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Cornell University Earth Source Heat Project: Preliminary Assessment of Geologic Factors Affecting Reservoir Structure and Seismic Hazard Analysis

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ABSTRACT

As part of a strategy to achieve carbon neutrality by 2015, Cornell University is exploring utilization of deep-source geothermal energy for direct-use heating (Earth Source Heat). A recently completed feasibility study indicated that geothermal energy could potentially provide as much as 80% of the renewable heat needed for the Cornell campus, with the rest provided by biomass and other sources. Multiple potential target bedrock units were identified in the lower sedimentary basin rocks and crystalline basement rocks at depths ranging from 2240 – 3500 m. Cornell intends to drill a test well through the sedimentary basin rocks and into the crystalline basement to investigate and confirm the bedrock and reservoir properties, including collecting data necessary to adequately characterize the risk of induced seismicity associated with development of the reservoir and operation of the geothermal system. Prior to test well installation, in order to make a preliminary assessment of geologic and technical factors including seismic risk, Cornell has undertaken a series of projects to collect, analyze, and interpret regional geologic data and geophysical measurements that can be made from the surface near our proposed well site. Information from these studies, and from a planned test well, ultimately will be incorporated into a methodical assessment of seismic hazard and risk. This report summarizes our data collection and analysis to date, which incorporated records of historical seismicity in Central NY; regional structural geology and stress maps; geological and geophysical logs from stratigraphic wells drilled in our region; active seismic imaging; passive seismic monitoring; and potential field (gravity and magnetic) data. Our preliminary analysis concludes that seismic hazard related to deep geothermal development at Cornell appears relatively low. This assessment, coupled with other geological and engineering evaluations that suggest a reasonable potential for producing significant geothermal heat from the deep bedrock layers beneath campus, supports Cornell's plans to proceed to the test well phase of the ESH project.

1. INTRODUCTION

As part of its commitment to become carbon neutral by 2035, Cornell University is exploring utilization of deep-source geothermal energy (Earth Source Heat) for direct-use heating (https://sustainablecampus.cornell.edu/our-leadership/cap). Under an award from the Department of Energy, Cornell completed a feasibility study of Deep Direct-Use (DDU) geothermal energy for meeting a minimum of 20% of the thermal energy needs of our main campus in Ithaca, NY. The study indicated that geothermal energy could potentially provide as much as 80% of the renewable heat needed for the Cornell campus, with the rest provided by biomass and other sources. We identified multiple potential target bedrock units at depths ranging from 2240 – 3500 m, with median estimated production temperatures of 72 – 90 °C. The shallower targets are in the lower sedimentary basin rocks, while the deeper targets are in the crystalline basement rocks. As the next step, Cornell intends to drill a test well through the sedimentary basin rocks and into the crystalline basement to investigate and confirm the bedrock and reservoir properties at each of the potential target depths. One goal of the test well will be to collect the data necessary to adequately characterize the risk of induced seismicity associated with development of the reservoir and operation of the geothermal system.

In recent years, induced seismicity (IS) has been the subject of publicity and concern among regulators and the general public. While examples of induced seismicity have been documented for decades (for example, the Rocky Mountain Arsenal earthquakes of 1962-66, up to M_L=5.2; Healy *et al.* 1968), more recent examples related to both geothermal energy development and the fossil fuel industry have raised the profile of induced seismicity. Highly publicized incidents related to geothermal development include the 2006 M_L=3.4 earthquake in Basel, Switzerland (Majer *et al.* 2007), and the 2017 M_w=5.4 earthquake near Pohang, South Korea (Grigoli *et al.* 2018;

Kim *et al.* 2018). Today, the most commonly reported induced seismicity events are related to fluid injection, especially wastewater injection that is unbalanced by withdrawal (Foulger *et al.* 2017). The dramatic increase in seismic activity in Oklahoma during the 2010s related to wastewater injection (almost 100 events >M_w=4.0 with a maximum of M_w=5.7 – USGS 2018; Keranen *et al.* 2014; Ellsworth *et al.* 2015) served to significantly raise the profile of IS in the public consciousness. Meanwhile, controversies related to hydrofracking for hydrocarbon extraction have enhanced concern about work involving boreholes and energy and created a degree of confusion among the public regarding the causes and potential risks of induced seismicity (Atkinson *et al.* 2016).

In order to make a preliminary assessment of geologic and technical factors including reservoir design and seismic risk, Cornell has undertaken a series of projects to collect, analyze, and interpret regional geologic data and geophysical measurements that can be made from the surface near our proposed well site. Information from these studies, and from a planned test well, ultimately will be incorporated into a methodical assessment of seismic hazard and risk, generally following the steps of the DOE protocol for induced seismicity (Majer *et al.* 2012) and the related "best practices" document (Majer *et al.* 2016). This will include a Probabilistic Seismic Hazard Assessment (PSHA) and development of an Induced Seismicity Mitigation Plan (ISMP; i.e. a "stop light" approach). Cornell is reviewing existing induced seismicity mitigation plans for past geothermal EGS projects, such as done by Levine *et al.* (2017). The PSHA and ISMP will incorporate a thorough analysis of the risk posed to surface infrastructure and facilities that might be especially vulnerable to ground accelerations caused by seismic activity so appropriate protections can be employed.

