GEOPHYSICAL INVESTIGATION OF SUBSURFACE MAGMA FEEDERS IN THE HENRY MOUNTAINS OF SOUTH-CENTRAL UTAH

Investigation of Subsurface Magma Feeders in the Henry Mountains of South-Central Utah

Taryn Serwatowski

Dr. Sven Morgan

Central Michigan University

August 27th, 2007

Abstract

Geologists continue to debate the formation of laccoliths. Two competing models that can explain their emplacement include a vertical feeder dike and a horizontal magma feeder. The Henry Mountains in south-central Utah provide an ideal location to study the formation of laccoliths. Numerous laccoliths in the area are now well exposed on the surface due to years of erosion of the overlying sediments. These laccoliths are believed to have been created from magma traveling through the Earth's layers from the larger igneous intrusions in the mountain range. The laccolith studied is the Trachyte Mesa laccolith (TML) and is thought to have been fed from the nearby Mount Hillers. The TML is Tertiary in age and intrudes Jurassic Entrada sandstone of the Colorado Plateau. Indirect evidence observed at the surface connects the two bodies, but subsurface data has proved inconclusive in confirming the connection. This project involved the acquisition of additional subsurface data using Seismic Reflection and Ground Penetrating Radar over five traverses. The data indicate that Ground Penetrating Radar was unable to image deep enough and therefore was not a viable method. Processed seismic data revealed a bedrock seismic velocity of approximately 7500 ft per second which corresponds to the velocity range of sandstone (4500-14,000 ft per second). Within this sandstone layer, highly reflective interfaces were detected at a depth of approximately 40 ft, the approximate depth to the base of the laccolith. The location of these reflectors is consistent with geophysical magnetic data that was collected in the same area in 2003. These reflectors can be traced between traverses consistent with pipe-like magma feeders and supports the hypothesis that a horizontal feeding system exists between Mount Hillers and the TML.

Introduction and Literature Review

Continents grow as magma intrudes into them and crystallizes below the Earth's surface. Magma is melted rock that is mostly generated below the continents. Rocks that crystallize from these magmas are called igneous rocks and geologists continue to debate how these hot, liquid magmas rise and displace solid rock of the continents.

One type of magma body that intrudes into continents forms a domed shape structure called a laccolith. The current model for how laccoliths form involves vertical magma "feeders" called "dikes". In this model, magma pushes its way upward through a crack and then spreads horizontally above the crack to form a sheet between the overlying layers of sedimentary rock (see figure 1). As magma continues to rise up through the crack, the sheet begins to swell upward and this forces the overlying layers into a domal shape (Corry, 1988). The Henry Mountains in south-central Utah contain great examples of laccoliths. After millions of years of erosion to the overlying rock layers, these laccoliths are now well exposed at the Earth's surface. Because the Henry Mountains have not been deformed by plate tectonic action, this is an ideal place to study a magma "plumbing" system. All deformation (folding, fracturing) in the area has been caused by the magma itself. If we are able to understand how these laccoliths were formed and fed by moving magma in a "simple" setting, we can gain a better understanding of how larger igneous bodies are created and how the Earth's crust forms in general.

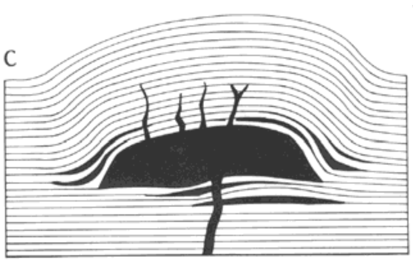

Figure 1: Diagram illustrating the current model for how laccoliths form.

Laccoliths are one of the most common igneous intrusions on our planet. Worldwide, the numbers of laccoliths range from 5,000 to 10,000 with over 1,000 of these being in North America alone (Corry, 1988). Therefore, the processes of their emplacement and growth can provide significant information on how magma travels through the subsurface and emplaces into host rock throughout different parts of the world. A common pattern seen among laccoliths is that they tend to form in "clusters" with the largest outcrop located near the center (Corry, 1988). Hunt (1953) proposed that in the Henry Mountains, the largest, central intrusions were not laccoliths but stocks, and these stocks were responsible for forming the smaller laccoliths by supplying magma and sending it out as horizontal feeders. The significant difference between a stock and a laccolith is that a laccolith terminates at a very shallow depth and has a flat, sedimentary base, where as a stock continues downward into the Earth (Morgan et al., 2005). Investigations done by Hyndman and Alt (1987) in the Adel Mountains in Montana reveal a similar pattern. The larger igneous intrusions in the area are surrounded by a "radial dike swarm" with a laccolith at each end. It was suggested that horizontally flowing magma is common and could be a typical behavior in the formation of laccoliths. Field observations made by Gudmundsson (2002) suggest that magma sheets travel horizontally along weak contacts between layers in the subsurface.

The Trachyte Mesa laccolith (TML) in the Henry Mountains of south-central Utah is one laccolith where both vertical feeders (Pollard and Johnson, 1973) and horizontal feeders (Morgan et al., 2006) have been suggested. It lies approximately 12 kilometers north-east of the larger igneous body, Mt. Hillers (see figure 2). This laccolith is 50 m thick on the SW margin, but thins to less than 20 m thick in the NE. The TML is 1.5 km long and 0.5 km wide. The small size of the laccolith allows easy access for scientists to conduct research.

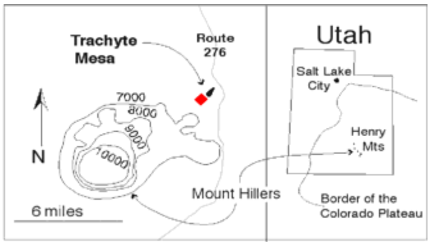

Figure 2: Diagram depicting the geographical location of the Henry Mountains and the orientation between the TML and Mount Hillers. The square southeast of the TML is the location of our geophysical investigation.

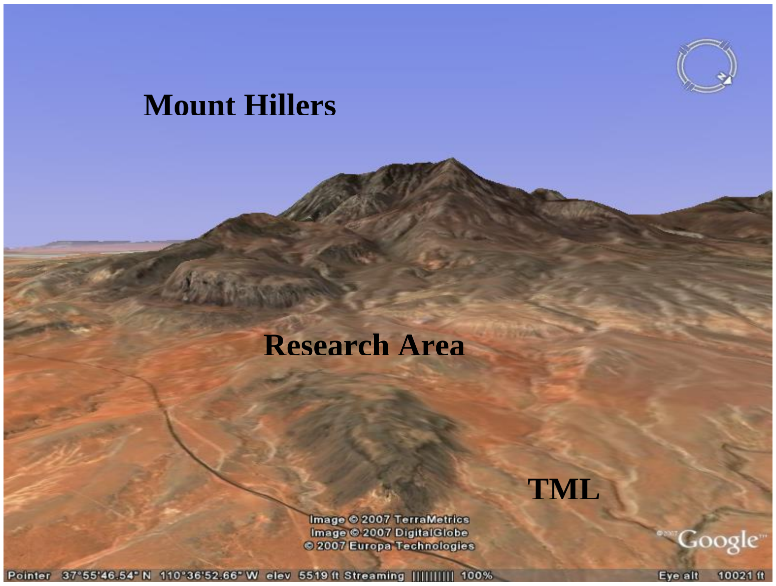

Figure 3: Diagram illustrating the TML-Mount Hillers axis. Notice how the two bodies appear to be directly in line with one another.

