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Detailed Analysis of Structures in the Foot Wall of the Champlain Thrust at Lone Rock Point, Burlington, Vermont

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Acknowledgements

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Abstract

The objective of this project was to identify a strain gradient and relative chronology within the foot wall of the Champlain Thrust Fault at Lone Rock Point, Burlington, Vermont in order to determine how the unique fault-bounded ellipsoidal lozenge structures formed and why they are contained to one area within the foot wall. Previously researched models seemed to suggest the fault bounded lozenges were a horse thrust system that followed the strong pre-existing limestone/dolostone bedding layers of the Iberville Shale. However, this paper indicates that the lozenges are a horse thrust system formed by an S-C fabric between the 1st and 2nd generation cleavages, not by bedding, and as such are a gauge of moderate strain within the foot wall. Also, by identifying a relative chronology within the foot wall, this paper lays the groundwork to explain why two wells drilled near Lone Rock Point by McGill University in the summer of 2014 observed the Champlain Thrust Fault to have a thirty five meter depth difference over a ten meter distance. The original hypothesis to explain this observation was that normal faults were crosscutting the main thrust and causing the displacement. However, this paper failed to conclusively support that hypothesis since the normal faults identified within the foot wall were found to neither cross the main thrust nor displace rock more than one centimeter. Further research should be conducted within the hanging wall at Lone Rock Point to conclusively interpret this observation.

Introduction

Along the shore of Lake Champlain at Lone Rock Point in Burlington (Fig. 1), there is a structure called the Champlain Thrust Fault. The Champlain Thrust is a major thrust within the Champlain Valley lithotectonic belt in the Taconian foreland (Fig. 2). It stretches about 320 kilometers from southern Quebec to eastern New York and is a prevalent factor controlling the geology of western Vermont. At Lone Rock Point, the Champlain Thrust marks the boundary between two different rock types; the Dunham formation (Cdu) and the Iberville formation (Oi). The Dunham formation is a tan weathering, grey dolostone deposited in the early Cambrian. The Iberville formation is comprised of thinly layered shale with interlayers of dolostone and limestone deposited in the middle Ordovician (Radcliffe et al. 2011). The Champlain Thrust is one of the latest in a series of thrusts associated with the Tectonic Orogeny around 455 million years ago (West et al., 2011), and was then later deformed by the Devonian and Arcadian Orogenies (Kim et al. 2011). The Taconic Orogeny was the collision of an ancient continent called Laurentia with the Shelburne Falls Island Arc (Karabinos et al. 1998). During orogeny events, rocks are heavily deformed and displaced kilometers away from where they were originally deposited. In the case of the Champlain Thrust Fault, the Dunham Dolostone was displaced approximately 60 kilometers to its current location on top of the younger Iberville Shale (Stanley, 1987). Since the Dunham Dolostone is the upper plate of this thrust, it is referred to as the 'hanging wall', while the Iberville Shale is referred to as the 'foot wall'. The fault is well exposed along the shoreline of Champlain Lake where it is gently folded and protrudes in cliff faces and outcrops along the lake shore (Fig. 3).

In the summer of 2014, McGill University drilled two wells ten meters apart a few hundred meters east from Lone Rock Point. Between the two wells there was approximately a

thirty five meter difference in the depth of the Champlain Thrust Fault. This means that something is happening to the fault underground in order to account for such a drastic vertical shift over ten meters that cannot be visibly seen on the surface. In hopes of answering this inquiry, this research originally set out to Lone Rock Point to find evidence that supported the hypothesis of normal faulting crosscutting the Champlain Thrust and causing the observed displacement. What was found instead was that the geologic structures within the foot wall have never been documented, so before the drilling observation can be interpreted, the foot wall had to be structurally analyzed. Therefore, this research focuses on the structural evolution of the foot wall. This paper serves to identify the structures within the foot wall of the Champlain Thrust at Lone Rock Point and to organize these structures relative to each other, both by chronological order and by gradient of strain. A strain gradient is documented by recording the amount of deformation, or strain, on the structures within the foot wall and putting it into the context of how far away the structures are from the main thrust. Specifically, this paper will focus on the lozenge-shaped structures that were found; answering how they formed, relatively when they formed, and what type of strain gradient they represent.

Going north along the beach at Lone Rock Point, the outcrop ground level gets progressively deeper below the thrust. This is because the fault was deformed by open folds with east-west striking axial surfaces (Fig. 3) due to the later Devonian and Arcadian Orogenies previously mentioned. This provided a unique experience to document the strain gradient from approximately 40 meters below the fault up to the fault contact itself. By investigating the structural chronology and strain gradient of the foot wall, this paper exaimines how the Iberville Shale responded to the stress caused by the Champlain Thrust. This research can also be used as ground work to explain why the Champlain Thrust, a potential major conduit for groundwater

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(Kim et al., 2011), had a thirty five meter depth difference in over ten meters. While it is possible that the gentle folding of the thrust seen at the shoreline could become more dramatic as it plunges underground, this research tried to support that there were normal faults crosscutting the Champlain Thrust that are not seen, but might be able to infer by researching the relative chronology of the foot wall. Aside from being an academic curiosity, it is significant to well drillers that they might be able to accurately project at what depth they will find important water-bearing structures. A greater understanding of the Champlain Thrust will give further insight to how thrust faults behave in general.

Hypothesis

Approximately 30 meters below the main thrust there are 'eye package' structures, called so due to the fact that they are shaped like eyes, with both sides pinched out, and seemed to be stacked together, yet also isolated, like packages. It was noted that these structures are similar to eye-shaped packages that have been described as 'lozenges' or 'horse thrusts' in other thrust systems (e.g., Ponce et al., 2010). It was also observed that the lozenges were bounded by thrust faults, stacked on top of each other, and only appeared in a certain area of the thrust, at site 4 (Fig. 4).

Some models for the behavior of the lozenges were taken from various papers which researched the relationship between lozenge-shaped structures, like seen in the foot wall of Lone Rock Point, and shear zones, which are zones of displacement as a fault (Czeck et al., 2010; Ponce et al., 2010; Cosgrove at al., 2012; Ponce et al., 2012). There is a classification of the lozenge shape into two categories, each with two subcategories (Ponce et al., 2012). Using this classification the lozenges were identified as sigmoidal lozenges. This means they are

asymmetric and have non-planar sides. Ponce assumed in this categorization that the lozenges were shaped by shearing that followed a pre-existing foliation. The lozenges can be assumed to follow a pre-existing foliation because they follow the same pattern of a lozenge shaped by conjugate sense of shears at a high angle to extension (Ponce et al., 2010). However, in order to create this shape, the lozenges would have to follow a very well defined pre-existing structure, which indicated that the lozenges found in the foot wall of the Champlain Thrust might follow the dolomitic and limestone layers within the shale. This could be possible due to an observation made that the dolomitic bedding layers within the shale seem to be completely torn apart close to the thrust, and were more continuous further away from the thrust, like at the location of the lozenges. Cleavage was not factored in to this because at first look cleavage was observed without distinction throughout the entire foot wall and had no relation to the lozenges.

Therefore, the hypothesis of this paper was that the lozenges are a horse thrust duplex system with a sense of motion related to the Champlain Thrust that formed along bedding planes of pre-existing weakness due to the higher appearance of bedding at this depth beneath the main thrust. This hypothesis agrees with the known model of horse thrusts that bedding is the key defining structure. Due to the observation that bedding behaves differently at different depths from the main thrust, this would have meant that the lozenges were also an indicator of strain gradient. The documentation of the strain gradient throughout the foot wall in order to classify the lozenges was able to be further interpreted to conclude a relative chronology. However, if the data collected does not support that the lozenges follow a pre-existing structure, they might have formed from the connecting of independent shear zones, causing rounded angles and diagonal cross shears over time (Czeck et al., 2010).

