Using Syndepositional Monoclines to Estimate Paleo-Elastic Properties of a Mixed Carbonate Siliciclastic Sequence, Guadalupe Mts, NM

by

Natchanan Doungkaew
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## Contents

Abstract .................................................................................................................................... 1

Introduction ............................................................................................................................. 3

Geologic Background .......................................................................................................... 5

Methods .................................................................................................................................. 10

Part I: Field Study .............................................................................................................. 10

Part II: Petrographic Study ................................................................................................. 12

Part III: Construction of photorealistic models ............................................................... 13

Part IV: Creating models in COMSOL Multiphysics ......................................................... 16

Model Definition .................................................................................................................. 17

Creating Physics and Defining Global Parameters ......................................................... 17

Creating geometry and defining boundaries, contacts, and continuity ......................... 18

Setting Material Properties and Mesh .............................................................................. 21

Set up Solid Mechanics ...................................................................................................... 23

Solving and Exporting Results ........................................................................................... 24

Results .................................................................................................................................... 26

Slaughter Canyon ............................................................................................................... 26

Field Study ............................................................................................................................ 26

Petrographic Analysis ......................................................................................................... 27

3D Photorealistic Models ..................................................................................................... 30

Stereonet ............................................................................................................................... 34

Indian Shelter ........................................................................................................................ 38

Field Study ............................................................................................................................ 38

Petrographic Study ............................................................................................................... 39

3D Photorealistic Models ..................................................................................................... 41

Stereonet ............................................................................................................................... 43

COMSOL Multiphysics Solid Mechanics Model .............................................................. 46

Discussion .............................................................................................................................. 58

Field Study, Petrographic Study and 3D Model ................................................................. 58

Slaughter Canyon ............................................................................................................... 59

Indian Shelter ....................................................................................................................... 60
Abstract

The ability to predict the paleo-mechanical property of rocks is vital to the exploration and production of oil, gas, and geothermal energy and ground water resource analysis. The goal of this thesis is to demonstrate a possible new approach to determining the paleo-mechanical property of sedimentary rock. I combined traditional field study, petrographic study, and 3D photorealistic modelling with finite element modelling to determine the stiffness of sedimentary rocks during the time of faulting and folding. I conducted a field study at the fault E monocline at Slaughter Canyon, and the Indian Shelter monocline at Walnut Canyon, both of which are located within the Capitan platform in the Guadalupe Mountains, New Mexico. The field study suggests that the preexisting strata controlled the orientations of the fractures along the two monoclines. The absence of soft sediment deformation structures and the presence of fractures at both sites indicate that folding occurred through brittle deformation. Petrographic and field studies showed that the depositional environment of packstone folded in the fault E monocline was deposited in shallow waters of the Capitan back reef. They also showed that the depositional environment of the sandstone that made up the Indian Shelter monocline was a peritidal shelf-crest environment. I used the geometries of the outcrops from my photorealistic models of the two monoclines to build finite element models in COMSOL Multiphysics. The models show the effects of changing fault depth and Young’s modulus on the shape of monoclines and the magnitude of fault slip. The
fault throw increases as fault dip increases, but decreases as the Young’s modulus increases. The solid mechanics models of fault E monocline suggest that the Young’s modulus of the packstone was 25 GPa, while the Indian Shelter models suggest that the Young’s modulus of the sandstone was 10 GPa at the time of folding. These values are more than 60% lower than the present-day elastic stiffness. Both of the rocks might have become stiffer due to further cementation and compaction by deposition of the other high-frequency sequences above them. Overall, the combination of field study, petrographic study, photorealistic modelling, and finite element modelling has demonstrated the potential to infer paleo-stiffness of ancient sediments, but further modelling is needed to verify the method.
Introduction

Sedimentary rocks deform in both fluid-like and elastic-plastic manners. The first case is usually referred to as soft sediment deformation, which is the rearrangement of un lithified sedimentary particles without internal deformation of the particles or any interstitial cement (Maltman, 1994; Waldron and Gagnon, 2011). The second type is usually referred to as brittle deformation. It tends to occur in consolidated or cemented rocks that experience stress greater than their yield strength and start to break. Below the yield strength, the rocks behave like elastic solids. However, above this limit, the rocks begin to behave plastically (David & Reynolds, 1942).

The goal of this thesis is to demonstrate a new approach to determining the paleo-mechanical property of sedimentary rock during the time it deformed. I combined traditional field study, petrographic study, and 3D photorealistic modelling with finite element modelling to determine how stiff sedimentary rocks were during the time of faulting and folding. Specifically, the field study and petrographic study can be used to infer depositional environment. The field study and the photorealistic modelling together give information about the geometry of the structure. The finite element model gives the last piece of information, the Young’s modulus (stiffness) that is consistent with the fold geometry. Lastly, by comparing the paleo-Young’s modulus and present Young’s modulus, I am able to tell how the rocks have changed over the intervening millions of years.
I visited a monocline on top of fault E (Hunt et al., 2002) at Slaughter Canyon and the monocline at the Indian shelter (Kosa and Hunt 2006) to conduct the field study. These two locations are parts of the Capitan platform in the Guadalupe Mountains, New Mexico. The changes in thickness, geometry, and facies of the Permian shelf strata at the Capitan platform indicate that syndepositional faults and fault-related deformation are an important factor that shapes the structures of the platform (Hunt et al., 2002; Kosa and Hunt, 2005). Because sedimentation occurred concurrently with faulting, the sedimentary rocks located at these two locations could have been either unlithified or cemented during folding.

The paleo-mechanical properties, including stiffness of the carbonate rock, can be used to evaluate the porosity and permeability of a formation. The ability to predict this mechanical property and distribution of deformation features of rocks is vital to oil, gas, and geothermal exploration and production and ground water resource analysis. This new approach will potentially aid geologists in studying paleo-mechanical properties of rock and in validating paleo-mechanical properties derived from other methods.
Geologic Background

The Guadalupe Mountains are located in southeast New Mexico and west Texas, USA (Fig. 1). During the late Mississippian to early Permian, the Permian Basin formed as a foreland basin of the Marathon Fold Belt. The Fold Belt was formed during the continental collision between Laurasia and Gondwana (Hill, 2000). In late Permian, the Mountains were located about 10° north of the equator (Osleger, 1998; Golonka et al., 1994). The development of broad coastal siliciclastic sabkha indicates that past climate was extremely arid. The uplift of the basin started at the western side of the basin by the Laramide orogeny in Late the Cretaceous to Eocene, and the further uplift due to NNW-SSE oriented faults occurred in the Oligocene-Pliocene (Fig. 2; Hill, 2000). This latest uplift is associated with the formation of the Basin and Range Province, and the Guadalupe Mountains are the easternmost range of the Basin and Range Province in southern New Mexico (Kosa and Hunt, 2005).
Figure 1 The Landsat image of the present-day Guadalupe and Delaware Mountains from Harris (2004).

Figure 2 The canyons located along the Guadalupe Mountains, and the Guadalupe Mountains. The mountains are uplifted along NNW-SSE-trending faults. The steronets show 1) orientation of uplift related faults and fractures, 2) orientation of syndepositional faults and fractures, and 3) trends of fault-and-fracture-controlled passage of Lechuguilla Cave (from Kosa and Hunt (2005)).
The Guadalupe Mountains consist of the Upper Permian Capitan platform, which is located on the Northwest edge of the Delaware Basin (Osleger, 1998; Harris, 2004). The Capitan platform is exposed along the southeast escarpment of the mountains. It is comprised of the Seven Rivers, Yates and Tansill formations. Growth strata, syndepositional folds, faults and fractures that are present along the Capitan platform between Double and Walnut Canyons (Fig. 2) indicate that syndepositional faults and fault-related deformation are important factors that shaped the structures of the platform (Hunt et al., 2002; Kosa and Hunt, 2005). Hunt and Fitchen (1999) and Rush and Kerans (2010) also suggest that during the syndepositional faulting, sedimentation exceeded tilting and growth faulting which resulted in a relief across the platform from shelf-crest to reef margin. This study examines the exposed syndepositional monoclines on top of fault E at Slaughter Canyon and at the Indian Shelter in Walnut Canyon (Fig. 3). Both monoclines are located within the Yates formation.

The Yates formation is divided into 5 complete high frequency sequences (Yates1-Yates5; Fig. 4) based on retrogradational, aggradational and progradational stacking patterns of meter-scale cycles in the formations (Osleger, 1998). All of the boundaries between Yates1 – Yates4 are exposure surfaces that show abrupt basinward shifts in facies and large scale lateral change. Overlying each of the boundaries is a thick siliciclastic bed. The lower parts of all of the high frequency sequences are characterized by higher volumes of siliciclastics whereas the upper parts of all of the sequences tend to be more carbonate-dominated (Osleger, 1998).
Figure 3 Locations of the study areas (shaded) in the Slaughter Canyon and the Walnut Canyon adapted from Osleger (1998).

