


Figure 4: High resolution image of the central Indio Mountain range. The lower Yucca formation is dark red and the upper Yucca is a mixture of red and white. The contact can be clearly seen from this image however is hard to follow on the ground. A clear idea of structure such as the Squaw and Bennett thrusts can be seen as well as folding. See figure 5 for geologic map.

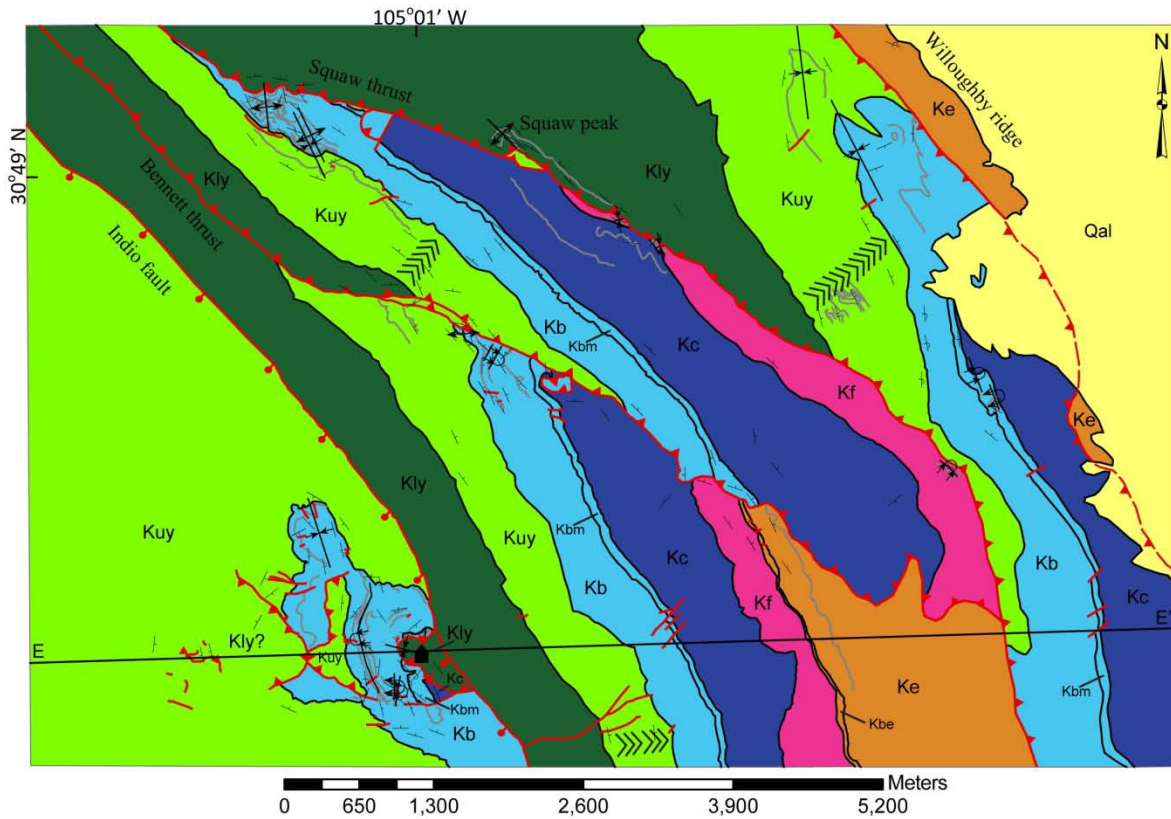
The Indio fault is a major west-side down normal fault that transects the entire range and divides the Indio Mountains into east and west blocks (Underwood, 1962). Underwood (1962) estimated between 1000-2000 m of offset and Rohrbaugh (2001) estimated a minimum 1685 m of offset across this fault. Rohrbaugh (2001) observed that the Espy formation is exposed in the footwall but not the hanging wall suggesting that the Espy formation had been down dropped into the subsurface. He used this relationship to indicate that the minimum displacement on the

Indio fault was the thickness of the Cretaceous strata exposed in the footwall, although he also suggested the displacement could be much higher. In this paper we re-evaluate this issue through cross-section restorations. The overall range has experienced a minimum of 18 degrees of eastward block rotation during basin and range extension (Rohrbaugh, 2001).

East of the Indio fault, Underwood (1962) mapped two major thrusts in the area: the Squaw and Bennett faults. The Squaw fault thrusts the Yucca, Bluff Mesa and Cox formations on top of the Espy formation to the south and on top of the Bluff Mesa and Espy to the north. The Squaw fault outcrops to the east along Willoughby Ridge as the Willoughby fault forming a partial klippe (fig. 5). The Bennett fault outcrops southwest of and parallels the Squaw fault until they connect to the southeast. The Bennett fault thrusts the Yucca, Bluff Mesa, Cox and Finlay formations on top of Bluff Mesa to the northwest and on top of Finlay and Espy to the southeast (fig. 5). Both Underwood (1962) and Rohrbaugh (2001) suggested duplex thrusts played an important role in the deformation history, however, they were unable to provide any details. Rohrbaugh (2001) evaluated the shortening due to Laramide deformation to be a minimum of 6 km in the Indio Mountains. This estimate came from measuring a straight line distance between the Squaw fault klippe on the east and a fenster (half window) on the west produced by the Indio fault.

West of the Indio fault lies a large area of the Yucca formation that is complexly deformed by thrusts and folds (Underwood, 1962). The ranch house is located on a half klippe of lower Yucca that was unmapped prior to this study. West and below this half klippe is a highly deformed section of the Bluff Mesa formation that has an arcuate, convex-westward shaped ridge.

Indio Mountains



Description

- Overturned bed
- Upright bed
- Anticline
- Overturned anticline
- Overturned syncline
- Syncline
- Fault
- Normal fault
- Thrust
- Formational contact
- Bedding trace
- Stratigraphic column
- Indio Mountain Ranch house

Rock Units

Qal	Quaternary alluvium	Kbm	Bluff Mesa marl
Ke	Espy limestone and younger units	Kb	Bluff Mesa
Kbe	Benivides sandstone	Kuy	Upper Yucca
Kf	Finlay limestone	Kly	Lower Yucca
Kc	Cox sandstone		

Figure 5: Geologic map of the central Indio Mountains showing previously unmapped division of the lower and upper Yucca formation and half klippe of lower Yucca beneath the Indio Mountain Ranch house.

3.3. *Folds*

Three types of folds are recognized at the Indio Mountains: broad fault-bend folds, detachment folds and drag folds. The detachment folds and drag folds are usually combined to create complex overturned fold geometries found in the footwall near thrusts. For example, the Bluff Mesa formation found just south in the footwall of the Bennett thrust as well as in the footwall of the newly mapped thrust found in the hanging wall of the Indio fault (fig. 5). The Bluff Mesa formation just south of the Squaw thrust shows a textbook example of a detachment box fold (fig. 6). Detachments are almost always located in a shale unit within the Yucca formation and below the Bluff Mesa marl. The Squaw thrust both in the hanging and footwall of the Indio fault appear to be co-folded with the underlying Bluff Mesa strata suggesting thrusts occurred prior to detachment folds. A broad fault bend anticline-syncline pair is found in the hanging wall of the Squaw thrust within the Yucca formation which produces a newly recognized hanging wall cutoff (fig. 7). This fold was amplified and over steepened by the Bennett duplex and possibly additional horses or additional fault bend folding from a lower decollement.

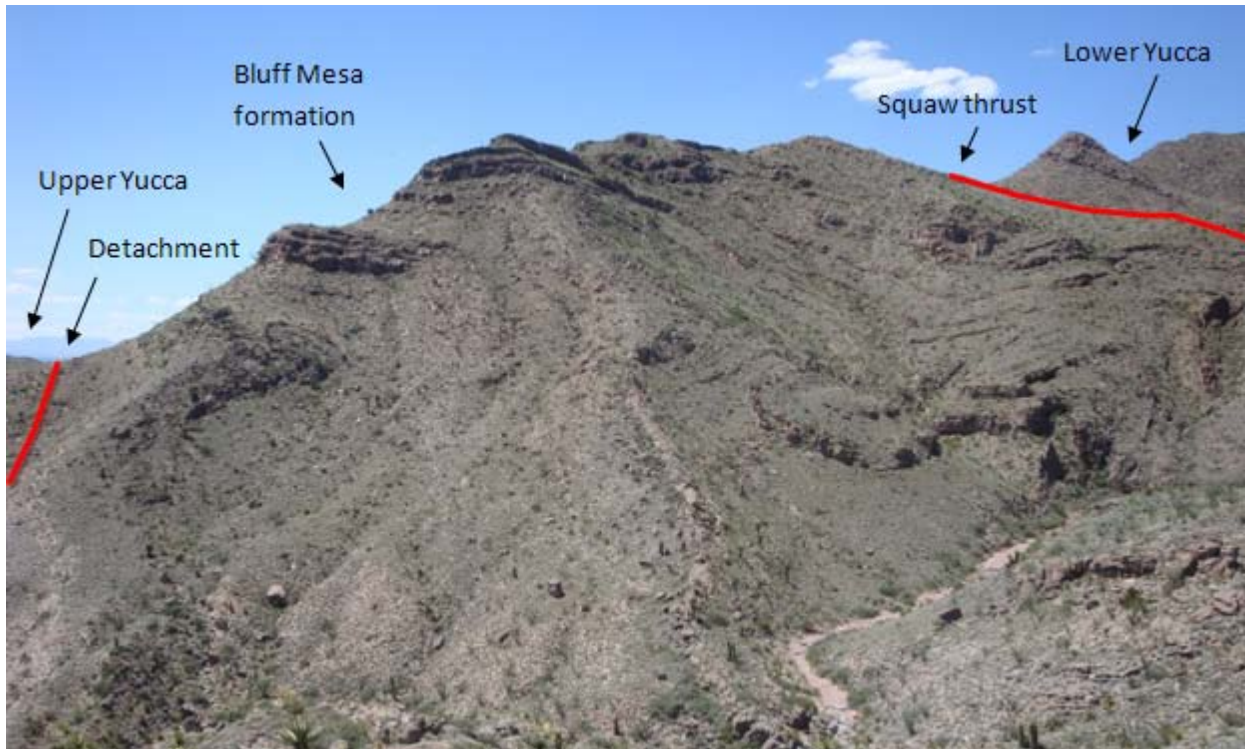


Figure 6: Picture looking northwest at a detachment fold contained within the Bluff Mesa formation in the Bennett duplex. The overriding Squaw thrust is folded suggesting detachment folding in the footwall occurred after thrusting along the Squaw thrust, or during duplex formation as slip stepped downward onto the floor thrust system.

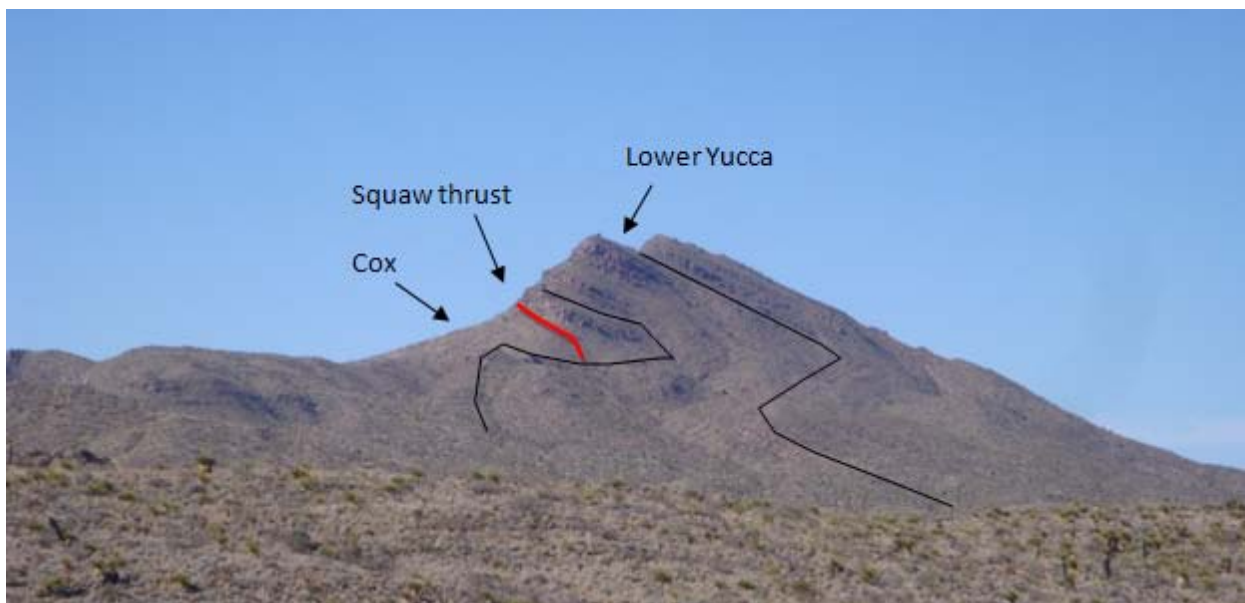


Figure 7: Picture looking North West at Squaw peak. The ledge cliff is the lower Yucca formation lying on top of the Cox Sandstone divided by the Squaw thrust. A hanging wall anticline produces the Z like outcrop patterns. Note: The Squaw thrust is not getting truncated by the bedding trace; it becomes hidden behind the ridge.

4. Methods

This study was accomplished through field mapping of structures and their orientations and analyzing field data in GIS and reconstruction software. Three questions were investigated: 1) What is the cause of the apparent thickening of the Yucca formation east of the Squaw thrust (fig. 3 and 5)? 2) What are the major deformation mechanisms along the margin of the basin where salt is absent? and 3), If duplexes are a major role of the deformation, how many fault horses are there, what are their geometries and can a reasonable reconstruction be produced to define shortening?

Initial field work in the Indio Mountains, focused on increasing the structural detail of the Squaw Peak area west of the Indio Mountain Ranch House (fig. 4 and 5). The Squaw Peak area was chosen because it appeared to contain spectacular exposures of hanging-wall cutoff relationships within the Yucca formation above the Squaw Peak thrust and showed an apparent thickening in the upper Yucca formation (fig. 7). The area west of the Indio Mountain ranch house was chosen because it is the only location west of the Indio fault with extensive exposures of the Bluff Mesa formation and Underwood's (1962) mapping was hard to reconcile with the apparent structure. Digital mapping was accomplished with the aid of a hand held computer system equipped with GPS and ArcPAD software which contained the generic mapping project of Pavlis et al. (2010). Mapping was aided by high resolution (~0.5 m) aerial photos which allowed routine projections of contacts in the field and during evening field compilations.

In order to understand the structure in this region, a critical first step was to examine the stratigraphic succession in the Yucca formation to identify and map the sub units of the Yucca formation described by Underwood (1962) as well as any other specific marker unit that could be used to correlate strata across duplexes. The base of the lower Yucca is not exposed, so finding a

horizon that is laterally extensive throughout the unit is important to produce a viable reconstruction and calculate displacement.

During field work it became apparent why Underwood (1962) did not routinely map the upper and lower Yucca formations as distinctive units because there is no distinct contact to define a simple mappable unit. Instead there are both lateral and vertical facies transitions from the lower nonmarine facies to upper, marine facies.

To clarify this relationship and as well as to better understand the apparent thickening of the upper Yucca in the hanging wall of the Squaw thrust, we measured 3 sections of the upper Yucca formation, one in each of the principal thrust sheets east of the Indio fault. The base of the upper Yucca used in the stratigraphic sections was defined with the help of aerial photography. The lower Yucca is dominantly conglomerate and sandstone, maroon in color and is clearly seen in the photo as is the upper Yucca which is dominantly shale and sandstone with alternating colors of maroon and white (fig. 4). The upper-lower Yucca contact was placed where the bulky maroon color transitioned to an alternating maroon and white color. Further ground investigation proved that although this line may not correspond to a specific contact between two lateral continuous rock units, east of this line was dominantly shale and sandstone, a coastal marine environment, and west of this line was dominantly conglomerate and sandstone, a fluvial environment. The identification of burrows in brown sandstones in close proximity west of the color change and abundantly east of the color change helped confirm this line as a reasonable choice for the contact between the upper and lower Yucca because abundant burrows is more characteristic of a coastal marine environment. The sections were measured using high resolution GPS with a resolution of .5 meters with thicknesses calculated from these spatial positions.