Methods

To document the strain gradient, and therefore explain the formation of the lozenges, measurements from the entire beach within the foot wall were collected at all different distances from the thrust, representing sites 5, 3, and 2, and then compared to the lozenges of site 4 (Fig. 4). Site 1 is located with the hanging wall, and was included to order to gather preliminary observations that might help interpret the results of McGill University's drilling.

In order to determine how the sense of motion of the lozenges relates to the Champlain thrust, structures that record the directions, sense, and type of motion along the faults that border the lozenges had to be compared with those that record motion along the Champlain Thrust Fault. These structures include slicken lines, fault plane orientations, and a wide range of sense of shear indicators. If the motions were similar, then it could be concluded that the lozenges are kinematically linked to motion on the Champlain Thrust Fault and therefore formed while the thrust was still active. The lozenges were measured in the correct orientation and in detail using meter stickers, poles, a compass, and measuring tape and then were projected on to a plane parallel to their sense of movement as notated by slickenlines found on the faults. This served to show how the lozenges were moving compared to the rest of the foot wall and the main thrust, and also document and record the behavior of the structures within the lozenges.

Sites 5, 3, and 2 that represented various depths in the foot wall beneath the thrust (Fig. 5) were broken down to 1 meter by 1 meter areas using a scangrid in order to sketch and record measurements in detail. A scangrid is a square made up of four meter sticks screwed together. The scangrid isolated the area in order to focus on how the structures were relating to each other and were used to take detailed photos. These photos were then digitized in adobe illustrator and

defined by observed structural characteristics. Data were also supplemented by measurements taken from across the entire beach in order to better document how each structure was behaving as they were got closer or further away from the Champlain Thrust. Measurements that were collected include; fault planes, slickenline trends, cleavage planes, fracture behavior, and recording cross cutting relationships.

These data were then plotted on a stereonet computer program called Stereonet 8 (Allmendinger, 2012). Measurements were plotted in pairs as they related to each other. For example, fault planes were plotted on the same stereonet as their corresponding slickenlines. Only S_1 cleavage was plotted on a stereonet and not S_2 cleavage because it was observed in the field that the S_1 cleavage is experiencing folding in a development of an S-C fabric which relates to the thrust faulting, therefore comparing the S_1 cleavage behavior directly with the thrust fault planes was the most beneficial. The digitized photographs were crucial with the stereonet plots because they served to exemplify the important details that could then be compared to the stereonets in order to better understand any patterns that might be present and characterize the strain gradient.

By comparing a structure's cross cutting relationship with another structure and its relative locational depth beneath the Champlain Thrust, the sites were then labeled as either low, moderate, or high strain, and thus were able to be dated relative to each other. This is because the lowest strain deformation will be furthest away from the stressor, which is the Champlain Thrust, thus will represent the first of the relative sequencing of events. Closer to the Champlain Thrust, the weight of the Dunham Dolostone dragging along the fault plane deforms the structures within the foot wall to a higher degree and for a longer period of time, so the highest strain gradient will also have the later generations of structures.

Results

A strain gradient was identified from Site 5 to Site 2, getting closer to the Champlain Thrust Fault (Fig. 5). The lowest strain is found furthest from the main thrust. This is characterized by dominant first generation folding (F_1) of the dolomitic layers (S_0) within the shale and first generation cleavage (S_1). At lowest strain, the S_1 cleavage is axial planar to the F_1 folds, and S_2 cleavage and F_2 folds are not present. Site 5 was the best example of low strain (Fig. 6). The next stage of strain is moderate strain. This is characterized by second generation folding (F_2) of the S_1 cleavage and an incipient development of a closely spaced second generation cleavage (S_2) associated with thrust faults. The thrust faults at moderate strain follow an S-C fabric caused by the S_1 cleavage folding into the orientation of the S_2 cleavage. At this stage, the dolomitic layers are present but cryptic and fragmented. Site 3 was the best example of moderate strain (Fig. 7). Lastly, there was the highest strain, which was found closest to the main thrust. High strain is characterized by dominate S_2 cleavage, which is axial planar to rootless isoclinal F_2 folds. While S_0 dolomitic layers and S_1 cleavage are both present, they are heavily disjointed. . Site 2 was the best example of high strain (Fig. 8).

Given these categories, the lozenges found at site 4 (Fig. 9) can be identified as a marker of moderate strain. The thrusts bounding the lozenges are a result of an S-C fabric between the S_1 cleavage and the S_2 cleavage. The S_1 cleavage within the lozenges is folded, and assimilates to the orientation of the fault as it approached the boundary. The S_2 cleavage is localized only to the bounding thrust faults, similarly to Fig. 7 (Fig. 10a). Additionally, the outcrop at site 4 has a corner to it, which provides the opportunity to project the horse thrusts on to a plane parallel to their sense of movement. The lozenges are parallel to their slickenlines near the bottom of the 3rd lozenge, but they are perpendicular to their slickenline near the top of the 1st lozenge. After

measuring and illustrating the lozenges in detail from Fig. 10a, the northern half of the lozenge was then able to be projected onto a plane that is representatively parallel to the slickenlines measurements taken from the bounding faults in the 3rd lozenge. This provided a view of the lozenges within the terms of their sense of movement (Fig. 10b). This view of the lozenges, in conjunction with the fault plane and slickenline data plotted on the stereonet included within the figure, shows that the lozenges rotate relative to each other by about 40 degrees as they are being thrusted up on top of each other out of the outcrop, and that they have the same kinetic sense of motion as the Champlain Thrust Fault. Given the realization that the lozenges are thrusting on top of each other, the horse thrusts of the foot wall can be identified with the horse thrust duplex antiformal stack model. (Boyer et al., 1982). The major difference between Boyer's model and the horse thrust duplex in the foot wall is that the controlling structure is bedding, not cleavage (Fig. 11). Within Boyer's horses, the bedding is being folded where S_1 cleavage is being folded, as seen in Figure 10a. Another difference between the model and the thrusts of site 4 is that the thrusts within the foot wall have a climbing floor thrust, whereas the model has a horizontal floor thrust. This can be explained by the fact that the model only has horizontal stressors, whereas the horse thrusts of site 4 had both horizontal and vertical stressors.

In comparison to the data from across the whole beach, the horse duplex system fits in nicely (Fig 12 and 13). The model explains the girdle pattern observed from the thrust faults and slickenlines, and the S_1 cleavage overlaps with the orientation of the thrust fault planes, as it would if the S-C fabric observation is correct.

Lastly, in order to the collected data into the greater context of the Champlain Thrust Fault as a system, the structures of foot wall needed to be compared to the structures within the hanging wall to try to find any structures that crossed the lithologies. In order to analyze the

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Champlain Thrust, both components of the thrust have to be analyzed to understand how each deformed and how they relate as a whole. If similar structures can be found between the hanging wall and the foot wall, it can be inferred that it is crosscutting and deforming the Champlain Thrust, and perhaps responsible for the drilling results of McGill University.

From Site 1, only brittle structures were observed. The hanging wall is dominated by two sets of fractures, each perpendicular to the outcrop face. One is nearly vertical and the other is nearly horizontal (Fig. 14), as noted by the contour stereonet. The spacing of these fractures are about a half a meter to a meter apart. While the foot wall also had fractures, they were only located in certain areas that were seemingly void of veins, and they had a different orientation of a SW/W strike (Fig. 15). Mostly the fractures were steep, but not as steep as the hanging wall, and the spacing between the fractures was at most around three centimeters. Since the fracture sets were not similar enough between the foot wall and the hanging wall, it cannot be concluded that the fractures crosscut the Champlain Thrust itself.

Conclusions

The earliest event was the deposition of the bedding planes (S_0), characterized by thin layers of dolostone/limestone within black shale. Next was the formation of rootless isoclinal folds (F_1) of the brittle dolomitic layers and the development of a spaced pressure solution cleavage (S_1) that is axial planar to the folds. The S_1 cleavage is then deformed into asymmetric S-C shear bands that merge into parallelism with, and are cut by, intraformational thrusts.