Prior to drilling the proposed ESH test well, it is not fruitful to attempt to implement a rigorous PSHA, because numerous necessary parameters are not well characterized for the area near Cornell. While waiting to obtain such data, we base our preliminary risk analysis on a general comparison of the site characteristics to factors demonstrated globally to correspond to enhanced risk of inducing an earthquake. Risk factors for induced seismicity include the rate and volume of fluid injection and withdrawal, injection pressures, depth of disturbance, state of stress in the crust, rock properties, and proximity to seismogenic faults (Majer *et al.* 2016). For geothermal projects, thermal and chemical changes in the reservoir resulting from fluid circulation during production can also contribute to induced seismicity. While many of these factors are appropriately addressed during the engineering design and operation of a geothermal system, some are important to consider during the site selection and conceptual design phases. Regarding site selection, fundamental factors influencing the potential for induced seismicity include stress conditions in the bedrock, the presence or absence of planes of weakness (faults) that could release some of that stress through brittle failure and their lengths, and the degree to which the proposed project could change the stress tensors acting on any faults. The potential magnitude of an induced seismic event is related to both the state of stress and the characteristics of the fault, since the energy released in an earthquake is proportional to the fault surface area, the displacement along the fault, and coefficient of friction between the opposing sides of the fault (Majer *et al.* 2016).

It should be noted that not all induced seismicity is undesirable. Microseismicity (i.e. events below M_w=2.0; NRC 2013) is generally too weak to produce damage at the surface. Reservoir stimulation, if performed, usually produces some level of microseismicity, which in practice is a useful tool to monitor, map, and evaluate stimulation efforts (Majer *et al.* 2012). Fluid circulation during system operation may also produce low levels of microseismicity; in some cases, such activity can be useful for assessing fluid flow patterns within the geothermal reservoir (e.g. Cladouhos *et al.* 2013).

2. DISCUSSION

In the sections below, this report summarizes our data collection and analysis to date to support a preliminary characterization of seismic risk. We have collected and analyzed the following types of data: records of historical seismicity in Central NY; regional structural geology and stress maps; geological and geophysical logs from stratigraphic wells drilled in our region; active seismic imaging; passive seismic monitoring; and potential field (gravity and magnetic) data.

2.1 Historical and current seismicity

An understanding of historical seismicity is an important starting point for any analysis of the risk of induced seismicity (Majer *et al.* 2016). A record of frequent earthquakes indicates that crustal stresses are near failure and that active faults are present in the area. Such records provide a general idea of the magnitude of events that could be induced, as well as a record of how surface infrastructure has been affected by the ground accelerations associated with the observed levels of seismic shaking. Of course, there are many examples of seismic events that exceeded previously known ranges, so knowledge of past events cannot guarantee that a stronger event will not occur; but an established record of relative quiescence is a useful indicator that relative risk may be lower. The USGS catalog of earthquakes in the eastern US of M 3.0 or greater is shown in Fig. 1 (inset for earthquakes 1920-2019). These records indicate that the Cornell campus is located within a generally aseismic region.

While this lack of observed seismic activity near Cornell could indicate insufficient crustal stress and/or a lack of faults in orientations susceptible to failure to produce earthquakes, it is possible that there are active faults hosting seismic events that are too small to be detected with the regional seismic networks. If lower magnitude seismicity is occurring, it might reveal structures capable of hosting a stronger earthquake in the future if the subsurface stress regime changes significantly. In order to detect and characterize any such microseismic activity that might be occurring near campus, Cornell installed and operated two passive seismic networks near campus: the first from October 2015 to November 2016, and the second starting in August 2019 and currently operating. In addition to potentially locating previously unknown faults, these networks serve the purpose of documenting baseline levels of natural and anthropogenic microseismicity for comparison once geothermal drilling or production has commenced.