Past research in the area has revealed a strong connection between the TML and Mount Hillers. Hunt (1953) and Nelson (1992) have determined the chemical composition of the two bodies to be precisely the same. This indicates that the intrusions were formed from the same magma. The TML is also narrow and elongated and lies along an axis that can be traced directly back to Mount Hillers (Morgan et al., 2005). This alignment can be seen in figure 3. The minerals in the TML are also aligned along this same axis (Morgan et al., 2005), similar to how logs in a stream would be aligned by flowing water. This tells us the flow direction of the magma and this is consistent with our hypothesis that the magma stemmed from Mount Hillers. The research from Pollard and others (1975) states that “cusp-shaped grooves” seen on the top of the TML are a result of horizontal magma fingers that have coalesced into sheets. This also agrees with the theory that the laccolith was fed horizontally.

Although there is much evidence seen above the surface for the connection, past research has not been able to find conclusive subsurface evidence. Magnetic data from Case and Joesting (1972) reveal no subsurface connection between Mount Hillers and the TML. Also, no surface evidence can be seen *between* the two outcrops. Magnetic data from Nugent (2005) revealed anomalies that could represent igneous feeders. The anomalies appeared to be more widespread close to Mount Hillers and became narrower as they become closer to the TML. If these anomalies are magma feeders, these data suggest that the fingers coalesce into the TML. The data, however, is inconclusive and the evidence was not strong enough to conclude the origin of these anomalies. Further testing was needed to image the subsurface to confirm if there are horizontal feeders connecting the two igneous rock bodies.

In this paper, I describe the results of three days of geophysical data collection between the TML and Mount Hillers. We collected Ground Penetrating Radar (GPR) data and Seismic Reflection (SR) data over five traverses to the SW of the TML (figure 2). GPR did not work and we think our antenna was not powerful enough to allow radio waves to penetrate to the depth required. SR seems to have worked and a series of strong reflectors can be traced between traverses consistent with the results from the magnetic anomaly traverses of Nugent et al (2003). Our raw data was processed with seismic processing software to apply specific corrections that allowed us to determine the seismic wave velocity and location and depth of the reflective anomalies. This software made certain corrections to the raw data and also removed some noise to highlight seismic reflections. Below I provide a basic explanation for how GPR and SR data is generated and collected, illustrate some raw data from the SR profiles, and compare the raw data to the processed results.

Methodology

Using shallow based geophysical tools such as GPR and SR, it is possible to acquire new data relating to the subsurface between the TML and the larger igneous body, Mount Hillers. Past research by Sven Morgan (2005) has determined the floor of the TML to be approximately 40 ft down. Therefore, the feeders to the laccolith cannot be below that, if they exist at all. These magma feeders are thought to be pipe-like in shape, and have pushed their way through sedimentary rocks on their way to the TML. The contrast in rock types (igneous vs. sedimentary), as well as the shallow levels, suggested that Ground Penetrating Radar and Seismic Reflection were viable tools to image the subsurface here.

Ground Penetrating Radar uses radio waves to view objects below the surface. A transmitter sends radio signals beneath the surface, and as the signals bounce back, they are picked up by a radio receiver (Burger et al., 2006). The data that is sent back provides a picture of what is beneath the ground. This picture is capable of providing 100 percent coverage of the shallow subsurface, as well as providing information regarding depth and position of a disturbance in the sediments (Miller, 1996). As radio waves travel through materials with varying composition and densities, their velocity changes. Radio waves with higher velocities will reflect back to the receiver more quickly than the slower radio waves. The speed at which the waves are picked up helps determine the type of materials that lie below. If there is an abrupt change in rock type below the surface, there will be an abrupt change in wave velocity, and this will show up in the data. Igneous rock feeders, being composed of denser igneous materials, should coincide with higher wave velocities.

Dr. Morgan and I conducted our geophysical analyses on a plateau just south-east of the TML, which is approximately 10 acres and is a flat. Four traverses were conducted across the plateau perpendicular to the Mount Hillers-TML axis. One traverse was also conducted parallel to this axis. The GPR system, which is a TerraSIRch SIR system-3000, was set to a frequency of 200 MHz and collected data as we walked across the traverses.

Seismic Reflection also uses wave velocities to acquire data. When there is a forceful impact on or within the Earth, rocks vibrate. This movement in the rocks creates waves that spread out similar to ripples on a lake's surface after a tossed pebble breaks the water (Burger et al., 2006). Similar to radio waves, seismic waves travel at different speeds through different materials. If the wave travels through the Earth and reaches material with a higher density called an "acoustic impedance boundary", the wave will be reflected and refracted (Burger et al., 2006). The angles of reflection and refraction can be measured to determine the speed at which the seismic wave is traveling and the depth and location of the higher density material (figure 4).

Along the same traverses that we collected our GPR data, we placed numerous seismic detectors called geophones. Dr. Morgan and I created seismic waves by impacting the surface with a 12 gauge shotgun shell blast from a Betsy air gun and used a recording device that measured the time it took for the waves to reach the geophones after the impact.

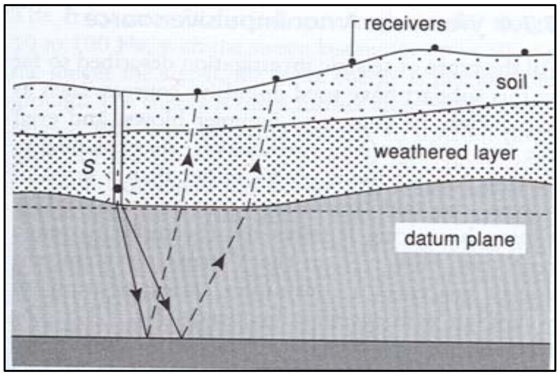

Figure 4: Diagram illustrating how seismic reflection works.

Approximately every 50 meters, we detonated a shotgun blast from the Betsy gun to send seismic waves into the subsurface. The seismic waves were picked up by the geophones and these data were sent back to a recording device known as a seismograph. Igneous rocks (feeders) below the overlying soils and sandstone between Mount Hillers and the TML are much denser than the overlying material and should produce strong reflectors for the waves to bounce up and be collected by the geophones.

Results/Discussion

The data obtained from the TerraSIRch SIR System-3000 GPR suggested that there was no structure beneath the traverses. Because we know there are layered rocks, we believe the data was faulty. We believe the radio waves emitted from the 200 MHz antenna could not penetrate to levels deep enough to reveal significant data. The signal receiver revealed depths no greater than 30 ft. The magma feeders would be found at an approximate depth of 40 ft, the same depth as the base of the laccolith. Erroneous data may also have been recorded due to the amount of sage brush along the traverses. It was extremely difficult, and in some places impossible, to have the GPR in direct contact with the ground. We felt it best not to rely on data from this method.

Preliminary analysis of the SR data revealed the presence of highly reflective interfaces that could represent magma fingers. Regardless of the strength of these reflectors, numerous corrections had to be applied to the raw seismic data in order to create the most accurate seismic record to interpret. Different variables affect the quality of raw seismic data, such as external seismic sources (wind, footsteps), and the geometry of the geophones which can give the illusion that a geologic formation exists below when it does not. This phenomenon is a result of delay in time simply due to the geometry of the geophone spacing. It takes a shorter time for seismic waves to go back and forth to the first geophone than it does for a geophone that is, for example, 10 meters away. The result is that horizontal structures seem to be deeper the farther they are away. The correction for this is called Normal Moveout (NMO). Burger (2006) defines NMO as “the difference in reflection travel times from a horizontal reflecting surface due to variations in the source-geophone distance”. The greater the geophone distance from the source, the greater the amount of NMO. The total amount of NMO can be found by taking the recorded travel time from the furthest geophone and subtracting from it the recorded travel time from the geophone closest to the source (Burger et al., 2006).