A second cleavage (S_2) defines a part of the S-C fabric and is intensified in thrust zones. The thrusts form eye-shaped lozenge structures that are stacked on top of one another forming horse duplexes with slip directions that fan up to 40 degrees with respect to one another. This

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feature highlights the geometry of the lozenges from site 4. Then, there is the second generation folds (F_2), to which the S_2 cleavage is axial planar. The last three phases consist of conjugate sets of normal faults that record top-down-to-the–north and -south kinematics within the foot wall, two sets of later folds, north (F_3) and east-striking (F_4) folds which warp the Champlain Thrust, and the formation of fracture sets in both the foot wall and the hanging wall. It is unclear the relative age of these last three phases as these structures appear separate from each other and therefore have no crosscutting relationship. However, as the normal faults are only observed in the foot wall, it can be inferred that the normal faulting happened before the formation of the fractures, since the fractures appear in both. Also, since folding of fractures was not observed in either the foot wall or hanging wall, it can be inferred that the F_3 and F_4 folds formed after the normal faulting, but before the formation of the fractures.

Given this chronology, this paper concluded that the observed lozenges, later defined as part of a duplex, do follow the kinematic motion of the Champlain Thrust Fault within 40 degrees of rotation (Fig 16). This paper also concludes that the horses developed along pre-existing cleavage structures that were a result of a moderate strain due to their depth beneath the thrust. This explains why the lozenges were only found in perfect condition at that one area of the beach. This conclusion is important to structural geology because it provides a new model for looking at horse thrusts, both for the Champlain Valley Belt and other similar geologic environments. Previously, horse duplexes have only been defined with bedding, whereas this new model works to explain the behavior of thrust faulting where cleavage is the dominate foliation. This research has shown that the key to understanding the foot wall is to understand the behavior of cleavage.

Future Work

The inclusion of normal faulting in the chronology laid out above is important in relation to the original hypothesis thought to explain the observation found by McGill University. However, as no evidence of normal faulting crosscutting the Champlain Thrust was found, this hypothesis is not supported by this paper. Furthermore, the normal faults that were found within the foot wall only displaced rock by approximately one centimeter. In order to account of the depth difference found the McGill's drilling, there would have to be about 3000 normal faults across the ten meter distance between the two wells. This seems improbable. A new possible hypothesis could be that there are horse thrusts within the hanging wall, close to the Champlain Thrust, which caught slivers of the foot wall within the hanging wall.

Research should be conducted to correlate the relative structural chronology of the foot wall across the competent lithologies and in relation to when the Champlain Thrust was active. The next step in doing this would be to conduct a detailed structural analysis of the hanging wall, and to continue to look for possible structures that might crosscut the Champlain Thrust.

Figure 1 – Tectonic Context of Lone Rock Point
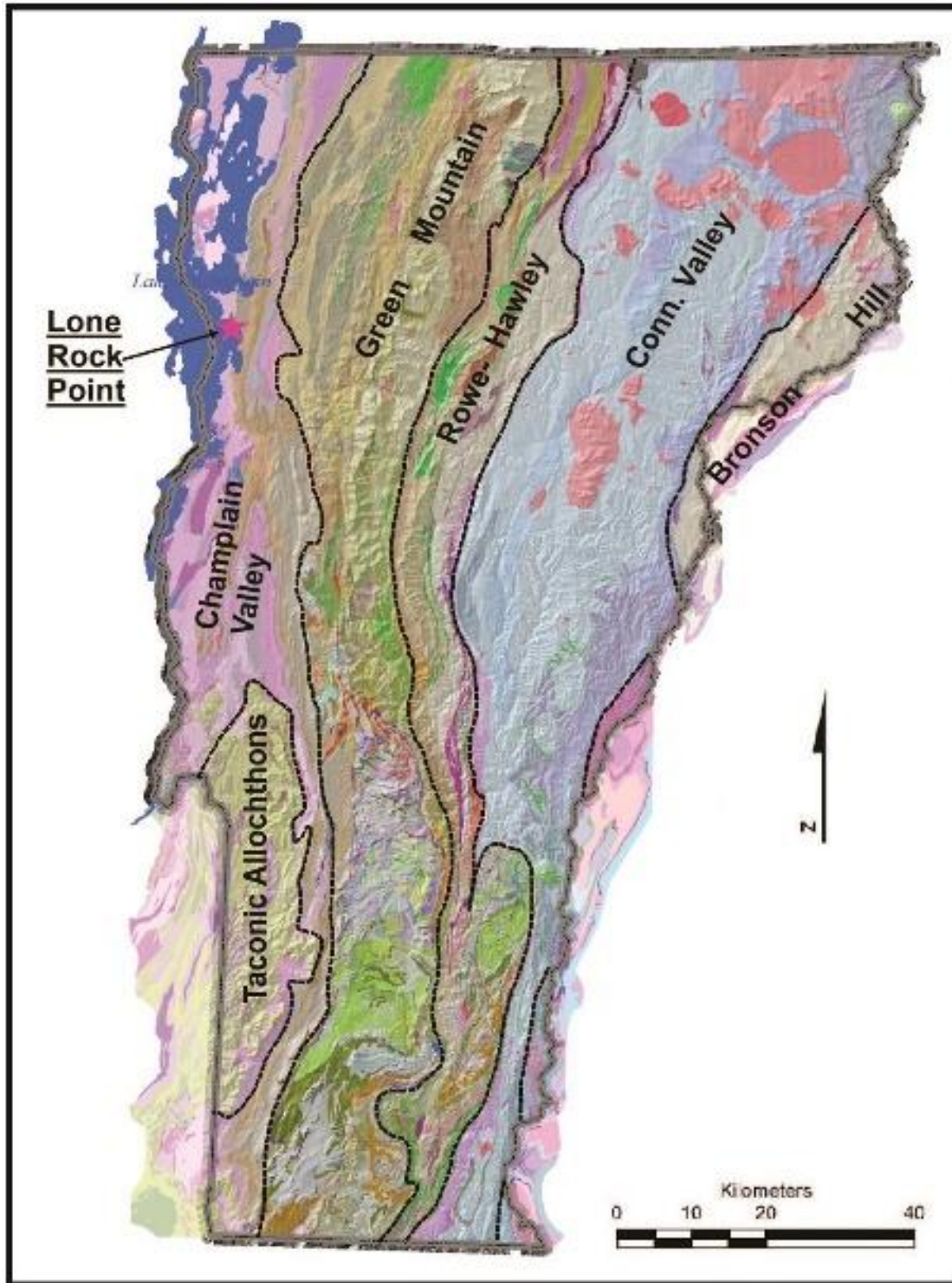
Modified from Ratcliffe et al. 2011, this figure shows the location of Lone Rock Point within the Champlain Valley lithotectonic belt in the Taconian foreland formed 455 Ma within the state of Vermont.

Figure 2 – The Champlain Thrust in NW Vermont

Modified from Ratcliffe et al. 2011, this figure shows a zoomed in area of the Champlain Valley; identifying the Champlain Thrust fault and location of Lone Rock Point. This figure also identifies the boundary between the Champlain Valley Belt and the Green Mountain Belt, which is the Hinesburg Thrust.

Figure 3 – Lone Rock Point Field Area From Lake Champlain

The figure shows the hanging wall and the foot wall of the Champlain Thrust at Lone Rock Point; the hanging wall being the Dunham formation (Cdu) and the foot wall being the Iberville formation (Oi). The red arrows are used to illustrate the gentle folding of the Champlain Thrust.