Abundant strike and dip as well as fault measurements from shear zones, using the technique of Cowan and Brandon (1994), were taken for accurate cross section construction and fault transport direction. Most of the orientation data were taken using a geoclinical digital compass.

After completion of the field work, the digital map was exported into the software package Move -2010 and 2011 where the orientation data were analyzed using stereonet and where the map can be refined for 3D structural visualization and cross-section restoration. Move contains three different programs: 2D, 3D and 4D (in Move 2011) that allows importation of a variety of different file types. In this project we used a workflow where the basic map data were collected in GIS, then exported to Move as shape files. The map data were then draped on a DEM of Indio Mountains in 4D Move for 3D visualization and analysis. 3D Move and 2D Move were then used to construct topographic profiles from the DEM for section construction. 2D Move also allows the user to project lines from the map onto cross-section profile for accurate construction of down-plunge structures.

2D Move was then used for all cross-section restoration. 2D Move has a number of algorithms that assists in reconstructing balanced cross-sections such as unfolding by means of simple shear or flexural slip and fault-slip algorithms that can be used for simple shear, fault parallel flow, fault bend fold, trishear folding, etc. During the reconstruction process, care was taken to insure the cross-sections balanced and could be reconstructed through forward progression. For example, sections were typically constructed by an interactive technique of section construction, restoration, section modification with forward motion tests, section reinterpretation, restoration, etc. For simplicity, the 18 degree eastward tilt estimated by Rohrbaugh (2001) was not incorporated into the restorations. Two models were developed to

help define duplex geometries within the Indio Mountains and shortening distance: one with a basal decollement and another with no basal decollement.

5. Results

5.1. Stratigraphy

After measuring the stratigraphic sections it became clear that the apparent thickening of the upper Yucca within the Squaw thrust was not due to repetition of section on thrusts within the unit. Instead, the unit is depositionally thicker, having been thrust from deeper within the Chihuahua Trough (fig. 8 and Appendix). In fact, it thickened over a hundred percent, from 280 meters within the footwall of the Indio fault to 650 meters within the hanging wall of Squaw thrust. Within the measured the section riding on the Squaw thrust, 100 meters of strata was repeated in a detachment fold. These 100 meters were not included in the total thickness of 650 meters. The upper Yucca section within the Bennett thrust is also thicker by 50 meters, measuring 320 meters. The consecutive thickening of the lower Yucca in the overriding thrust sheets is in agreement with the well data of Reaser (1982), which penetrated over 2 km of Yucca to the north west of the Indio Mountains. The extreme thickening of the Yucca formation is interpreted as occurring along syn-depositional faults that formed the Chihuahua Trough. This structure was then overprinted during the inversion process by the Squaw thrust carrying the structurally thickened Yucca formation on top of the thinner section.

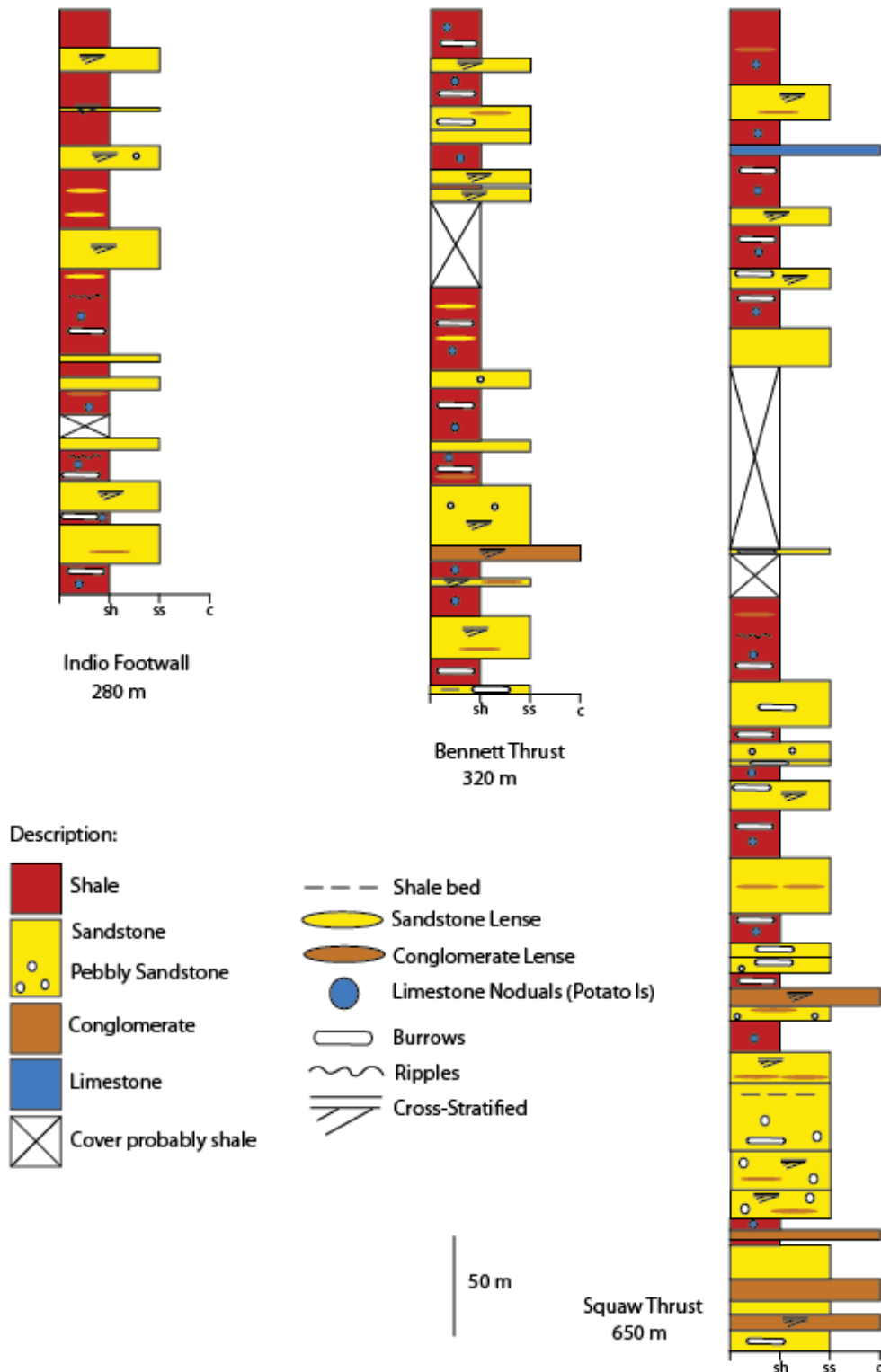


Figure 8: Stratigraphic sections of the upper Yucca in the Squaw thrust, Bennett thrust and Indio footwall respectively showing 300 m thickening in the section above the Squaw thrust. For a more detailed description see Appendix.

5.2. *Fault kinematics*

Newly recognized fault rock that represents a shear zone is seen along the major thrusts, namely the Squaw thrust, Bennett thrust and a previously unmapped thrust that underlies the Indio Ranch house (figs. 4, 5 and 9). The fault rock is only exposed along zones of the thrusts but the fault rock found in all three thrust are identical in character. Exposed regions of the shear zone can be up to a meter thick and is a yellowish orange highly deformed limestone. The exposed shear zones were all found along the fault where it was cutting up the Bluff Mesa, Finlay or Espy limestone. The fault rock contains three distinct planar features that are interpreted as Riedel structures and were used to calculate the slip direction as outlined by Cowan and Brandon (1994; fig. 9).

The Squaw thrust and a previously unmapped thrust west of the ranch house in the hanging wall of the Indio fault showed slip direction to the east with azimuths of 090 and 095 respectively (fig.6). These values are more easterly than those of Haenggi (2002) and Hennings (1994) and much more easterly than that of Reaser (1982). The slip direction of the Bennett thrust was measured as 076 which agree with transport azimuths reported by Haenggi (2002) and Hennings (1994). This fault had previously been interpreted by Underwood (1962) to be a back thrust but in reality is a basal thrust of a large horse within a duplex, as shown by its easterly sense of motion (fig. 9D).

The unmapped thrust in the hanging wall of the Indio fault is interpreted to be the Squaw thrust displaced downward by the Indio fault. Both of these faults have footwall cutoffs of the Bluff Mesa and Cox formations with the lower Yucca above as well as show almost identical slip directions.

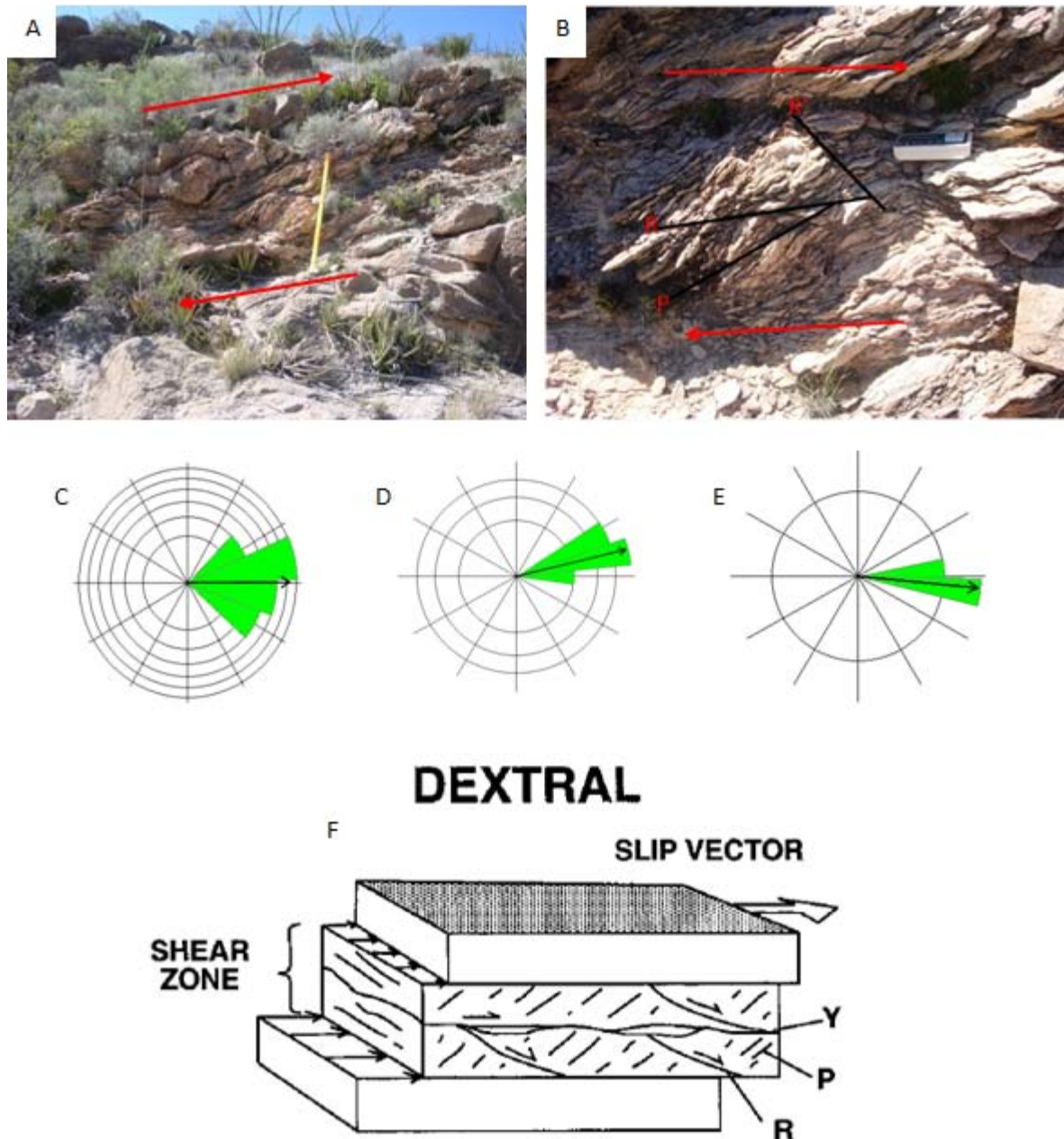


Figure 9: A) An example of an outcrop of an exposed shear zone, jacob staff is 1.5 m. B) Close up image of (A) showing sense of motion. C) Rose diagram for 15 measurements taken on the Squaw thrust showing a 090 degree sense of motion. D) Rose diagram for 8 measurements taken of the Bennett thrust showing a 075 degree sense of motion. E) Rose diagram for 3 measurements taken on the thrust just west of the ranch house showing a 095 degree sense of motion. E is thought to be the squaw thrust dropped down by the Indio fault. F) Block diagram showing an ideal dextral shear zone and the corresponding Riedel structures that form. By measuring the trend of the intersection point of the Y, R and P structures and then adding 90 degrees, the slip vector is obtained (Cowan and Brandon, 1994).

By identifying the previously unmapped thrust just west of the Indio Ranch house as the Squaw thrust dropped down by the Indio fault, displacement along the Indio fault has been highly constrained by projection of these thrusts onto the Indio fault. Reconstruction of the Indio fault gives a displacement of 1550 meters. These new map relationships makes unlikely the suggestion given by Rohrbaugh (2001) that the Espy formation had been down dropped into the subsurface in the hanging wall of the Indio fault and possibly repeated by duplexes because the Squaw thrust does not cut the Espy formation until further to the east and the underlying thrusts would not contain the Espy formation.

5.3. *Folds*

The strata in the study area were divided into domains (Squaw thrust hanging wall, Bennett duplex, Indio hanging wall and Indio footwall below the Bennett thrust) (fig. 5). Stereonets were used to compare folds in the different domains. Folds were also classified by type (fault bend fold or detachment fold; fig. 10-13) and compared on stereonets. Most fold axis measurements trend between 030-330 or 135-180 which corresponds with a west-southwest east-northeast transport direction (fig. 10-13). The lone exception is found in the hanging wall of the Indio fault just west of the ranch house that shows an east-trending and plunging syncline folding both the Yucca above the Squaw thrust and the Bluff Mesa below (fig. 5 and 13F). It is interpreted that this exception is due to preferential slippage along the tip of a classic “bow” shaped thrust (fig. 5, bow shaped thrust west of Indio Ranch house putting upper Yucca on Bluff Mesa) described by Elliot (1976). Drag along the northern and southern limits of the fault with displacement occurring on a ramp would form a syncline with an eastward trend and plunge. A single lateral ramp, however, could also create this geometry.