Figure 4 Yates High Frequency Sequences from Osleger (1998)
The study area at the tip of fault E at Slaughter Canyon consists of sequences Yates1 – Yates3. At Slaughter Canyon, faulting and fault-related deformation primarily controlled changes in thickness, facies and stratal geometry, and resulted in the local steepening, shallowing and the reversal of dip in shelf strata of Slaughter Canyon. Besides faulting, evidence found at Slaughter Canyon also suggests that tilting is another factor that controlled the shape of the Capitan platform. After fault growth, a further 4–6 degree basinward inclination of the Capitan platform occurred, most likely during and after the deposition of the tansil formation (Hunt et. al, 2003; Kosa and Hunt, 2006b).

Walnut Canyon is located within the outermost 5-6 km of the Capitan platform (Hunt et. al, 2003). The study area at the Indian Shelter, Walnut Canyon comprises the Yates4 -Yates5 sequences. Besides this fault growth monocline, syndepositional fractures and growth strata are other syndepositional indicators (Kosa and Hunt, 2006a; Tinker 1998; Rush and Kerans, 2010).
Methods

Part I: Field Study

The goal of the field study is to record the geometries of monoclines and the orientations of fractures along the monoclines, and to take photos for 3D model construction. The chosen monoclines are a fold located at the tip of Fault E in Slaughter Canyon, and the Indian Shelter at Walnut Canyon.

I use the informal names ‘Triplet’, ’Hairpin’, and ‘Primitive Road’ to describe specific layers in the sequences Yates5, Yates4 and Yates3 at the Indian Shelter monocline, respectively. I also use the term ‘Corral’ to refer to the siliciclastic facies in Yates4. These terms are described in Pray et al. (1977). In addition to the five complete high frequency sequences proposed by Osleger (1998), I used the strata surface numbers system listed by Hunt et al. (2002) to describe the exposed surfaces at the study sites. The surface numbers range from 1-20. The stratal surfaces at the field site in the Slaughter Canyon ranges from surface number 7-15, while the field site at the Walnut Canyon consists of surface numbers 16-20.

At each location, we took pictures of the monocline at various distances and angles. We mapped the stratigraphy and outcrop scale structure on the images in ArcMap. Then, we looked for changes in facies, fractures including veins, joints and bedding, and recorded the features and the beds’ dips and dip directions as layer attributes. We also used a laser range finder to locate control points on the photos of the monoclines, and to record precise relative locations in horizontal and vertical axes and azimuthal distance. These distances were later used for coordinate calculation.
Additionally, a handheld GPS was used to locate the points where we took the measurements.

For each facies we saw in the outcrops at both locations, we took rock samples for later petrographic study, and used a handheld GPS to record locations where the samples were taken from. Additionally, we used a type M Schmidt hammer to record the rebound numbers of the facies. Later, the rebound numbers were used to calculate the modern Young’s moduli of the facies.

The correlation between a shear modulus (G – in GPa), a dry density (ρ – in g/cm$^3$), and a rebound number(R) has the form of the equation:

$$G = 1.55 + 0.035ρ^2R \text{ (Shackleton, 2005)}$$

The Young’s modulus ($\varepsilon$ – in GPa) can also be derived from a shear modulus by the equation

$$\varepsilon = 2G(1 + \nu) \text{ , when } \nu \text{ is a Poisson’s ratio. (Shackleton, 2005)}$$

I also calculated the dry density of the sample by measuring weights and volumes of the samples. I measured the volume by immersing the samples in water and measuring the volume of the water they displaced. This technique could be implemented on all of the samples taken from Slaughter Canyon since they contained less than 5% pore spaces. However, the same technique could not be applied to the samples from the Indian Shelter because they contained more than 10% pore spaces. Therefore, I used the average dry densities of limestone and sandstone reported in Manger (1963) instead.
Part II: Petrographic Study

The purpose of the petrographic study is to determine the depositional environment, mineralogy, and diagenesis of each sample. The slides were vacuum impregnated with blue epoxy to make the natural pore spaces more visible. Calcite staining was implemented on the thin section for the rapid identification of calcite. The reaction between carbonates and dilute acid was controlled so that the more reactive minerals, such as calcite, stain red, but less reactive ones, such as dolomite, remain unstained. This technique helps differentiate calcite from dolomite.

After I obtained the thin sections, I identified minerals and fossils under a petrographic microscope in both plane polar light and cross polar light. I then estimated average percentage of present-day pore spaces in the thin sections in order to determine 2 dimensions porosity of the samples. The pore geometry and volume determines permeability, or ability of a fluid to pass through a porous medium, or the rock, and more importantly, influence the mechanical properties of rock and the ability of the rock to contain water and produce oil and gas.

To increase the accuracy of mineral identification, I also looked at the Energy Dispersive Spectroscopy (EDS) spectra of several grains of various minerals on a scanning electron microscope (SEM).
Part III: Construction of photorealistic models

Photorealistic modelling has overcome the limits of the 2D traditional field work. This technique not only allows geologists to visualize the structure of the whole outcrop and its surroundings, but also to rotate the model to view the outcrops at different angles, including from a bird's-eye view. The photorealistic model enables geologists to measure bed thicknesses, fold widths and other structures of the outcrop, and then compare them to the field measurements.

I created my photorealistic model by using Agisoft Photoscan (http://www.agisoft.ru/). The program uses Photogrammetry to construct a 3D model including a Digital Elevation Model (DEM) and orthophotos from a suite of photos taken at various angles. After creating 3D models, I calculated 56 and 60 UTM coordinates of control points from the monocline at Slaughter Canyon and the Indian Shelter, respectively. The UTM coordinates were calculated from vertical distance, horizontal distance and azimuth. After that, I used the coordinates to create geographic models of the two monoclines (Please see Appendix I for more details).

Digitizing fractures and recording field measurements of the beddings orientation in ArcScene

I imported the orthophoto and the DEM of each fold as Scene layers in ArcScene. I used the DEM as the base height, and then draped the orthophoto over it. I also used the hillshade effect to enhance the model. I set the z value exaggeration to 5 and set the transparency to 50 percent. After that, I carefully used the field locations of fractures to digitize the fractures as polylines on the orthophoto, and recorded the
dip and dip direction taken in the field as attribute data. Besides fractures, I also marked points where I recorded the dip directions and dip of bedding on the 3D models and added the measurements as attribute data. By setting the DEM to be transparent, I could look at the orientation of the fracture from various angles, especially from behind the monocline. This helped me visualize the arrangement of the fractures along the fold.

**Digitizing sedimentary strata in Adobe Illustrator**

I took screenshots of the 3D models of the two monoclines looking in the strike direction to create dip sections. Then, I imported them to Adobe Illustrator and digitized the stratigraphic surfaces following the work of Osleger (1998) and Hunt et al. (2002). The program enabled raster to vector conversions, which created sharp views of the layers when one zooms in to the images. The Illustrator output clearly shows the stratigraphic profiles, the distribution of carbonate facies, and the shape of the monoclines.

**Plotting the orientation of the fractures.**

In the field, we collected dip and dip direction of 314 fractures at the fault E monocline, and dip and direction of 202 fractures at the Indian Shelter. After digitizing the fractures in ArcScence and digitizing the bedding in Adobe Illustrator, I partitioned the monoclines based on the change of the orientation of the fractures and bedding within the monoclines. Then, I created stereonets that represent the orientation of the fractures in each structural domain in the program Steronet.
(http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html).

Specifically, after exporting the attributes of the fractures in each structure domain into .csv format, I imported the table files to Stereonet to plot a rose diagram that shows the frequency of the strike values of the fractures.

Then I used the function in Stereonet to calculate poles from the planar data. The pole data was needed for the Fisher Vector Distribution calculation. The strike and dip were converted to trend and plunge after this step.

After converting the data from strike and dip to trend and plunge (polar to planar orientation), I plotted the polar orientation of the fractures located each domain and plotted a Kamb contour map on each stereonet.

### Rotating the data relative to the bedding

A Fisher Distribution is commonly used for modeling the distribution of 3-dimensional orientation vectors. The Fisher Distribution gives the mean orientations of the fracture within each domain with respect to the mean bedding orientation.