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Figure 4 – Lone Rock Point Field Station Map

The figure shows the location of the 5 sites along the beach at Lone Rock Point

Figure 5 – Components of the Champlain Thrust with Field Sites
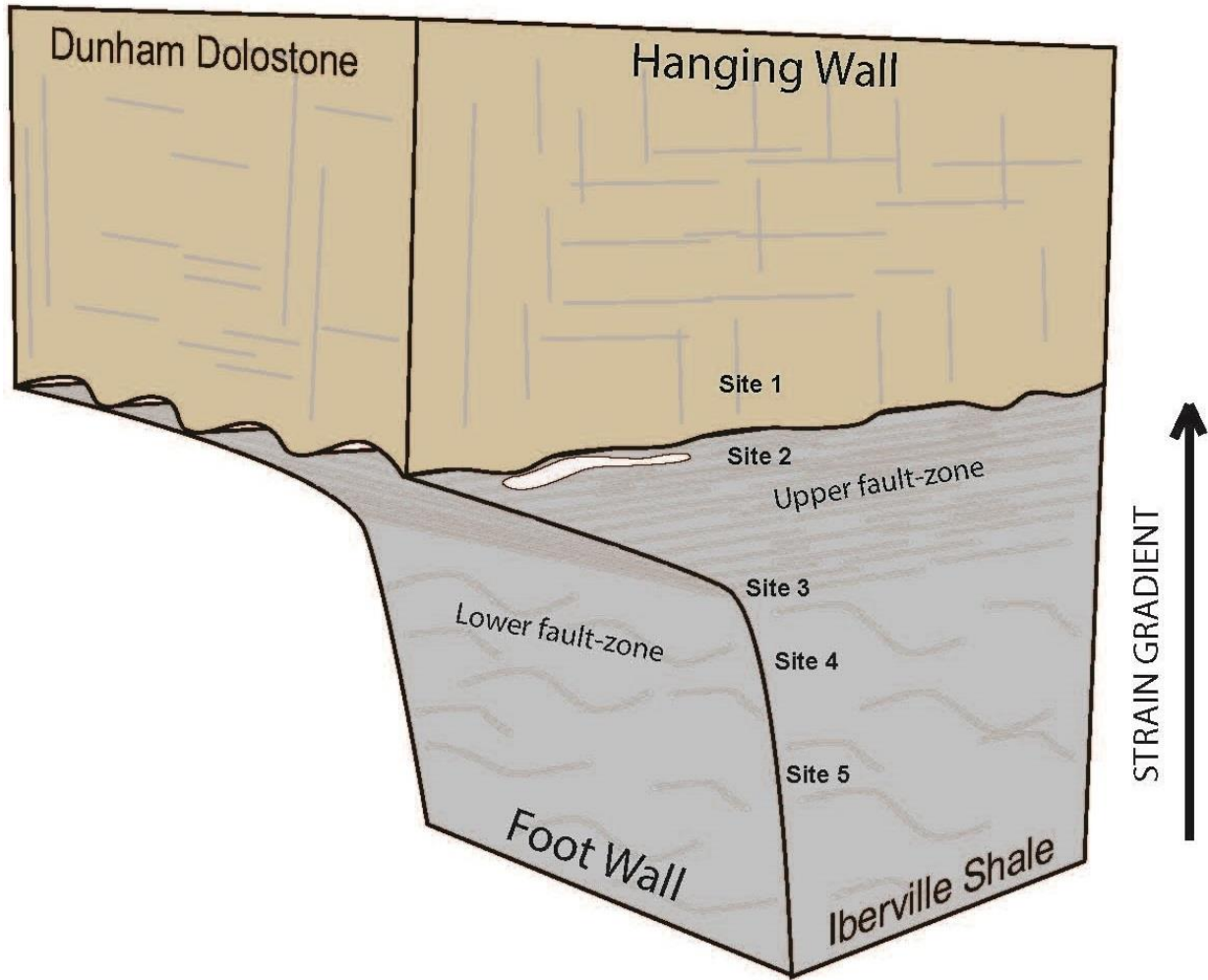
Modified from West et al. 2011, this figure shows the relative position to the main thrust of the 5 sites in both the hanging wall and the foot wall. In the foot wall, the strain gradient increases going towards the thrust, which makes site 5 of the lowest strain, and site 2 of the highest strain.

Figure 6 – Digitized Scangrid of Site 5
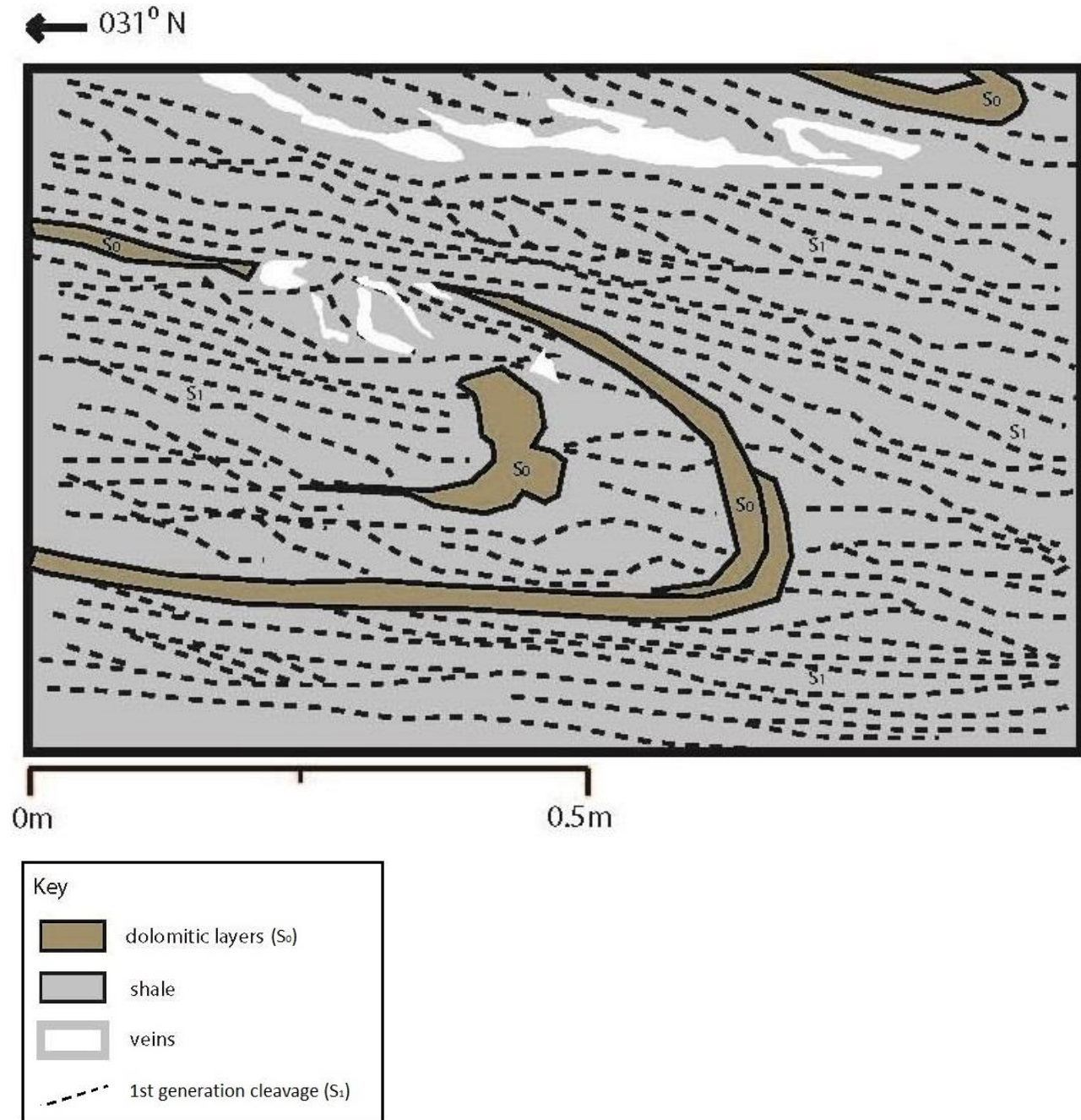
Site 5 shows isoclinal recumbent folds of dolomitic layers (S_0) with axial planar, spaced pressure solution cleavage (S_1).