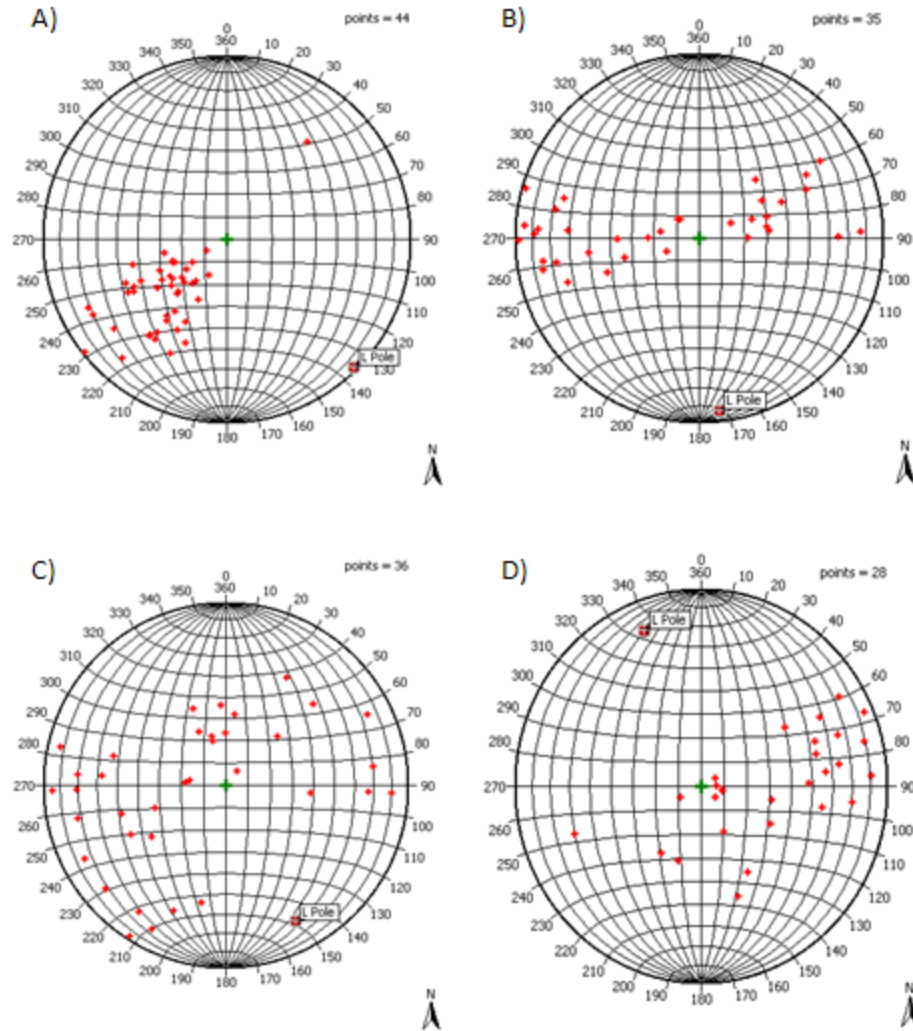


Figure 10: Stereonet analysis for folds found in the Squaw thrust block. Plotted are poles to planes with the 'L Pole' representing the trend and plunge of the fold axes also included in parentheses below. A) Squaw Peak overturned anticline shown in figure 6 (02,135). B) Syncline in upper Yucca (07,173). C) Syncline in lower Bluff Mesa (17,153). A-C are interpreted as fault bend folding and are encountered starting with (A) at Squaw Peak followed by (B) and (C) going east. D) Overturned detachment fold in Bluff Mesa marl, located center and east on figure 5 (16,339).

Three fault bend folds were indentified and all were located in the Squaw thrust hanging wall with fold axes trending southwest with a shallow plunge. Detachment folds where plentiful and found in all blocks with fold axes trending for the most part in a northwest direction with plunges ranging from gentle to steep. The presence of folds with a range of trends and plunges

may suggest transpression as the deformation mechanism which would cause rotation of trends and plunges (Reaser, 1982; Drewes, 1988; Rohrbaugh, 2001).

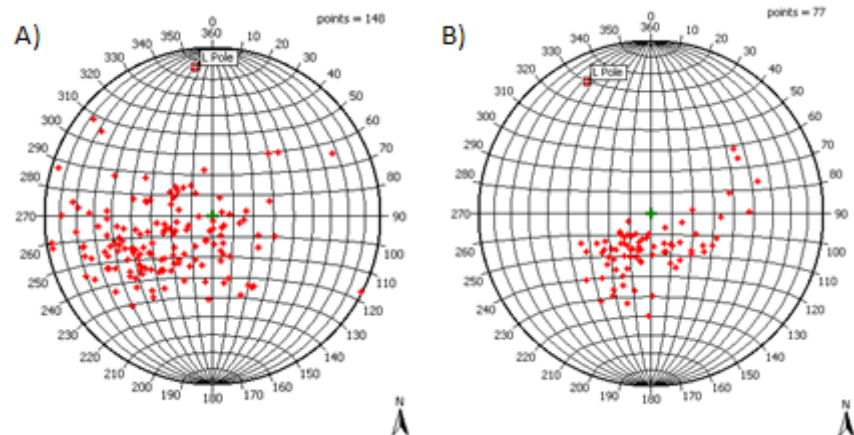


Figure 11: Stereonet analysis for folds found in the Bennett duplex block; located in the northwest portion of Figure 5 just south of the Squaw thrust. Plotted are poles to planes with the 'L Pole' representing the trend and plunge of the fold axes also included in parentheses below. A) Detachment fold shown in figure 7(12,354). B) Detachment fold southeast of (A) (16,334).

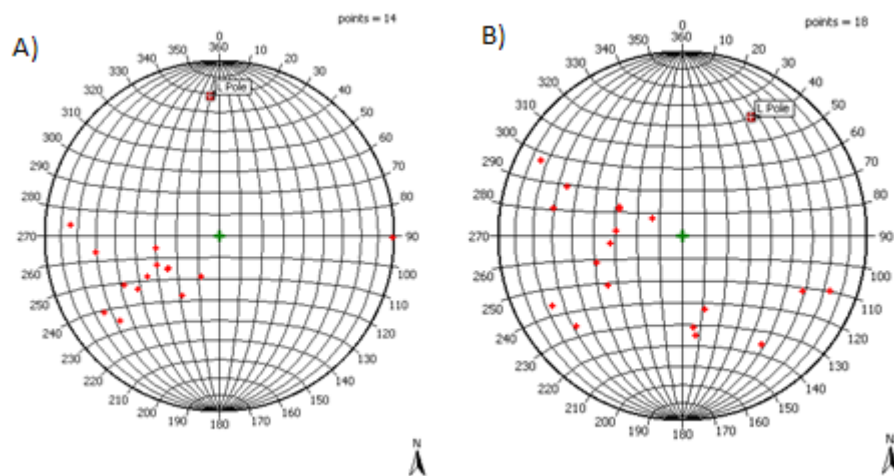


Figure 12: Stereonet analysis for folds found in the footwall of the Bennett thrust and Indio fault. Plotted are poles to planes with the 'L Pole' representing the trend and plunge of the fold axes also included in parentheses below. A) Overturned detachment fold in lower Bluff Mesa (21,356). B) Overturned detachment fold in middle Bluff Mesa (27,030). Both fold are located at the center of Figure 4 south of the Bennett thrust.

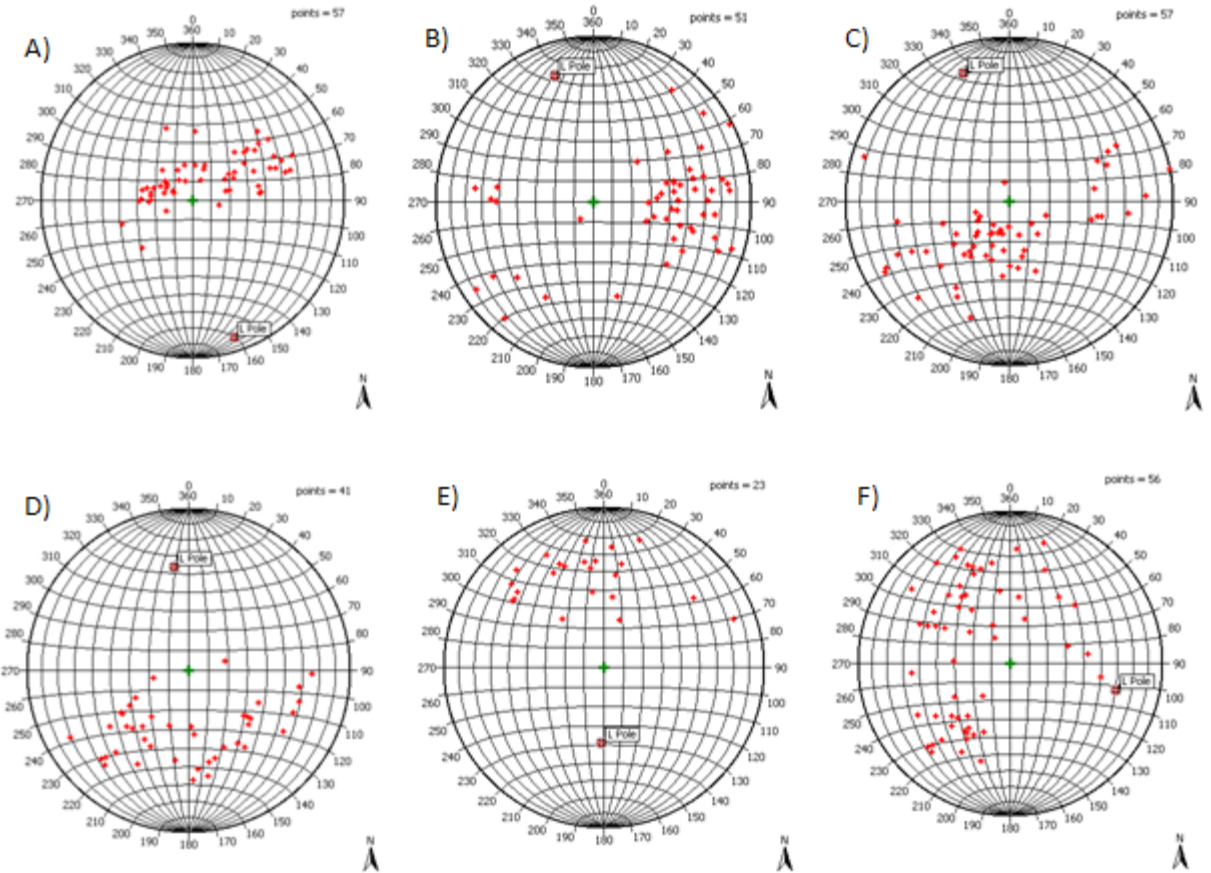


Figure 13: Stereonet analysis for folds found in the hanging wall of the Indio fault. Plotted are poles to planes with the 'L Pole' representing the trend and plunge of the fold axes also included in parentheses below. A) Open syncline in the upper Yucca and lower Bluff Mesa (10,162). B) Overturned syncline in the upper Yucca and lower Bluff Mesa (21,342). C) Overturned anticline-syncline pair in the middle Bluff Mesa (18,340). D) Overturned anticline-syncline pair in the Bluff Mesa marl (35,352). E) Overturned anticline in the Bluff Mesa marl (51,182). B-E are interpreted as detachment folds and are located west of the ranch house. F) This fold is interpreted to have formed by dragging along the flanks as the detachment moved (29,104).

5.4. Cross-Section Reconstruction

Contacts and orientations were used to create two cross sections along E-E' (fig. 5) in which deformation could be modeled. The section line trends east-west to parallel displacement direction and the geometry of the Bennett duplex, Squaw thrust and their associated strata were projected above the surface of the topography to be included in the section. The deformation observed was reconstructed using two models. These models assume the Yucca formation is

present in the southwest portion of the Van Horn Mountains (fig. 2 for location of Van Horn Mountains) as mentioned by Twiss (1959) and provide a displacement mechanism to connect structures in the Indio Mountains to a larger-scale thrust system.

The first, more realistic model (fig. 14) assumes a deeper decollement to account for Yucca formation exposures near the Van Horn Mountains. This model is favored because the decollement not only provides an easier solution to putting the Yucca formation over the Van Horn Mountains, it also provides a mechanism for producing the east-tilt and production of the homoclinal strata in the footwall of the Bennett and Squaw thrusts through movement along a ramp on the decollement. The homoclinal strata were unfolded by restoring displacement along the decollement using the fault bend fold algorithm and the Bennett and Squaw thrusts were restored by the fault parallel flow algorithm. This model is in agreement with the sections of Hennings (1991, 1994) to the north and south in which a decollement thrusts syn-rift thickened strata over the thinner strata and then daylighted as the frontal thrust.

The second model (fig. 14) calls for a hypothetical thrust that is older than, and structurally above, the squaw thrust that would have displaced the Yucca formation to produce the reported Yucca exposures in the Van Horn Mountains. In this scenario, this thrust is needed because the strata in the hanging wall of the Squaw thrust are involved in a clear hanging-wall cut-off in the eastern part of the mapped area where the thrust cuts up section in the hanging wall from upper Yucca northwest of the Bennett-Squaw thrust intersection to Bluff Mesa and Cox formations to the south and east at Willoughby Ridge (fig 5). Thus, the Squaw thrust is at the level of the Bluff Mesa formation at its eastern limit of exposure and could not have transported Yucca formation eastward to the Van Horn Mountains. A disadvantage for this model is that there is no mechanism for unfolding the homoclinal strata found in the footwall of the Bennett

and Squaw thrusts and the existence of a major thrust, now completely eroded away, is theoretical at best.

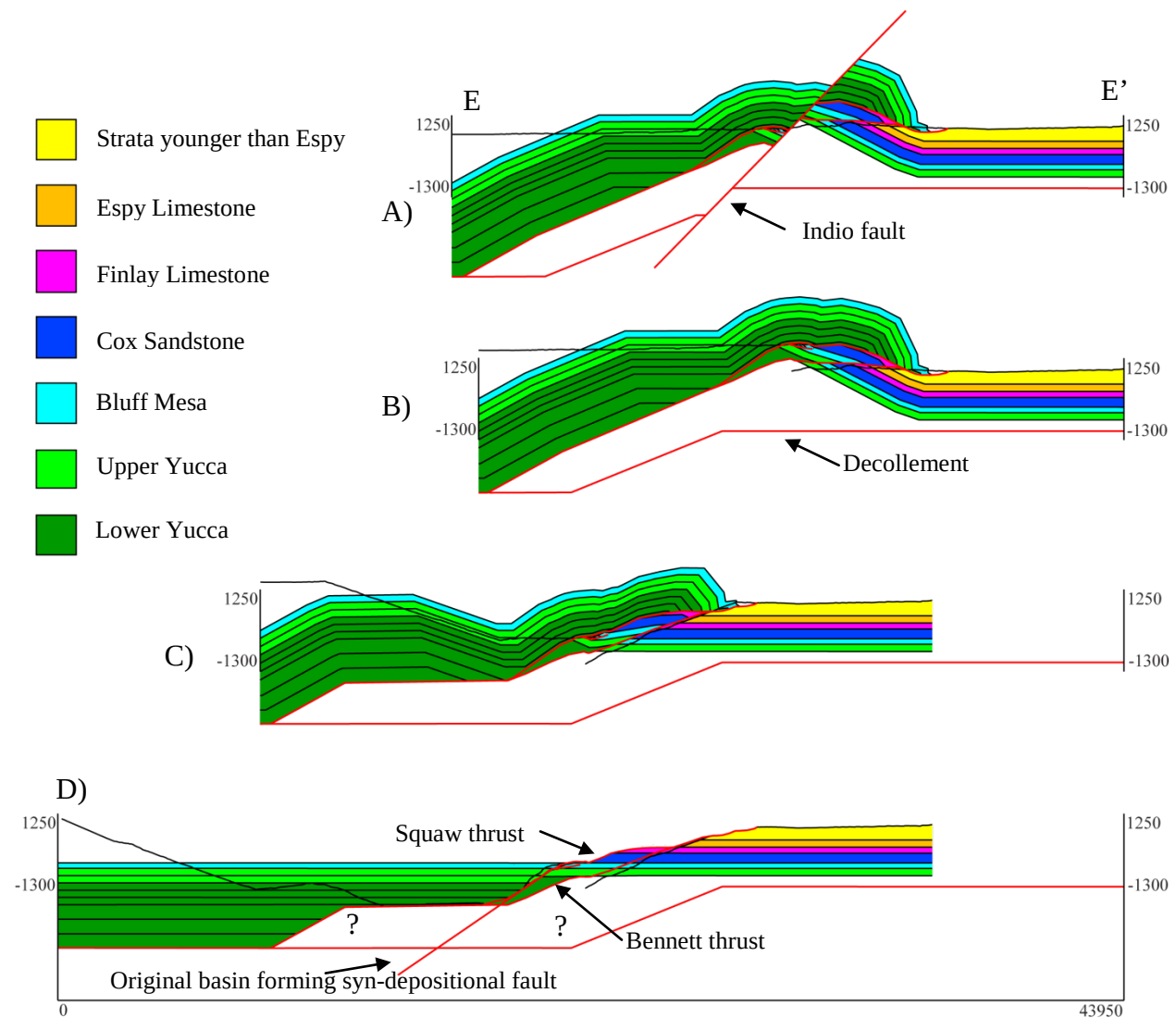
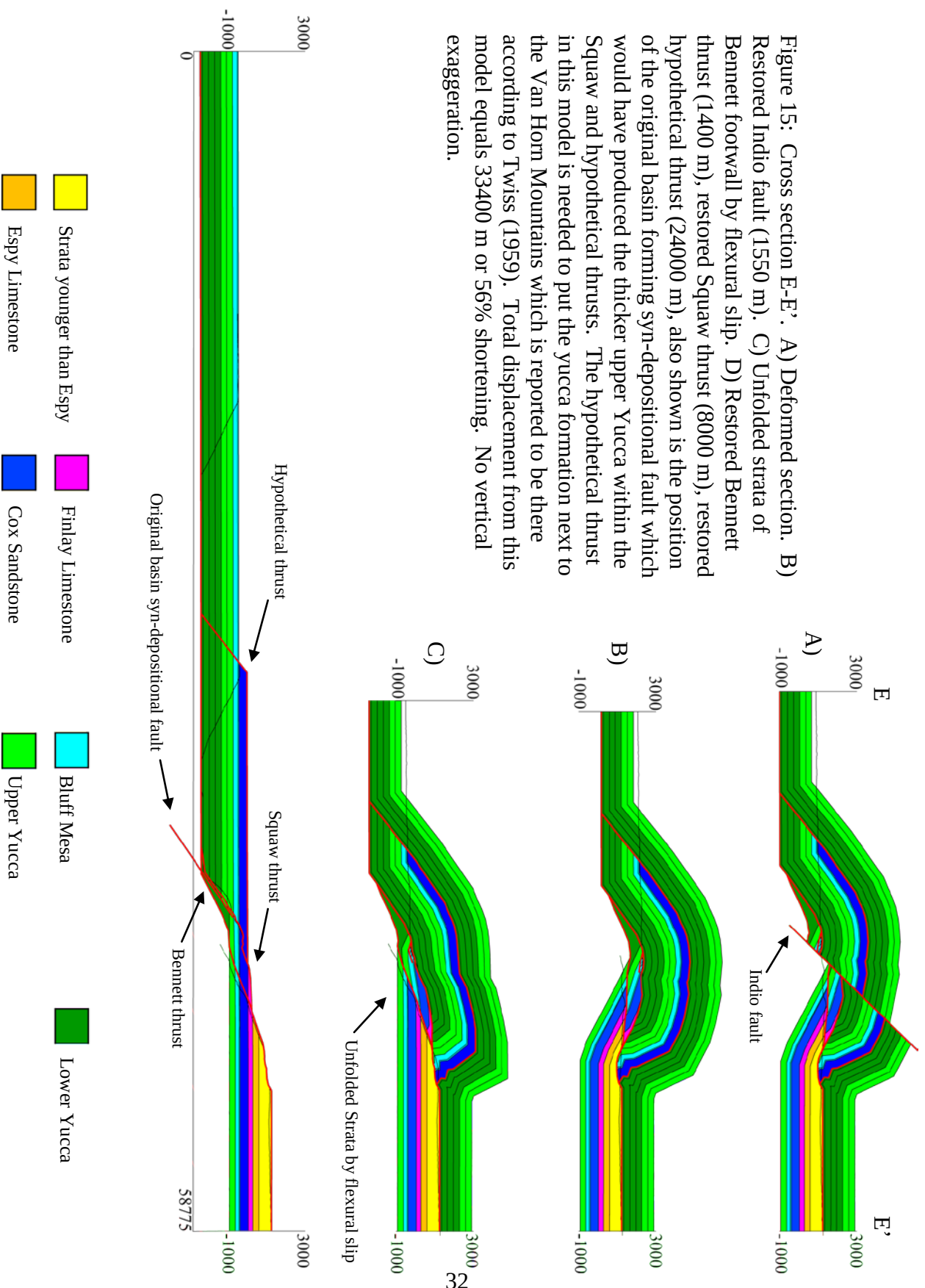