Fig. 1

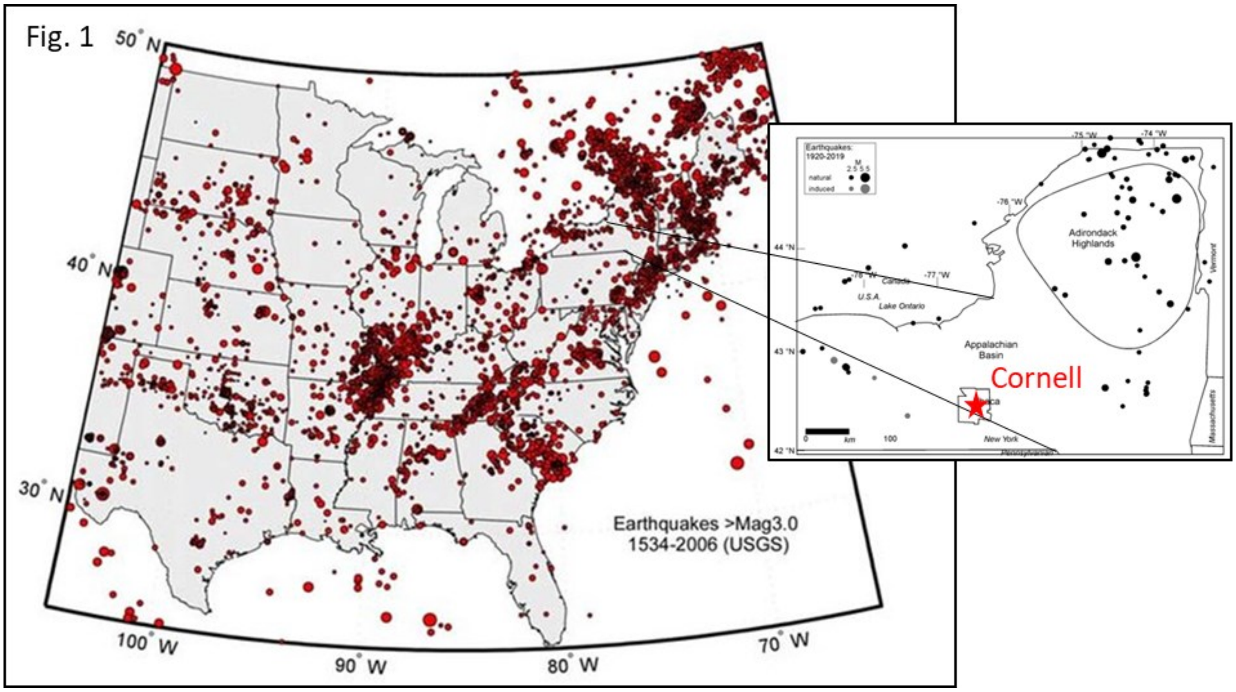

Figure 1. Eastern USA historical seismic activity through 2006. Inset map: central and northern New York state seismic activity 1920-2019. For both, the data are from the USGS, and minimum earthquake magnitude reported is M 3.0.

The first seismograph deployment (CorNET) consisted of twelve instruments installed within 1 m depth of the ground surface. Approximately 90 events were detected, 64 of which are likely to be earthquakes with hypocenters in central New York (Fig. 2). The absolute magnitudes of these events were not well constrained by our network, but relative magnitude is indicated by the size of each marker. Only four of these likely earthquakes were located within Tompkins County, the site of the proposed geothermal wells. The lack of apparent linear alignment of these events (Fig. 2) suggests that none of the geological faults known or suspected in the Ithaca area (see below; Jacobi 2002) are active at present. None of these local events are reported in the national and regional catalogs produced by permanent networks operating in the area (Fig. 1, inset), supporting the hypothesis that the apparent aseismicity of the Ithaca area is an artifact of the detection limits of conventional networks rather than complete lack of natural seismic events. No events were found in the immediate vicinity of the proposed drilling site for Earth Source Heat. Although the locations of events well beyond the limits of the CorNET array are poorly constrained, most occur within the Finger Lakes region to the northwest of the array.

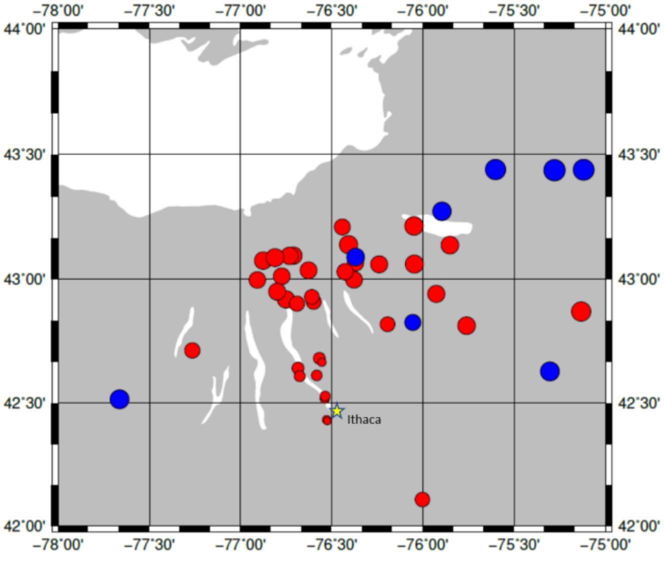

Figure 2. Epicenters of events recorded by CorNET and interpreted as likely earthquakes near Ithaca, New York. Events that were also included in either the USGS or LDCSN catalog are shown in blue; all other events are shown in red. Marker size is proportional to event magnitude (McLeod *et al.*, 2020).

The second seismograph deployment consists of 15 instruments, eight just below the ground surface and seven in 30-foot deep boreholes. Based on the results from CorNET, the design of this second array was altered to increase the aperture and include stations farther to the north, in order to better locate and characterize local events which were apparently centered just outside the footprint of the first array. Inclusion of borehole instruments should significantly lower the detection threshold compared to the first array, and the borehole installations may become part of a permanent monitoring network should the ESH project proceed to the production phase. Results from the second array are not yet available.