Figure 7 – Digitized Scangrid of Site 3
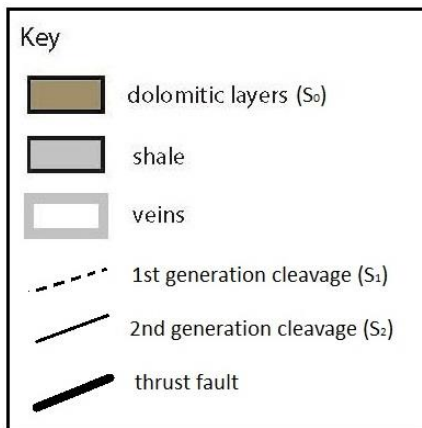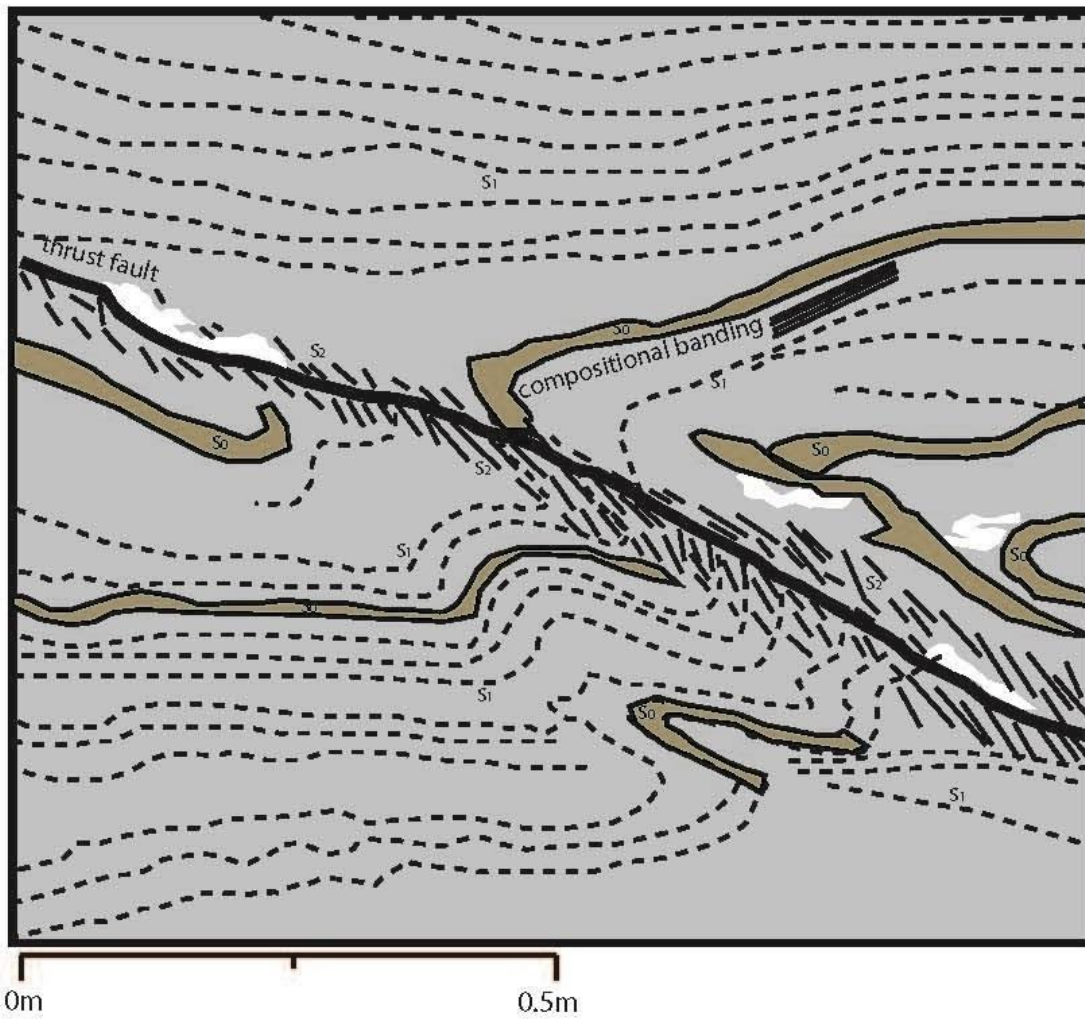
Site 3 shows folding of S_1 pressure solution cleavage and closely spaced S_2 fault cleavage within thrust fault zones.

Figure 8 – Digitized Scangrid of Site 2
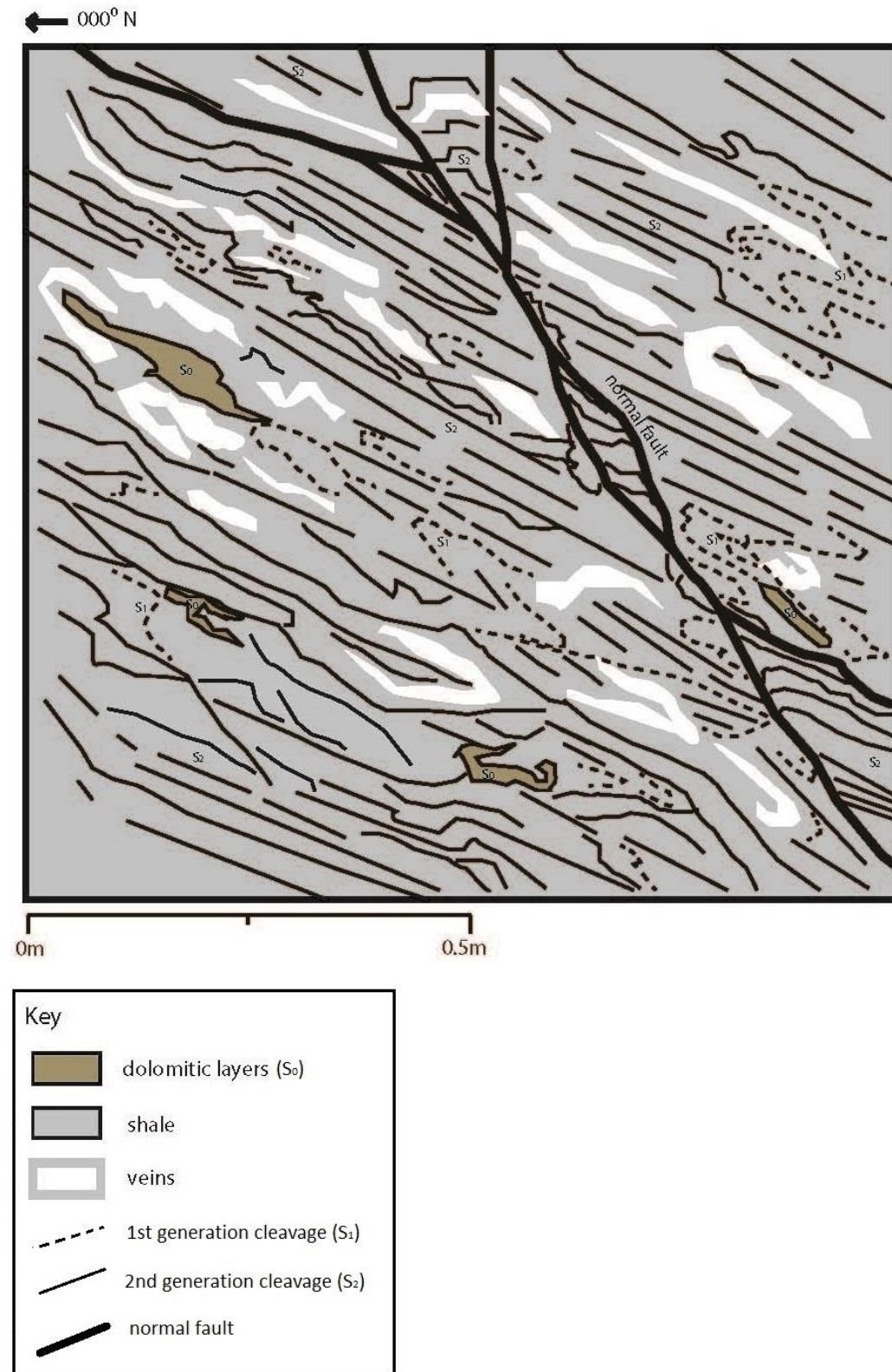
Site 2 shows dominant presence of S_2 cleavage and rootless F_2 folds.