Figure 14: Cross-section E-E'. A) Deformed section. B) Restored Indio fault (1550 m). C) Unfolded strata along decollement (9000 m). D) Restored Bennett thrust (1200 m) and Squaw thrust (7100 m), also shown is position of original basin forming syn-depositional fault. The decollement provides the mechanism needed to fold the strata in the foot wall of the Bennett and Squaw thrusts as well as thrusting the yucca formation up to the Van Horn Mountains along a ramp which would lie more east of this section. Total displacement from this model equals 17300 m or 39% shortening. No vertical exaggeration.

Figure 15: Cross section E-E'. A) Deformed section. B) Restored Indio fault (1550 m). C) Unfolded strata of Bennett footwall by flexural slip. D) Restored Bennett thrust (1400 m), restored Squaw thrust (8000 m), restored hypothetical thrust (24000 m), also shown is the position of the original basin forming syn-depositional fault which would have produced the thicker upper Yucca within the Squaw and hypothetical thrusts. The hypothetical thrust in this model is needed to put the yucca formation next to the Van Horn Mountains which is reported to be there according to Twiss (1959). Total displacement from this model equals 33400 m or 56% shortening. No vertical exaggeration.



5.5. Shortening

Reconstruction of the second model resulted in a total displacement of 33.4 km; 1.4 km along the Bennett thrust, 8 km along the Squaw thrust, and 24 km along the hypothetical thrust. Total displacement for the first model is 17.3 km; 9 km along the decollement, 1.2 km along the Bennett thrust and 7.1 km along the Squaw thrust.

The amount of shortening suggested by the second model, 33.4 km, which suggests an older and structurally higher thrust above the Squaw thrust, is much greater than previous studies. However, shortening in the first model, 17.3 km, is similar to the 18.5 – 27.5 km of shortening produced by Hennings' (1991) in sections just to the northwest. These values, however, are a minimum, because they do not take into account any of the micro shortening such as the abundant smaller scale thrusting and folding, nor any duplex that may be present west of the Indio fault beneath the Yucca formation.

6. Discussion

The difference between the two slip directions determined for the Squaw thrust and the Bennett thrust is large enough (15-20 degrees; fig. 6) that the difference is unlikely to be the result of measurement error suggesting that some parameter may have changed during the deformation. One possibility is that as the deformation front stepped eastward and slip transitioned from the Squaw thrust to the Bennett thrust, another original basin forming normal fault, or a transfer zone with a different geometry than that of the Squaw thrust was encountered, which partitioned the slip direction (Konstantinovskaya et al., 2007). Additional along-strike stratigraphic sections of the upper Yucca in the Bennett duplex should be collected in order to confirm thickening of the upper Yucca in the Bennett duplex which would then test the hypothesis of another original syn-rift fault.

Although the first reconstruction scenario is more reasonable, some issues remain unresolved. For example, the thrust systems of the Indio Mountains are not known in the vicinity of the Van Horn Mountains. Thus, the depth to the inferred decollement is poorly constrained. Figure 14 shows the best fit from many attempts of restoration with different depths and geometries that unfold the footwall strata but a range of solutions is possible. Identifying the Yucca formation present in the Van Horn Mountains would help constrain the possible depth to at least within the upper or lower Yucca formations on the east side of the section. It is more reasonable to suggest the decollement lies within the upper Yucca where much more shale is present.

Also, the minimum thickness of the lower Yucca on the west side of the model cross section is 2675 m. This value, measured from the upper/lower Yucca contact to the decollement, is greater than the total thickness of the Yucca formation measured by Reaser (1982); however it

is now reasonable to suggest the possibility of multiple original en echelon basin forming syn-depositional faults which would greatly thicken the Yucca formation westward. In the decollement model, there are three possible syn-depositional faults: the one labeled which created the thickened upper Yucca section in the hanging wall of the Squaw thrust, one that slightly thickened the upper Yucca section in the hanging wall of the Bennett thrust and one that could be where the Squaw thrust first ramps up from the decollement.

Another mechanism and equally plausible for thickening the lower Yucca formation to the west is duplexes confined within the Yucca formation, increasing its structural thickness. It is possible that we could be dealing with multiple decollements at depth within the lower Yucca in the west which has also been suggested by Beauchamp et al., (1999) as a possibility in inverted basins. Also assumed in the Indio Mountain models is a pure shear model of extension with non listric faults. The presence of listric faults that turn in to low angle detachments would decrease the amount of thickening required west of the Indio Mountains because thickening would have only occurred in a half graben (fig 17).

A key assumption in this model is the possibility that the decollement cuts below the Mesozoic rock, presumably incorporating underlying Paleozoic strata, Precambrian basement, or both. Without knowing the thickness of the lower Yucca or the depth to the decollement, a section of the basement very well could have been incorporated.

Another model that has received some attention but cannot be completely reported on here, but should be considered in future studies, is a series of multiple horses within the Yucca formation forming the regional antiformal structure seen near squaw peak. Problems arise with insufficient room for adding an addition horses beneath the Bennett horse with the correct geometry. This uncertainty is due to lack of sufficient data of true thickness of the lower Yucca

formation and depth to the decollement, but a model of this type would require a deeper fault, like the model if figure 14.

7. The Atlas Mountains: A modern analog?

The Atlas Mountains are located in Morocco, northwest Africa (fig. 16), and are a mountain range that has experienced a deformation history similar to the Chihuahua trough. The area now covered by the Atlas Mountains, with peaks over 4000 m, began as an intercontinental rift system that started in the Triassic and was active through the Jurassic. This paleo-Atlas rift system was an oblique side track of the Atlantic rift and extended from the Atlantic margin of Morocco to the Mediterranean coast of Tunisia. The inversion process began in the early Cretaceous and continues today; however the major uplift phase occurred between the Oligocene and Miocene corresponding to the Alpine orogeny (Beauchamp et al., 1997, 1999; Teixell et al., 2003; El Harfi et al., 2006).

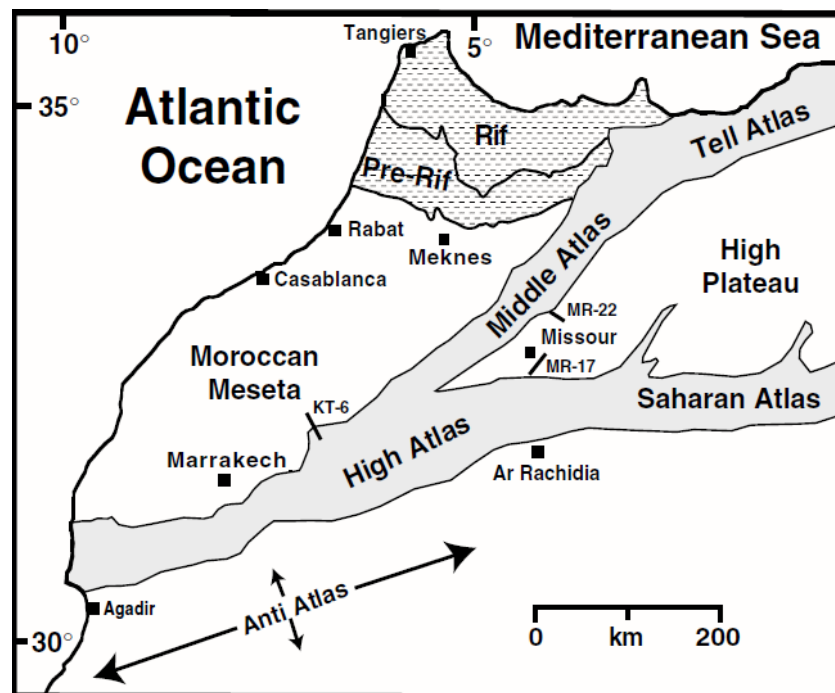


Figure 16: Map showing location of the Atlas Mountains from Beauchamp et al., (1997). MR-22, MR-17 and KT-6 are seismic lines. MR-22 is shown in figure 16.

There are two models describing the mechanism for inversion: the thick skinned model (Teixell et al., 2003; El Harfi et al., 2006) and the thin skinned model (Beauchamp et al., 1997, 1999; Lowell, 1995). The thick skinned model suggests that most thrust faults, newly formed or reactivated normal faults, and buckle folding involve basement and that the formation of low-angle thrusts as detached thin skin zones is limited to a small portion of the southern margin of the mountain belt. The thin skinned model proposes that the syn-rift normal faults were reactivated and inverted until an angle was reached where it would be mechanically easier to form low angle thrusts. The proponents of this model have reported structures such as low angle faults, fault bend folding and detachment folds and short cut thrusts similar to those seen in the Indio Mountains. For example figure 17 shows seismic line MR-22 of the Middle Atlas range (see fig. 16 for location) where a short cut thrust is formed. The geometry of the short cut thrust is very similar to the Bennett thrust. The difference would be that not sufficient displacement has occurred to form a decollement at the base of the syn-rift strata to thrust it over the short cut fault forming a duplex.

The overall model for the High Atlas Mountains is shown in figure 18 where initial inversion occurs along an original syn-rift fault. A decollement then forms between the pre-rift and syn-rift/post-rift strata displacing the thickened syn-rift strata over the pre-rift formation also forming the ramp anticline and fault bend folding. The ramp anticline, fault bend folding and decollement are comparable to the Squaw Peak anticline, fault bend folding and frontal thrust seen at the Indio Mountains. Although not shown in this model, Beauchamp et al. (1999) favors multiple duplexes in his section within the thickened syn-rift strata as the regional uplift mechanism.

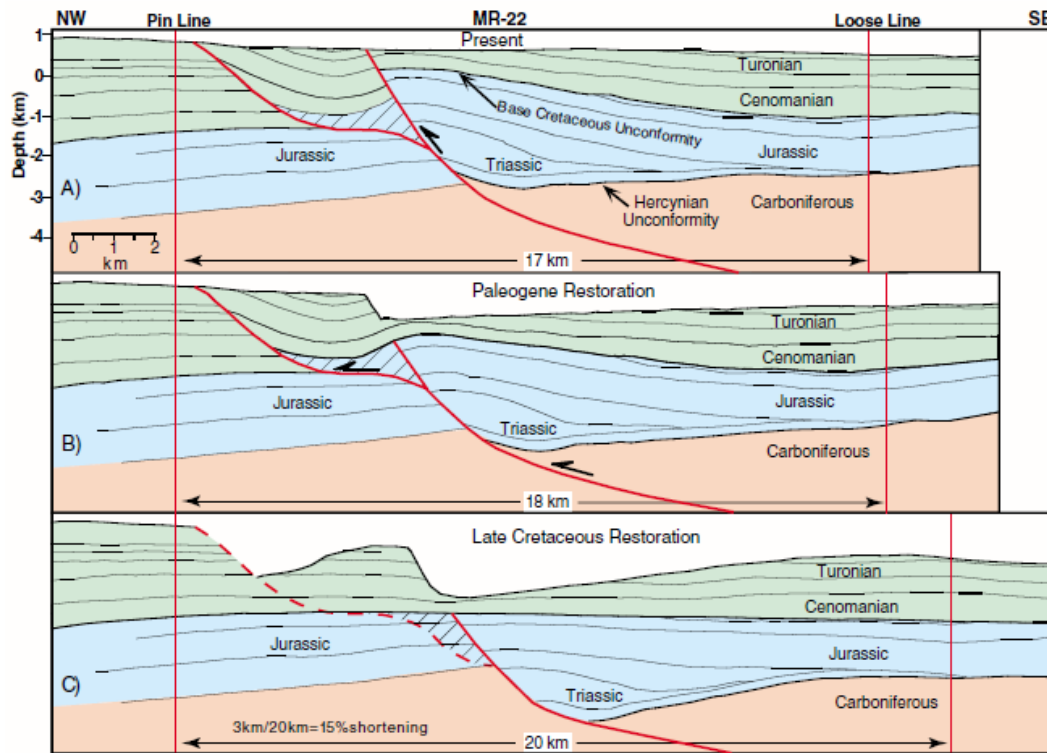


Figure 17: Interpreted seismic line MR-22 and reconstruction from Beauchamp et al., (1997). Initial inversion occurs along an original syn-rift listric fault where thickening has occurred within the half graben. After reaching an unfavorably high angle along the listric fault a short cut thrust forms. The Geometry of the short cut fault is similar to that of the Bennett thrust. This model is similar to that seen in the Indio Mountains but with less shortening. With time a decollement could form and thrust the thickened syn-rift strata completely over the short cut fault as seen at the Indio Mountains (compare with figure 18 and 14).