After I calculated the mean orientation of the bedding in Stereonet, I used the strike of the mean vector for the azimuth of rotation axis, and used the dip of the mean vector for the magnitude of rotation. The strike and dip used for each domains are followings:

<table>
<thead>
<tr>
<th>Structure Domain</th>
<th>Trend</th>
<th>Plunge</th>
<th>Strike</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_1 )</td>
<td>108</td>
<td>86.7</td>
<td>176.7</td>
<td>3.3</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>152</td>
<td>67</td>
<td>242</td>
<td>23</td>
</tr>
<tr>
<td>( b_4 )</td>
<td>357</td>
<td>79.6</td>
<td>87</td>
<td>10.4</td>
</tr>
<tr>
<td>( b_5 )</td>
<td>119.3</td>
<td>76.5</td>
<td>209.3</td>
<td>13.5</td>
</tr>
</tbody>
</table>
After rotating the fracture orientations, I plotted the trend and plunge of the fractures and plotted the Kamb contour again. This allowed me to compare the stereonets of the rotated and unrotated fractures.

**Part IV: Creating models in COMSOL Multiphysics**

After obtaining layer thicknesses and fold geometries from the field study and the 3D models, and after learning about possible depositional environments and mechanical properties from the thin sections and the study of fractures, the next step is to simulate the formation of folds under various mechanical properties and sedimentary structures. In this step, I created models of monoclines in COMSOL Multiphysics with a variety of fault depths and Young’s moduli. The models demonstrate how elasticity of the host rock, the heterogeneity of sedimentary layers, and the depth of the fault tips affect the shape of the monocline and the displacement of the body of rock caused by faulting.
The solid body of rocks under body load due to gravity is forced to deform by faulting (Fig. 5). A boundary load applied horizontally. This is a large sliding problem that includes pressure and friction at the contact. A boundary contact pair is created and the contact functionality of the Structural Mechanics model is used to solve the contact/friction problem.

Creating Physics and Defining Global Parameters

COMSOL Multiphysics (http://www.comsol.com/) allows users to construct finite element models to simulate physics-based systems. Structural Mechanics Module, which is the analysis of mechanical structures that are subject to static or dynamic loads, is one of the built-in models.
The problem is set to a stationary 2D solid mechanic problem. I defined the global parameters, or the input for the models, as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>$14000[N]$</td>
<td>Applied Force - $\sigma_1$ or the least compressive stress</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$0.6$</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>$g$</td>
<td>$9.81[m/s^2]$</td>
<td>acceleration of gravity</td>
</tr>
</tbody>
</table>

The least compressive stress is used as the boundary load. It is set to be roughly 60% of the most compressive stress. The most compressive stress ($\sigma_3$) is $g \times$ density of the rocks. I used the average bulk density of water-saturated sandstone and limestone from the USGS porosity and bulk density of sedimentary rock reported in Manger (1963)

<table>
<thead>
<tr>
<th>Sedimentary Facies</th>
<th>Rock Density ( g/cm$^3$)</th>
<th>Rock Density ( kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2.35</td>
<td>2350</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.72</td>
<td>2720</td>
</tr>
</tbody>
</table>

Creating geometry and defining boundaries, contacts, and continuity

Part I and II: The study of the effect of the depth of the fault tip and the stiffness of the limestone on the slip of the fault and the width of the folds.

The geometry of the model consists of 4 domains: 2 Bézier polygons and 2 rectangles.
The model is 600 meters long. I varied the fault depth by changing the height of the top rectangle r1. Specifically, I set the thickness of the top rectangle, r1, to 3, 15, 30 and 50 meters. The fault is the contact between the two Bézier polygons. Both Bézier polygons are 100 meters thick. The fault line starts at (120, 100) and ends at (177.4, 0). The bottom rectangle r3 represents a soft elastic layer, which acts to limit fault slip. The high of r2 is constant at 20 meters. At each fault depth, I varied the Young’s modulus of the whole model (Fig. 6).

Part III: the effect of the heterogeneity of the sediment on the slip of the fault and the width of the folds

In this third experiment, I constructed another rectangle, r3, on top of r1. The heights of both r1 and r3 were kept constant at 10 and 30 meters respectively when I modeled the Indian Shelter, and they were kept constant at 20 and 10 meters.
respectively when I modeled the Slaughter Canyon (Fig. 7). These heights are measured from the 3D photorealistic model.

Figure 7 Geometry of the Slaughter Canyon model (top) and Indian Shelter model (bottom) in which the Young’s modulus of the top layer $r3$ is varied.
Setting Material Properties and Mesh

To determine the effect of the elasticity of the model on fold widths and slip of the fault, I set the Young’s modulus of the model to 15, 25, 35, 45, and 55 GPa. These values are within the range of possible Young’s modulus of limestone (Zhu, 2012). The properties are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>15, 25, 35, 45, and 55</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.3 (Zhu, 2012; Resor and Flodin, 2010)</td>
<td>Unitless</td>
</tr>
<tr>
<td>Density</td>
<td>2720</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

The properties of the bottom layer (rectangle r2) are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>Constant at 40 MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0</td>
<td>Unitless</td>
</tr>
<tr>
<td>Density</td>
<td>1900</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

When the Poisson’s ratio is set to zero, the layer will not show lateral expansion when compressed.

In the third experiment where there are two beds on top of the fault tip, the properties of the bottom bed (r1) and the two Bézier polygons are constant. The Young’s modulus, Poisson’s ratio, and the density of these layers are set to 25 GPa, 0.3 and 2720 kg/m³ respectively. These are values that give the output fold geometry closest to that of the real Slaughter Canyon outcrop.

To model the fault E monocline, I set the Young’s modulus of the top layer (r3) to 5, 15, 35, 45, and 55 GPa to examine the effect of the change in Young’s
modulus of the top layer on the slip of the fault and on the fold width. The Poisson’s ratio and the density of r3 are set to the same values as r1 and the Bézier polygons, since Yates 1 and Yates 2 consist of carbonate rocks.

To model the Indian Shelter, the Young’s modulus of the top layer (r3) is set to 1, 5, 10, 40, and 50 GPa. All of these values are possible Young’s moduli of sandstone (Zhu, 2012). The Poisson’s ratio is set to 0.29, and the density is 2350 kg/m³. These two values are typical properties of sandstone that makes up the Hairpin sandstone layer.

After specifying the properties, I built the physics-controlled mesh of the two geometries and specified the element size to be extremely fine (Fig. 8).
Set up Solid Mechanics

![Figure 9 Boundary nodes in the model](image)

All materials are linear elastic. All of the domains are under body load, which represents gravitational pressure. The body load is stress or force per unit volume. The boundary where the two Bézier polygons meets represents the normal fault. It is defined as a “contact.” The contact node defines boundaries where the parts can come into contact but cannot penetrate each other under deformation. I also set the friction at the contact to the variable $\mu$ defined as a global parameter. The boundary load represents the tensile force acting on the body of rocks. The roller nodes constrain the displacement in the direction perpendicular to them. The boundary is free to move in the tangential direction to the rollers. The continuity nodes prescribe that the material is continuous across the pairs. In this model, they merge the two Bézier polygons to $r1$. 
Solving and Exporting Results

The shapes of the outputs were determined by the built-in quadratic Lagrange function. After I constructed the models, I created plots of vertical displacement plots. Additionally, I divided the model to a grid of 100 m by maximum y value ($y_{\text{max}}$) m. Each cell of the grid has a dimension of 6 m by 1 m. Then I exported the vertical displacement of the row $y = 0$ and $y = y_{\text{max}}$ or the topmost row in the .txt format to study fold shape. After importing the files in Microsoft Excel, I calculated the fault throw by looking at the maximum change in the displacement of the bottommost layer. Specifically, the bottom layer is where the vertical displacement is greatest. By plotting the displacement value, I could easily identify where the maximum and minimum vertical displacements are. For example, in the graph below, the throw is the difference between the y values at $x=168$ meter where the displacement is smallest and at $x = 186$ meter where the displacement is largest.

Figure 10 Example of the graph used to determine the throw of the fault
I used curvature to determine the width of folds. Specifically, I calculated the rate of the change of the vertical displacement along the top layer of the model by using a finite different approach. Then, I calculated $y''$, or rate of change of $y'$, by using the same equation. The curvature ($\kappa$) of the graph can be calculated by the equation

$$\kappa = \frac{|y''|}{(1+y'^2)^{3/2}}.$$ 

The points where the monocline starts and ends are where the curvature of the graph abruptly changes from increasing to decreasing and vice versa.
Results

Slaughter Canyon

Field Study

Our outcrop extends from surfaces 8 to 10 of Hunt et al. (2002) and is about 10 meters tall and 43 meters wide. Fault E tips out below a growth monocline bounded between surface 8 and 10 or within the Yates 2 layer. The monocline in this study is located on the east side of the canyon.