Figure 9 – Lozenges of Site 4

This figure shows the outcrop at site 4. The thrust faults that bound the lozenges are outlined with orange field tape. The lozenges are labelled 1, 2, and 3 in order to follow their location in the next few figures. Also labelled is the outcrop surface corner, as indicated by the red line. The outcrop corner is at an angle because the photo was taken looking ENE, not perpendicular to the outcrop surface.

# Figure 10a – North South Cross Section of Horse Duplex System
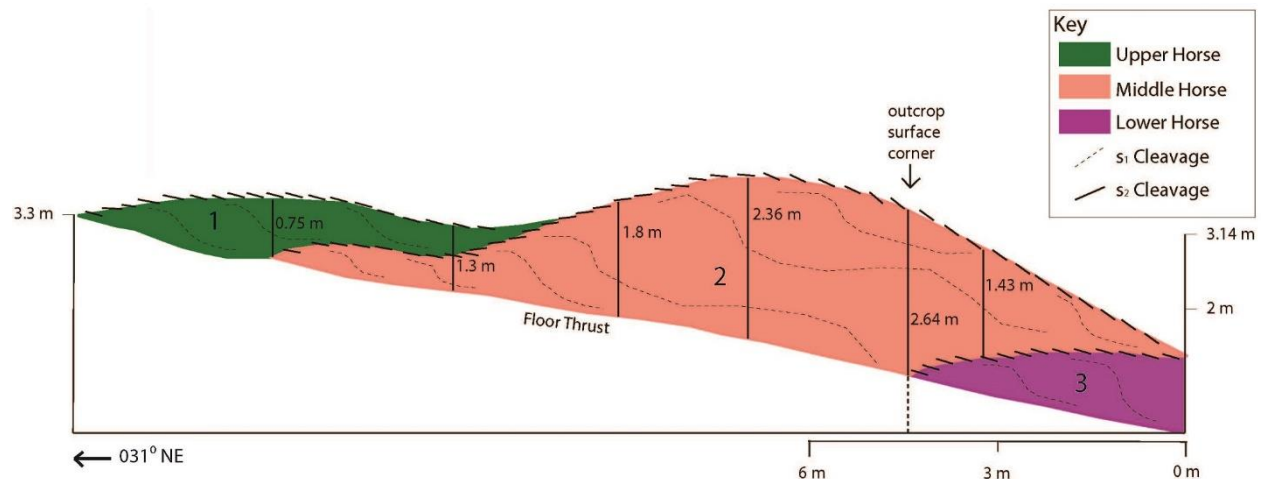
The diagram above shows detailed measurements of the height and width of the horse thrusts. This is the digitized version of Figure 9, indicating where lozenge 1, 2, and 3 are located. Also indicated on the figure is the corner of the outcrop.

# Figure 10b – East West Cross Section of Horse Duplex System
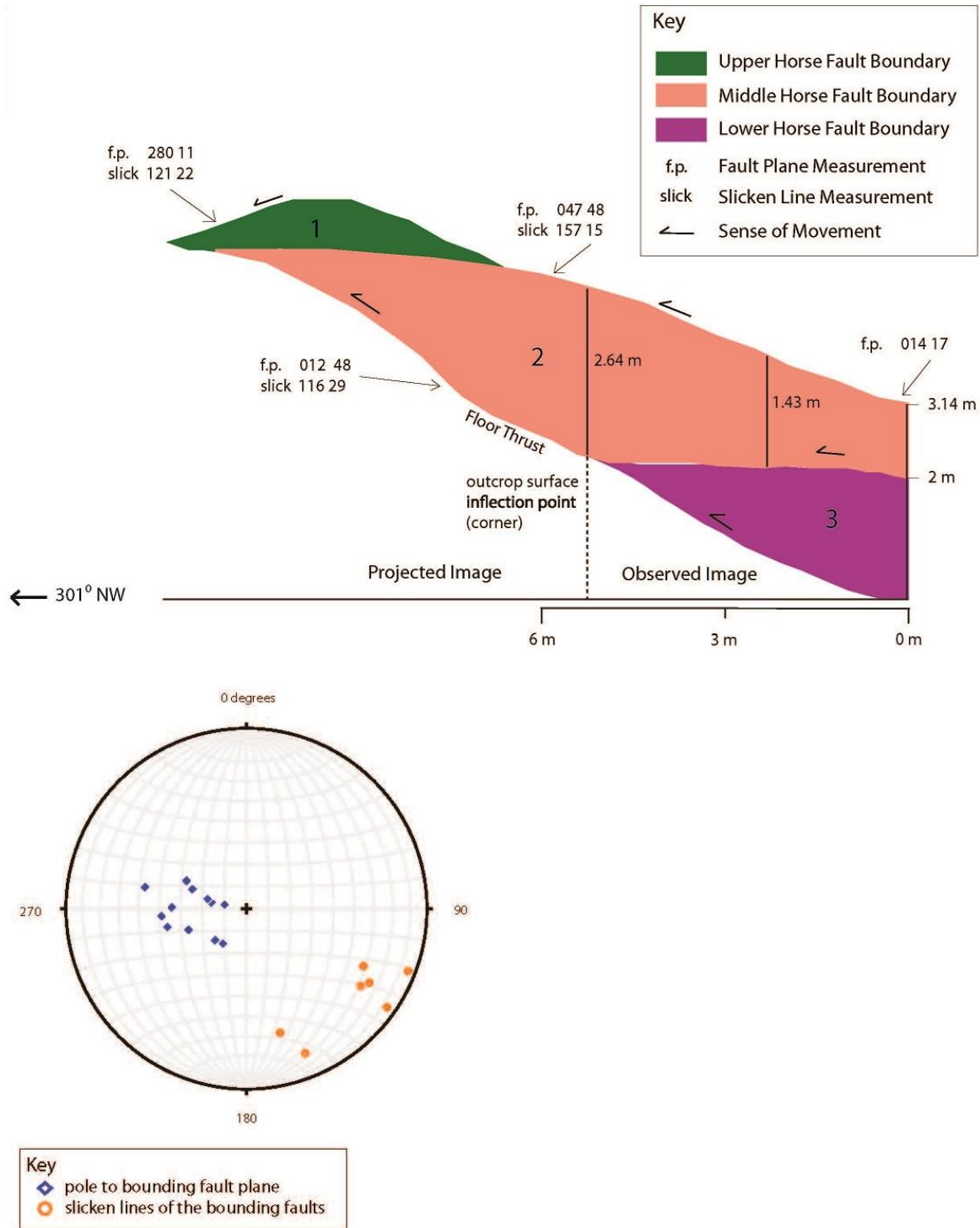
West of the inflection point (outcrop corner) has been projected to show what the horse thrusts would look like from a plane that is parallel to the slickenlines. This figure is orthogonal to Figure 10a. The stereonet plots the thrust fault and slickenline measurements taken from the horse thrusts. Some locations of the measurements are indicated on the figure.