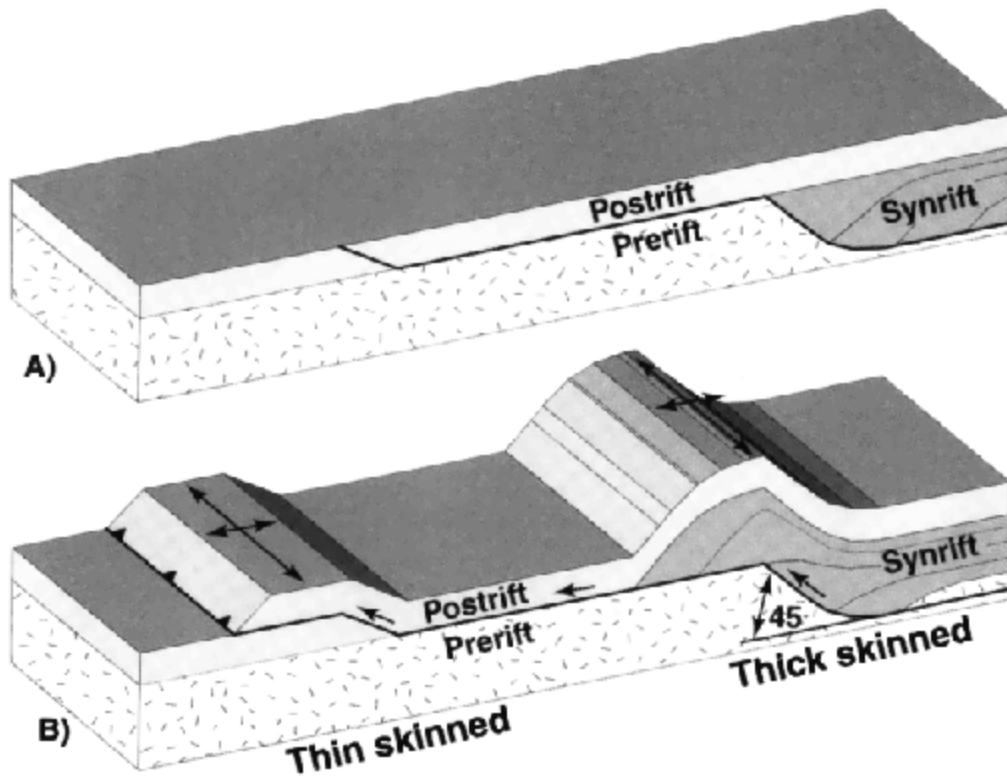


Figure 18: General inversion model for the High Atlas Mountains from Beauchamp et al., (1999). This model is similar to that shown in figure 16 but with more shortening producing a ramp anticline and decollement between the pre and post rift strata. This model is very similar to that seen at the Indio mountains with the ramp anticline being the Squaw peak anticline and the decollement being the frontal decollement that daylights at the Van horn Mountains (compare with figure 14).

8. Conclusion

An updated geological map of the central Indio Mountains shows a contact between the upper and lower Yucca formation that was previously not mapped. This contact provides a piercing point needed to produce viable reconstructions of the area. Measurements taken on shear zones along the Squaw, Bennett and a previously unmapped thrust west of the ranch house show an eastern displacement direction. The newly recognized thrust is interpreted to be the Squaw thrust dropped down by the Indio fault. The Bennett thrust, previously interpreted as a back thrust, is actually a thrust within a small duplex developed beneath the Squaw thrust. Stratigraphic columns show an increase in thickness of the upper Yucca formation in the hanging wall of the Squaw thrust. This thickening is interpreted as syn-rift thickening being thrust over the thinner strata. Two cross sectional models were constructed. The favored model suggests a decollement at depth which daylights as the frontal thrust at the Van Horn Mountains. A new minimum of 17.3 km or 39% shortening is recorded by this model which is in agreement to previous models for the Chihuahua trough. The thin skinned model of Atlas Mountains shows it to have similar structures to those of the Indio Mountains and could be used as an analogue for how the Indio Mountains have formed vice versa. Due to the absence of geophysical data such as seismic or gravity profiles constraining these models further would be difficult. Additional detailed mapping of the Yucca formation in the hanging wall of the Indio fault may shed light on the duplex hypothesis for thickening the Yucca strata in the deeper portion of the basin.

9. References

- Beauchamp, W., Barazangi, M., Demnati, A., and El Alji, M., 1997, Inversion of synrift normal faults in the High Atlas Mountains, Morocco: *The Leading Edge*, p. 1171-1175.
- Beauchamp, W., Allmendinger, R.W., Barazangi, M., Demnati, A., El Alji, M., and Dahmani, M., 1999, Inversion tectonics and the evolution of the High Atlas Mountains, Morocco, based on a geological-geophysical transect: *Tectonics*, v. 18, no. 18, p. 163-184.
- Carciamaru, D., 2006, Structural Geology and Tectonics on the Northern Chihuahua Trough: Doctors Dissertation, the University of Texas at El Paso.
- Cather, S.M., Chamberlin, C.E., Chapin, C.E., and McIntosh, W.C., 1994, Stratigraphic consequences of episodic extension in the Lemitar Mountains, central Rio Grande rift: *Geological Society of America, Special Paper*, 291, p. 157-170.
- Cowan, D.S., and Brandon, M.T., 1994, A symmetry-based method for kinematic analysis of large-slip brittle fault zones: *American Journal of Science*, v. 294, p. 257-306
- DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: *American Journal of Science*, v. 304, p. 105-168.
- DeFord, R.K., 1958, Cretaceous platform and geosyncline, Culbertson and Hudspeth counties, Texas: Van Horn, Texas: *Society of Economic Paleontologists and Mineralogists, Permian Section, Guidebook 1958 Field Trip*, 90 p.
- Denison, H.W., Burke, W.J. Jr., Hetherington, E.A., and Otto, J.B., 1970, Basement rock framework of parts of Texas, southern New Mexico and northern Mexico, in *The Gologic Framework of Chihuahua Tectonic Belt; Symposium in honor of Professor Ronald K. Deford*: West Texas Geological Society and The University of Texas at Austin, 3-14.
- Dickerson, P.W., 1985, Evidence for Late Cretaceous-early Tertiary transpression in Trans-Pecos Texas and adjacent Mexico, *in Structure and Tectonics of Trans-Pecos Texas*: West Texas Geological Society, Publication 85-81, 185-194.
- Dickinson, W. R., Lawton, T. F., 2001, Carboniferous to Cretaceous assembly and fragmentation of Mexico: *Geological society of America Bulletin*, v. 113, p. 1149-1160.
- Drewes, H., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: *Geological Society of America, Bulletin*, v. 89, p. 641-657.
- Drewes, H., 1988, Development of the forland zone and adjacent teranes of the Cordilleran orogenic belt near the U.S. Mexican border: *Geological Society of America, Memoir* 171, p. 447-463.

- Drewes, H., 1991, Description and development of the Cordilleran orogenic belt in the southwestern United States and northern Mexico: United States Geological Survey, professional Paper, 1512, 92 p.
- El Harfi, A., Guiraud, M., and Lang, J., 2006, Deep-rooted “thick skinned” model for the high Atlas Mountains (Morocco). Implications for the structural inheritance of the southern Tethys passive margin: *Journal of Structural Geology*, p. 1958-1976.
- Elliot, D., 1976, The energy balance and deformation mechanisms of thrust sheets: *Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences*, v. 283, p. 289-312.
- Haenggi, W. T., 2002, Tectonic history of the Chihuahua trough, Mexico and adjacent USA, Part II: Mesozoic and Cenozoic: *Boletín de la Sociedad Geológica Mexicana*, Tomo LV, Num. 1, p. 38-94.
- Haenggi, W.T., Gries, J.F., 1970, Structural evolution of northeastern Chihuahua Tectonic Belt, *in* *Geology of the Southern Quitman Mountains Area, Trans-Pecos Texas: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication 70-12*, p. 55-69.
- Hennings, P.H., 1991, Structural studies of the Chihuahua Tectonic Belt: Dissertation, University of Texas at Austin.
- Hennings, P.H., 1994, Structural transect of the southern Chihuahua Fold Belt between Ojinaga and Aldama, Chihuahua, Mexico: *Tectonics*, v. 13, p. 1445-1460.
- Henry, C.D., Price, J.G., James, E.W., 1991, Mid-Cenozoic stress evolution and magmatism in the southern Cordillera, Texas and Mexico: Transition from continental arc to intraplate extension: *Journal of Geophysical Research*, 96, 13,545, 13,560.
- Konstantinovskaya, E.A., Harris, L.B., Poulin, J., and Ivanov, G.M., 2007, Transfer zones and fault reactivation in inverted rift basins: Insights from physical modeling: *Tectonophysics*, v. 441, p. 1-26.
- Langford, R.P., Jackson, M.L.W., Whitelaw, M.J., 1999, The Miocene to Pleistocene filling of a mature extensional basin in Trans-Pecos Texas: geomorphic and hydrologic controls on deposition: *Sedimentary Geology*, p. 131-153.
- Lawton, T.F., McMillan, N.J., 1999, Arc abandonment as a cause for passive continental rifting: Comparison of the Jurassic Mexican Borderland rift and the Cenozoic Rio Grande rift: *Geology*, v. 27, p. 779-782.
- Lehman, T.M., 1991, Sedimentation and tectonism in the Laramide Tornillo Basin of west Texas: *Sedimentary Geology*, v. 75, p. 9-28.

- Lopez-Ramos, E., 1988, Geologia y aprovechamiento integral de las perforaciones in el altiplano Mexicano: Geomimet, v. 151, p. 84-100.
- Lowell, J.D., 1995, Mechanics of basin inversion from worldwide examples: Geological Society Special Publications, No. 88, p. 39-57.
- Mattioni, L., Sassi, W., and Callot, J.P., 2007, Analogue models of basin inversion by transpression: role of structural heterogeneity: Geological Society of London, Special Publications, v. 272, p. 397-417.
- May, S.J., and Russell, L.R., 1994, Thickness of the syn-rift Santa Fe Group in the Albuquerque Basin and its relation to structural style: Geological Society of America, Special Paper 291, p. 113-123.
- McDowell, F.W., and Maugher, R.L., 1994, K-Ar and U-Pb zircon chronology of Late Cretaceous and Tertiary magmatism in central Chihuahua State, Mexico: Geological Society of America, Bulletin, v. 106, p. 118-132.
- Pavlis, T.L., Langford, R., Hurtado, J., and Serpa, L., 2010, Computer-based acquisition and visualization system in field geology: Results from 12 years of experimentation and future potential: Geosphere, v. 6, no. 3, p. 275-294.
- Reaser, D.F., 1982, Geometry and deformational environment of the Cineguilla-Quitman range in northeastern Chihuahua, Mexico and western Trans-Pecos Texas, USA: *in* Powers, R.B. (ed.), Geologic studies of the Cordilleran thrust belt, v. 1: Denver, Co., Rocky Mountain Association of Geologists, 425-449.
- Reyes-Cortes, I.A., Goodell, P.C., 2000, Geologic setting and mineralization: Sierra Pena Blanca, Chihuahua, Mexico, in Cuarta Reunion Sobre la Geologia del Noroeste de Mexico y Areas Adyacentes, Estacion Regional del Noroeste: Universidad Nacional Autonoma de Mexico, Instituto de Geologia, Estacion Regional del Noreste, Publicaciones Ocasionales, no. 2, 101.
- Rohrbaugh, R. T., 2001, Contractional and extensional deformation kinematics of the southern Indio Mountains, Trans-Pecos Texas: Master Thesis, The University of Texas at El Paso.
- Teixell, A., Arboleya, M.A., and Julivert, M., 2003, Tectonic shortening and topography in the central High Atlas (Morocco): Tectonics, v. 22, no. 5, p. 1-13.
- Twiss, P.C., 1959, Geology of the Van Horn Mountains, Trans-Pecos Texas: Dissertation, The University of Texas at Austin.
- Underwood, J. R., 1962, Geologic map of Eagle Mountains and Vicinity, Hudspeth County, Texas: The University of Texas at Austin, Bur. Econ. Geol. Quad. Map No. 26, 32 page text.

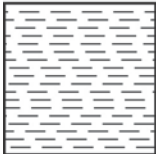
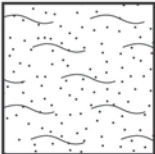
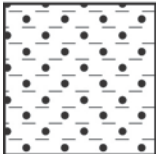
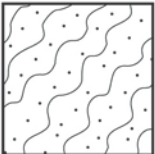
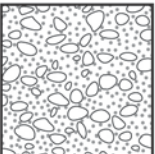
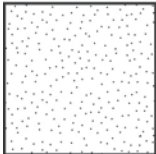
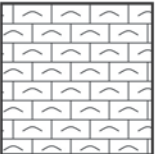
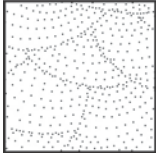
Underwood, J.R., 1962, Geology of the Eagle Mountains and Vicinity, Hudspeth County, Texas: Dissertation, The University of Texas at Austin.

Underwood, J.R., 1980, Physiographic features, Trans-Pecos region: New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos Region, p. 57-58.

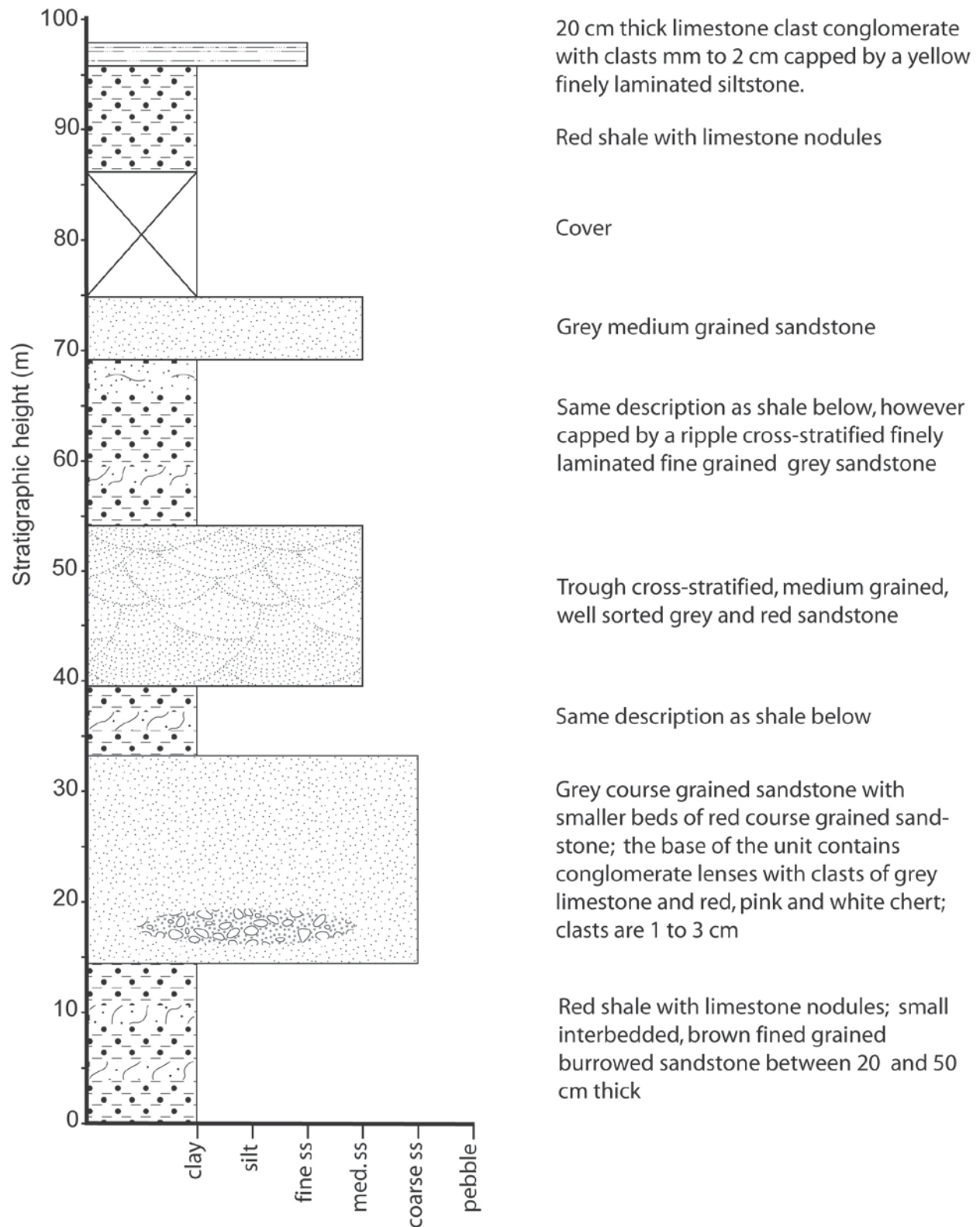
Appendix

The following is a detailed description of the three stratigraphic sections of the upper Yucca. The location of the sections can be found on the map (fig. 5). Sections were done in the hanging wall of the Squaw and Bennett thrusts and in the footwall of the Indio fault to show a thickening in strata of the section in the Squaw thrust. One hundred meters of repeated strata was encountered in the section above the squaw thrust and was subtracted from the total thickness. The total measured thicknesses are as follows: Section in footwall of Indio fault 280 m, Bennett thrust hanging wall 320 m, and Squaw thrust hanging wall 650 m. The thickening is interpreted as thickening along an original syn-rift fault then thrust over the thinner section. The following are the symbols used in the stratigraphic columns.

