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Application of Active Seismic and Electrical Methods to Detect and Characterize Subsurface Effects of an Underground Explosion

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Background

During the period of underground nuclear testing in the U.S., now ended for over 20 years, the focus of work was to conduct the test and analyze the data as quickly as possible; there was little concern about application of technologies that could be used to detect and characterize the location and depth of the explosion. Thus, there is little experience with applying geophysical methods in places where an underground nuclear explosion (UNE) has taken place. On the other hand, application of geophysical methods to the detection of shallow artifacts and water table depth is commonly applied in the environmental remediation and site characterization realm of commercial geophysical surveys. For nuclear nonproliferation treaty applications which may incorporate both shallow and deep geophysical probing methods (such as on-site inspection (OSI) under the Comprehensive Nuclear Test Ban Treaty [CTBT]), there thus remains a need to better understand detection capabilities of the deeper targets: anomalies related to an explosion cavity or rubble zone that may be located several hundred meters below the ground surface. The purpose of this Coordinated Inspection Technologies (CIT) project was to gain experience in applying active seismic methods and electrical methods at a site in Nevada where an underground nuclear test (UNE) had been conducted in the past to get a better understanding of the capabilities of these methods for detection and characterization of deep subsurface effects of the explosion.

In order to determine the parameters of a geophysical survey, the characteristics of the target need to be investigated. For this study, the target is the cavity, rubble zone, and enhanced fracture network that result from an underground explosive detonation. The cavity and rubble zone of an UNE has a radius that scales with explosive yield and rock type. A nominal explosion with a yield of 1-150 kT may be expected to produce an explosion cavity with a radius in the range of about 15-60 meters. Depth of burial also scales with yield and geology and is expected to range from 200 to 600 meters depth or more. Depending on the geology, the cavity may be unstable and collapse after a time ranging from hours to years after a detonation, forming a rubble zone extending upward from the cavity, with a radius similar to that of the cavity. If the cavity extends to the surface, there will be a surface crater that will be an obvious signature of a UNE. However, depending on the geology, a strong layer or zone in the overlying rock may stop the upward migration of the rubble zone and form the top of the chimney. There may also be an apical void near the top of the chimney. With experience in testing in particular geologic media, it may be possible to predict which areas are more likely to form surface craters, as at Yucca Flat in Nevada (where crater commonly form in alluvium) or Pahute Mesa (where craters often do not form), but it is much more difficult to predict the exact behavior (height of the rubble zone) of the collapse process. Other factors that affect the specific geophysical anomalies expected from a UNE will be discussed below.

Field Campaign and Site Access Issues

After an initial 2-day survey of possible sites for the application of CIT technologies and an exhaustive comparison of them, two sites were selected for CIT campaigns: the Tiny Tot site in Area 15 of the Nevada Nuclear Security Site (NNSS – formerly the Nevada Test Site) (host rock granite) and the Salute site in area 20 (U20ak, host rock bedded tuff). After some initial surveys at Tiny Tot, a decision was made by National Center for Nuclear Security (NCNS) management to focus efforts at U20ak for budgetary reasons.

The Area 20 site was chosen for several reasons:

- The Salut UNE had a relatively large yield and thus the underground features were good targets.
- The surface was relatively flat and road access to the site was good.
- A lot of surface artifacts (cables, communications wire, construction debris, cased emplacement and drill-back holes, and other artifacts) were still present at the site.
- The site provided the ability to carry out multiple inspection technology techniques and thus assess aspects of their integration.

One major unknown for the U20ak site was whether access to surface ground zero (SGZ) could be allowed for safety reasons. We had to be assured that a collapse at the site could not occur while personnel and equipment were within the stand-off zone (a radius of about 250 m from SGZ). Surveys of all the known data for a dozen UNE sites within several kilometers of U20ak and U20bb (Tenabo site, about 1000 meters west of U20ak) were carried out (Pawloski, 2012) which revealed that the collapse potential at the two sites was quite low. In addition, calculations of the known weight of the winter maximum snow load over the site showed that snow loads per unit area in the past far exceeded loads expected from light vehicle or human traffic within the stand-off zone and thus a safety review resulted in the decision to allow light vehicle and human traffic within the stand-off area. This allowed surveys with data collection over SGZ to be carried out. However, the vibroseis source for the active seismic survey, being a heavy vehicle that puts vibrations into the earth, was deemed not safe for access within the stand-off zone. This restriction did affect our ability to image the site with active seismic methods; better results may have been obtained had we been able to apply the source directly over the target.

Electrical measurements

Background

A wide variety of methods are available for surveying the relative conductivity of the subsurface at depths of 100 m or greater. These include direct current (DC) and induction methods in both controlled source and passive modes. For DC controlled source methods alone, there are a wide variety of configurations for source and receivers that depend on the type of target to be investigated. DC methods are limited by the amount of current (e.g. energy) that can be put into the ground and generally are restricted to probing depths of 100-200 m. Alternating current induction methods follow the general rule of geophysical methods, that lower frequencies probe deep and higher frequencies are restricted to shallower targets. Resolution is inversely related to frequency, and hence depth; high resolution for shallow anomalies, low resolution for deep anomalies. Specific induction tools have been designed to carry out quick surveys for shallow targets (30 m or less, such as the Geonics EM-31 and Geonics EM-34).