# Figure 11 – Model Horse Thrust Duplex
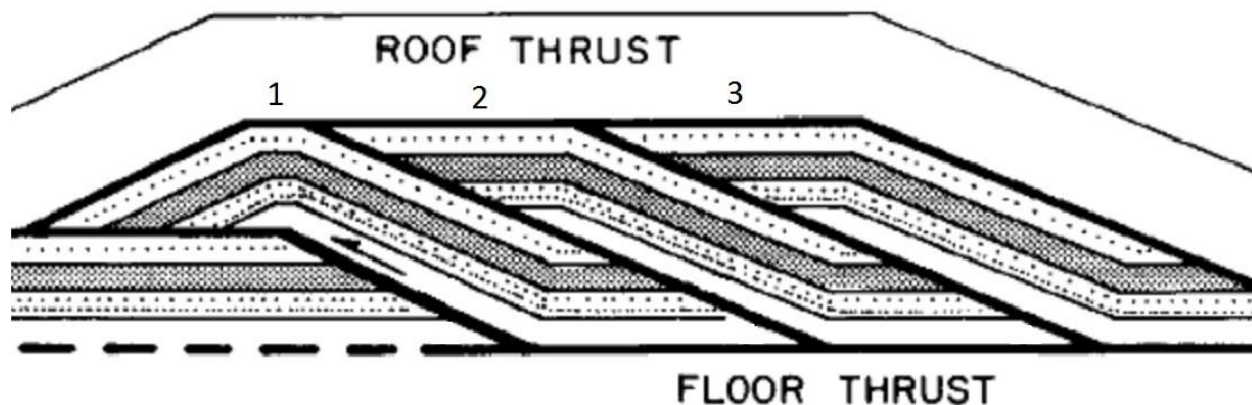
Modified from Boyer et al. 1982, this figure shows the model horse thrust duplex system. Bedding represented the dominate foliation in this model, and is folded inside of the horses. The three horse thrusts have been labelled 1, 2, and 3 in order to easily compare them to the horse thrusts of site 4 within the foot wall.

# Figure 12 – S_1 Cleavage Measurements across the Foot Wall
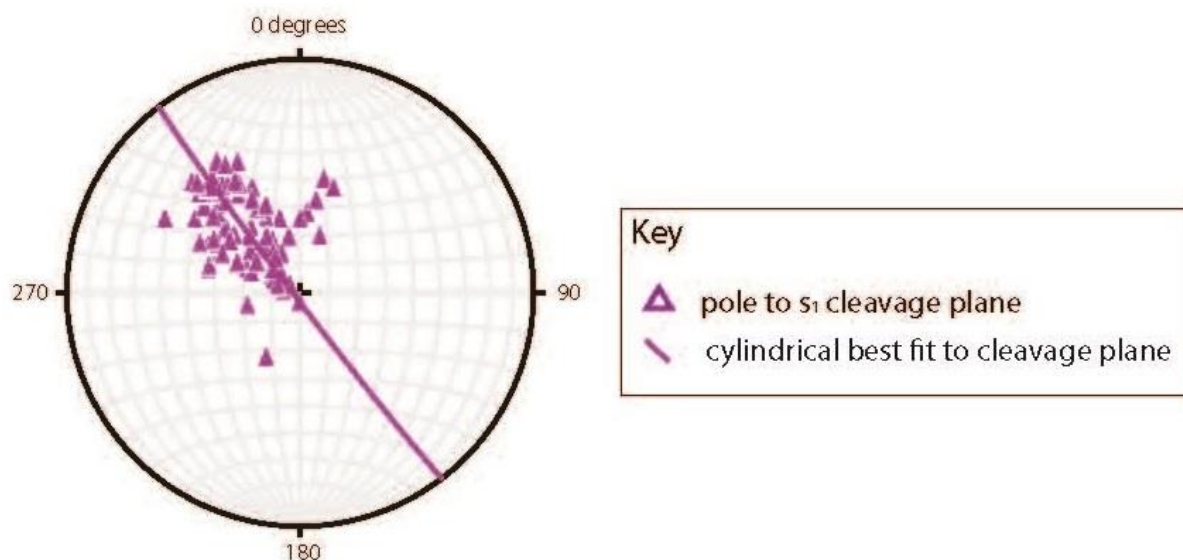
This stereonet shows the S_1 cleavage is deformed into S-shaped structures that results in a spreading out of the data along a NW-SE girdle.

# Figure 13 – Thrust Fault and Slickenline Measurements across the Foot Wall
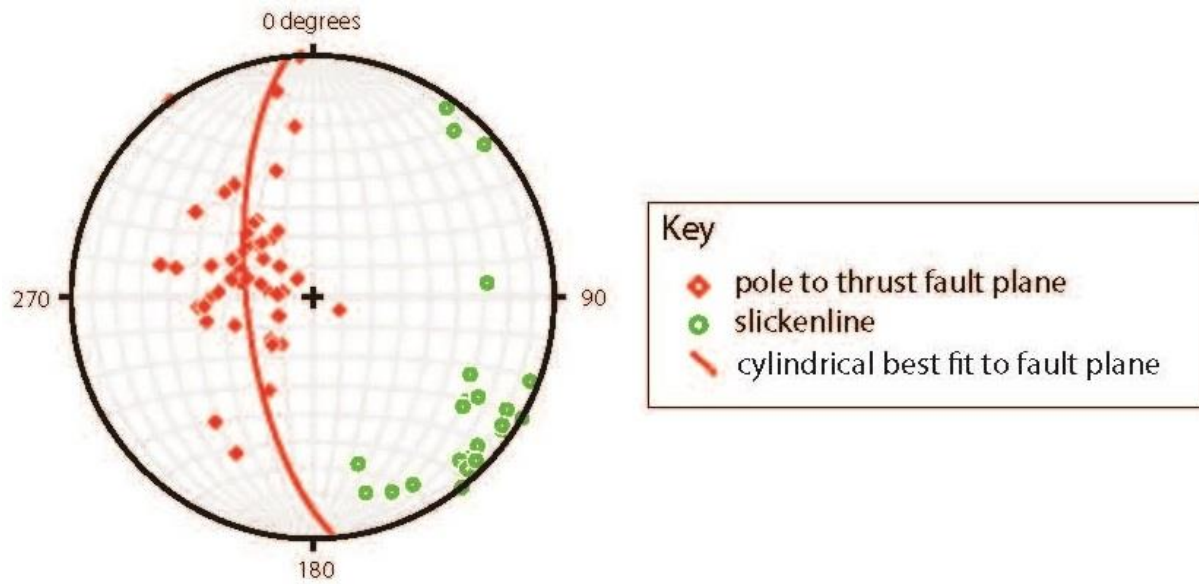
This thrust fault data shows a spreading along an N-S girdle which can be explained by the lozenge horse thrusts observed in the foot wall.