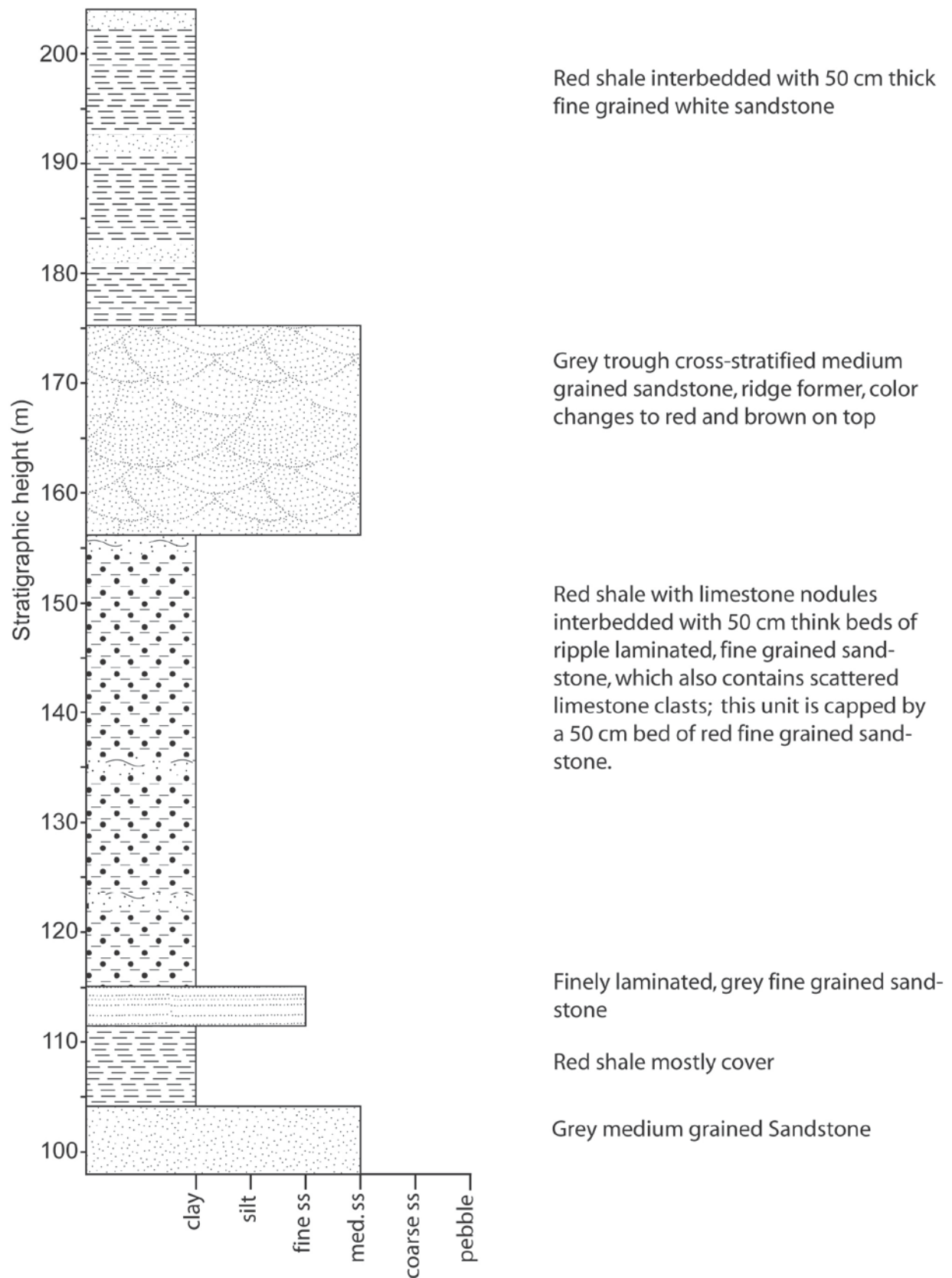
Description of Symbols used in stratigraphic column

	Shale		Rippled Sandstone
	Shale with limestone nodules		Burrowed Sandstone
	Siltstone		Conglomerate
	Sandstone		Fossiliferous Limestone
	Laminated Sandstone		Cover material
	Cross Bedded Sandstone		

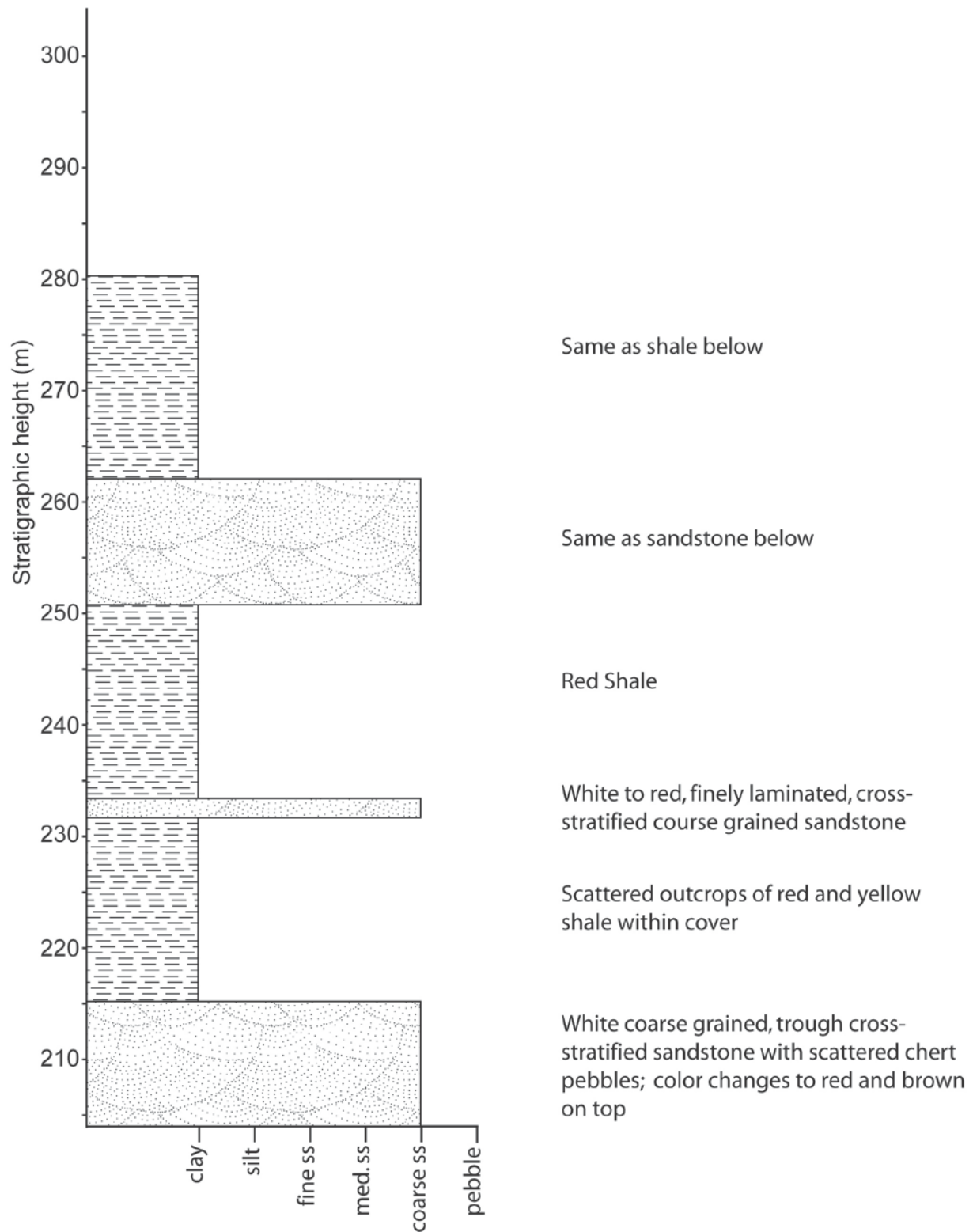
Upper Yucca Section in the Indio Foot wall 0-100 m



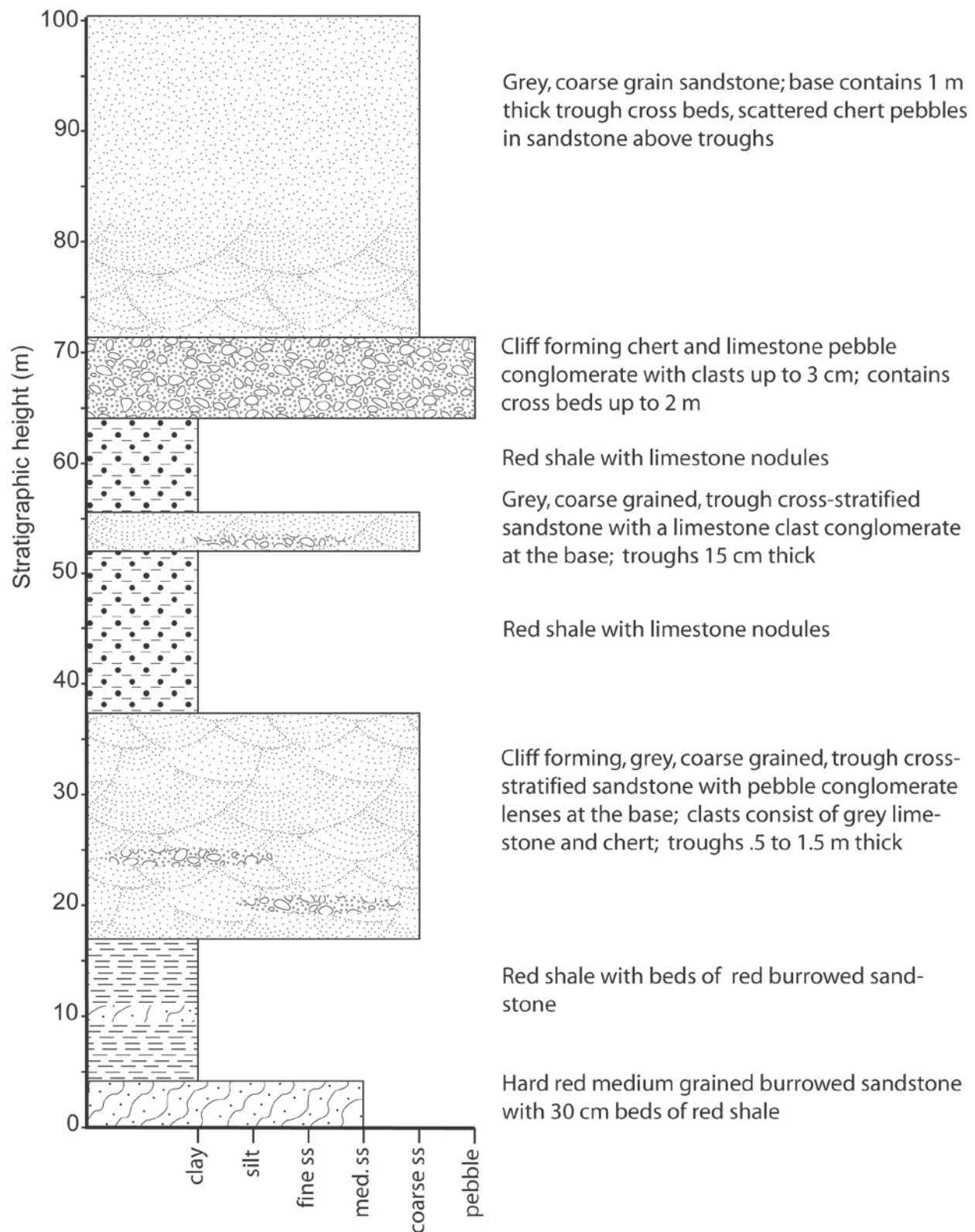
Upper Yucca Section in the Indio Foot wall 100-200 m



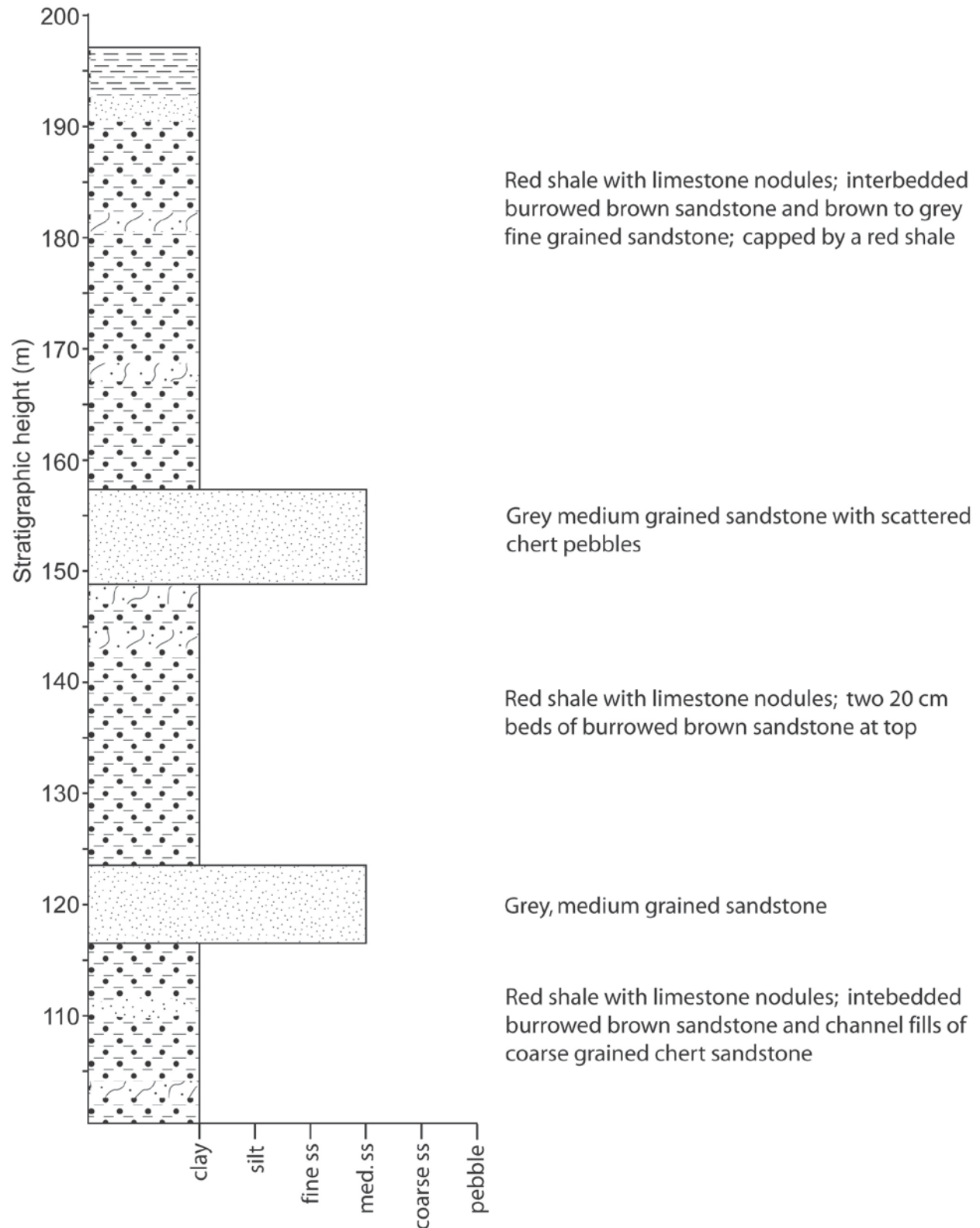
Upper Yucca Section in the Indio Foot wall 200-280 m