For the electrical surveys at U20ak, our primary interest was in the application of methods that can probe deep and detect the cavity or rubble zone. We knew that shallow artifacts (cables, borehole casing) would have an effect on the surveys, and assessing the effects of these on the deep probing methods would also be an objective. For reasons outlined below, we decided to conduct two types of surveys at the U20ak site: dipole-dipole resistivity (a DC method that includes induced polarization -- IP) and controlled source audiomagnetotellurics, or CSAMT.

The dipole-dipole DC electrical method is a commonly used technique to map depth to groundwater, shallow voids, and other electrical anomalies occurring within 100 m from the surface. It is also used to get fairly high-resolution images of the resistivity profile (and thus geology) in an area. Data analysis for the method is easy and good forward modeling and inversion modeling codes are readily available. In addition, equipment used for dipole-dipole surveys also does an induced polarization (IP) measurement at the same time at each measurement site. IP effects produce anomalies where there are strong electrical contrasts due to the presence of ions in groundwater or highly mineralized zones. Even though we knew that dipole-dipole/IP methods were unlikely to reveal anomalies from the cavity or rubble zone at U20ak, we felt it was useful to conduct such a survey in order to learn more about the capabilities and response of such measurements in the dry tuff environment at the U20ak site.

CSAMT measurements rely on the induction of a low frequency electromagnetic field in the ground at a distant location and then measuring the plane wave response (which is affected by subsurface resistivity structure) of the induced field at the survey site. Frequencies used range from 1 Hz up to tens of kilohertz. The method can generally probe to several kilometers depth when very low frequencies are used. The method is best applied when looking for a conductive target embedded in a resistive (non-conductive) medium, such as looking for an ore deposit within hard, low permeability igneous or metamorphic rock. In the case of the U20ak site, we have a very dry medium, with fairly high resistivity. The UNE at U20ak was conducted in 1985 (USDOE, 2000) and thus 27 years have passed until the CSAMT survey was conducted (July 2012). Immediately after detonation of a UNE, and for months to years afterward, the cavity will contain cooling melted rock and possibly steam. Such an environment will lead to a conductive target, but it is not clear what the environment of the cavity will be 27 years later. Similarly, migration of steam and other volatiles within the rubble chimney from cavity pressure or convective effects will affect its electrical properties, but most likely after 27 years they will be resistive. CSAMT is one of the only electrical methods able to probe deep enough to detect an anomaly due to the chimney or cavity, thus it is a primary choice for use of electrical survey methods.

It was not cost effective for LLNL to purchase an expensive set of equipment and carry out the field surveys with inexperienced personnel at the NNSS for a one-time deployment, so we chose to contract Zonge International to carry out dipole-dipole/IP and CSAMT surveys at the U20ak site. As well as being a contractor who conducts surveys, Zonge International is also a manufacturer of geophysical electrical survey equipment used worldwide. LLNL did the planning of the surveys and is ultimately responsible for the interpretation of the data. Zonge International carried out the surveys, processed the data, provided their interpretation of the data, and produced a report on the results (Zonge, 2012). Nevada Security Technologies (NSTec) and LLNL personnel coordinated logistics and access to the site, provided environmental safety and health (ES&H) guidance, produced and followed the integrated work system (IWS) procedures, performed some site preparation, and monitored the work in the field. Full details of the survey and equipment used at U20ak can be found in the Zonge report (Zonge, 2012).

Dipole-dipole/IP survey procedure and results

A dipole-dipole/IP survey is carried out by applying a square wave current signal via two electrodes (the transmitter, or Tx) in the earth and then observing a voltage response between two separate electrodes (the receiver, or Rx) a fixed distance away. The distance between the electrodes is referred to as the dipole spacing and this distance is the same for the Tx and Rx electrodes. The Rx electrodes are progressively moved away from the Tx electrodes by increments of one dipole spacing, n. A measurement point (the ratio of Rx voltage to Tx current) is considered to be an "apparent resistivity" at a point equidistant and below the center point of the Tx and Rx electrodes, thus as the distance between Tx and Rx increases, an apparent resistivity at greater depths is measured. The IP effect is observed at each measurement site by looking at the deviation from a square wave in the Rx signal. A high IP signal is indicated by a slow decay of the square wave at the Rx. Data from a series of repeated waveforms is stacked and averaged at each configuration to increase the reliability of the measurements. A computer processor in the Zonge receiver unit collects the data and does the initial data processing. At U20ak we were able to get good measurements out to 15 increments of spacing with 20 m dipoles (N = 15, or 300 m distance); this represents an apparent resistivity value at a maximum depth of about 150 m, the limit for this method at this site.

Two dipole-dipole/IP survey lines were run at the U20ak site; refer to Figure 1. Line 1 started 760 meters south of U20ak SGZ and ended 1400 m to the north. Line 3 started 580 m west of U20ak SGZ and ended 1300 m to the east. (Line 2 was only used for the CSAMT survey.) Note that line 1 crosses SGZ for the Tenabo UNE about 460 m west of the U20ak SGZ.

