Seismic Refraction: A Geologic Exploration of the Jeffersonville Landslide

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Thesis

Seismic profiling is an important technique for analyzing the underlying geologic structure of regions. Implementing seismic refraction techniques to better understand the structure of Deer Run Heights, just above the Brewster River, will provide additional information about the potential for slope failure along the ridge. The relationship between the depth, slope and composition of the underlying materials correlates to the tendencies of mass wasting events. A comprehensive analysis of the structure, materials and environmental factors that characterize the ridge will present data regarding the impending frequency of landslides in our communities, helping communities prepare for impending dangers.

Abstract

The 2009 seismic refraction survey revealed material velocities of nearly 18,000 ft/s. Velocities greater than 12,000 ft/s indicate metamorphic rocks. The velocities obtained along the ridge, as well as the parallel survey lines (one atop and one at the base of the ridge), confirmed a horizon far beneath the sand couplets. This layer slopes toward the Brewster River, with a deeper layer of accumulation nearer the face of the Brewster River Ridge. At the base of the slide, beyond the river toward the elementary school, a third layer was revealed at only 12 feet below the surface. The high velocity of this particular layer, which was 17,825 ft/s, suggests that it is the metamorphic rock that has shaped Vermont's rugged slopes. Figure 1 shows a topographic map of the region, as well as the location of the three seismic survey lines.

Figure 1. Map of Jeffersonville (G-REF, 1996).

Introduction

The landslides that have occurred in Jeffersonville are associated with a ridge known as Deer Run Ridge. The ridge extends nearly 1500', confined at its base by the Brewster River (G-REF, 1996). The ridge, which is adjacent to the village of Jeffersonville, is difficult to define. It precedes the relatively flat farmland that lies to the west of the Green Mountains and extends to Lake Champlain. The ridge is at the base of Mount Mansfield, steeped both in rugged history and terrain. The geologic history of the region includes the repeated submergence by glacial lakes from ice-dammed rivers. The upper portion of the ridge was deposited as the last glacial lake receded (Wright, 2003). The ridge is bound on either side by a river, the Brewster to the west, and an unnamed brook to the east. The Brewster is constricted at the far south of the ridge by the rugged bedrock at Jeffersonville Falls. From the falls, the river carves toward the ridge and flows adjacent to its steep banks to its outlet at the Lamoille River, which is just beyond the ridge.

The intersection of the Jeffersonville alluvial fan, which the village is built upon, and the northern edge of Mount Mansfield's slopes, from which the Brewster River flows, provides an ideal location for slope failure. It is the junction of steep slopes, high flow rates and the valley. These factors collide with the added dimension of the unstable ridge of glacio-lacustrine deposits (Forsberg, 2007). The Jeffersonville Landslide has been a persistent location for the erosion caused by slope failure due to the shearing soil types that are present at this location (Nichols, 2002). The primary cause of slope failure is the steep slope that persists along the ridge and the statigraphy. A significant contribution to this failure is the increased pore pressure of the silt and fine sand, which comprise the ridge (Forsberg, 2007). When above average rainfall persists, these fine materials become saturated. As the saturation of these materials subsides, the air voids in the medium intensify the overall instability of the ridge (Wright, 2003).

The aim of the seismic research at Jeffersonville was to define the geology of the Deer Run Ridge. Understanding the composition and depth of the materials that the ridge is composed of, specifically the bedrock geology, will provide assistance us in projecting the longevity of sliding tendencies along the ridge.