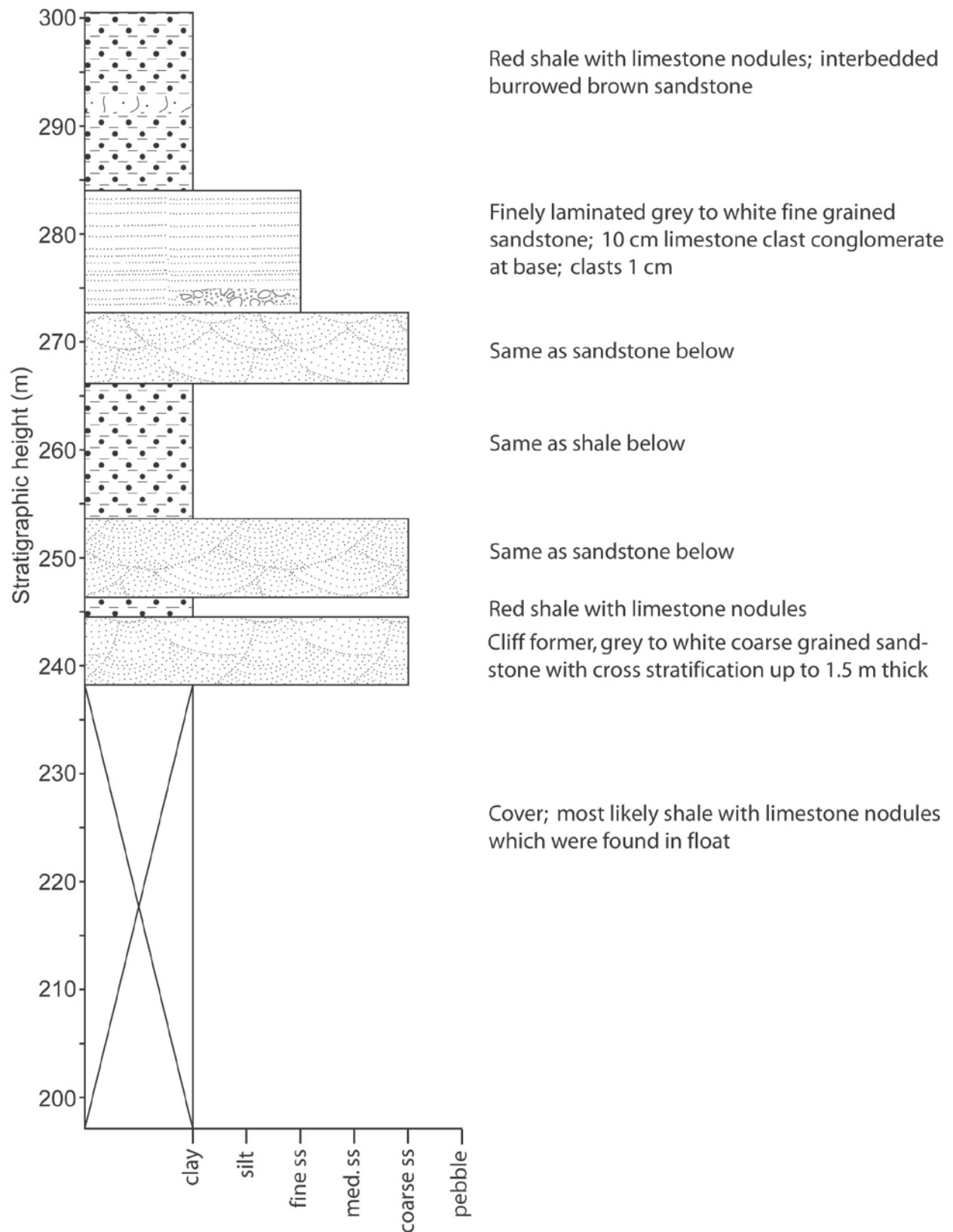
Upper Yucca section in Bennett Thrust 0-100 m



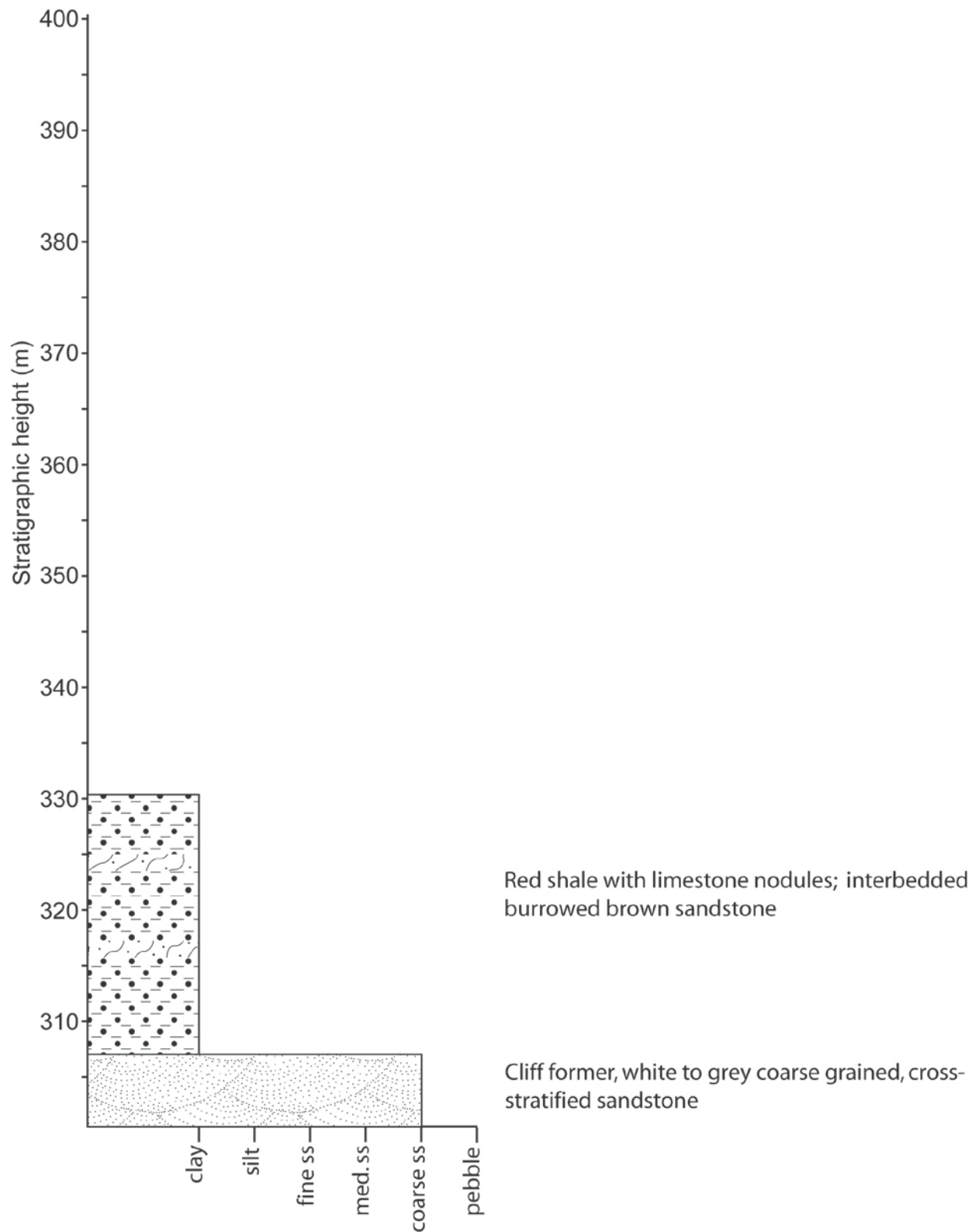
Upper Yucca section in Bennett Thrust 100-200 m



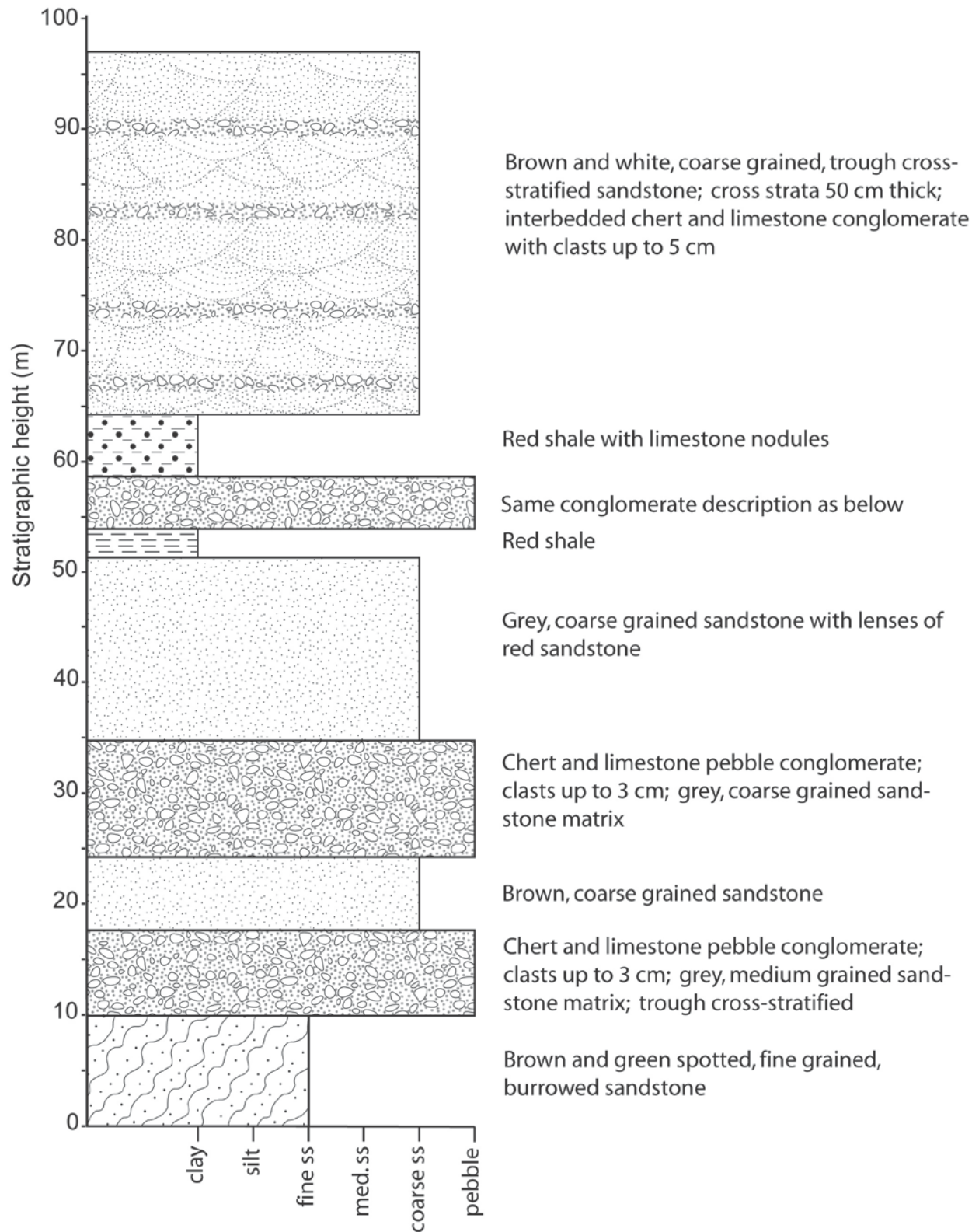
Upper Yucca section in Bennett Thrust 200-300 m



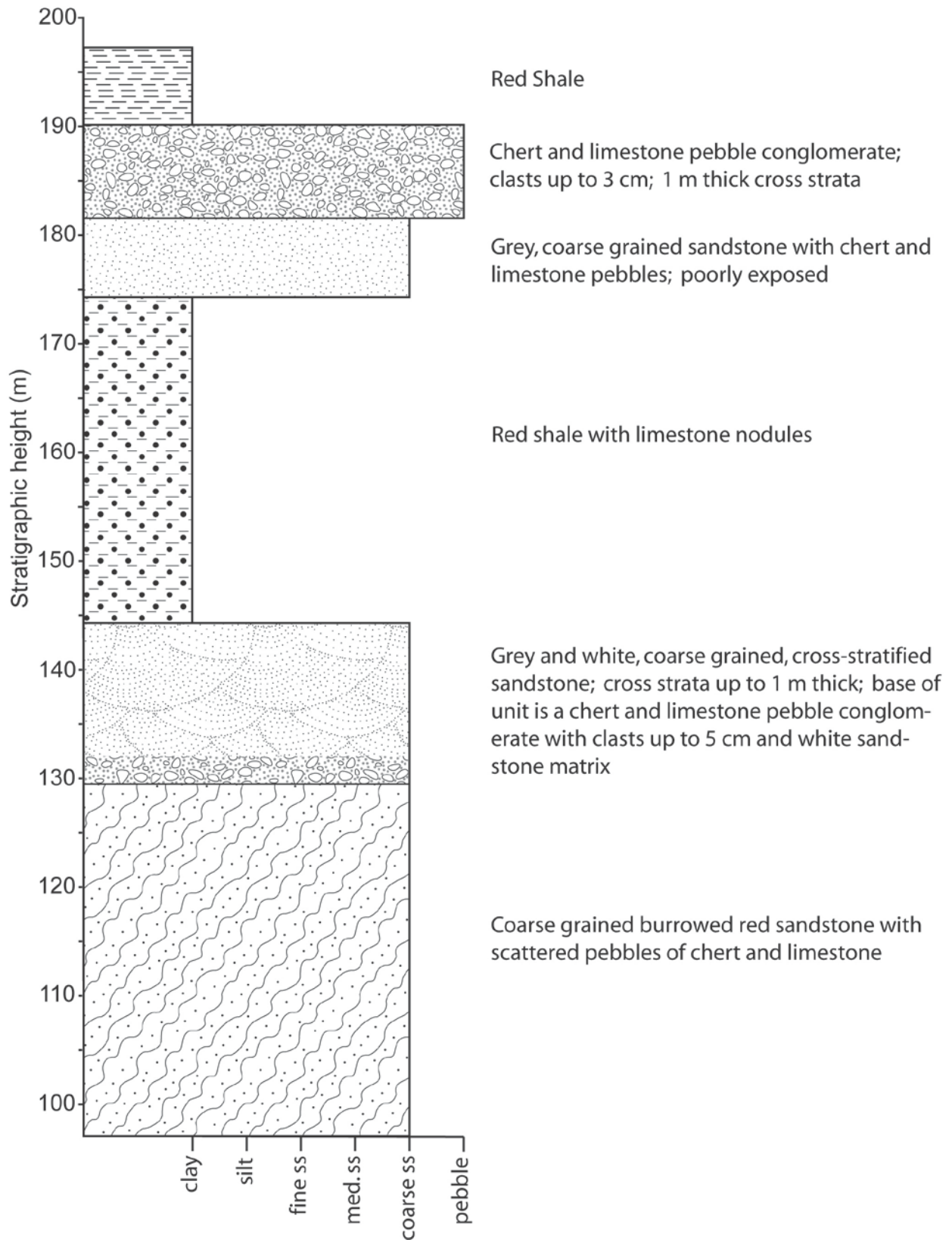
Upper Yucca section in Bennett Thrust 300-330 m