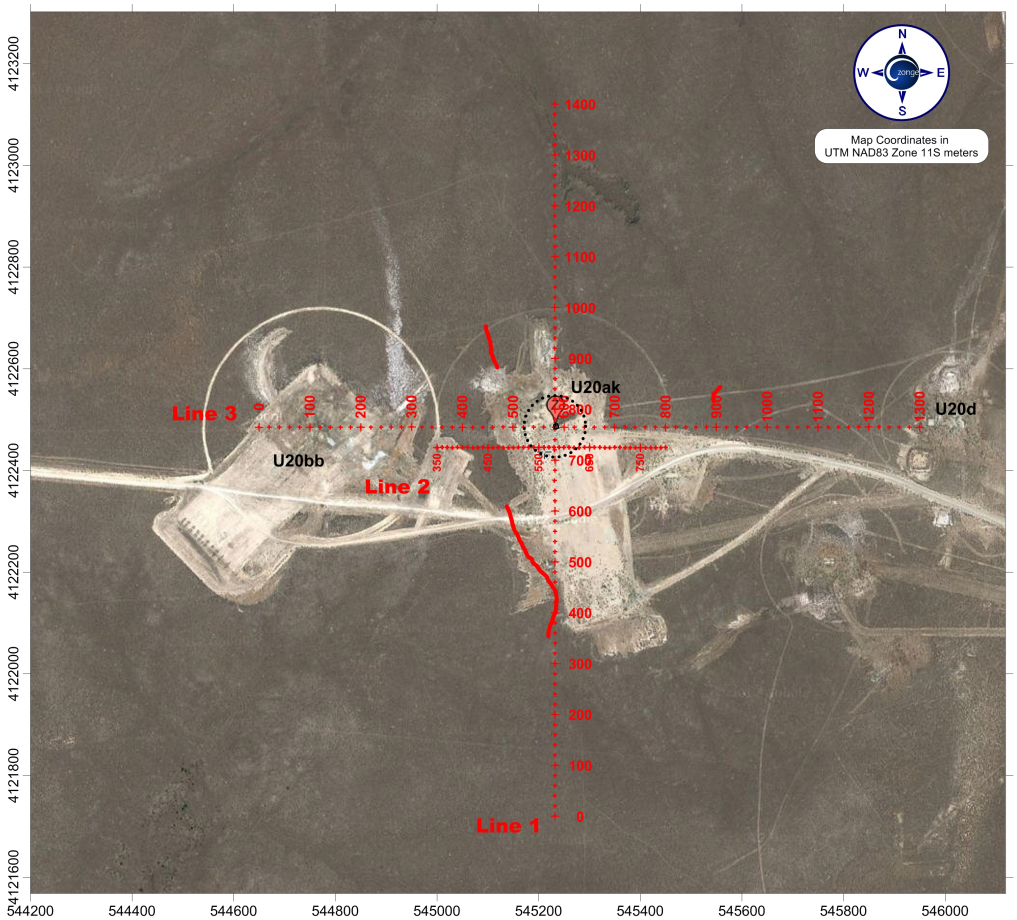

Figure 1. Plan view of electrical surveys carried out in the vicinity of U20ak, Pahute Mesa, NNSS. Lines 1 and 3 were used for both the dipole-dipole/IP surveys and the CSAMT survey. The solid red lines are approximate traces of prominent fractures that were observed on the surface. Light areas in the photo are cleared areas of roads or pads prepared for conduct of the UNEs 27 years ago. The circles mark safety exclusion areas about 250 m radius from SGZ of each site.

Results of the dipole-dipole surveys are shown in Figure 2.