History

Records of slope failure have been documented throughout the Twentieth century. According to the Vermont Geological Survey, the most recent slides were in 2008, 2006 and 1999, with three landslides occurring in 1999. During the 1999 trilogy, a home was lost to the slope failure that the slides created (Becker et al., 2009). The slope continues to deteriorate, amplifying the prospects of a catastrophe (Forsberg, 2007). According to the 2009 geologic map in Figure 2, there are two predominant metamorphic layers in the immediate region. The rock type (Chg) that strikes through the center of the map in Figure 2, which is a member of the Belvidere Mountain formation (amphibolite and green stone), is the location of the landslides and the seismic survey, which is discussed below. The surrounding formation (Cug) is another green stone formation. The thin, green lines represent the major roads that traverse the region. Route 15 travels from east to west (lower horizontal line), route 108 travels from north to south and the Hogback Road travels to the east from route 108. Deer Run Heights is the only access to the north side of the ridge, where the most recent slides and a handful of residences exist. The access to this steep, windy road is to the east of the Belvidere formation from route 15. If this region, as well as the entirety of the ridge continues to erode, the future of the flood plain known as the town of Jeffersonville and the recreation field of Cambridge Elementary is uncertain.

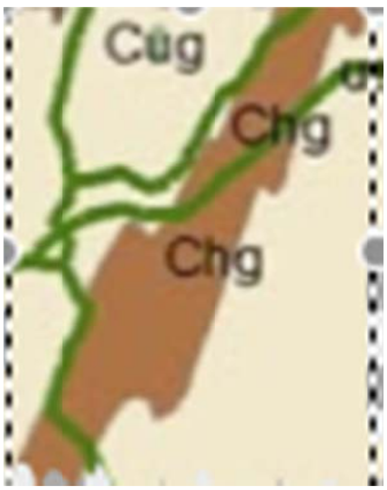

Figure 2. Jeffersonville Geology (VGS, 2009).

Vermont's mountains were folded during the Taconic and Acadian orogenies, and then weathered as the glaciers advanced and retreated, shearing their surface (Wright, 2003). From the steep banks of the Jeffersonville Landslide to the alluvial fan on the west of the river, the vertical distance is more than forty-six meters (Nichols, 2002). The slope of the Brewster River Ridge ranges from 25 to 50% (Forsberg, 2007). The face of the Jeffersonville Landslide strikes north at the northern edge of Mount Mansfield's forest and the eastern edge of the Brewster River. The Brewster is a north flowing tributary of the Lamoille River, which flows west through the region toward Lake Champlain. The soils of the landslide are mostly sand and clay, with silty clay sills and gravel undertones, which increase to glacial till atop sedimentary rock (Wright, 2003).

The geophysical exploration of Deer Run Heights and the Brewster River has been an ongoing process by students and professionals throughout the northeastern United States. In order to better understand the geologic structures of the region, many techniques have been employed during the Twentieth Century. Recently, Specialty Drilling and Investigations of Burlington, VT installed four monitoring wells on the Brewster River Ridge (Becker et al., 2009). These depths will be referred to in the discussion section of this paper.

Survey Methods and Equipment

Two surveys were recently completed at the site: a topographic survey and a seismic refraction survey. The topographic survey data were analyzed by Norwich University. This provided researchers with an accurate definition of the region's contours. The seismic refraction survey was completed by Johnson State College (JSC) students, in conjunction with George Springston, a research associate at Norwich University. The depth of the soil horizons and the depth of bedrock were estimated using the data obtained from this surveying technique.

Figure 3. Geophone Detail. (Kanat, 2009)

The topographic survey of the Brewster River Ridge was completed using a total mapping station, which has a built-in data collector. First, a loop was surveyed in the field above the landslide to establish the location. Then, the wooded banks leading to the Brewster River were surveyed. This allowed the definition of alluvial fans, gullies, wash-outs, cut backs and the banks of the Brewster River below. Erosion persists along the ridge, with two prominent gullies cutting into the ridge along the western face of the field. Trees and sediment are washing toward the river from the top of the ridge within these gullies.