Equation 1: $$[T_{NMO} = t_x - t_o]$$

The effect of NMO can be seen in figures 5(a) and 5(b). On a time vs. distance graph, the seismic wave patterns appear to be dipping, indicating that the geologic layer below is dipping. This also gives the illusion that the reflector is deeper down than it actually is. An example of this can be seen in our acquired raw data in Figures 6, 7, and 8. These reflections are from an area where there is no magma feeder below but simply a sand on sandstone horizontal acoustic impedance boundary. All three images are of the same traverse, but the shotgun blast (source) was detonated from the left end (Fig. 6), then the center (Fig. 7), and finally the right end (Fig. 8) to produce three views of the same area. Figure 6 is a data image where the shot was taken near geophone #1. The furthest geophone (#12) from the shot is approximately 53 meters away. As the waves proceed toward geophone #12, the seismic peaks (waves with greater amplitude) appear to be sloping downward, indicating that the reflector is deeper below at geophone #12. In actuality, the reflector is a horizontal boundary and it only appears to be dipping toward geophone #12 because this geophone is further away. This can be viewed again in figures 7 and 8. Figure 7 is a center shot taken between geophones #6 and #7. In this image, the seismic peaks appear to be dipping away at evenly spaced intervals from the central seismic source, giving a hyperbolic shape. In figure 8, the shot was taken at the right side of the power cable closest to geophone #12. It is evident, when comparing Figures 6 and 8, dipping reflectors take on a reverse pattern when the shot is taken from the opposite side.

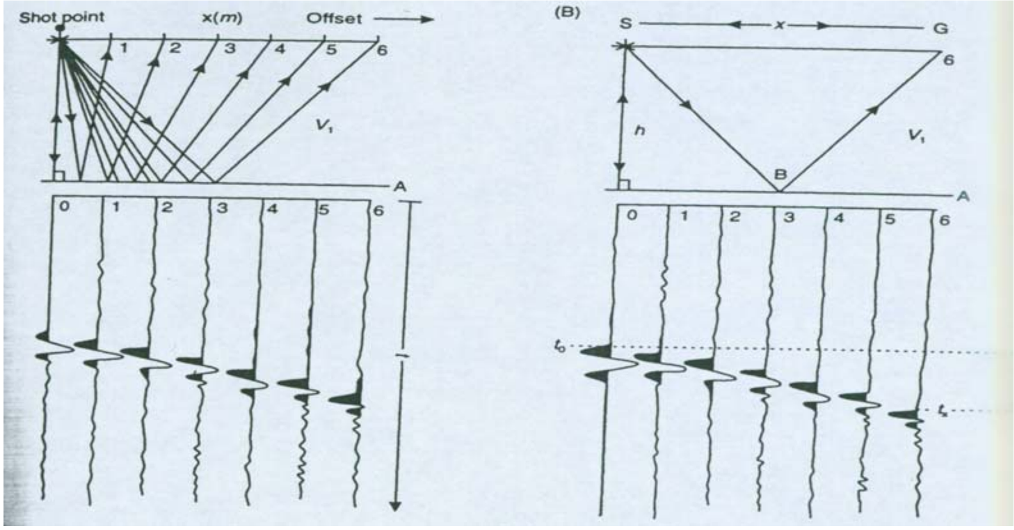

Figure 5(a) **Figure 5(b)**

These figures show the effect of NMO due to geophone spacing in a seismic survey. The total NMO correction is the difference between the final arrival time (tx) and the original (to). Note how the strong seismic reflector is found at deeper levels although the structure (line marked with the A) is actually at a constant depth across the traverse. From Reynolds (1997).

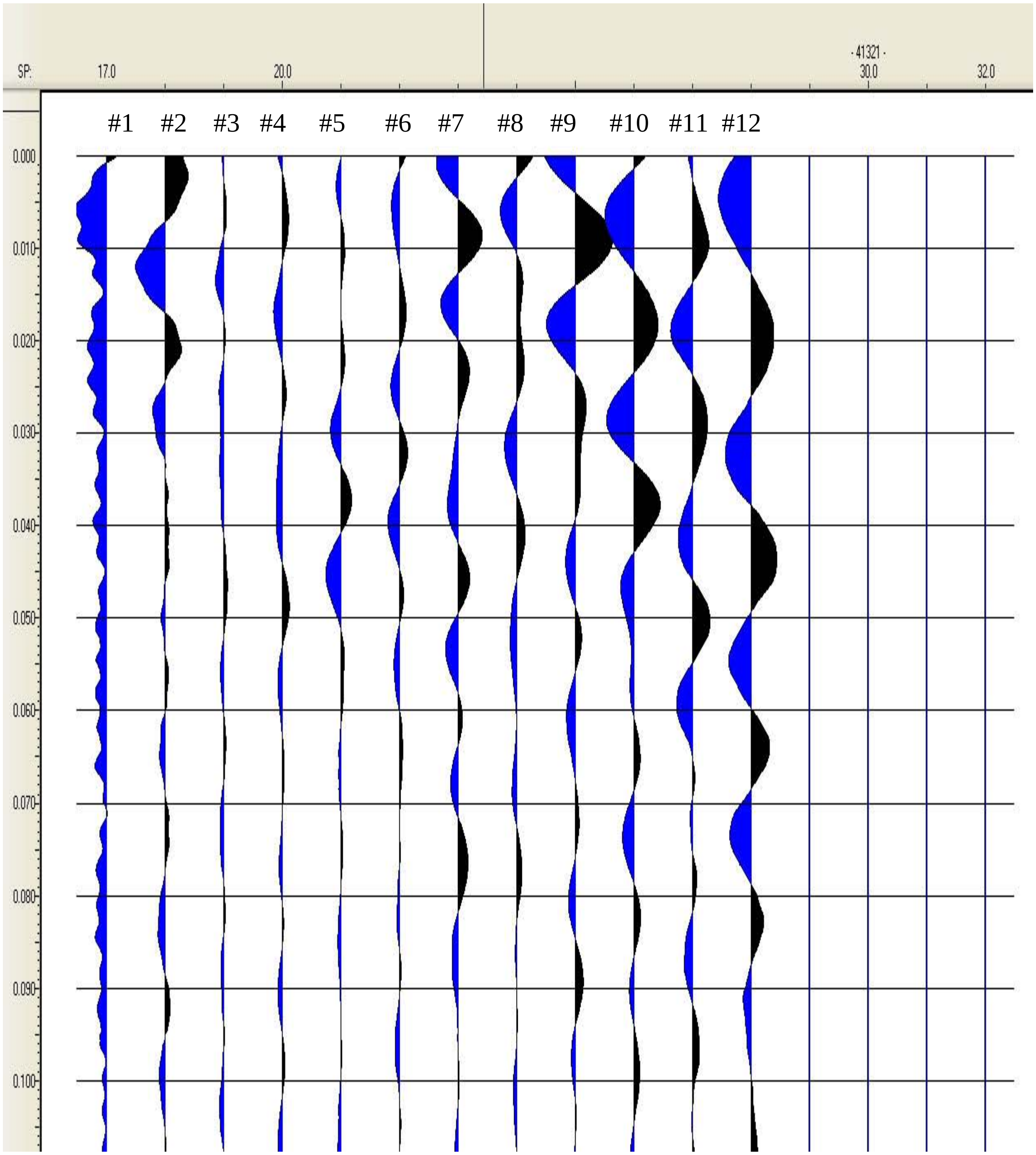

Figure 6: Raw seismic data illustrating NMO. Shot blast was taken on the left near geophone #1.