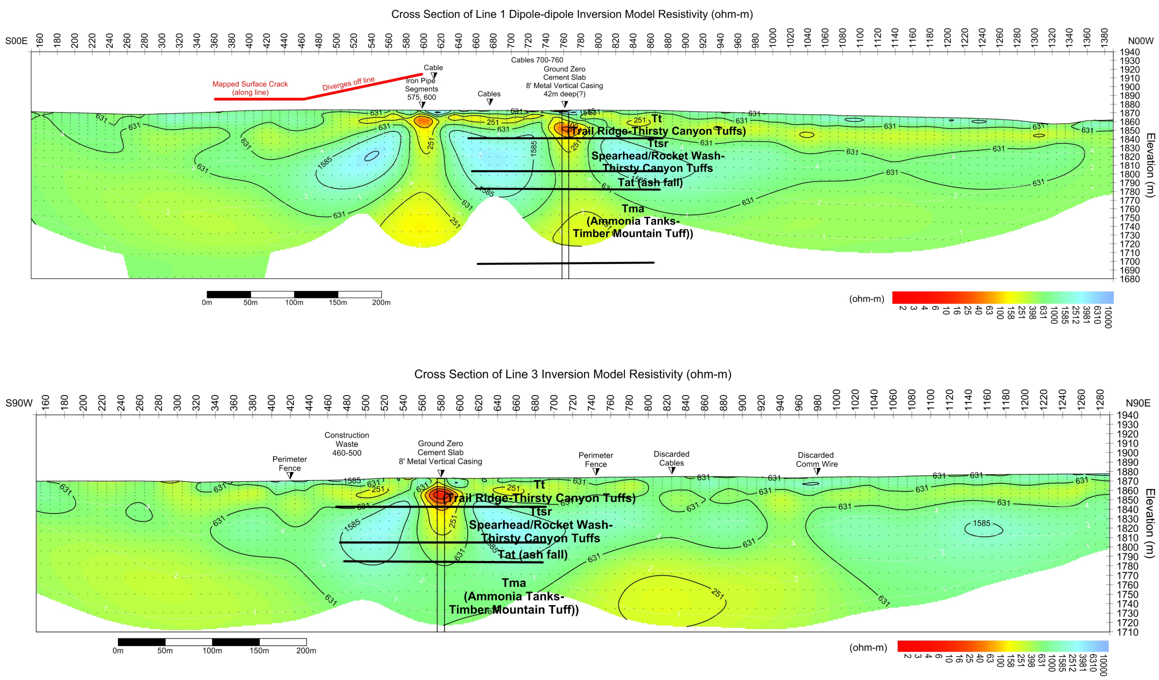

Figure 2. Dipole-dipole inversion models of data collected along line 1 (top, S-N line) and line 3 (bottom, W-E line). Resistivity color contours are in ohm-meters, with hot colors for low resistivity (high conductivity). Locations of surface artifacts and SGZ for U20ak, are noted on the sections.

Dipole-dipole survey results are generally displayed in the form of cross sections of apparent resistivity along the profile versus depth. A better understanding of the true conductivity of the subsurface is obtained by creating either forward models (where a conductivity model of the surface is made that matches the data) or inversions of the data. The data shown here are model results produced by Zonge that best fit the raw data. The IP results are quite similar to the dipole-dipole results and will not be shown here. The background green/yellow colors are indicative of the local flat-lying tuff units with resistivity of 250-1500 ohm-meters. Some contrasts in the shallow units with lower resistivity are continuous across most of the section, following the flat and continuous layering of the tuffs. Two anomalies are prominent in these sections, one is due to the presence of the UNE emplacement pipe at U20ak, which is 8 feet (2.44 m) in diameter and 140 feet (42.67 m) long, and the other is apparently caused by the presence of segments of iron pipe lying on the ground. Aside from the anomalies caused by the artifacts related to the UNE test, the data here are consistent with the known geology. The survey method does not probe deep enough to be affected by the rubble chimney or explosion cavity.

CSAMT Procedures and Results

The CSAMT surveys were run along lines 1, 2, and 3 as shown in Fig. 1. Details of the survey are given in the Zonge report. Lines 1 and 3 cross through SGZ of U20ak, but Line 3, the east-west line, also extended over SGZ of the U20bb UNE site as well. Line 2 was run along an east-west traverse 40 meters to the south of Line 3 in order to assess the effect of an off-line conductor (the emplacement hole casing for U20ak) on the survey results. For the CSAMT surveys, a transmitter line current source was set up about 6-7 km to the east of the site (along the road north of U20az) in configurations (N-S and E-W) that would be perpendicular to the survey line being run. The current source induces an electric field that is horizontal at the surface at the survey line and a perpendicular magnetic field. The local field orientations (electric parallel to the line and horizontal magnetic field perpendicular to the line) and magnitudes are collected every 10 meters along the survey lines as a function of frequency. Frequency in the transmitter is varied in 15 discrete increments from 1 to 8192 Hz. The low frequencies "see" deeper than the high frequencies; ratios of the electric and magnetic fields measured at different frequencies provide a measurement of apparent resistivity versus frequency. Modeling analysis (as for the dipole-dipole survey) results in a model of resistivity versus depth that is consistent with the measurements. Results of the CSAMT surveys on Lines 1, 2, and 3 are shown in Figures 3, 4, and 5.