The relief and dip of strata in the limbs of the monocline progressively decrease upward in younger strata. The indicator of growth folding, which can be seen in the field, is the gradual basinward thickening of the strata across the limbs of the monocline. The folded layers consist of limestone. Small shell and millimeter-scaled fusulinid fossils are visible on the packstone beds on surfaces numbered 8 to 10. The average rebound numbers, dry densities, shear moduli, Young’s moduli, and Poisson’s Ratio of the samples are shown in table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Rebound number</th>
<th>Dry density (g/cm³)</th>
<th>Shear Modulus (GPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guad 07</td>
<td>62.563</td>
<td>2.678</td>
<td>17.255</td>
<td>44.863</td>
<td></td>
</tr>
<tr>
<td>Guad 08</td>
<td>59.625</td>
<td>2.562</td>
<td>15.243</td>
<td>39.632</td>
<td>0.3 (Zhu, 2012; Resor and Flodin, 2010)</td>
</tr>
<tr>
<td>Guad 09</td>
<td>52</td>
<td>2.557</td>
<td>13.454</td>
<td>34.979</td>
<td></td>
</tr>
<tr>
<td>Guad 10</td>
<td>63.875</td>
<td>3.045</td>
<td>22.277</td>
<td>57.920</td>
<td></td>
</tr>
<tr>
<td>Guad 11</td>
<td>60.778</td>
<td>2.590</td>
<td>15.815</td>
<td>41.120</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 the average rebound numbers, dry densities, shear moduli, Young’s moduli, and Poisson’s Ratio of the samples collected from the monocline on top of fault E, Slaughter Canyon
The sandstone layer at surface number 10 is dolomitic sandstone. At the site, we recorded 341 fracture orientations as we walked along the outcrop.

**Petrographic Analysis**

The dominant type of mineral found in all of the thin sections is dolomite, and the dominant types of fossils are fusulinid foraminifera and gastropods. Although all of the samples are classified as packstones, the texture, matrices, and pore spaces presented on the thin sections change as we move along the bed between surfaces 9 and 10 from north to south.

Guad07 is located at the furthest north among all of the samples. On this thin section, both fusulinid foraminifera and gastropod fossils, which make up about 85 percent on thin section, are not disfigured. The matrix is composed of large sparry dolomite and calcite grains that form drusy cement around the fossils and blocky cement toward the center of the void space. (See Appendix II for detailed descriptions of all the samples, SEM images, and EDS spectra).

*Figure 11 Guad07 under plain polar light(left) and under cross polar light(right)*
At about 10 meters south of Guad 07, where we took Guad08 sample, the fusulinid foraminifera are smaller and more deformed. Some of the fossils are even broken. Peloids are also present. Throughout the thin section, the matrix is still composed of large sparry calcite and dolomite that results from diagenesis. However, the grains that make up the drusy and blocky cement are smaller than the grains in Guad07.

![Figure 12 Guad08 under plain polar light(left) and under cross polar light(right)](image)

Guad11, which was taken from the southernmost end of our study site, is drastically different from Guad07. The fragments of fossils and peloids are scattered through the thin section. Most of the fossils at one end of the thin section are replaced by magnetite, which is reddish brown under both cross polar light and plain polar light. Most of the matrix is made up of calcite and dolomite. There is no drusy cement present. The size of the matrix also varies from very fine to large crystals at the center of the spaces.
Figure 13 Guad11 under plain polar light(left) and under cross polar light(right)
3D Photorealistic Models

The 3D model covers a larger area than the area in the field study. The model expands from surface number 7 up to surface number 15. The fold width is about 45 meters measured from point A to B in the 3D model.

Figure 14 3D photorealistic model of the fault E monocline viewed from the west side of the outcrop. East is the direction into the page. North is to the left of the page.
Figure 15 314 fractures recorded from the field were digitized as polylines in ArcScene. The fractures’ orientations are recorded as the attribution of the polylines.
Figure 16 Cross sections of the strata on top of fault E created from the 3D photorealistic model. The red lines at the bottom of the cross sections represent fault E.
Figure 17 Thicknesses of the layer between surface number 8 and 10. Note that the lateral variation of the strata thickness (the growth stratum) is the indication of syndepositional environment.
**Stereonet**

Surfaces 8-10 were divided into 5 structure domains. The first domain starts from the southernmost side of the outcrop. The bed between surface 9 and 10 contains domains 1, 2 and 3. The layer in between surface 8 and 9 contains domains 4 and 5 from north to south.

*Figure 18 The Structure domains used to divide fractures into five groups. The first domain starts from the southernmost part of the outcrop*
Figure 19 Rose Diagrams and Kamb Contour of all the trend of the Unrotated (top) and rotated (bottom) fractures of all of the five structure domains
Structure domains 1, 2 and 5 are located on the east side of the monocline.

The Fisher mean values of the trends of the rotated fractures are 358.4, 350.0 and 317.4 degrees respectively. Additionally, most of the fractures in the first domain are located within 312 to 330 degrees, most of the fractures in the second domain are located within 341 to 350 degrees, and most of the fractures in the fifth domain are located within 311 to 320 degrees. The fractures east of the monocline dip in the opposite direction of the fractures west of the monocline. The Fisher Vector Distribution value of the trends of the rotated fractures are 139.1 degree for domain 4.

Most of the fractures in domain 4 have the trends within 121 and 130 degrees.
Kosa and Hunt (2005) state that the average trend of the Capitan platform is 52.6/232.6 degrees. Although the mode strikes of the fractures in all of the structure domains are parallel to the Capitan platform strike, more fractures in domains 3 and 4, which are the center of the fold, are oriented perpendicular to the platform compared to the other domains.

The dips of the rotated fractures are also not uniform along the monocline. Along the top domains, which include domains 1 and 2, the dips of the fractures decrease from east to west. Specifically, the plunges decrease from 43.1 to 41.8 degrees. The bottom layer displays a different pattern in which the average plunge increases westward from 21.9 to 34.6 degree.
Indian Shelter

Field Study

The outcrop is located in the Hairpin and Corral layers. Our study area includes a small portion of surfaces 15 and 16. We covered an area of 2 meters in height and 60 meters in length, and collected 202 fracture orientations. At the site, the lowstand siliciclastic Corral layer is well-exposed. No fossils are present. At the north side of the study area, a tepee complex is present in the Hairpin. Above the teepee layer, a fault propagation fold develops over a shelfward dipping normal fault. The important visible minerals are calcite and quartz. Pore spaces are also visible in the sample we took. Another sandstone bed in the Hairpin layer about 20 meters above the ground thickens in a shelfward direction. The average rebound numbers, dry densities, shear moduli, Young’s moduli, and Poisson’s Ratio of the samples are:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average rebound number</th>
<th>Dry density (g/cm³)</th>
<th>Shear Modulus (GPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guad 20a</td>
<td>49.875</td>
<td>2.3 (Manger, 1963)</td>
<td>10.784</td>
<td>28.039</td>
<td>0.3 (Zhu, 2012; Resor and Flodin, 2010).</td>
</tr>
<tr>
<td>Guad 20b</td>
<td>55.375</td>
<td></td>
<td>11.803</td>
<td>30.687</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3 the average rebound numbers, dry densities, shear moduli, Young’s moduli, and Poisson’s Ratio of the samples collected from the Indian Shelter monocline, Walnut Canyon*
**Petrographic Study**

Both of the thin sections contain quartz and dolomite. No fossils are present in either of them. They are both classified as dolomitic sandstone. The distinct features in Guad20a are large-grained calcite cement and fenestral fabric. Pore spaces are present in the fenestral pattern, especially at the area where magnetite grains reside. Guad20a also contains fewer quartz content, and the grains are less well-sorted compared to the other thin section.

Both thin sections also contained grains of a mineral that has a brownish tint under plain polar light and is isotropic under cross polar light. Based on the EDS spectrum, the mineral is magnetite.

The Guad20b thin section, which is from the area south of Guad20a, is composed of about 70 percent small and angular quartz grains. The grains are well sorted and angular to sub-angular. The size of the quartz grains in both thin sections are the same. Guad20b contains about 30 percent of pore spaces, while Guad20a contains only 20 percent of pore spaces. However, the average size of the pore spaces in Guad20b is smaller compared to Guad20a. (See Appendix II for detailed descriptions of all the samples, SEM images, and EDS spectra).
Figure 21 Guad20a under plain polar light (left) and under cross polar light (right)

Figure 22 Guad20b under plain polar light (left) and under cross polar light (right)
3D Photorealistic Models

The 3D photorealistic Models reveal the Hairpin dolomite, the Hairpin sandstone, and the Triplet layer above the Corral bed. The 3D model clearly shows that the Hairpin sandstone layer thickens across the structure. This growth stratum is evidence of the syndepositional nature of the fold. The tepee structure and two 12 and 10 meter long fractures are also visible on the north end of the model. The fold width is difficult to measure because in the northern side of the model, the Corral layer is located at the very base of the exposure. Assuming that the monoclines ends at the center of the tepee, measured from point A to B in the photorealistic model, the fold width is approximately 50 m.