2.2 Regional crustal stress

Crustal stress state is one of the fundamental considerations in evaluating the potential for induced seismicity (Majer *et al.* 2016). Both the orientation and magnitude of stresses are important; shear stress along the strike of a fault will tend to make it slip, while normal stress across a fault plane inhibits slip by increasing the frictional coupling. Pore fluid pressure reduces the effective normal stress, so increases in pore fluid pressure can induce slip along a fault even without an increase in shear stress. If faults are present that are oriented close to the direction of maximum horizontal stress, a careful evaluation must be made to determine the stress magnitudes and ensure that any fluid circulation during geothermal production does not destabilize the fault. Since each fault and its setting are is unique, there is no universal “safe” distance from a fault to circulate fluids. Sometimes faults are actually targeted for circulation of fluids, such as at the United Downs Deep Geothermal Power project (https://www.uniteddownsgeothermal.co.uk/project-overview). In other instances, stress conditions dictate that faults must be avoided.

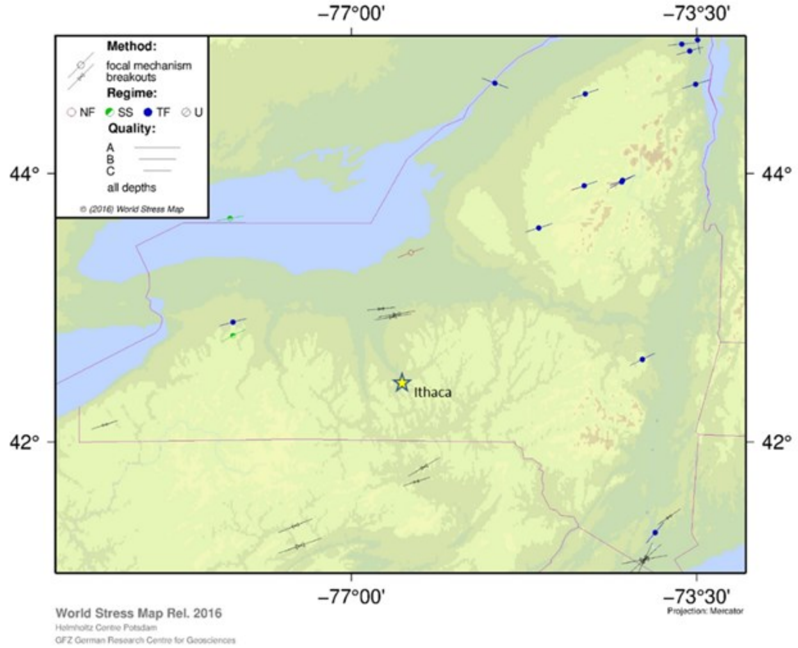

Figure 3. Portion of World Stress Map showing Upstate NY (Heidbach *et al.* 2016) http://www.world-stress-map.org/

Stress measurements are primarily obtained from borehole measurements and from analysis of fault movement during earthquakes. Prior to drilling a test borehole at the Cornell campus, we have limited bedrock stress data. However, regional stress data (Fig. 3; Heidbach *et al.* 2016) indicate that stress orientations are quite consistent across the Ithaca region, trending NE-SW. Therefore, the highest risk for induced seismicity would be associated with faults striking in a similar orientation. No likely faults have been identified within 2 km of the Cornell campus in the published literature (e.g. Jacobi 2002), and our investigation of bedrock structures using active seismic imaging (see below) has likewise not identified any vertical or sub-vertical faults beneath our proposed ESH well site. Further analysis will be required to determine the potential radius of influence of any changes to subsurface pressure or stress that might result from geothermal reservoir creation or utilization, and if there are any faults farther from campus that might be destabilized by such changes. Obtaining measurements of local bedrock stress magnitude and orientation, including any variation with depth, will be a high priority objective for the initial ESH test well.

2.3 Stratigraphy from well logs

While no deep wells have been drilled at Cornell’s proposed ESH well site, several wells have been drilled through the sedimentary basin bedrock section in the Ithaca region within 30 km of campus. Logs from several of these deep wells have been analyzed and synthesized by Smith *et al.* (2010) and Al Aswad (2019). Figure 4 presents a model stratigraphic column, the lower portion of which is expected to host potential geothermal reservoir targets. Knowledge of the overall stratigraphy as well as the identity of potential zones for geothermal production is important for characterization of potential seismic risk and was essential to enable meaningful interpretation of structural features from the seismic reflection data described below.