Figure 14 –Hanging Wall Fractures at Site 1
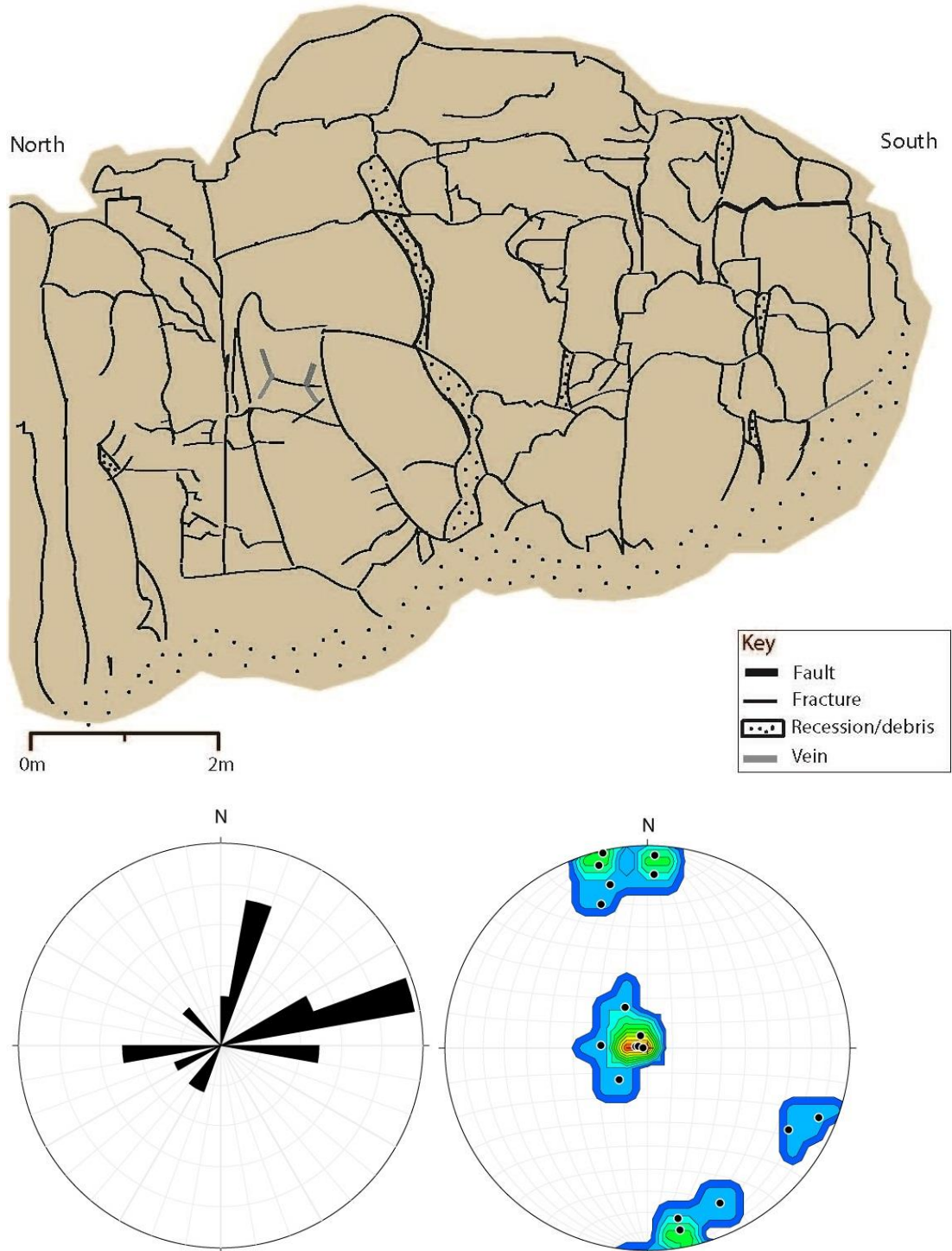
Above is a vertical profile of the Dunham formation in the hanging wall showing key fracture sets. The bottom left is a rose diagram showing the standard deviation of azimuths for the 18 fracture measurements. The bottom right is a contour stereonet of poles to the fracture planes, indicating high pole frequency with warmer colors.

Figure 15 –Foot Wall Fractures
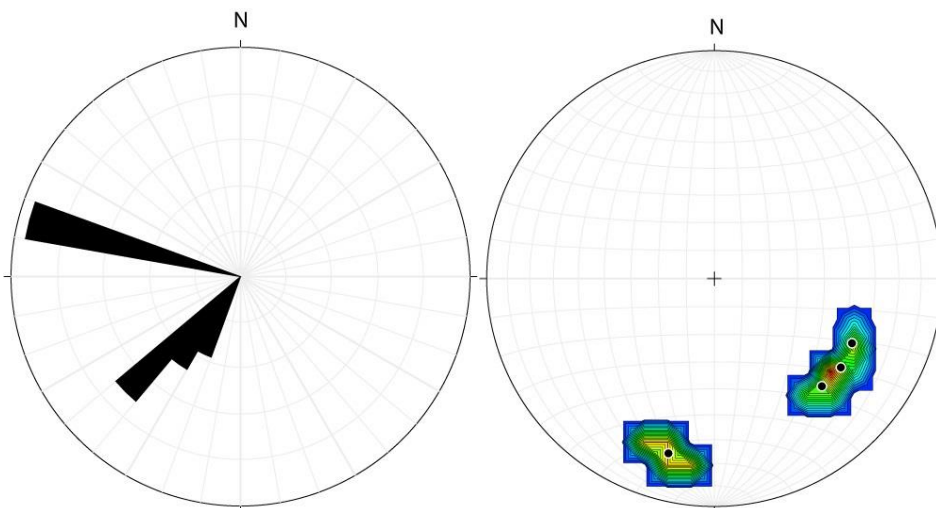
Above is photo taken near site 4 of fractures in the foot wall striking 255 SW. The bottom left is a rose diagram showing the standard deviation of azimuths for the 134 fracture measurements from across the foot wall. The bottom right is a contour stereonet of poles to the fracture planes, indicating high pole frequency with warmer colors.

Figure 16 – Horse Thrust Duplex Diagram
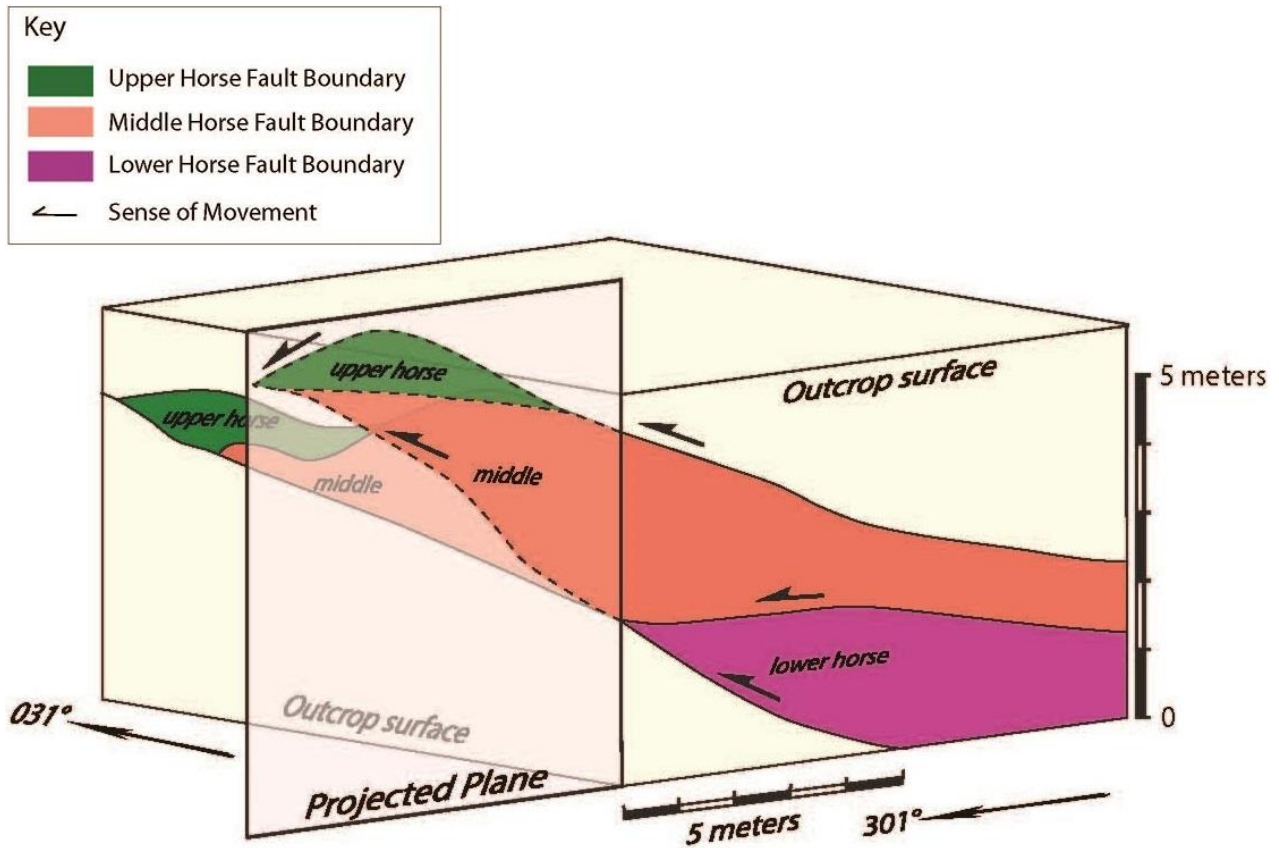
This figure represents a combination of figure 10a and 10b. The outcrop surface side of the diagram is from Figure 10a. The projected surface is 90 degrees from the outcrop surface at the inflection point, which was identified in both Figure 10a and 10b. This shows the true movement and direction of the horse thrusts relative to what is seen at the outcrop.

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