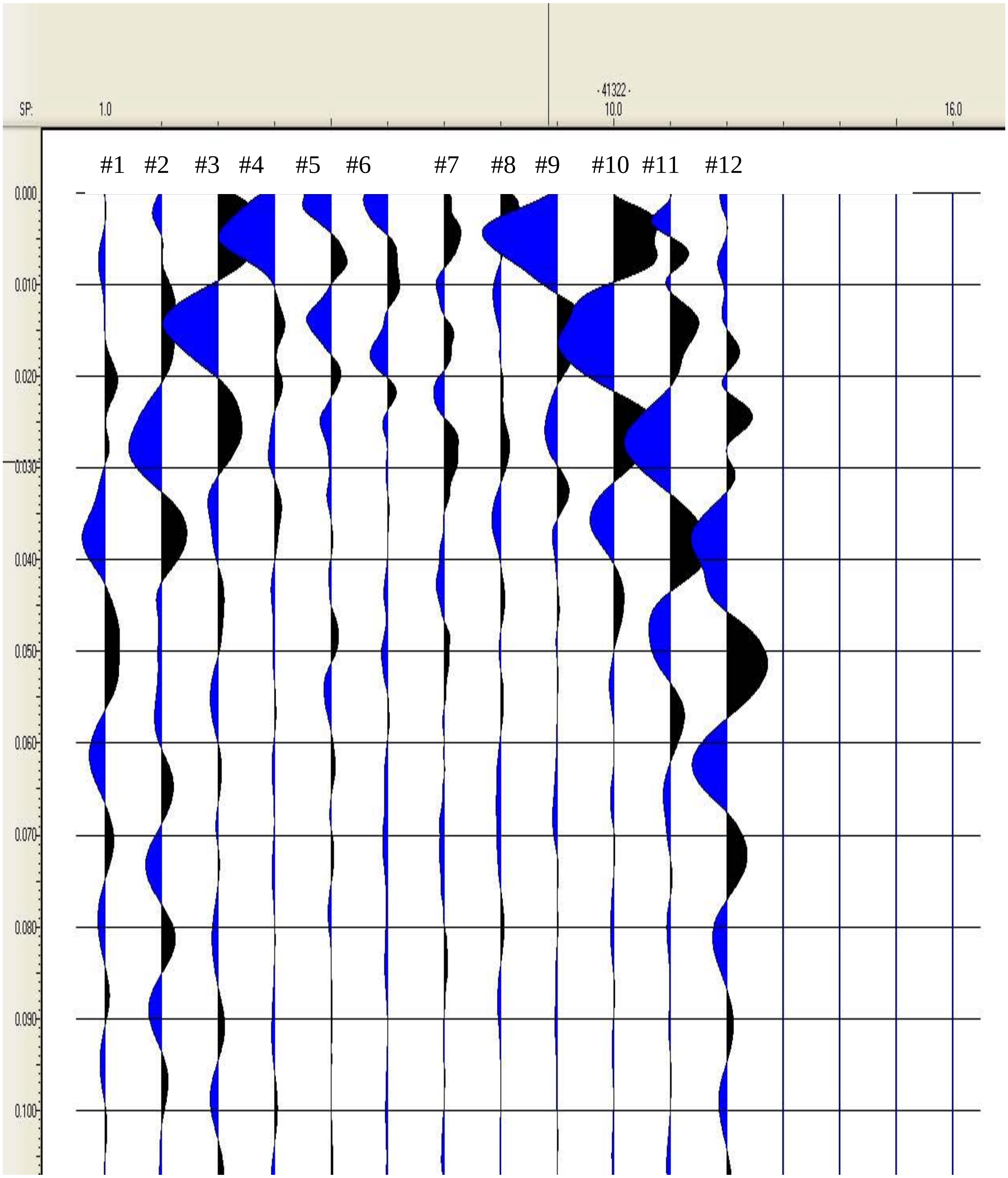

Figure 7: Raw seismic data illustrating NMO. Shot blast was taken in the center between geophones #6 and #7.

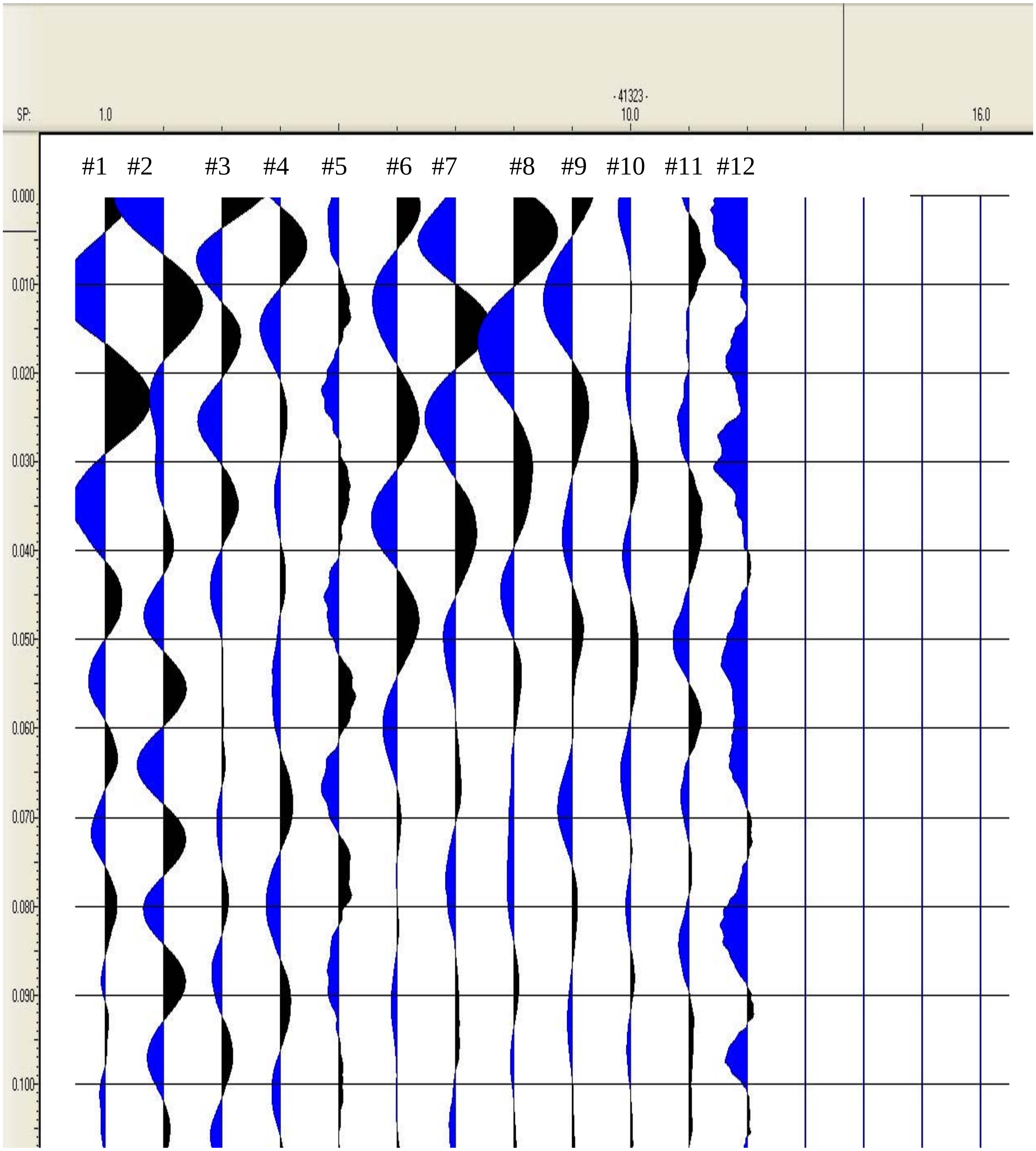

Figure 8: Raw seismic data illustrating NMO. Shot blast was taken on the right near geophone #12.