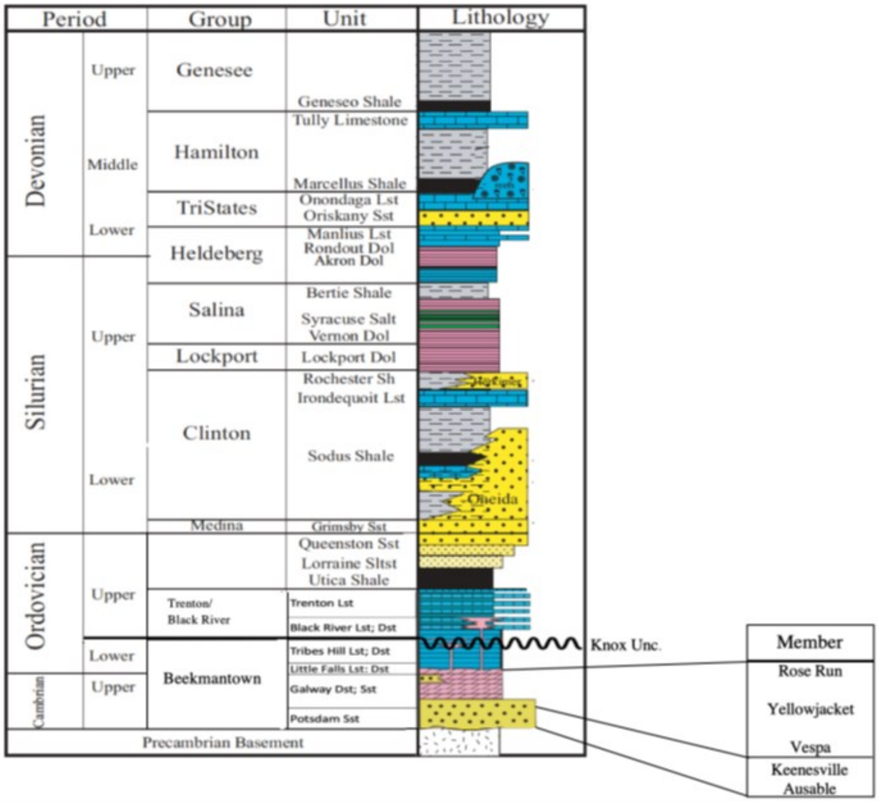

Figure 4 - Stratigraphic succession in the subsurface of Central New York, from Precambrian to Devonian (Smith *et al.*, 2005; Al Aswad, 2019)

2.4 Mapped faults and other geologic structures

Geologic maps and other publications often identify large-scale faults and other significant geological structures; these are a good starting point for identifying features that might be relevant to an assessment of the risk of induced seismicity. In the vicinity of the Cornell campus, known faults and other lineaments have been summarized by Jacobi (2002); the closest potential fault is mapped about 2 km west of the proposed drilling site.

2.5 Active seismic testing – industry data

In order to assess major structural features of the sedimentary basin bedrock geology near the Cornell campus, we analyzed 2D hydrocarbon-industry seismic reflection profiles obtained from a commercial data broker. The vertical distribution of sedimentary rocks known from deep hydrocarbon boreholes was used as the basis for the approximate sedimentary unit identification of packages of seismic reflections to a depth of about 3 km. The lower limit of sedimentary rocks, which overlie a crystalline basement, can be identified readily in only a minority of the seismic profiles; in most of the data, there is a large uncertainty on position of the basement contact. Sedimentary units with possible interest as geothermal reservoirs are expected within the lowest 300-600 m of sedimentary rocks near Cornell.

Disruptions to the positions or continuities of these reflective sedimentary rock units were identified as either folds, which are smooth undulatory waveforms of the rocks, or faults, which are breaks in the units. Two classes of faults, one sub-vertical and one sub-horizontal (i.e., thrusts) were differentiated such that their different roles in technical and environmental risk could be individually evaluated. The seismic profiles revealed five categories of structural deformation, two of which were not expected based on publicly available reports for Tompkins and neighboring counties (Fig. 5).

Among the three expected categories of structural deformation, folds of the uppermost sedimentary layers are widespread; these should impact an ESH project only by making predictions of depths to horizons of interest slightly more uncertain. Folds and thrusts within the Syracuse and Vernon Formations are highly likely to occur under the proposed ESH project site, in a depth range of 750-1200 m. Standard practices exist in central New York for drilling through and isolating this interval of deformed, weak rocks. The seismic reflection profiles revealed that the third expected category, sub-vertical faults known by the hydrocarbon industry as "Trenton-Black River" (TBR) structures, occurs in some sectors of Tompkins County. A Trenton-Black River fault cluster is not expected near the Cornell campus. An uncertain individual TBR-type fault is located about 1.4 km, and a more reliable single fault about 3.4 km, north of the proposed drilling site (Jordan 2019).

Figure 5 – Geologic structures interpreted from hydrocarbon industry 2D seismic line collected a few km east of the proposed Cornell ESH well site. Image is vertically exaggerated ~3.3 X. Purple = faults; Light green = synclines; Dark green = anticlines (Jordan, 2019)

The first unexpected category of structures is a widespread set of sub-horizontal thrust faults within the Cambrian and Ordovician sedimentary rocks, in an interval of rocks predicted from boreholes to be about 350 m thick at Cornell's campus. The near-Cornell industry-quality seismic reflection profiles reveal thrust faults in these sedimentary units. A seismic depth model with high uncertainty implies that these thrusts may be as shallow as 2.1 km or as deep as 3.0 km near the east end of campus. Because of their sub-horizontal disposition, these disruptions may have more relevance to analyzing reservoir potential than to seismic hazard analysis.