Figure 23 3D photorealistic model of the Indian Shelter viewed from the west side of the outcrop. East is the direction into the page. North is to the left of the page.
Figure 24 212 fractures recorded from the field were digitized as polylines in ArcScene. The fractures' orientations are recorded as the attribution of the polylines.

Figure 25 Cross sections of the Indian Shelter monocline created from the 3D model.
Stereonet

The lowermost Hairpin layer is divided into 5 structure domains, starting from South to North.
Table 4 Fisher mean vectors and modes of all fracture orientations on each structure domain of the Indian Shelter

The fractures in domains 1 and 2, which are on the southernmost side of the monocline, are mostly trending within 341 to 350 degrees. At the curving zone/hinge of the fold, the dominant fracture trend changes to between 331 and 340 degrees, and decreases to between 121 and 130 degrees in domains 3 and 4 respectively. At domain 5, where the bending ceases, the dominant trend of the fractures increases to between 181 and 190 degrees.
Kosa and Hunt (2006b) states that the average strike of the strata is 80.4-260.4 degrees. The fractures in all of the structure domains have the strikes parallel to the strata. The fracture orientations are also parallel to the Capitan Platform average strike. However, more fractures in structure domains 3 and 4 are perpendicular to the strata and the platform in comparison to the fractures in the other domains.

The plunges of the fractures in the monocline are more consistent those of the monocline on top of fault E. The values of the plunge are between 45 and 55 degrees.
COMSOL Multiphysics Solid Mechanics Model

Part I: one layer on top of the fault; varied thickness of the top layer and Young’s modulus

**Fault Throw (Vertical displacement of the fault)**

*Thickness of the top layer (meters)*

<table>
<thead>
<tr>
<th>Young’s Modulus(GPa)</th>
<th>3</th>
<th>15</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.008802984</td>
<td>0.009074337</td>
<td>0.010028106</td>
<td>0.011497485</td>
</tr>
<tr>
<td>25</td>
<td>0.005323867</td>
<td>0.005480278</td>
<td>0.006045268</td>
<td>0.006924914</td>
</tr>
<tr>
<td>35</td>
<td>0.003822023</td>
<td>0.003925398</td>
<td>0.004326402</td>
<td>0.004954228</td>
</tr>
<tr>
<td>45</td>
<td>0.002981594</td>
<td>0.003057776</td>
<td>0.003368484</td>
<td>0.003856623</td>
</tr>
<tr>
<td>55</td>
<td>0.002444355</td>
<td>0.002504243</td>
<td>0.002757817</td>
<td>0.003157133</td>
</tr>
</tbody>
</table>

*Table 5 Fault slips derived from the models of all thicknesses and Young’s moduli*

The throw of the normal fault decreases as the stiffness (Young’s modulus) of the folded layer increases, while the throw increases as the thickness of the top layer increases.
Examples of the model outputs (Fig. 29-31) with the constant Young’s modulus of 15 GPa, Poisson’s ratio = 0.3, Density = 2700 kg/m³, and various fault depth.

**Figure 29A** Line = original structure, color = displacement field, y component arrows = Surface displacement field. Fault Depth = 3 m

**Figure 30** Fault Depth = 15 m
Figure 31 Fault Depth = 50 m
Examples of the model outputs (Fig. 32-35) with the constant fault depth of 15 meters, Poisson’s ratio = 0.3, Density = 2700 kg/m$^3$, and various Young’s moduli.

**Figure 32** Line = original structure, color = displacement field, y component arrows = Surface displacement field. Young’s modulus = 15 GPa

**Figure 33** Young’s modulus = 25 GPa
Figure 34 Young's modulus = 35 GPa

Figure 35 Young's modulus = 55 GPa
### Fold width

<table>
<thead>
<tr>
<th>Thickness of the top layer (meters)</th>
<th>3</th>
<th>15</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>42</td>
<td>48</td>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>25</td>
<td>36</td>
<td>36</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td>35</td>
<td>24</td>
<td>24</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>18</td>
<td>18</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>6</td>
<td>12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6 Fold widths derived from the models of all thicknesses and Young’s moduli

Fold width increases as the Young’s modulus of all the domains increases. It also increases as the thickness of the top layer increases. Fold height, however, decreases as the fold width increases. The blank cells in the tables are the areas where there are no significant changes in the curvatures, so there are no clear start and end points of the monocline. The plots of the vertical displacements of the top layer also show that the fold widths in these conditions are large, but the fold heights are extremely small compared to the fold widths.
Part II: two layers on top of the fault; varied young’s modulus of the top layer

Models of the monocline on top of fault E

These are examples of the model outputs (Fig 36-38). The conditions of the models are the following: there are two beds on top of the fault tip, the properties of the limestone bed at the bottom are constant: Young’s modulus = 25 GPa, Poisson’s ratio = 0.3 and the density = 2720 kg/m³.

The Young’s modulus of the top layer is set to 5, 15, 35, 45, and 55 GPa, all are possible Young’s moduli of limestone. Poisson’s ratio and density are set to be the same with the bottom bed.

![Image](image.png)

*Figure 36 Line = original structure, color = displacement field, y component arrows = Surface displacement field. Young’s modulus of the top layer = 5 GPa*
Figure 37 Young’s modulus of the top layer = 35 GPa

Figure 38 Young’s modulus of the top layer = 55 GPa
Fault Throw (Vertical displacement of the fault)

In the fault E monocline models, Fault throw decreases as the Young’s modulus of the top layer increases.

<table>
<thead>
<tr>
<th>Young’s moduli of the top layer (GPa)</th>
<th>Vertical Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.005565299</td>
</tr>
<tr>
<td>15</td>
<td>0.005451193</td>
</tr>
<tr>
<td>35</td>
<td>0.005322935</td>
</tr>
<tr>
<td>45</td>
<td>0.00528217</td>
</tr>
<tr>
<td>55</td>
<td>0.005249885</td>
</tr>
</tbody>
</table>

*Table 7 Fault slips derived from the models of all Young’s moduli*

Fold width

Fold width increases as the Young’s modulus of the top layer increases.

<table>
<thead>
<tr>
<th>Young’s moduli of the top layer (GPa)</th>
<th>Fold width(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>35</td>
<td>54</td>
</tr>
<tr>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>55</td>
<td>60</td>
</tr>
</tbody>
</table>

*Table 8 Fold widths derived from the models of all Young’s moduli*

Models of the Indian Shelter monocline

These are examples of the model outputs (Fig. 39-41). The conditions of the models are the following: there are two beds on top of the fault tip, the properties of the limestone bed at the bottom are constant: Young’s modulus = 25 GPa, Poisson’s ratio = 0.3 and the density = 2720 kg/m³.
The Young’s modulus of the top layer is set to 1, 5, 10, 15, 20, 40, and 50 GPa, all are possible Young’s moduli of sandstone. Poisson’s ratio is set to 0.29, and the density is 2350 kg/m³.

Figure 39 Line = original structure, color = displacement field, y component arrows = Surface displacement field. Young’s modulus of the top layer = 1 GPa
Figure 40 Young's modulus of the top layer = 10 GPa

Figure 41 Young's modulus of the top layer = 50 GPa
In the models of the Indian Shelter monocline, fault throw decreases as the Young’s modulus of the top layer increases. This result is similar to the outputs from the models of the fault E monocline,

### Fault Throw (Vertical displacement of the fault)

<table>
<thead>
<tr>
<th>Young’s moduli of the top layer (GPa)</th>
<th>Vertical Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.003785282</td>
</tr>
<tr>
<td>5</td>
<td>0.003643475</td>
</tr>
<tr>
<td>10</td>
<td>0.003524672</td>
</tr>
<tr>
<td>40</td>
<td>0.003236375</td>
</tr>
<tr>
<td>50</td>
<td>0.003193633</td>
</tr>
</tbody>
</table>

*Table 9 Fault slips derived from the models of all Young’s moduli*

### Fold width

Fold width increases as the Young’s modulus of the top layer increases

<table>
<thead>
<tr>
<th>Young’s moduli of the top layer (GPa)</th>
<th>Fold width(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
</tr>
<tr>
<td>10</td>
<td>48</td>
</tr>
<tr>
<td>40</td>
<td>72</td>
</tr>
<tr>
<td>50</td>
<td>84</td>
</tr>
</tbody>
</table>

*Table 10 Fold widths derived from the models of all Young’s moduli*
Discussion

Field Study, Petrographic Study and 3D Model

Unlike traditional geology maps and block diagrams that present geologic structures in 2 dimensions, the photorealistic models in this study express not only the monoclines, but also the layers surrounding them in 3 dimensions. Furthermore, this technique allows geologists to look at the monocline from various angles by simply rotating the models. The gradual change in thickness that is difficult to see in the fields can be easily perceived in the 3D model. More importantly, fold widths and bed thicknesses, which are difficult to measure in the field, can be easily measured in the photorealistic model.