Seismic refraction techniques were also employed at Deer Run Ridge. The locations of the three survey lines are marked in Figure 1. The map in this figure shows the Brewster River cutting sharply along the western base of the Brewster River Ridge to the Lamoille River. Seismic surveying has been used since the early 1920's to explore geologic structures for petroleum deposits (Haeni, 1988). This geophysical method measures the travel time of compressional waves through the subsurface materials to a series of geophones (Figure 3), which transmit the data to a seismograph. The underside of the geophone is a spike, which is secured in the ground and the red and black connectors are attached to the seismic line, which transmits the data to the seismograph. The application of physics, specifically Snell's Law, to these data allows the inference of the subsurface geology based on mathematical calculations (Haeni, 1988). George Springston of Norwich University was instrumental not only in the survey, but in the interpretation of the raw data that were obtained.

Willebrord van Roijen Snell studied geometric optics and initiated the foundation of geodesy during the Seventeenth Century. Snell's Law, which was the highlight of Snell's work, is known as the Law of Refraction. The equation is:

$$\sin \vartheta = V_1/V_2,$$

where V=velocity and ϑ = angle of incidence (Redpath, 1973). This law governs the refraction of sound waves across the boundary between layers having different velocities. Figure 4 models the path of a wave through the ground, as it is refracted and as the wave reflects the remaining energy of the wave. Part of the transmitted energy is refracted and part of the energy is reflected when the wave intersects the adjacent layer. When the angle of incidence equals the critical angle, the compression energy is transmitted along the upper surface of the second layer at the velocity of sound in the second layer. This energy creates new sound waves in the upper medium (Huygens' principle- every point on an advancing wave front can be considered the source of a sound wave), which propagate back to the surface through the initial layer at an angle equal to the critical angle and at the velocity of sound in layer one. When the refracted wave arrives at the surface, it activates a geophone and the arrival energy is recorded on a seismograph. If geophones were spread out on the ground in a geometric array, arrival times would be plotted yielding a time-distance curve (Griffiths and King, 1988).

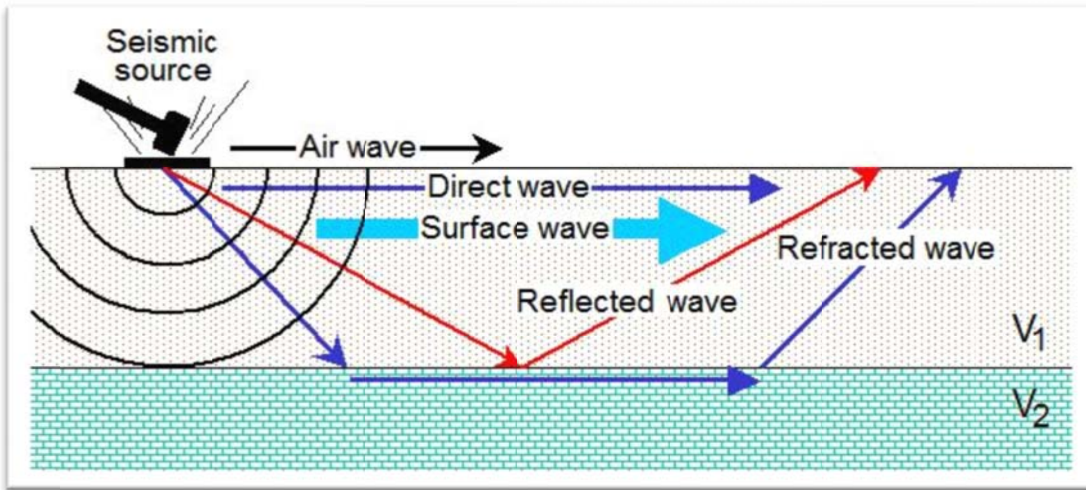

Figure 4. Propagation of Seismic Waves. (Park, 2007).

According to Snell's Law, sound waves differentiate layers and the velocity of the sound waves that travel through the ground where it is impacted, describe the density and identify the underlying material. The sound waves in the ridge ranged from 1,273 ft/s to 15,052 ft/s, indicating weathered surface material overlaying sedimentary rock. The third survey revealed another layer beneath these two, with a velocity of 17,825 ft/s, indicative of metamorphic rock.