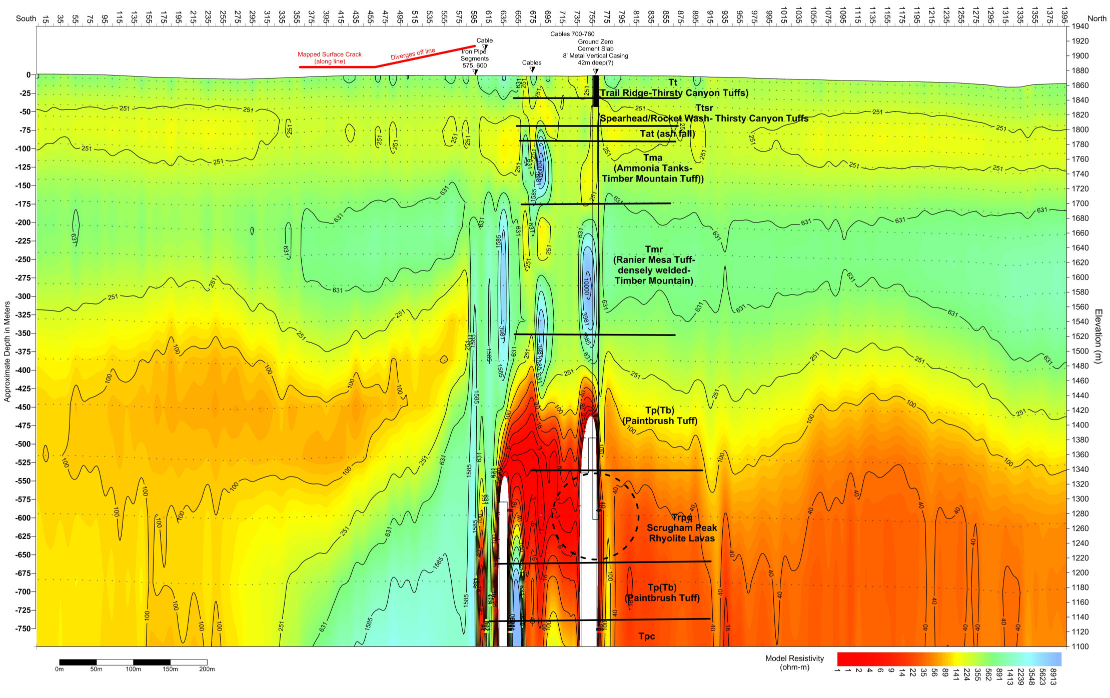

Figure 3. South to north CSAMT modeling results along Line 1. Hot colors indicate low resistivity; cooler colors indicate high resistivity. Boundaries of geologic units are shown as

well as the locations of the borehole casing, cables, pipe segments, and a surface crack. The dotted circle indicates approximate location of the UNE cavity.

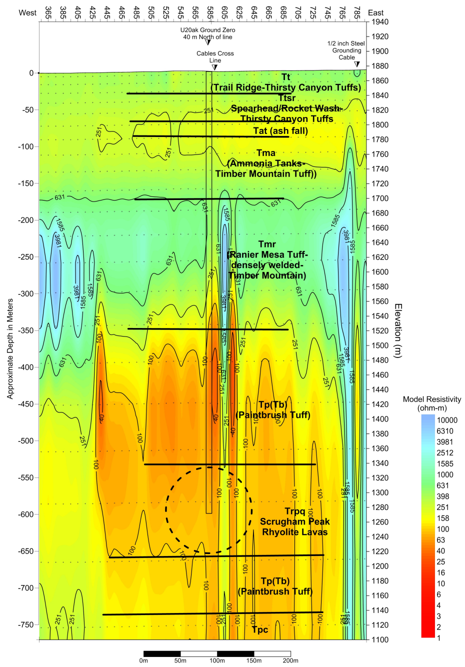

Figure 4. West to east CSAMT modeling results along Line 2. Hot colors indicate low resistivity; cooler colors indicate high resistivity. Boundaries of geologic units are shown as well as the locations of the borehole casing (located 40 m north of the line) and a cable at the surface. The dotted circle indicates approximate location of the UNE cavity.

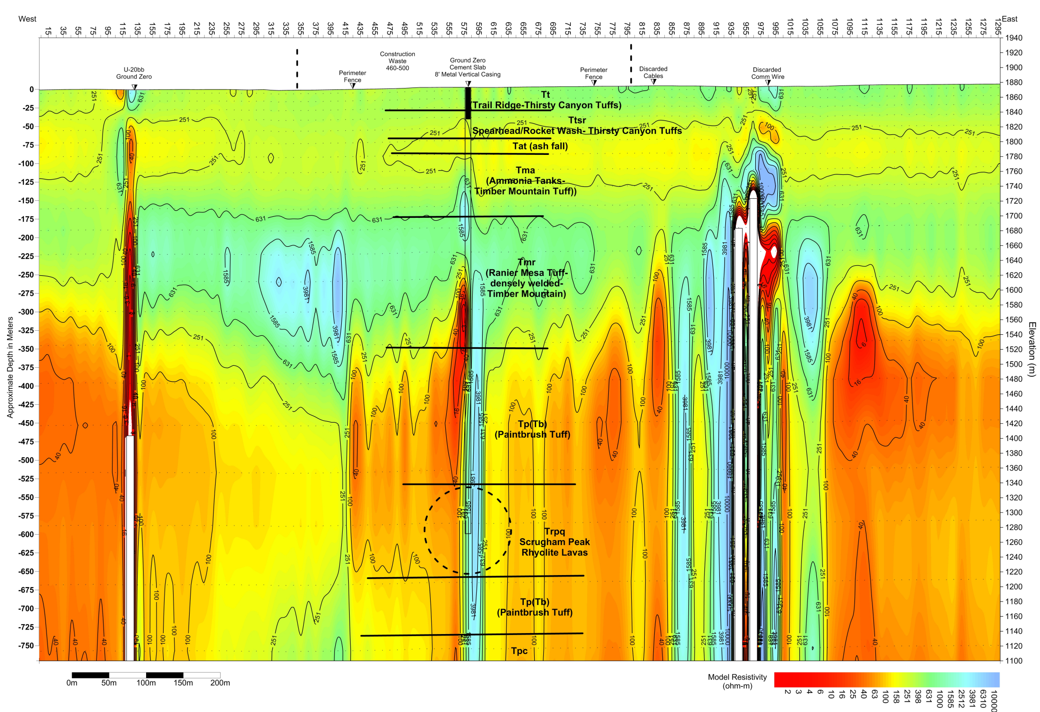

Figure 5. West to east CSAMT modeling results along Line 3. Hot colors indicate low resistivity; cooler colors indicate high resistivity. Boundaries of geologic units are shown as well as the locations of the borehole casing at U20bb and U20ak and other conductive artifacts on the surface. The dotted circle indicates approximate location of the UNE cavity.