The second unexpected category of structures is of greater uncertainty than any of the other features described here. Within Tompkins County, there are a small number of fold-forms in the deepest well-imaged sedimentary units, including within the seismic line shown in Fig. 5 near Cornell's campus. There is a significant degree of uncertainty that some or all of these fold-forms are physically real parts of the rocks. Conventional geological wisdom suggests that these undulations may be associated with faults that are not imaged by the seismic reflection data. Hypothetically, either of two markedly different types of faults could be related to deep folds: near-vertical faults (like the TBR faults) that offset rocks in the basement, or sub-horizontal thrust faults within the poorly imaged deeper sedimentary rocks or at the sedimentary rock-basement contact.

This study, supplemented by the Vibroseis survey described below, has illuminated relatively well the nature of the sedimentary rocks near the proposed ESH drilling site. Subvertical faults the cut the strata and project down toward the basement were not revealed close to campus; such features would represent the greatest risk for reactivation during fluid circulation. However, existing seismic reflection data reveal very limited information about structures in the crystalline basement rocks.

2.6 Active seismic testing – Cornell Vibroseis project

To complement the gas industry seismic data analysis described above and extend the seismic reflection analysis to the bedrock directly beneath the proposed ESH well site, Cornell completed a multichannel seismic reflection survey. The survey utilized ~400 nodal receivers and a T-Rex Vibroseis vibrator source. Ten-second sweeps were completed from frequencies of 5 to 80hz. These parameters were chosen to mimic those used by prior industry surveys in the area. The sweep interval was followed by a 20 second listening period before the next sweep. Multiple sweeps were made at each vibration station, or shot point, for later summation (vertical stacking) to enhance reflection signals and reduce noise. These data were collected over a two-week period in September of 2018 with the help of student volunteers, and subsequently processed to produce seismic reflection images of the subsurface near the proposed drill site.

Conclusive interpretation of the reflections mapped by the ESH seismic reflection sections near the proposed drill sites will require calibration against future well data. However, a reasonable basic interpretation can be derived by comparison of the reflection character apparent on the ESH seismic sections with that seen on relatively nearby seismic reflection sections collected by the oil and gas industry, described above, which have been constrained by well data. Since these industry lines were collected with different equipment and significantly different acquisition parameters (most notably aperture, or the maximum source receiver offset available), the character of the two different datasets should not be expected to match in detail. However, the reflection character of various geological strata appears to be sufficiently distinct to make convincing correlations between the two types of images.