Seismic refraction survey techniques measure the time that it takes for a compression sound wave generated by a sound source to travel through layers of earth and back up to detectors on the surface. As the sound waves enter the individual layers they refract, abruptly changing the wave velocity. This sudden change in velocity identifies a variation in the material. This variation is characterized by density, which permits the identity of the material and the depth of the material beneath the survey line (McCarthy, 1998).

Procedure

The seismic survey involved laying out 12 geophones along a 110-foot line. The line was connected to a seismograph and a 12-volt battery. An aluminum block

Figure 4. Sledge-hammer with Seismogram Cable (Kanat 2009).

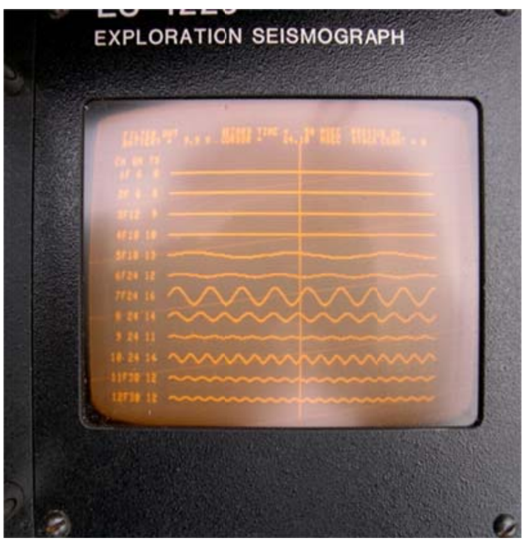

Figure 5. Exploration Seismogram Screen (Kanat 2009).

was placed one meter perpendicular to the line at geophone one, which was one meter from the beginning of the line. A sledge-hammer was connected to the seismograph via a cable, as shown in Figure 5, which was taped to the upper part of the hammer's handle. The hammer was used to strike the block with as much force as possible. The energy that the ground received was transmitted to the seismograph as sound waves. The velocity of the waves through the ground is relatively constant throughout a given medium. When the sound waves enter a different horizon of material, the velocity reflects and refracts. The arrival time of the waves at the seismograph indicates the velocity of the waves. An image of the seismograph screen is in Figure 6. These data are used to determine the type and depth of each soil horizon beneath the geophones.

Three lines were surveyed, each striking near north, roughly parallel to the ridge's westerly face at the northern edge of the Brewster River Uplands Community Trust Field. This field is the only portion of the ridge top that is not wooded; the eroding slopes are wooded. In some of these areas the trees are being consumed by rotational slumping as the fine underlying materials are eroded. Two of the seismic surveys were east of the Brewster, on the western and eastern sides of the ridge, respectively. The third survey was on the west side of the Brewster River, at the edge of the school property. The first survey was completed on the sixth of November 2009, the second on the thirteenth and the third on the twentieth of December 2009. For each survey, the data was plotted on a time versus distance plot. Steady slopes and clear velocities were sought. Figure 6 shows the third graph that was created at the second survey sight. Best-fit lines were drawn through the points, revealing a steady slope for each material detected. Shorter slope distances on the time-distance plot indicate shallower layers, and conversely longer distance indicate deeper layer. The accuracy of a time-distance plot can be confirmed by vertically aligned points on the graph (Griffiths, 1988).

Each survey was shot forward from geophone one to twelve, and then was reversed from geophone twelve to one. The horizontal distance from the origin represents the distance of each geophone from the point of impact and the seismograph. Each series of points at the geophone locations represent the various recordings that were obtained using the forward, reverse and center-reverse shots (Figure 6). When the arrival times of the waves were consistent and strong at a particular geophone, that geophone was locked to prevent the distortion of the data by loud vehicles and equipment that were operating in the vicinity. During a portion of each survey, the two center geophones were also disconnected. This allowed the sound waves to concentrate toward the ends of each line. This converged the wave reception to the outer geophones. Each survey line was shot one meter beyond the end of the line, providing affirmation about the material's characteristics. The velocities and the distances were plotted, as shown in Figure 6 on the next page. Images of the survey plots, spreadsheets of the field book data and images of the calculations are included in the appendix. The line segments on the plots were interpreted mathematically in order to identify information about each material's characteristics. This is examined in the following section.