From Figs. 3-5 it is clear that the CSAMT can easily resolve resistivity differences down to depths of 700 m, below the emplacement depth of the UNEs conducted at U20bb and U20ak. It is also clear that the borehole casing has a huge effect on the modeled results and influences the resolution of resistivity changes at depth. The contours of the resistivity agree well with the geology, with significantly lower resistivity of the deeper formations. The shallow resistivity values agree well with the results from the dipole-dipole surveys. The strong anomaly on the eastern side of the Line 3 profile, caused presumably by the presence of communications wire lying on the surface at that location, as well as the anomalies due to the borehole casing, illustrate the strong effect that surface conductors can have on this kind of sounding survey. The effect of the borehole casing makes it difficult to resolve effects of the cavity and rubble zone at depth at both UNE locations. Zones of high resistivity adjacent to low resistivity zones, seen at depths of about 200-400 m seen in Figs. 3 and 4 and somewhat in Fig. 5 are suggestive of an anomaly due to a rubble zone that is more resistive than the surrounding media. Modeling to try to remove the effects of the borehole casing may help resolve this zone further, but we have not yet done such an analysis.

A note from the Zonge report is relevant here: "…normally well casings have minimal effect on CSAMT…because they are in a minimally coupling configuration …" (perpendicular to the electric field measurement). The strong anomalies seen in Figs. 3-5 are probably due to the very large size of the casing used for UNEs and would be an important anomaly to acquire, especially if there is no surface evidence of an emplacement casing. It is notable that the borehole casing effect can still be seen on Line 2, even though it is 40 m to the south of SGZ. The high resistivity values from 200-400 m depth below SGZ on this line may be due to the rubble chimney, but there seems to be no signature related to the cavity at 600 m depth in the low resistivity zones on all of the survey lines. The other artifacts at the surface (cables, communication wire, fences) presumably create large anomalies because they are oriented at the surface in a configuration favorable to inducing secondary currents. In the case of buried conductors, CSAMT surveys could be used to detect such artifacts and to get some idea of their orientation.

Summary of Electrical Survey Results

The dipole-dipole and IP surveys provided fairly good resolution of the geology to depths about 150 m, but were unable to probe deep enough to resolve any anomalies due to the UNE explosion cavity or rubble chimney. Surface artifacts of pipe segments and the emplacement borehole casing produced prominent conductive anomalies. The CSAMT survey lines provided soundings sensitive to conductive anomalies at depths of up to 700 meters. Shallow resolution of geology by this method agrees well with dipole-dipole results. Surface artifacts (emplacement hole casing, pipe segments, cables, communication wires, fences) produced strong anomalies. Anomalies due to the emplacement hole casing masked deeper effects due to the chimney or rubble zone, so anomalies due to these features could not be imaged.

Active Seismic Measurements

Background

The goal of the active seismic part of the project was to try to image the rubble zone and cavity of a UNE using an active seismic survey with a relatively small active seismic source. We also wanted to go a bit beyond the standard type of survey, and collect three component data that could be used in a research mode so that data analysis could go well beyond standard methods and be able to use non-standard analyses, such as refraction microtremor, or ReMi (Louie, 2001; Pancha etal., 2008). Another reason for using sources and receivers capable of producing and detecting shear waves is that theoretically shear waves should be more sensitive to subsurface fracturing as is known to occur out to distances of several times the cavity radius of a UNE. As mentioned above, there has been no active seismic data collected over a UNE at the NNSS and little, if any, similar surveys elsewhere. Both the University of Nevada Reno and Optim, Inc. , in the process of developing the ReMi method, have had extensive experience in conducting shallow active seismic surveys in Nevada, and they had the capability of collecting standard reflection/refraction data as well as three-component data and carrying out extensive analysis. Thus we chose Optim, Inc. to run the active seismic surveys over U20ak and perform ReMi analysis, with the University of Nevada Reno to carry out standard reflection/refraction processing in addition to the reflection/refraction processing and modeling carried out at LLNL.

On advice based on the experience of Optim, Inc., we chose to use a relatively small vibroseis source, capable of generating both vertical and shear wave seismic modes for the surveys at U20ak. Although we knew that it would be difficult to transmit energy through the bedded tuff formations that make up the geology at U20ak because of high seismic attenuation, we chose not to use a very large vibroseis like those used by the oil and gas industry for reasons of cost and because we wanted to use a source similar to what is likely to be used during an OSI under the CTBT. For best results for refraction/reflection analysis, explosive charges would have been the source of choice, but this would have greatly complicated the deployment logistics and added considerable expense. Ultimately, the choice of source was a compromise between budget, practicality, and realism for OSI applications.