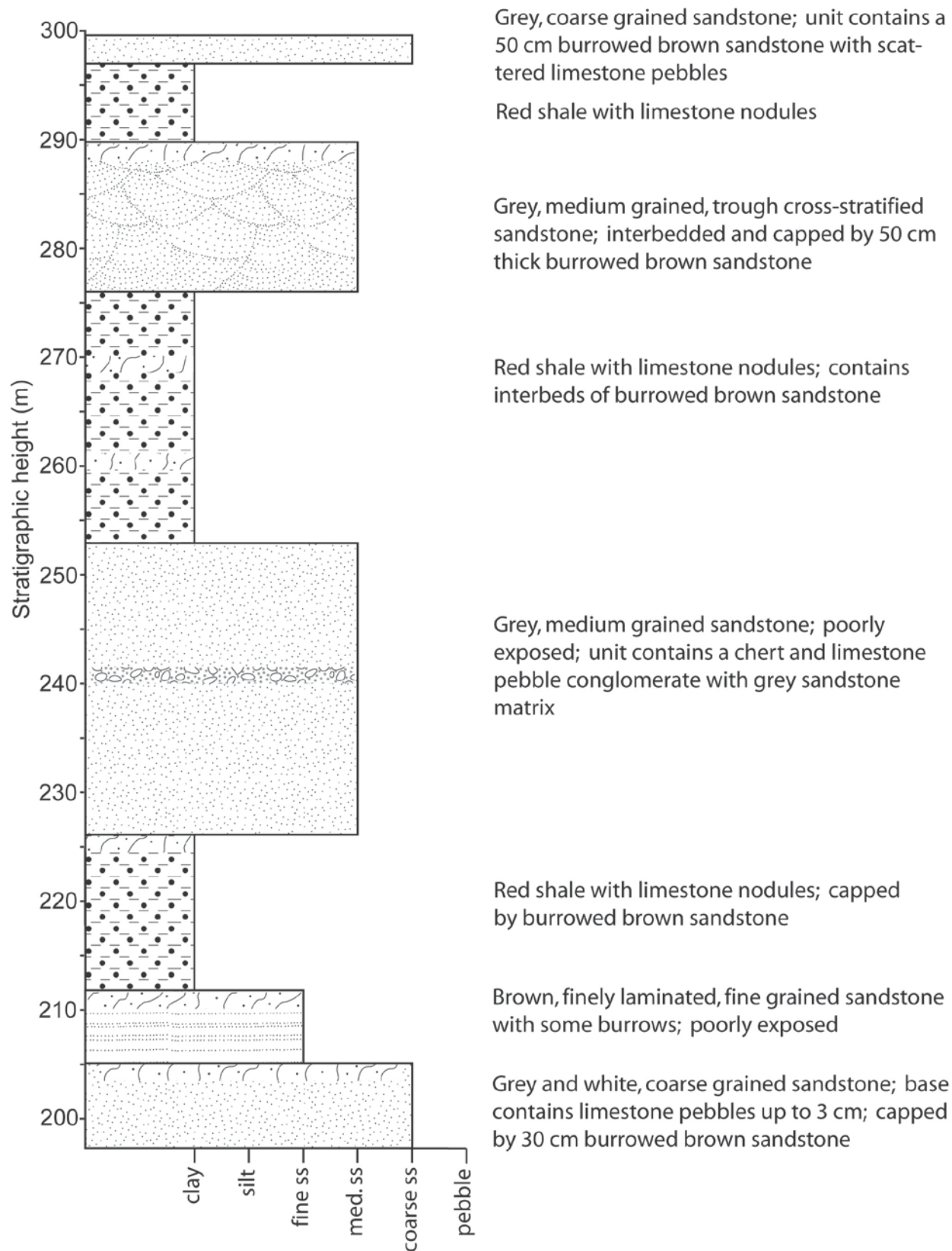
Upper Yucca section in Squaw Thrust 0-100 m



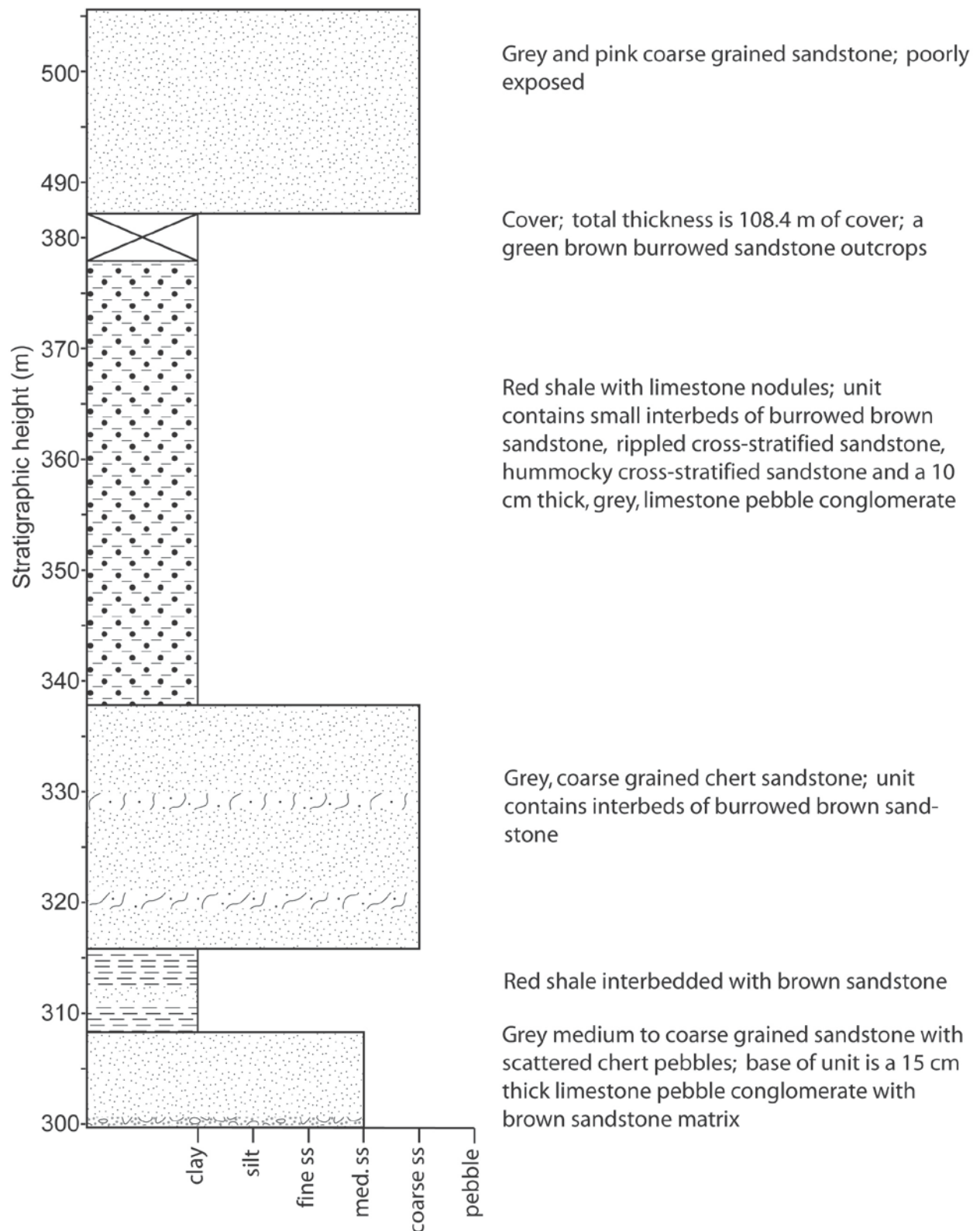
Upper Yucca section in Squaw Thrust 100-200 m



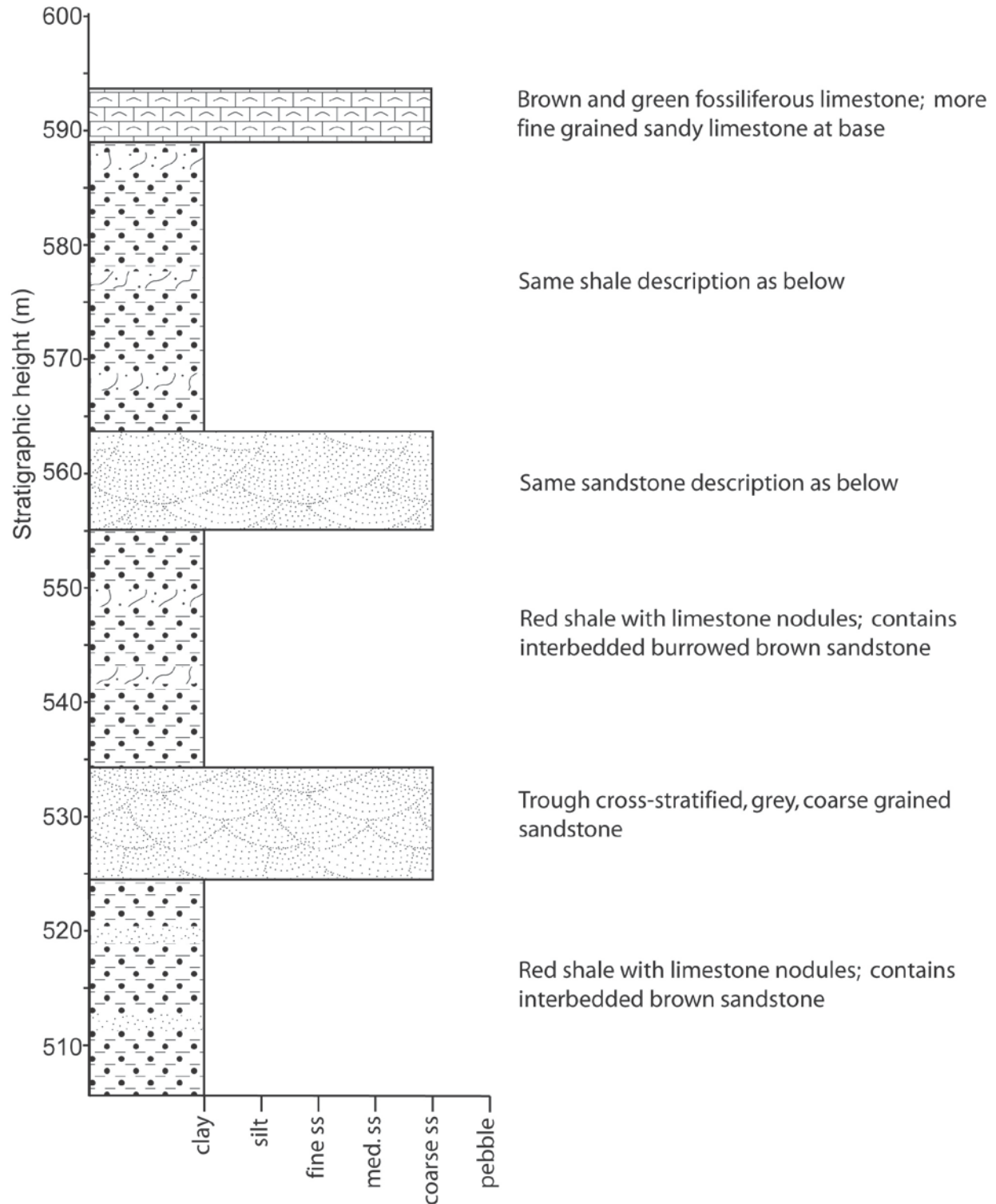
Upper Yucca section in Squaw Thrust 200-300 m



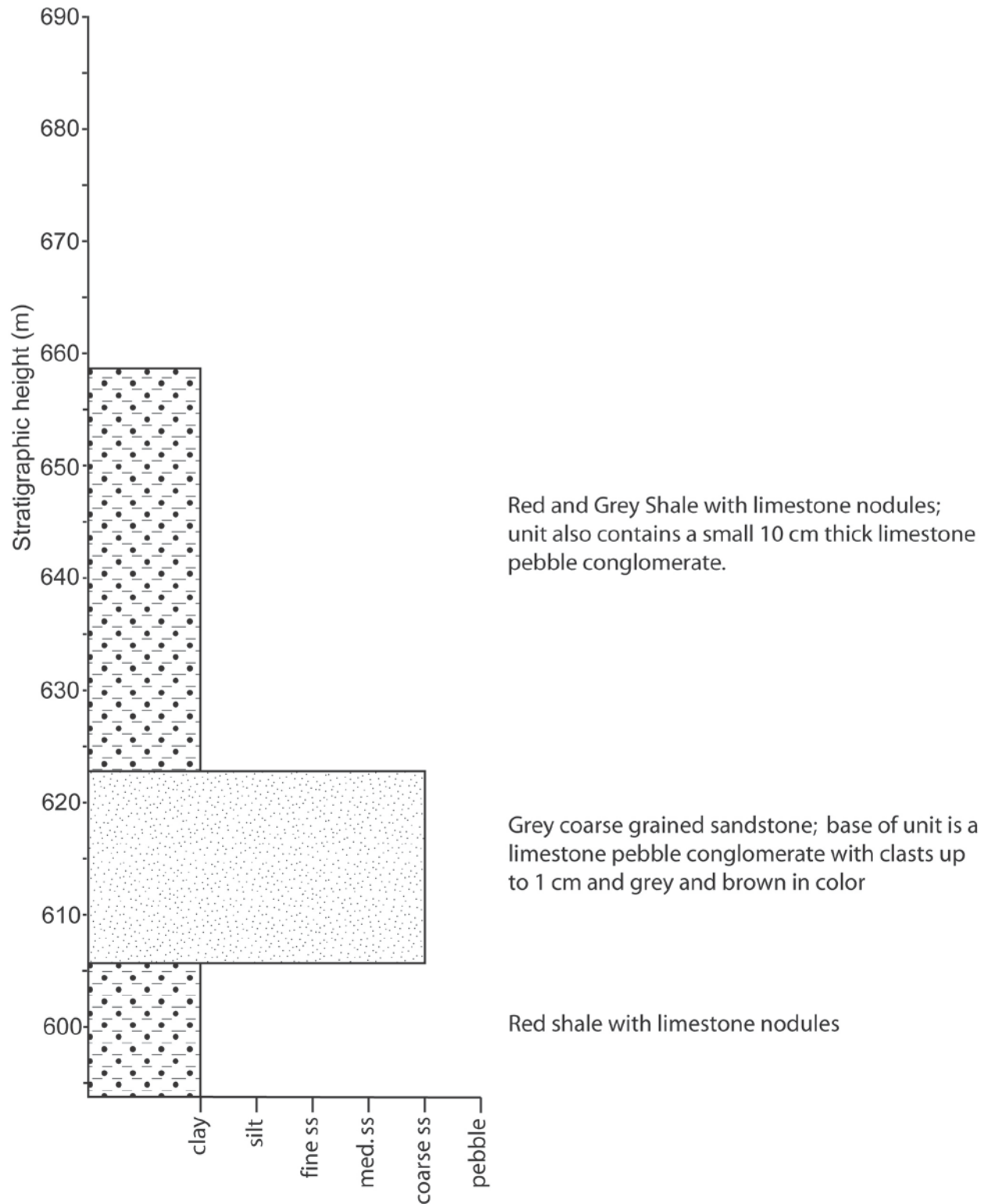
Upper Yucca section in Squaw Thrust 300-500 m



Upper Yucca section in Squaw Thrust 500-600 m



Upper Yucca section in Squaw Thrust 600-657 m



Curriculum Vita

Seth J. Page was born in Cedar City, Utah; the seventh child of Leland and Silvia Page. He graduated from Silverado High School in Henderson, Nevada, in the spring of 2001 and graduated from the University of Nevada, Las Vegas with a bachelor's degree in Geology in the spring of 2009. He married his wife Barvara (Daisy) Garcia-Amaya in 2006. Seth and Daisy moved to El Paso, Texas in 2009 to pursue his masters in Geology. Seth worked for Marathon Oil as a summer intern in 2011.

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