To have a successful, accurate seismic survey interpretation, we have to correct the data so that the reflections from each geophone trace appear as if the seismic source was directly over each geophone, thus eliminating NMO. This would make the seismic record appear that the wave traveled vertically down and reflected back up along the same vertical path. When the NMO correction is applied, the velocity of the geologic material and the accurate depth to the reflector can be found. Figure 9 shows our collected data after the NMO correction has been applied. A horizontal layer can now clearly be seen near the very top of the traverse. This horizontal layer is the sandstone bedrock that lies very near the surface under the loose sand and sediments in the area. The seismic velocity of this horizontal layer was determined to be approximately 7500 ft per second. This lies within the range for sandstone which is 4500-14500 ft per second (Reynolds, 1997).

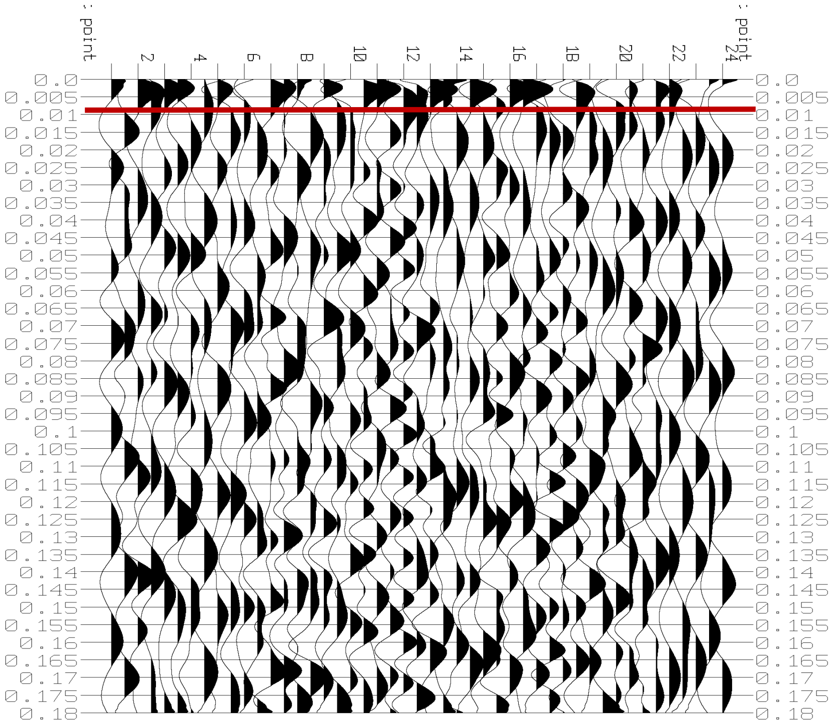

Figure 9: Horizontal bedrock layer after NMO corrections have brought the seismic waves to their correct geometrical position. Note the strong horizontal reflector above the solid line.

Equation 1 for the total NMO correction is equivalent to, and can also be expressed as, the following:

Equation 2: $T_{NMO} = x^2/(2)(v^2)(t_o)$

In this equation, x represents the distance traveled by the wave, v represents the velocity the wave is traveling, and t_o represents the travel time. The velocity in this equation is the root-mean-square velocity or V_{RMS}. According to Reynolds (1997), the V_{RMS} can be found by creating an $X^2 – T^2$ graph. This is done by squaring the travel time and travel distance on the raw seismic data and making a graph of distance vs. arrival time. The plots on the graph are then calculated with a linear fit and the slope of this line is equal to $1/V_{RMS}$. Plugging this velocity into equation 2 can correct for NMO for any recorded time and distance on the seismic record.

The root-mean-square velocity is not the velocity that is diagnostic of particular geologic material. However, it is needed to find this velocity from the following equation from Reynolds (1997).

Equation 3: $V_{INT} = [(V_{RMS\,n})^2(t_n) - (V_{RMS\,n-1})^2(t_{n-1})/(t_n - t_{n-1})]$

In this equation, V_{INT} (interval velocity) represents the velocity of geologic materials at varying acoustic impedance boundaries. Each different boundary is represented by an n, and t_n is the travel time to the boundary. This equation will give us the velocity of the geologic materials below.

Another correction that is important in seismic data processing is called migration. Migration is necessary due to complex structures and dipping reflectors that may be below. The purpose behind migration is to place a seismic anomaly in its correct place on a time vs. distance seismic record (Reynolds 1997). In the case of NMO, a horizontal interface gave the illusion of a dipping structure below. When the reflector is in fact dipping, or has an odd shape such as a magma finger (which would be rounded), the odd geometry of the structure causes the waves to be reflected in a way that reveals an incorrect geometrical position underneath (Reynolds, 1997). As previously mentioned, the goal in seismic reflection surveys is to correct the data so that the reflections from each geophone trace appear as if the seismic source was directly over each geophone. Odd geometrical shapes, such as magma fingers, prevent this from happening (see figure 10). The abnormal shape causes the wave paths to be reflected away and be detected from a geophone that is not directly above. This is what causes the false geometrical image.

Because a magma finger has an irregular circular shape, migration corrections can be made to determine the true subsurface location. A summary of how migration corrections are made involves basic circular geometry. According to Burger (2006) and making reference to figures 10(a) and 10(b), the true location of the reflector lies on a circular arc made between the reflecting point and the apparent reflecting point. The radius of the circular arc is equal to the velocity of the wave multiplied by half the travel time.

Equation 4: $\mathbf{R = V*(to/2)}$

If each apparent reflecting point is placed along this circular arc, a tangent line is made that represents the true location of the reflector.

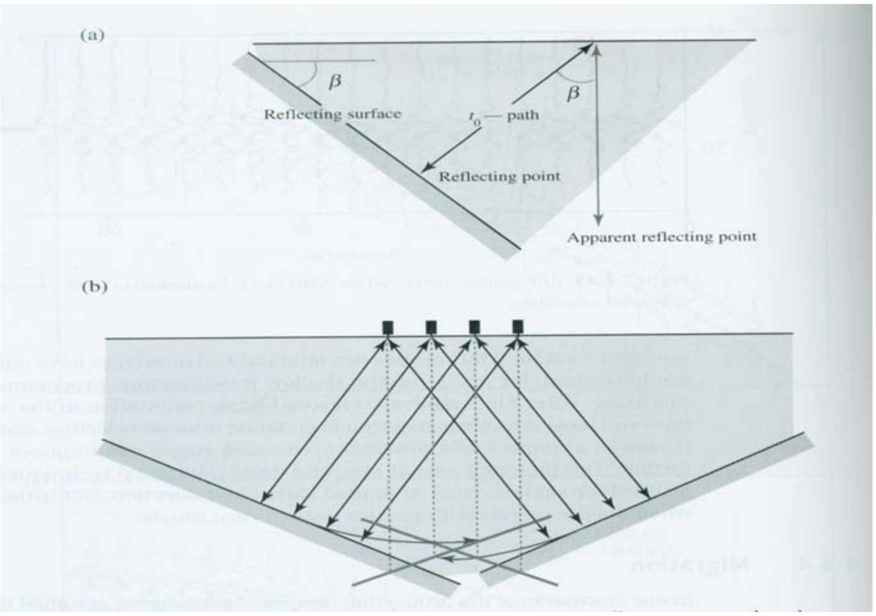

Figure 9: Diagram illustrating migration and migration correction. Dashed lines represent the apparent reflecting point. Rays represent the reflected point. The crossed lines represent the true location of the reflector. From Burger (2006).