Discussion

The two surveys in the field revealed two horizons on the graphs, while the third survey showed three clear horizons. These data suggest the underlying geologic structure of this localized region. Nichols (2002) found that the landslide soils are glacial lake sediments composed mostly of silt and fine sand couplets. This layer is overlain by less than two meters of gravel and sand.

The findings of the seismic survey are that a metamorphic rock formation lies beneath the deep layer of material atop the ridge. This layer slopes steeply toward the river. The Brewster River has not only eroded its basin as it roars from its mountainous origin, but it has contributed to the weakness of the ridge's toe, as fine saturated materials succumb to both moisture and gravity. The ridge protrudes nearly 150 feet above the river. The survey revealed a solid horizon at 66 beneath the surface to the west (toward the river) and at 46 feet to the east of the field atop the ridge. At the base of the ridge the horizon was 33 feet beneath the surface. This means that there is a change in elevation of more than one hundred feet from the river side of the field to the base of the ridge across the Brewster River, with about the same horizontal distance.

The velocities of the materials do not parallel one another at all horizons, indicating that there may be a horizon that is exclusive to surveys 1 and 3. This would further support the risk of mass wasting at this site. A horizon of rock that does not extend across the field could be a strong indication of an even steeper slope of bedrock along the face of the ridge toward the opposite side of the Brewster River. This is suspected as the initial survey did not reveal velocities high enough to be indicative of metamorphic rock. This means that the metamorphic rock is buried far beneath the horizon of sedimentary rock , but the metamorphic rock is seismically visible at the second survey. A comprehensive exploration of the collective data that has been compiled would clarify and strengthen the basis of the findings of all research.