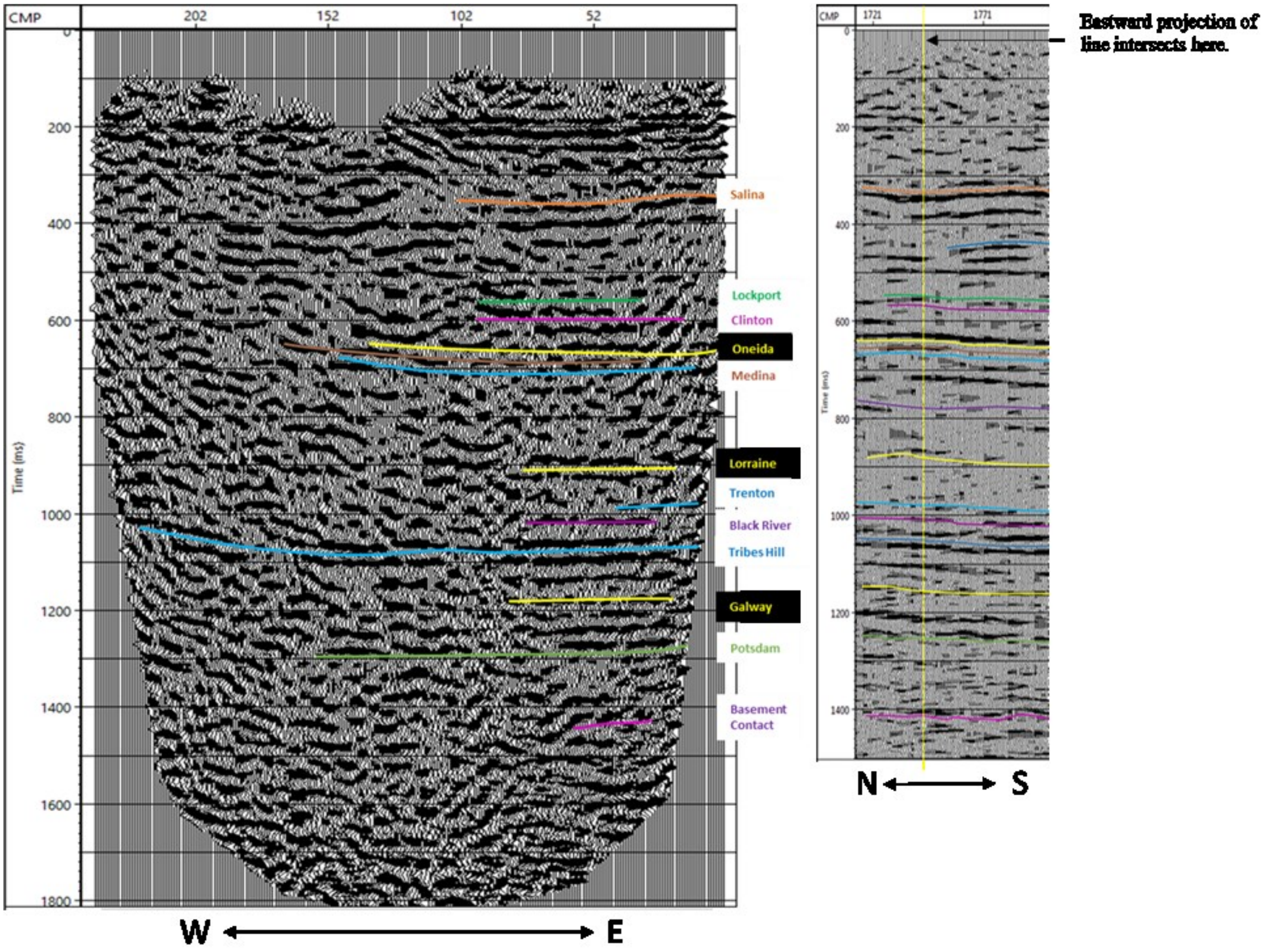

Figure 6 - Left: Stevenson/Road Facilities seismic time section after migration and FX deconvolution. Right: Interpretations of matching strong reflectors on the industry profile at a projected point of intersection. The pair of strong reflectors, between 1060 and 1100 ms, are interpreted to represent the same two strong reflectors straddling the blue line on the industry profile marking the Tribes Hill formation (May *et al.*, 2019)

An example seismic time section beneath the proposed ESH drilling site is shown in Figure 6, along with a portion of the industry seismic section obtained ~2 km to the east, which was used to aid in identification of reflectors. Strong reflectivity at depths less than 500 m, which correspond to Silurian formations such as the Salina, show evidence of disruption by folding and or faulting that we interpret to represent salt tectonics that appears to be decoupled from any deformation below. Of more relevance to ESH drilling are the underlying Paleozoic formations. A zone of weak reflectivity is evident below the Medina Formation followed by a pair of reflectors straddling the top of the Tribes Hill formation. Further down, another pair of strong reflectors are interpreted to be a horizon within the Galway Formation and the contact between the Galway and Potsdam formations, respectively. Below the Potsdam, faint signs of the contact between sedimentary strata and basement rock can be seen.

Although systematic noise from surface waves was found to be pervasive in the nodal recordings, basic stratigraphy was delineated and identified with geological formations based on correlations with the regional industry seismic survey data. Overall, the seismic imagery confirms the expectation of a relatively simple southward dipping sedimentary sequence, though with a broad fold resulting in southwestward dips at the eastern border of the survey area. Local structural disruptions in the dominant layer-cake stratigraphy at the target depths for geothermal drilling were found to be few and relatively minor in terms of offsets to geological units. These seismic images did not reveal any major fault offsets that might be of concern for induced seismicity; however, they do not provide useful information about the nature of possible faults in the crystalline basement.

2.7 Gravity and magnetic potential field analysis

Two well-established exploration geophysical techniques for potentially identifying geological structures beneath the Cornell campus are analysis of small variations in the gravity and magnetic fields measured at (or near) the ground surface. These techniques are complementary to seismic reflection methods in that they are able to detect structures within the crystalline basement as deep as 5000 m, a region that is poorly resolved in the seismic data. In the case of gravity, a gravimeter takes readings of the local value of the acceleration due to Earth's mass at various locations. Those measurements can be reduced to a so-called "gravity anomaly" field, which is then further analyzed. A high accuracy, short-measurement-time gravimeter was used to perform a survey containing 395 measurements on a reasonably regular grid on approximately 500-meter centers over our proposed project area.

In the case of magnetic fields, a similar measurement strategy was employed using an airborne magnetometer. A high-resolution magnetic survey was flown over Cornell and surrounding areas in the 1990s for oil-and-gas exploration purposes. These data were licensed from a commercial data broker. These data are much higher resolution than publicly available magnetic field estimates – being collected on flight lines about 500 meters apart with along-line measurement distances of approximately 25 meters.