All raw seismic data was taken to Jerry Blaxton of Integrity Geophysical in Shepard, Michigan. Mr. Blaxton used geophysical processing software that allowed us to analyze and make corrections to our raw data. To ensure correct data, accurate geometrical locations of the geophone placing had to be entered into the processing software. The total number of 12 geophones was recorded along with the 16 ft intervals between each one. Once the correct geometry had been entered and the NMO corrections were applied, we began stacking common depth points (CDP) in order to increase the signal to noise ratio. When in the field, the shot taken at the center of the traverse and the shots taken at each end reflect back the same reflective interface but only from different angles. If the seismic records from each shot blast along the traverse are added together, the real reflections will be enhanced and unwanted noise will be diminished (Burger, 2006). This will allow anomalies to stand out and be more easily detected. The process can be compared to water wave motion. If two waves pass the same point at the same time, the waves combine together to form a larger wave. The amplitude of the larger wave equals the sum of the two smaller waves. If we add together the seismic waves that have reflected the same point in the subsurface (CDP), we can greatly increase the wave amplitude of this anomaly in the seismic record. Noise and unwanted signals then become obsolete. Stacking the common depth points also allows the reflector to be represented in its correct geometrical position because we have added together the various angles in which the reflection was recorded (Burger, 2006).

A frequency filter was also applied to our data to minimize noise and enhance true reflectors. The software used frequency-bandwidth filtering which allowed us to take out frequencies that are insignificant and just clutter up the data. An example of such a frequency would be ground roll, or surface waves. Ground roll is a result of the initial blast from the seismic gun. The air from the seismic blast creates its own seismic waves that travel along the surface and can be picked up by the geophones and obscure our reflections. For this project we used a frequency filter set to 25/50 Hz on the low cut end and 100/200 Hz on the high cut end. This means that all frequencies that are below 25 Hz and above 200 Hz will be eliminated from the seismic record. All data between the frequencies of 50-100 Hz will be preserved. On the low-cut end, the frequencies between 25-50 Hz will be reduced but not totally eliminated. The closer the frequency is to 25 Hz the greater it will be reduced. The same situation occurs on the high cut end. All frequencies between 100-200 Hz will be reduced with more reduction closer to the 200 Hz endpoint. This procedure greatly reduces unwanted frequencies and allows us to concentrate on the frequencies that are most likely to correspond to layers of sedimentary rock and possible magma feeders.

After applying all of the above corrections to our seismic data, we now have a seismic record in which we can check to see if anomalies exist that could represent magma feeders. We have predicted the magma feeders to be approximately 40 ft below the surface because that is where the base of the laccolith lies. I estimated, using the best fit velocity, the velocity of the seismic waves traveling through the surrounding sandstone to be 7500 ft per second. A seismic wave traveling at this speed would reach a depth of 40 ft and be reflected back up in approximately .01 millisecond. On three of the five traverses made, there were reflective interfaces that were reached at a time of .01 millisecond. When the locations of these anomalies were plotted due to their location on a map of the area, they all appeared to be in line with one another. They also were along the same axis that links the TML to Mt. Hillers (see figure 10). These data support the theory that the laccolith was formed by horizontal feeders that stemmed from Mount Hillers.

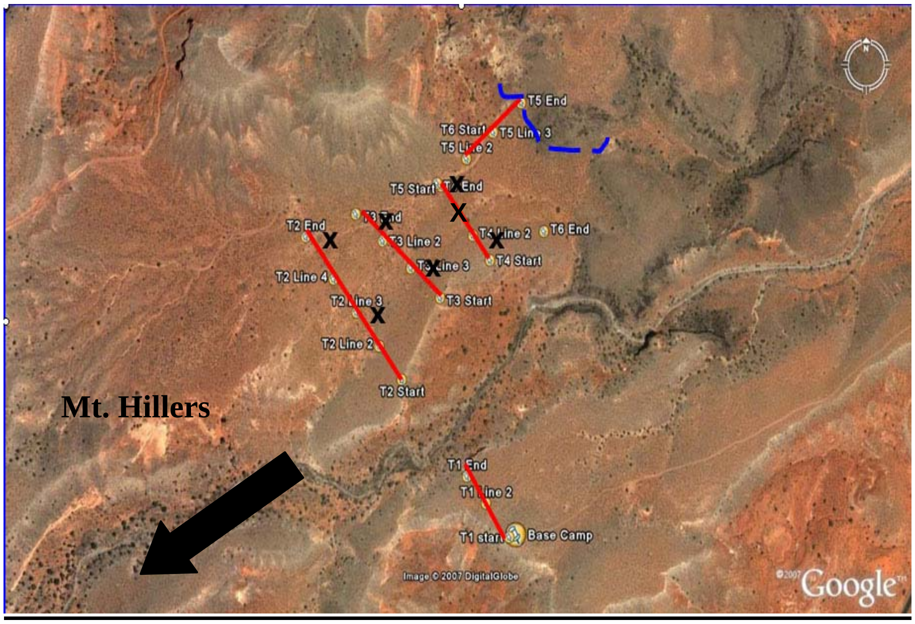

Figure 10: Map of research area. Lines represent traverses made and each anomaly found is marked with an X. Notice that the anomalies tend to line up with one another and are in line with the TML-Mt. Hillers axis. Dashed line indicates laccolith contact.

We decided to compare this data with a previous geophysical survey that was done in the area using magnetic intensity. Nugent (2003) collected data along the same traverses and came across magnetic anomalies that could represent magma feeders. Igneous materials (magma feeders) contain higher amounts of magnetic material and therefore could explain the higher magnetic readings. The locations of Nugent's anomalies were plotted on a map of the area. I compared those locations with the locations of the seismic anomalies and there was a match in most instances. Figures 11, 12, and 13 show reflectors circled in red that correlate with the location of Nugent's magnetic anomalies. On figure 13, a very high reflector circled matched the same location as Nugent's; however, this reflector is further down than the estimated 40 ft because it was reflected at a time longer that .01 millisecond. This could represent a finger that originated at a deeper depth and rose to a depth of 40 ft closer to the laccolith, or it could not be a finger at all. Two locations where Nugent had an anomaly, seismic data revealed nothing. One location revealed a seismic anomaly but no magnetic data. Although we used corrections to help enhance the reflectors and reduce noise, there still was much "clutter" in the data that prevented a pronounced reflection compared with the rest of the record. A reason for this is that we did not have many common depth points to stack together to enhance the signal to noise ratio. We took 3 shots at each traverse (a left, a center, and a right) which gave us three different reflectors to stack that correlate to the same sub-surface location. The day the seismic data was collected was extremely windy. There were wind gusts up to 40 mph which can greatly affect the data. The slightest movement at the surface can create unwanted noise and vibrations on the geophones. This may be one reason why reflectors were not noticed in some locations that had magnetic intensity. A simple solution to this problem would have been to create a seismic impact at each of the 12 geophones using a sledge hammer. A sledge hammer would have been a more ideal