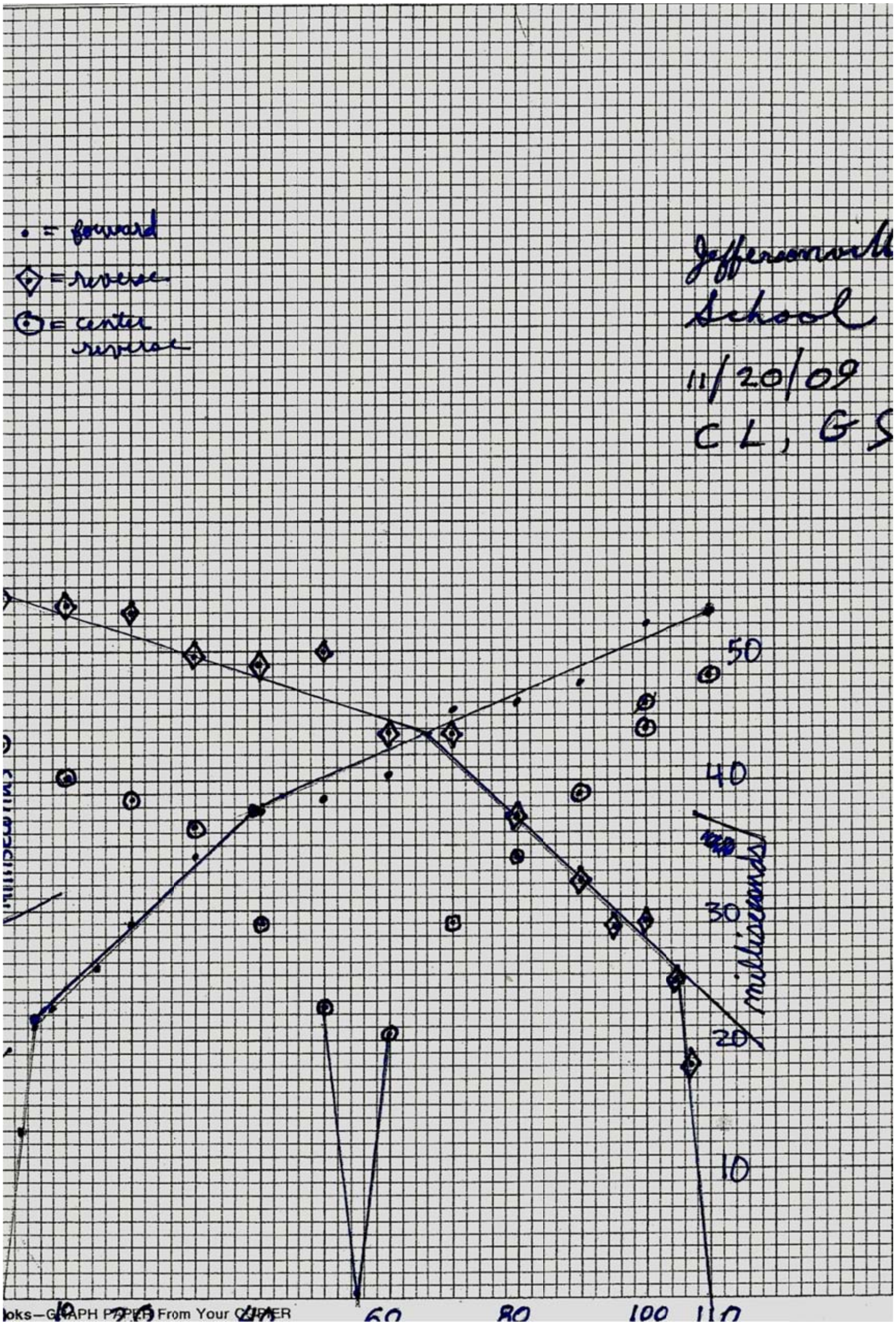

Figure 6. Time-distance Plot of Seismic Survey at Cambridge Elementary School

Horizon	Velocity (ft/s)	Depth to sub-layer (feet)	Corresponding Materials
West Side of Brewster River Ridge 11/6			
Layer 1	1342	66	Dry sand, gravel or weathered surface material
Layer 2	9140		Sandstone, shale or limestone
East Side of Brewster River Ridge 11/13			
Layer 1	1365	46	Dry sand, gravel or weathered surface material
Layer 2	13,655		Metamorphic rock or limestone
Base of Ridge at Cambridge Elementary and Brewster River 11/20			
Layer 1	653	7	Weathered surface material
Layer 2	6749	33	Sandstone
Layer 3	17825		Granite or metamorphic rock

Table 1. Seismic Survey Results and Comparative Data (Redpath, 1973)

This survey reveals the depth and type of material within the horizons beneath the field, as well as the riverbank opposite the slide area. The calculations of the depths of the material horizons are based on Springston (2009), Redpath (1973) and Haeni's (1988) resources. The velocities of the different materials indicate that the deepest layers on the ridge are metamorphic rock. The tables in which these data were found are in the appendices of the Redpath document (1973). The deepest layer on the school side of the river was determined to be either igneous or metamorphic rock. Table 1 is the compilation of the calculated data from the seismic survey. The sketch in Figure 7 depicts the findings of the survey, as well as the depths of the monitoring wells. The wells were installed July of 2009 by Specialty Drilling and Investigation of Burlington, Vermont. Their data and field notes were of interest as the borings depths that they obtained were similar to the horizon revealed by the seismic survey at the Brewster River Ridge.