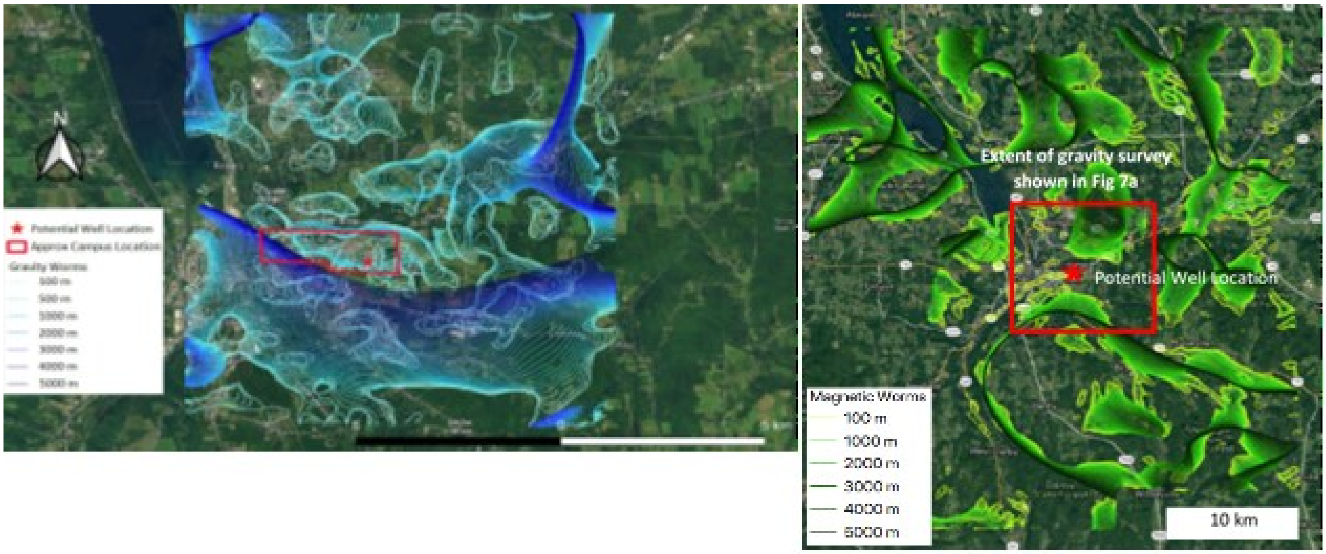

Figure 7a (left) – Contours of subsurface density boundaries inferred from gravity data; Figure 7b (right) - Contours of subsurface rock property boundaries inferred from magnetic data. The areal extent of the gravity survey in Fig. 7a is shown by the red box. (Horowitz, 2019)

In addition to standard potential field analysis techniques, a Poisson wavelet-based method was employed to analyze both sets of potential field data (Hornby *et al.*, 1999). This technique yields estimates of the underground 3D positions of steeply dipping "lateral discontinuities" – i.e. faults and other geological structures (Fig. 7). While the geologic interpretation of what these discontinuities physically represent is uncertain, the 3D maps can be compared to seismic reflection data to further illuminate potential structural features. In the case of gravity, the discontinuities represent contacts between rock units of different mass-density that are in steeply-dipping (e.g. ~30-90 degree) contact under our study area; these contacts could potentially be faults, folds, or other compositional boundaries. In the case of magnetics, the discontinuities represent contacts between rock units of differing magnetization strength (primarily related to the amount of magnetite present in the rock units). The greatest strength of these analyses is the capacity to identify lithological boundaries within the shallow basement rocks, which cannot be resolved by the seismic reflection data, hence the "worms" at depths below 3000 m (Fig. 7) are of particular interest. Our analysis of the potential field data indicates that there is a potential compositional or structural boundary approximately 1 km south of the proposed ESH well site, but no significant structures beneath the site. This analysis agrees with the interpretation of the seismic reflection data sets, which also did not identify any significant faults directly beneath the proposed ESH well site.

2.8 Data relevant to IS to be obtained from test well

Cornell is currently in the planning phase for drilling a test well to gather the data necessary for design of a functioning geothermal well pair. As part of that effort, Cornell recently hosted an International Continental Scientific Drilling Program (ICDP) Workshop to discuss and plan scientific tests and observations that could be conducted in association with the geothermal test well. A variety of creative and innovative ideas were developed during the workshop for experiments and tests to address a wide range of scientific questions, details of which will be presented in the upcoming ICDP Workshop Report. Observations, measurements, tests, and other tasks tentatively planned for the test well phase that are specifically relevant to characterization of the risk of induced seismicity include the following:

- Measure stress magnitude, orientation, and changes with depth
    - Borehole shape, breakouts
    - Mini-fracs
    - Fiber optic strain meter cables

- Create refined geological model from cuttings/cores/logging
- Map fault locations (if encountered)
- Characterize fracture distribution and properties
- Identify permeable zones and measure permeability

3. CONCLUSIONS

Cornell has completed a number of geological and geophysical studies to support an initial characterization of reservoir structure and the potential risk of induced seismicity associated with its planned Earth Source Heat geothermal project. Data and records analyzed include historical seismicity in Central NY, regional structural geology and stress maps, geological and geophysical logs from deep stratigraphic wells drilled in our region, active seismic imaging, passive seismic monitoring, and potential field (gravity and magnetic) data. Our preliminary analysis concludes that seismic hazard appears relatively low, based on the following:

- Cornell is located in a region of historically low seismicity;
- Published reports and maps do not identify significant faults near campus;
- Local microseismic monitoring has not identified any seismogenic faults near campus;
- Active seismic imaging has not identified any steeply dipping faults in the sedimentary basin rocks beneath campus (but do not shed light on potential faults in the basement);
- Gravity and magnetic field analyses have not located any significant bedrock discontinuities beneath campus in the depth range corresponding to the crystalline basement; and
- Regional crustal stresses are consistent in orientation.

Based on these observations regarding seismic risk, coupled with other geological and engineering evaluations that suggest a reasonable potential for producing significant geothermal heat from the deep bedrock layers beneath campus, Cornell is planning to proceed to the test well phase of the ESH project.

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