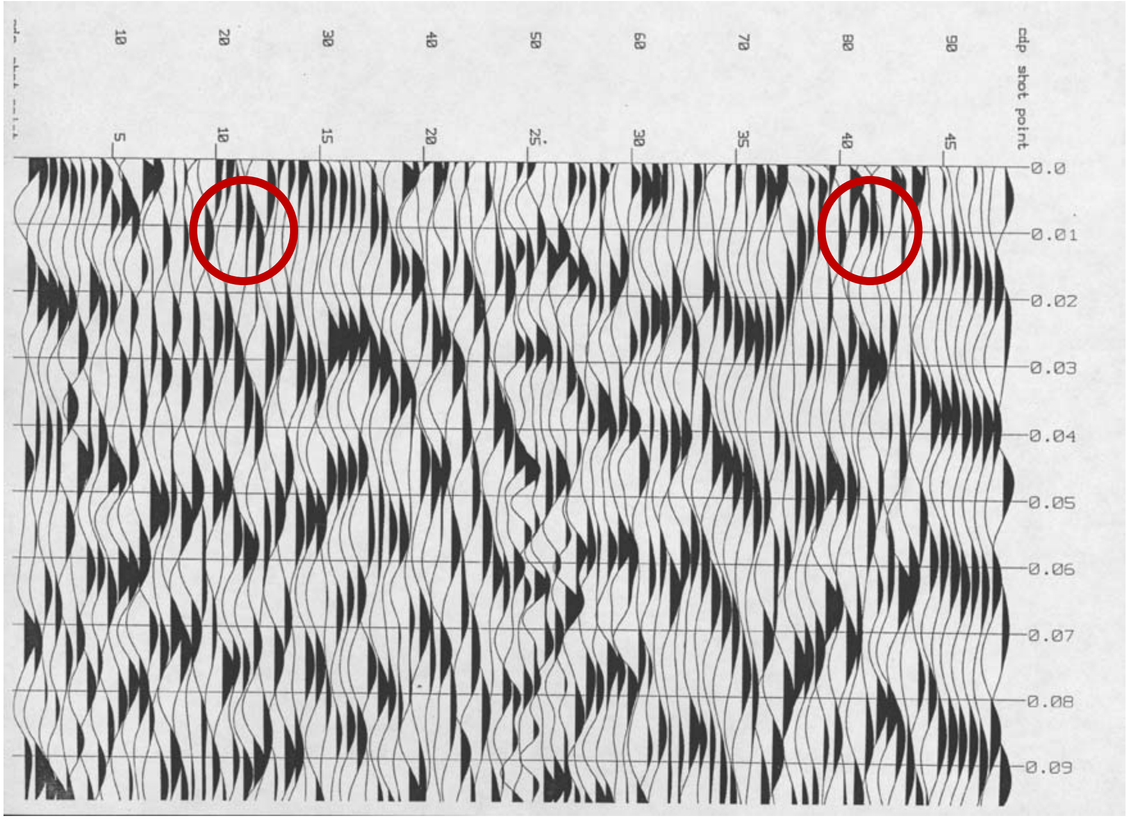

Figure 11: Processed seismic data along T-2 with anomalies at .01 millisecond. The two anomalies circled are anomalies that matched the exact location of Nugent's magnetic data. Magnetic anomalies that do not match a seismic anomaly are not marked, as well as seismic anomalies that do not match magnetic. Note that we are only interested in reflectors along and above the .01 millisecond line because this time corresponds to a 40 meter depth, the estimated depth to the base of the laccolith. The time can be read off the right vertical axis.

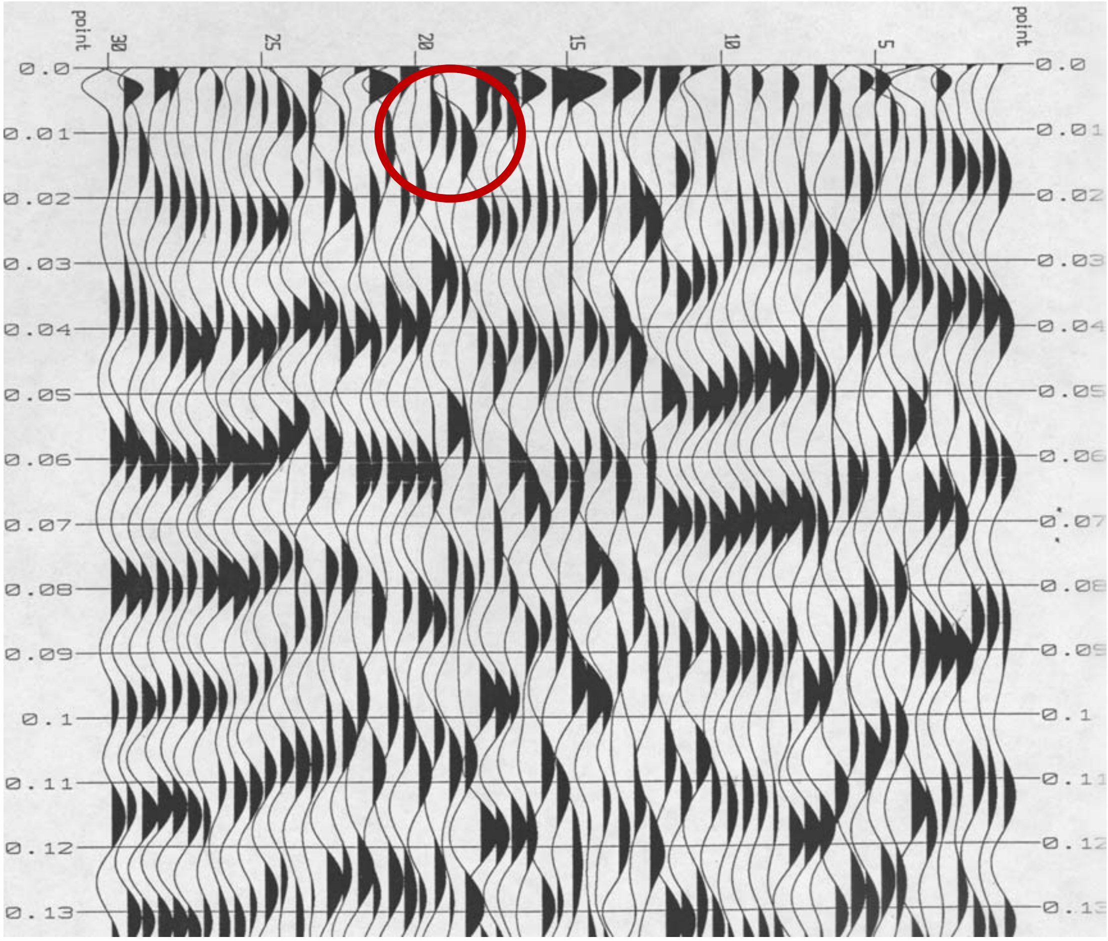

Figure 12: Processed seismic data of T-3 showing seismic anomaly at .01 millisecond that matches the location of a magnetic anomaly.