Future Work

The monitoring wells that were placed in the Brewster River Uplands Community Trust Field allow researchers to observe the subsurface saturation points throughout the year. Time Domain Reflectometry (TDR) cables have also been drilled into the field. TDR cables present information about any horizontal shearing that might occur as the land slumps toward the Brewster. The western face of the field is continually being measured for material loss along the bank. Forsberg (2009) calculated a loss of 0.61 meter per year. A stream gage has been installed so that the Brewster may be monitored for seasonal changes in velocity and depth, which may correlate to mass wasting events. A rain gauge has also been installed at one of the residences on Deer Run Heights. Norwich University examined the stability of the soil types that were presented in soil borings on the Brewster River Ridge. These data will be compiled and analyzed elsewhere.

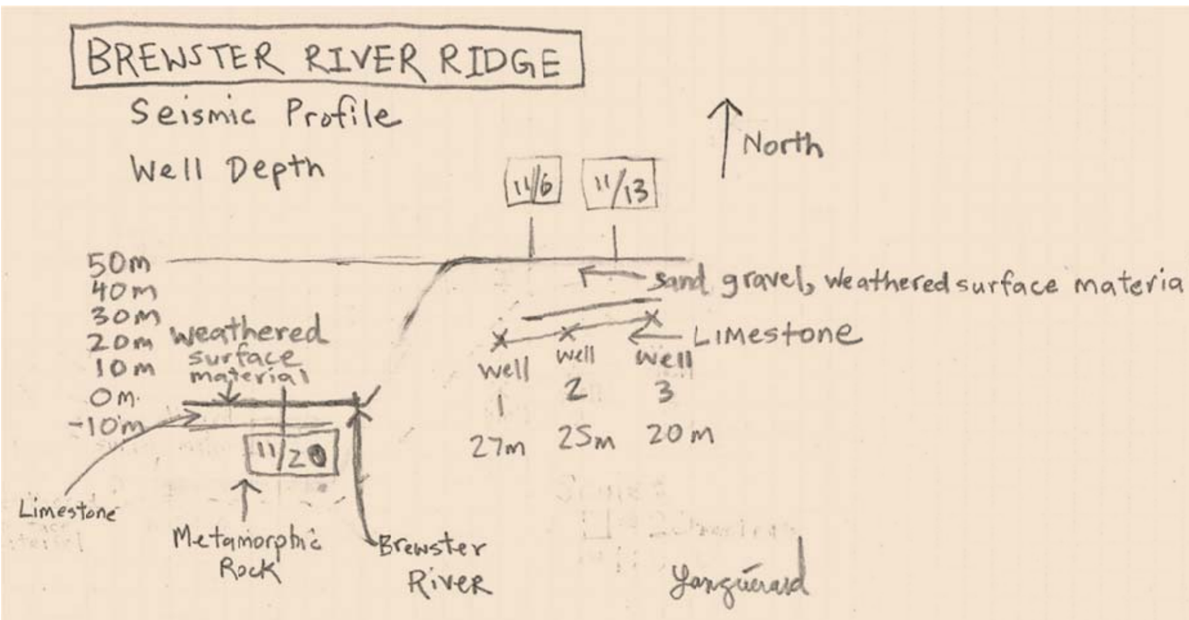

Figure 7. Profile of Brewster River Ridge

Conclusion

The Jeffersonville Landslide is an active site of slope instability. The bedrock geology of the immediate area suggests that the ridge will continue to experience cutbacks until the ridge is sufficiently eroded. The steep angle at which the subsurface geology folds, affirms the tendencies of the fine overlain materials to succumb to gravitational forces. The weak pore pressure in these materials due to void space, as well as the steep slopes of the Brewster River Ridge and the erosion of the river below can only assure the continued failure of the glacial sediments. This site will continue to be an ideal location for research by students and professionals. As more data are collected by the array of techniques that are being implemented and employed, we will be better informed about the tendencies and hazards that are imminent along the Brewster River Ridge and the town below. The amalgamation of the data and research that has developed within individual projects will be an important process. It will present the ridge as an accrual of data that represents the slope as a shearing force. Continued monitoring of the area will help the community plan for the future, as well as provide a unique learning opportunity for its citizens.

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