Active seismic survey and results

The layout of the active seismic survey lines in the vicinity of U20ak is shown in Figure 6. The yellow and orange dots are locations of geophones and associated seismic acquisition units (SAUs). The red and green dots are locations where the vibroseis produced seismic signals. Locations of the vibroseis operation were restricted by the safety requirement that the heavy vehicle not be driven or operated within a possible surface collapse zone above the U20ak UNE, thus the lines for deployment 1 ran along the roughly west-east access road to the west of

U20ak, and along a new road east of U20ak that was made with a road grader by NSTec. The green dots of deployment 2 are vibroseis locations run just outside of the exclusion fence for U20ak. Most of the geophone locations for Deployment 1 were at 30 m intervals, with some at 45 m or 60 m. The same 30 m interval was used for vibroseis shot points. For deployment 2, spacings of 15 m and 30 m were used for the geophones. Because of the smaller spatial extent, Deployment 2 took less time to put in place.

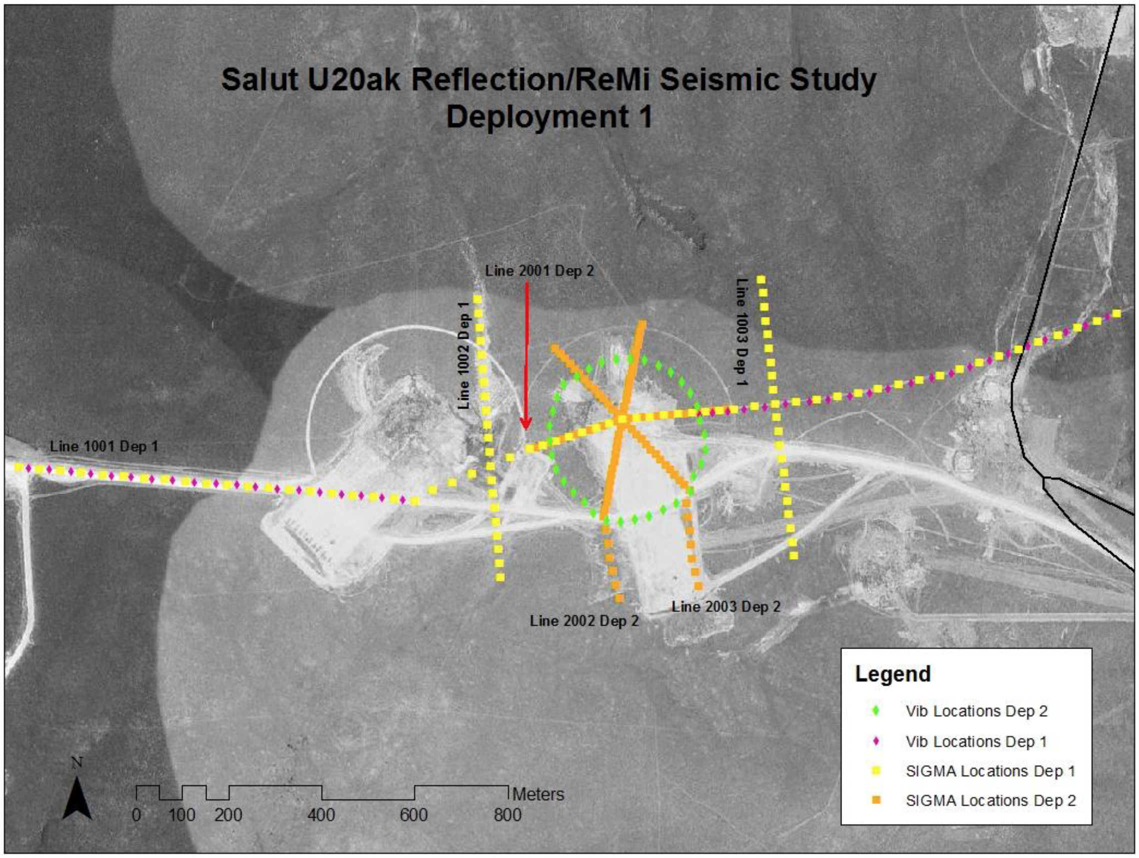

Figure 6. Survey layout for the two deployments of the active seismic survey. Geophone locations are shown as yellow dots (deployment 1) and orange dots (deployment 2). Source vibroseis locations are shown as red dots (deployment 1) and green dots (deployment 2).

A three-component geophone, data recorder, and battery are shown in Fig. 7. The Sigma™ data recorders are wireless recorders that collect and digitize the data from the geophones. Once the geophone lines are deployed, the SAUs are interrogated wirelessly from a portable computer to ensure that all units are working properly. The actual data collected cannot be viewed during the field campaign; it is collected on memory cards that are collected at the end of the survey and later downloaded and put into the data processing pipeline. This inability to assess the quality of the data could be a liability for an inexperienced deployment team, but the Optim, Inc.

team has done this many times and a successful data collect was achieved. After checking the operation of all the SAUs, the vibroseis survey is started. Each survey run is done in one orientation mode (see below) before changing modes and running the source line again. Data is collected passively at a 1 ms sampling rate across the entire array at one time. Each SAU was programmed to collect 30 second records for each vibroseis location.