The angle at which the photos were taken and the distance between the camera and the monocline have significant effects on the quality of the 3D models. For instance, for the fault E monocline at the Slaughter Canyon, most of the photos were taken from south of the folds. This results in a higher resolution on the northern side of the model than on the southern side.

The 3D models created from Agisoft Photoscan in the DEM and orthophoto formats, when imported to ArcScene, lost their high resolution and became distorted. Although the rendering tool in ArcScene helped increase the resolutions of the DEMs and the orthophotos displayed, both files were still distorted.

In addition, the fracture orientations collected from the field study are not Terzhagi corrected so that the average orientation will reflect a bias of the orientation
of the outcrop face. The rose diagrams and the Kamb contour can only qualitatively
describe the orientation of the fractures. Since I did not measure all of the fractures
present, fracture density could not be calculated from the field data.

**Slaughter Canyon**

The 3D model shows that the fusulinid strata between surfaces 7 and 9 thin
and overlap the flanks of the monocline. This suggests that as the fold developed, it
induced topographic relief of the concurrent sea floor. Fault E grew in a shallow
water environment of the Capitan backreef, as evidenced by deposition of packstone (in Yates 2) alternating with sandstone (in Yates 3) in strata 8–16.

The drusy cement and blockly cement on Guad07, 08, and 10 are the first and second generations of cement precipitated within the pores, respectively. Dolomite
found in the cement might have come from reflux of magnesium-rich fluids flowing basinward down the dip of back-reef strata (Melim and Scholle, 2002). Melim and Scholle (2002) explain that the dolomitization occurred during seepage reflux of mainly mesosaline brines derived from the near-backreef carbonate lagoon. The fractures are also regarded as major conduits for the magnesium-rich fluids. (Melim and Scholle, 2002). More importantly, preexisting open vertical fractures played a critical role as pathways for dolomitising fluids. As we can see from the thin section, the large dolomite grains have occupied spaces between the fusilinid fossil.

Fractures parallel to the orientation of the Capitan platform margin indicate
that the margin controlled the least compressive stress orientation. The fractures are perpendicular to the beds throughout the structure. This suggests that bedding also
controls the stress as well. The fault, fractures, and lack of soft sediment deformation indicate that the structures formed in a brittle manner. In other words, when the fault slipped, the sediments were not likely to be unconsolidated.

**Indian Shelter**

The growth strata are clearly visible in the 3D photorealistic model in which the thicknesses of strata increase across the structure. For example, the thickness of the Hairpin sandstone increases from 3.6 to 10 meters. The fold width is approximately 50 meters.

The tepee complex indicates that the depositional environment was peritidal, specifically at the shelf-crest. The tepee exposed at our study site reveals a 5-cm wide fracture that spans multiple generations of fenestral laminit and internal sediment (Rush and Kerans, 2010). Fracture margins and voids were subsequently filled with sediments and cements. The tepee might have developed in an arid, upper intertidal setting. The fenestrae, films of sand, and magnetite are evidence of subaerial exposure.

The sample we collected from the Corral layer is dolomitic sandstone. The sample form the base Hairpin is sand dolomite with fenestral lamination. The depositional environment of the Corral could have been in the subtidal lagoon, further away from the basin than the tepee. However, quartz grains are present in all of the thin sections. The presence of sand in the subtidal area indicates that the Corral
formed at the time when most sands from the basin were carried across the shelf. These shelf sands are interpreted as being the transgressive portions of shelf cycles, with final deposition by a reworking of eolian dune sands and sand blown into adjacent subtidal environments. Later when the flooding of the shelf continued, carbonates formed in the Hairpin and Triplet layers.

Similar to the fault E monocline, the Indian Shelter monocline is oriented parallel to the strata and the Capitan platform. This indicates that the orientation of the structure is controlled by the platform geometry. The mean Fisher Distribution vector of the trend of the fractures in domain 4, which is at the hinge of the fold, is significantly different from the mean vector of the other domains. It could be because of a lithological difference along the fold. Specifically, domain 4 includes the spot where we collected Guad20a sample. Guad20a sample is notably different from Guad20b sample, which was collected from the point within domain 2. Moreover, the fracture orientation could be different because the fractures formed on a different occasion than the fractures in the other domains.

Similar to the fault E monocline, the absence of soft sediment deformation structures and the fractures indicate the strata were likely to deform in a brittle manner.
COMSOL Multiphysics Solid Mechanics Models

For the first part of modelling, I set the model geometry and material properties to determine how the changes in depth of the fault tip and Young’s modulus influence the vertical slip of the fault and the width of the folds.

The solid mechanical models reveal that the throw of the normal fault decreases as the value of the Young’s modulus increases. However, it increases as the thickness of the top layer increases.

*Graph 1 Graph of the fault throws derived from all of the Young’s modulus and bed thicknesses. Vertical displacements of fault increases as the thickness of the top layer increases*
Graph 2 Graph of the fault throws derived from all of the Young’s modulus and bed thicknesses. Fault throw decreases as the Young’s modulus increases.

Fold width increases as thickness of the top layer increases (when the fault is buried deeper). However, it decreases as the Young’s modulus of the host rocks increases.
Graph 3 Fold Width vs Thickness of the top layer. Fold width increases as thickness of the top layer increases. However, it decreases as the Young’s modulus increases.

Both the Young’s modulus and the depth of the upper fault tip are factors that determine the slip of the fault and the shape of the monocline.

Young’s modulus is used to describe elasticity of a material when it is stretched or compressed. The higher the Young’s modulus, the higher the stress required to yield the same strain as a lower Young’s modulus value. With constant boundary load and body load, the material of high Young’s modulus deforms less, resulting in smaller vertical displacement and fold height.

In my model in COMSOL, the body load can be regarded as lithospheric pressure. When the fault underlies a thicker layer of sediment, it experiences greater lithospheric pressure/stress. Therefore, the blocks of rocks deform more when the thickness of the top layer increases.
In the second part of the model, I set up the geometry to investigate the effect of the heterogeneity of the layer about the fault on fault slip and fold width. The output models show that as the material on top of the fault becomes stiffer, the throw decreases. As described above, when the material’s Young’s modulus is high, the strain of the block in the COMSOL model decreases.

*Graph 4* Graph of fault throws vs Young’s modulus of the fault E model (top) and the Indian Shelter model (bottom). As materials become stiffer, the throw of the fault decreases.
However, when the layer containing the fault becomes less stiff, the width of the monoclines increases.

![Graph 5: Graph of fold width vs Young's modulus of the fault E monocline model (top) and the Indian shelter monocline model (bottom). As materials becomes stiffer, the fold width increases.]

The relationship between Young’s modulus and folding in this multi-layer model is different from the results of the single layer model. This result demonstrates
how differences in the Young’s modulus of the layer where the fault resides and the layer above it affect the shape of the monocline. When the Young’s modulus of the top layer is greater than the Young’s modulus of the layer that contains the fault, the region above the fault tip within the top layer experiences almost the same amount of stress as the region around the fault tip. This contributes to more deformation of the top surface.

Specifically, when the material becomes stiffer, more differential stresses is required to make the fault slip. Note that the principal stresses are calculated from the body load and the boundary load. The thicker the top layer, the higher the most compressive stress. The distributions of the third principal stress ($\sigma_3$ – most compressive stress –vertical) and the first principal stress ($\sigma_1$ –less compressive stress –horizontal), explain why the fold width is higher when the Young’s modulus is high. When the material is soft, elastic stress accumulates at the fault tip. However, when the material is stiff, the stress tends to spread out more around the fault tip, causing a larger area in the block to deform.

However, when the fault slips under another layer that has a different Young’s modulus from the bed where the fault exists, the results are opposite to the results of the other models. The fold width increases when the Young’s modulus of the overlying layer (r3) increases. When the Young’s modulus of the top layer is lower than the Young’s modulus of the slipping layer, the top layer experiences less stress. On the other hand, when the top layer is stiffer than the bottom layer, a large amount of stress migrates upward to the top layer. Since the vertical displacement of the fault
decreases as the top layer becomes stiffer, less stress is released after faulting. The stress then migrates upward in the opposite direction to the slip direction, away from the fault tip, and accumulates in the top layer instead.