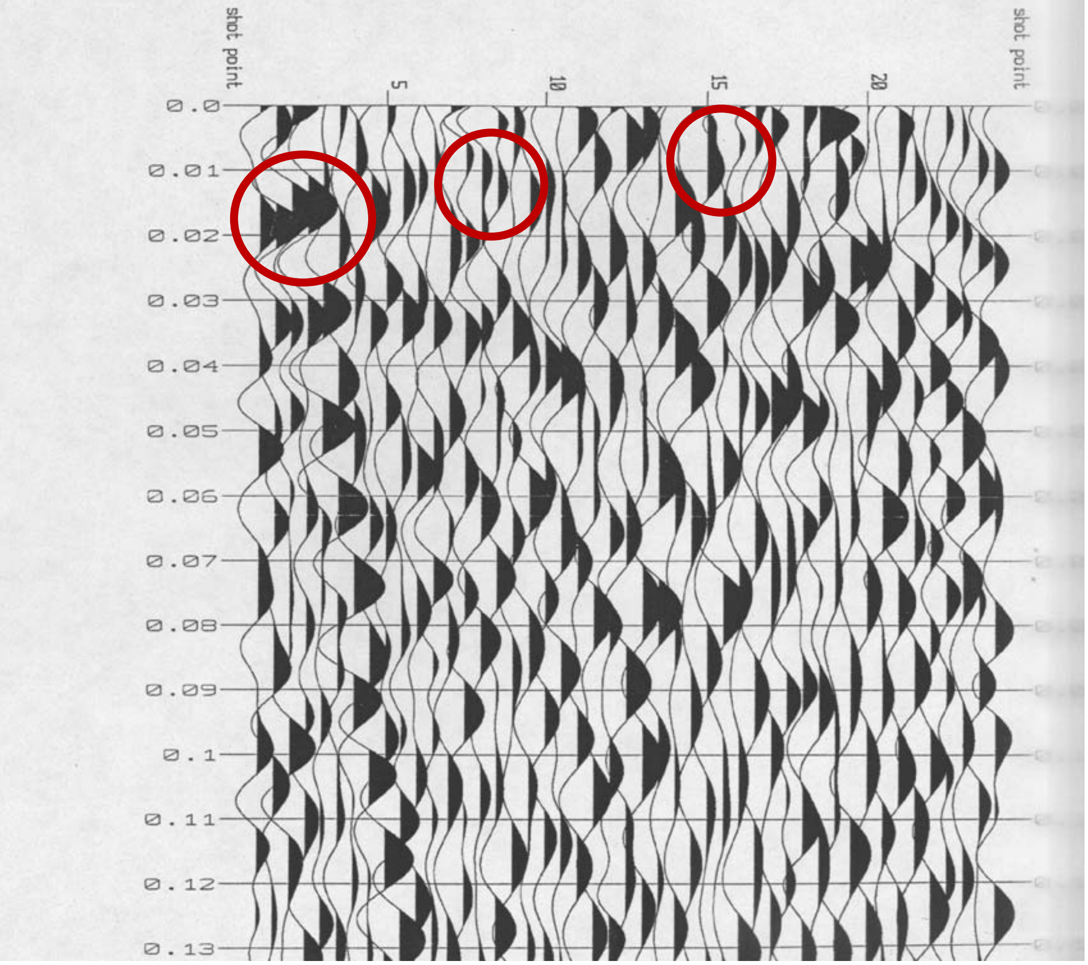

Figure 13: Processed seismic data of T-4 showing two anomalies at .01 millisecond and a larger anomaly at .015-.02 millisecond. All anomalies match the location of magnetic anomalies.

tool for the area because the bedrock was so close to the surface. The shot gun shell striking bedrock at such shallow levels often caused the seismic gun to rebound out of the ground. If a sledge hammer was used at each of the 12 geophones, there would be 12 different CDP to use to stack and enhance the reflector. This would have significantly reduced the signal to noise ratio and greatly enhanced reflectors.

Although the signal to noise ratio was not as great as we had anticipated for an object with such a high density like a magma feeder, we did find seismic anomalies that were located in the same position as magnetic anomalies in the area. The location of these anomalies, being in direct line with the TML-Mount Hillers axis and lining up with one another, is further evidence that suggests these feeders exist. Another investigation involving the collection of a greater number of stackable traces could help support this theory as well.

Acknowledgements

I would like the thank Jerry Blaxton of Integrity Geophysical for his help in processing our collected data, Sven Morgan for his guidance and knowledge during this project, and Pat Kinnicutt for his help out in the field with the equipment and record keeping. Without the help of all three, this project would not have been able to be completed.

References

Burger, R. H., Sheehan, A. F., & Jones, C. H. (2006). *Introduction to Applied Geophysics: Exploring the Shallow Subsurface*. New York: W. W. Norton & Co.

Case, J. E., & Joesting, H. R. (1972). Regional geophysical investigations in the Colorado Plateau. *U.S. Geological Survey Professional Paper*, 736, 31 p.

Corry, C. E. (1988). Laccoliths; Mechanics of emplacement and growth: *Geological Society of America Special Paper*, 220, 110 p.

Gudmundsson, A. (2002). Emplacement and arrest of sheets and dykes in central volcanoes: *Journal of Volcanology and Geothermal Research*, 116, 279-298.

Hunt, C. (1953). Geology and geography of the Henry Mountains region, Utah: *U. S. Geological Survey Professional Paper*, 228, 234p.

Hyndman, D. W. & Alt, D. (1987). *Radial Dikes, Laccoliths, and Gelatin Models*. Journal of Geology, 95, 763-773. .

Lowrie, W. (1997). *Fundamentals of Geophysics*. London: University of Cambridge Press.

Miller, P. S. (1996). Disturbances in the soil: Finding Buried Bodies and Other Evidence Using Ground Penetrating Radar: *Journal of forensic sciences*, 41, 648-652.

Morgan, S. S., Horsman, E., Tikoff, B., Saint Blanquat, M., Nugent, A., & Habert, G. (2005). Sheet-like emplacement of satellite laccoliths, sills, and bysmaliths of the Henry Mountains, southern Utah, In Pederson, J., & Dehler, C. M., (Eds.), *Interior Western United States: Geological Society of America Field Guide*, 6, 28 p.

Nelson, S. T., & Davidson, J. P. (1993). Interactions between mantle-derived magmas and mafic crust, Henry Mountains, Utah: *Journal of Geophysical Research*, 98, 1837-1852.

Nelson, S. T., Davidson, J. P., & Sullivan, K. R. (1992). New age determinations of central Colorado Plateau laccoliths, Utah: Recognizing disturbed K–Ar systematics and re-evaluating tectonomagmatic relationships: *Geological Society of America Bulletin*, 104, 1547–1560.

Nugent, A., Morgan, S. S., Boyd, B., Saint Blanquat, M., & Horsman, E. (2003). Magnetic anomaly based interpretation of the magma feeders to the Trachyte Mesa Laccolith, Henry Mts., Utah: *Geological Society of America Abstracts with Programs*, 35, Abstract No.6 (200311), 339.

Pollard, D. D., Muller, O. H., & Dockstader, D. R. (1975). The Form and Growth of Fingered Sheet Intrusions: *Geological Society of America Bulletin*, 86, 351-363.

Reynolds, J. M. (1997). *An Introduction to Applied and Environmental Geophysics*. West Sussex, England: John Wiley & Sons.