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<th>Top layer’s Young modulus = 50 GPa</th>
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<td>Bottom layer’s Young Modulus = 25 GPa</td>
<td>Bottom layer’s Young Modulus = 25 GPa</td>
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<tr>
<td>Fault Depth = 40 m</td>
<td>Fault Depth = 40 m</td>
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</table>

*Table 11 Examples of the first and the third principal stresses around the fault tips from the Indian Shelter model*
The Geometry of the Monoclinoes and COMSOL Models

Slaughter Canyon

The displacement of fault E is 24 meters (Kosa and Hunt, 2006). The photorealistic model of the fault E monocline shows that the fold width is about 45 meters, and the average thickness of the folded Yates 2 layer above the fault is approximately 30 meters. Based on Kosa and Hunt (2006), the thickness of the Yates 1 layer, which is the layer that fault E resides, is roughly 100±15 meters, while the whole Slaughter Canyon is about 2400 meters in length. In the COMSOL solid mechanics model, the thickness of the layer that contains the fault is 100 km. This layer represents the Yates 1 layer.

In the first and the second experiments, I assume that the Young’s modulus is homogeneous throughout the block. In other words, I assumed that Yates 1 and Yates 2 had the same stiffness. Based on the fold width outputs from the solid mechanics models, when the fault depth is 30 meters, the Young’s modulus value that yields the fold width closest to 45 meters is 25 GPa. For the vertical displacement of the fault, there is no correlation between the model output and the actual fault throw. This could be an issue with boundary conditions.

In the third experiment, I assume that the stiffness of the Yates 1 and the Yates 2 are not the same and that the Young’s modulus of Yates 1 is 25 GPa. When the Young’s modulus of the top layer (Yates 2) is 35 GPa, the fold width is 54 meters, and when it is 15 GPa, the fold width is 24 meters. These two widths indicate that the
Young’s modulus should be less than 35 GPa, but a lot larger than 15 GPa, so that the fold width is close to 45 meters. This corresponds to the first and the second experiments, in which the homogeneous Young’s modulus of 25 GPa yields the fold width of 48 meters.

The average value of the present day Young’s modulus calculated from the samples is 43.7 GPa, which is 74.81% greater than the model output. After the deformation, the packstone became stiffer, probably due to cementation and later compaction due to the deposition of the Yates 3, Yates 4, Yates 5 and Tansill.

Indian Shelter

The fault tip is buried under the Indian Shelter monocline. I assume that the fault is buried 10 meters below the surface in a limestone layer, and the limestone layer underlies a sandstone layer. From the photorealistic model, the sandstone layer is approximately 30 m. According to the COMSOL solid mechanical model of the Indian shelter, the Young’s modulus of the top sandstone layer should be about 10 GPa, so that the fold width is close to 50 meters.

The average value of the present day Young’s modulus calculated from the samples is 29.36 GPa, which is 65.94% greater than the value derived from the model. Similar to the limestone at the fault E monocline, the sandstone might have become stiffer due to further cementation and compaction.
Conclusion

By combining field study, petrographic study, 3D photorealistic modelling, and finite element modelling, I can potentially determine the stiffness of sedimentary rocks when they deformed.

The fracture orientations collected along the fault E monoclines and the Indian Shelter monocline indicate that the preexisting strata controlled the orientations of the fractures. The joints and the absence of soft sediment deformation structures suggest that the packstone and sandstone did not deform in a fluid-like manner. The rock might have been lithified, but their pore spaces might have not been fully filled, which would explain why their Young’s moduli are lower than the current values.

The solid mechanics model shows the way changing the fault depth and Young’s modulus affects the shape of the monocline and fault slip. Fault throw increases as fault dip increases, but decreases as Young’s modulus increases. The solid mechanics models of the fault E monocline suggest that the Young’s modulus of the Yates 2 packstone should have been 25 GPa, while the Indian Shelter models suggest that the Young’s modulus of the sandstone should have been 10 GPa. These two values are more than 60% lower than the present values. Both rocks might have become stiffer due to further cementation and compaction by deposition of the other high-frequency sequences above them.

Overall, the solid mechanical models yield possible paleo-Young’s moduli of sedimentary rocks. The combination of several disciplines including geology,
geography, and computer modelling that I used to determine Young’s modulus from fold widths could potentially allow one to infer paleo-stiffness. However, further study of the finite element models is required to verify the accuracy of this method.
References


Appendices

Appendix I: Suggestions for Future work

To improve the quality of the field data, the fracture orientations should be Terzhagi corrected. In addition, the scanline method should be implemented to determine fracture density. Because COMSOL Multiphysics allows Coulomb stress modelling, the next step will be comparing the spatial distribution of Coulomb stress to the spatial distribution of fractures.

COMSOL is a powerful tool. The models will be more accurate if the layers are more heterogeneous, and if the geometries of the models imitate the actual outcrops more closely. Also, this approach relies only on fold width to choose the right Young’s moduli. The output will be more accurate the Young’s moduli are determined using the fold width, the fracture density, and the Coulomb stress.

Appendix II: Methods of Constructing the Photorealistic Models

Step 1: calculate the geometric coordinates of the features

The first step in creating a 3D model is to derive the coordinates of each marked feature from the horizontal distance\((hd)\), vertical distance\((yd)\) and azimuth\((\Delta A)\) between the laser range finder and the objects. Because I wanted to create outcrop scale maps, I chose the Universal Transvers Mercator (UTM) system, which allowed me to simply calculate the coordinate of the features I marked by
adding the northing and easting changes in meters to the known coordinate of the base.

![Diagram](image)

Figure 42 A horizontal distance, a change in a vertical distance and an azimuth form a right triangle. By using the simple geometric function, I can calculate the coordinates of all of the control points.

Specifically, the coordinate of the object \((X_1, Y_1)\) is equal to the coordinate of the laser range finder \((X_0, Y_o)\) plus the change in easting\((\Delta x)\) and northing\((\Delta y)\):

\[
(X_1, Y_1) = (X_0 + \Delta x, Y_o + \Delta y), \quad \text{while}
\]

\[
\Delta x = h \cdot \sin(\Delta A), \quad \text{and} \quad \Delta y = h \cdot \cos(\Delta A)
\]

The elevation of the object \((Z)\) is the elevation of the laser range finder + the vertical distance, or

\[
Z = \text{elevation of the laser range finder} + v_d
\]

The \(\Delta x, \Delta y\) and \(Z\) are in meters. I have created an excel spreadsheet that contains the coordinates of all objects for later use in the 3D model construction process.
The coordinates of all of the control points collected from the fault E and the Indian shelter are listed on table 12 and table 13, respectively.

### Table 12 coordinates of all of the control points collected from the fault E monocline

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*Table 12 coordinates of all of the control points collected from the fault E monocline*
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Table 13 coordinates of all of the control points collected from the Indian Shelter monocline

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**Step 2: Create a photogrammetric 3D model**

The photos used to create the models were taken from different angles. Firstly, I imported them to a photogrammetric 3D model generator program called Agisoft Photoscan.

When building the geometry on my model, I created an arbitrary object that has a smooth geometry type with 200,000 face count. Then I created place markers, which are used to optimize camera position and orientation data. On all imported photos, I located the features that I marked and placed a marker on the corresponding points.
After creating markers for all of the objects on the entire suite of photos, I imported the excel file that I created previously into Agisoft as the coordinates of each marker. Then I set the coordinate system of the model to Northern Hemisphere’s WGS 84/UTM zone 13 and rebuilt the geometry of the model with the same face count. After the new geometry was built, I edited it by increasing the face count (which increases the resolution of the model but also exponentially increases the file size). Finally, I built model texture by choosing Orthophoto as my Mapping mode and Mosaic as my Blending mode. I also set atlas width and height to 8192 pixels.

After the 3D model was successfully built, I exported a Digital Elevation Model (DEM) and Orthophoto for later use in ArcScene.
Figure 44 Screen Capture of Agisoft Photoscan: 3D models of the Indian Shelter Monocline

Figure 45 3D model of the monocline on top of fault E at the Slaughter Canyon
Appendix III: Petrographic Analysis

Guad07

Sample taken from the facie locate between layer 9 and 10 at Latitude:
32°08.095214’ N, Longitude: 104°34.018062’ W, and at 1577.1 m above sea level.

Classification: Packstone

Texture

Grains – Almost all of the fossils are whole fossils of both circular and elongated fusulinid foraminifera. The size of the fossil ranges from 2 mm to 8 mm. Some void spaces inside of gastropod and fusulinid fossil are completely filled with crystalline calcite.

Matrix – Throughout the thin section, the matrix is composed of large sparry dolomite and calcite. The cement results from diagenesis. Specifically, the first generation of cement forms crystals that radiate away from the rim of the fossils.

Figure 46 Guad07 under plain polar light(left) and under cross polar light(right)
toward the center of the void spaces. This texture is called drusy cement. Toward the center of the void spaces, the matrix consists of large, irregular patches and mosaics of sparry dolomite. This texture is called blocky cement, which fills the remaining void space as a second generation of cement.

*Pore space:* There is no pore space.

**Guad08**

Sample taken from the facie locate between layer 8 and 9 at Latitude: 32°08.11135’ N, Longitude: 104°34.015283’ W, and at 1551.9 m above sea level. It is about 10 meters north of the Guad07.

*Classification:* Packstone
Texture

Grains – Almost all of the fossils seen in the thin section are whole fossils of fusulinid foraminifera, both circular and elongated. The fossils are more fragmented than the fossils in Guad07. The fossils at the bottom part of the slide are more fragmented and broken compared to the fossils at the top of the slide. The size of the fossil ranges from 1 mm to 5 mm. There are also a few circular calcic peloids that are about 2 mm in diameter. Some spaces inside both the gastropod and fusulinid fossils are completely filled with calcite crystal.

Matrix – Throughout the thin section, the matrix is composed of large sparry dolomite and calcite that results from diagenesis. The void spaces are filled with drusy and blocky cement. Specifically, the dolomite and calcite grains surrounding the fossils are a lot smaller than the grains in the space between the fossils. At one edge of the slide, the matrix consists of pink stained calcite grains that are smaller than the dolomite grains. The calcite cements enclose deformed fusilinid and gastropod fossils that are greenish blue in color under cross polar and plain polar lig. The shell fossil might have been replaced by other minerals.

Pore space

The thin section contains no pore space.
**Guad09**

Sample taken from the facie locate between layer 9 and 10 at Latitude:

32°08.115358’ N, Longitude: 104°34.02514’ W, and at 1560.4 m above sea level.

*Figure 48 Guad09 under plain polar light(left) and under cross polar light(right)*

*Classification:* Packstone with higher percentage of matrix compared to the first two thin sections.

*Texture*

Grains – The fossils are smaller and broken. One piece of gastropod shell has been completely replaced by large pink calcite grains. The fossils are small fusulinid and gastropod, which make up about 30 percent of the slide. The other 40 percent is made of ooids, whose centers are filled with fine carbonate mineral.

Matrix – The thin section contains about 30 percent matrix. The matrix is made up of dolomite and calcite grains that are smaller than the matrix grains in the first two thin sections.
Pore Space

No pore space presented.

Guad10

Sample taken from the facie locate between layer 9 and 10 at Latitude:
32°08.112649’ N, Longitude: 104°34.015490’ W at 1563.9 m above sea level. It is
above the Guad08.

Classification: Packstone

Texture

Grain –The thin section is composed of large round and elongated fusilinid
fossils. It also contains small percent of ooids. The fossil and ooids together made
about 90 percent of the thin section. The center of some ooids are still unfilled.
Matrix – Most of the cement are sparry dolomite and calcite. The dolomite grains are smaller than the grains in Guad07.

*Pore Space*

Some spaces between fossils and inside fossils have not been completely filled with calcite. The pore space occupied only less than 10 percent of the whole thin section.

**Guad11**

Sample taken from the facie locate between layer 9 and 10 at Latitude: 32°08.102289’ N, Longitude: 104°34.001744’ W, and at 1562.0 m above sea level.

*Classification:* Packstone (This thin section contains about 40 percent matrix and 50 percent deformed fossils).
Texture

Grains – Most of the grains are deformed and the fossils lack a distinct shape. The fragments of carbonate lumps/fossils are scattered throughout the thin section. The edges of some fossils also appeared to be dissolved. Most of the fossils at one end of the thin section are replaced by a mineral that is reddish brown under both cross polar and plain polar, which could be magnetite.

Matrix – Most of the matrix is made up of sparry dolomite and calcite. There is no drusy cement present. At the top part, the grains are as large as the grains in section Guad 07. The size of the matrix also varies from very fine to large crystals.

Pore Space

No pore space presented.
Guad 20a

Sample taken from the Corral layer at Latitude: 32°11.200325’ N, Longitude: 104°25.284303’, and at 1200.2 m above sea level. The dip direction/dip of the sample is 330/90

Classification: dolomitic sandstone

Texture:

Grains – Large grains of pink calcite made up about 30 percent of the thin section. Some of the calcite grains display twinning. The thin section also contains about 20 percent small quartz grains and a small percentage of magnetite. Neither fossils nor ooids are present.

Matrix – The matrix is made up of mainly very fine dolomite grains.

Pore Space

Pore spaces are present in fenestral pattern, especially at the area where magnetite grains reside.
Guad 20b

Sample taken from Latitude: 32°11.200327’ N, Longitude: 104°25.286987’ W at 1203.0 m above sea level. The dip direction/dip of the sample is 324/56

Classification: Dolomitic Sandstone

Grains – This thin section is composed of about 70 percent small and angular quartz grains. There are also brownish color magnetite that occupy about 10 percent of the thin section. The magnetite grains are smaller than the magnetite grains found in the other slides. There are two types of layers of quartz. In the first type, the quartz grains are surrounded by fine-grained dolomitic matrix, while in the other type, the quartz grains are surrounded by void spaces.

Matrix – The matrix is made up of mostly very fine dolomite grains.

Pore Space – Pore spaces are present in the second type of layer. There are two bands of quartz, which can easily be seen on the thin section without the aid of the
petrographic microscope. There is no matrix between the quartz grains within the bands. Specifically, the pore spaces between the grains have been filled with very fine grains of dolomite. Overall, the pore spaces make up about 30 percent of the thin section.

**Energy Dispersive Spectroscopy**

**Calcite**

![Figure 53 the areas on Guad20a where I obtained the EDS spectra. Under the petrographic microscope, these areas are inside large pink grains that have twining](image-url)
Figure 54: The EDS spectrum of the EDS2 point (top). The peaks at Ca and O indicate that the pink grains are calcite. The peaks on the spectrum are also similar to the characteristic EDS peaks of calcite reported in Welton (1984).
Magnetite

Figure S5 the areas on Guad20a where I obtained the EDS spectrum. Under the petrographic microscope, this area displays brownish tint under cross polar light and it is isotropic under cross polar light.
Figure 56: The EDS spectrum of the EDS1 point (top). The peaks at Fe2+ and Fe3+ indicate that the isotropic mineral is magnetite. The peaks on the spectrum are also similar to the characteristic EDS peaks of magnetite reported in Welton (1984).
Appendix IV: Coulomb Stress

The orientations of the potential fractures are dependent on the coefficient of internal friction. The fractures are oblique to the principle stress axes and at equal acute angles of 45° or less to the direction of least principal (most compressive) stress, $\sigma_3$.

The critical Coulomb stress ($\sigma_{cc}$) defines the value of stress at which a frictional material will start to fail.

$$\sigma_{cc} = \frac{1}{2} (\sigma_1 - \sigma_3) \sqrt{1 + \mu^2} + \frac{1}{2} (\sigma_1 + \sigma_3) \mu$$

Where $\sigma_{cc}$ is the critical coulomb stress, $\sigma_1$ is the least compressive stress, $\sigma_3$ is the most compressive stress, and $\mu$ is the coefficient of friction.

Later, I divided my models into 1m × 1m grids, imported the grids as a text files, and calculated the maximum Coulomb stress in Microsoft Excel.
Examples of Coulomb Stress Models

Model Output: Examples of the model output with the constant Young's modulus of 15 GPa, Poisson's ratio = 0.3, Density = 2700 kg/m³, and various fault depth.

Figure 57 Fault Depth = 3 m
Figure 58 Fault Depth = 15m

Figure 59 Fault Depth = 50 m
Model Output: Examples of the model output with the constant fault depth of 15 meters, Poisson’s ratio = 0.3, Density = 2700 kg/m³, and various Young’s moduli.

*Figure 60 Young’s modulus = 15 GPa*

*Figure 61 Young’s modulus = 35 GPa*
Figure 62 Young’s modulus = 55 GPa

As the Young’s modulus increases, the maximum Coulomb stress increases, and the stress distribute more widely and more evenly throughout the material. When the thickness of the top layer increase, the maximum Coulomb stress increases as well.

Part II

Model Output: There are two beds on top of the fault tip, the properties of the limestone bed at the bottom are constant: Young’s modulus = 25 GPa, Poisson’s ratio = 0.3 and the density = 2720 kg/m³. I chose 25 GPa because it yields the fault throw and the monocline’s width that are closest to the real outcrop.
The Young’s modulus of the top layer is set to 1, 5, 10, 15, 20, 40, 50 and 100 GPa, all of which except the last one are possible Young’s moduli of sandstone. Poisson’s ratio is set to 0.29, and the density is 2350 kg/m³.

**Examples of Coulomb Stress Models**

*Figure 63 Young’s modulus of the top layer = 1 GPa*
Figure 64 Figure 37 Young’s modulus of the top layer = 10 GPa

Figure 65 Figure 44 Figure 37 Young’s modulus of the top layer = 50 GPa
Figure 37 Young’s modulus of the top layer = 100 GPa