The EnViroVib vibroseis (Fig. 8) incorporates three different configurations: compressional, or vertical (Vp) mode; transverse shear (VsT) with motion perpendicular to the survey line; and radial shear (VsR) with motion along the survey line. Each vibroseis sweep was continuous between 10 and 100 Hz over 5 seconds, and 3-5 sweeps were run (and later stacked) for processing at each source location.

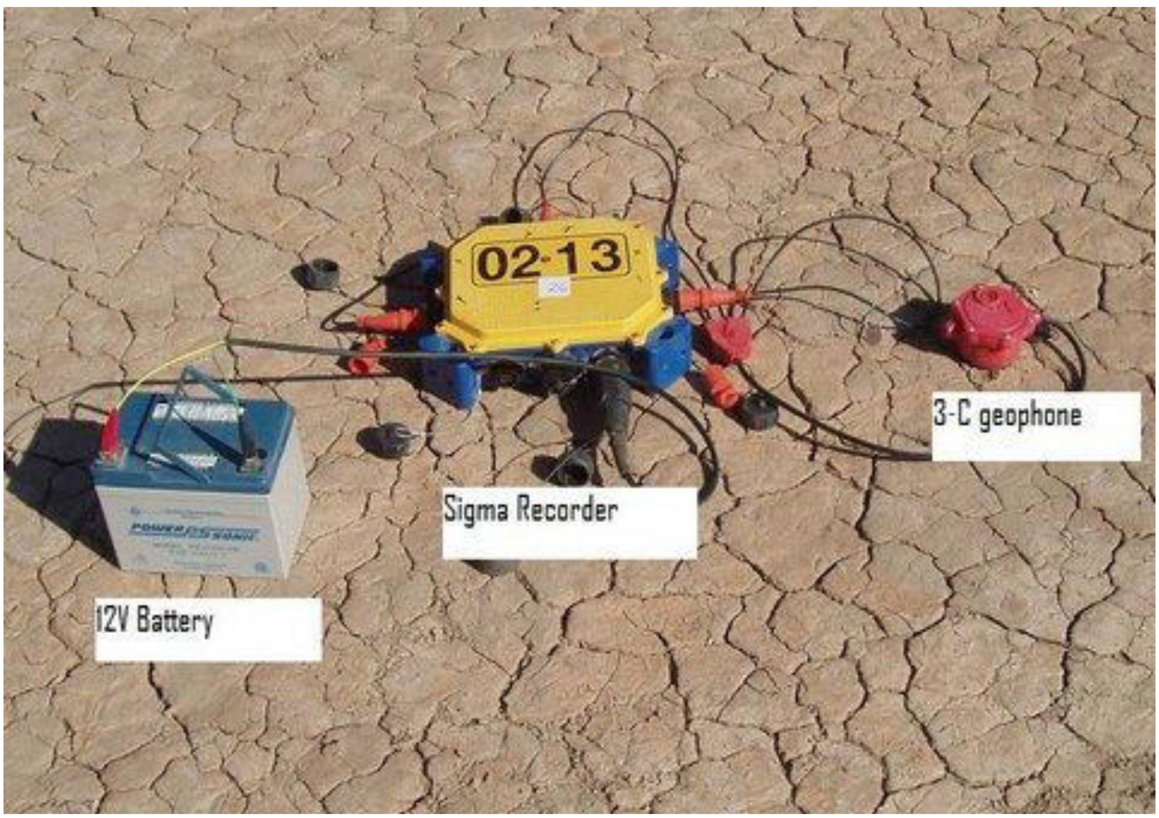

Figure 7. The seismic acquisition unit (SAU) Sigma™ recorder, 3-component geophone, and battery used for one data collection point. The geophone is wired to the SAU, but the SAU itself operates wirelessly.

The deployment process consisted of the following steps for a five person crew:

- Survey and flag stations for source and receiver locations (one day).
- Set out geophones and SAUs, then lay out the survey lines and emplace geophones (two days).

- Check out the system for operational status; run vibroseis surveys (one day).
- Lay out second deployment, collect data and demobilize (three days).

Figure 8. The EnViroVib vibroseis source shown in operation at the U20ak site. The plate just behind the front wheel applies the vertical or shear vibrational energy to the ground. The vibroseis operates in a 5 s sweep between 10 and 100 Hz.

After demobilizing the survey, the data cards (16 Gb memory) are collected from each SAU to start the data management and retrieval process. Because the data is collected as 30 s data intervals, it can be used for both ReMi analysis and standard reflection/refraction processing. The data management process is automated with specialized software that allows for data gathers and cross-correlations for later processing and interpretation.

ReMi processing results

The Optim report describes the ReMi methods as "…a volume-averaging surface-wave measurement, averaging velocities where geology is laterally variable, thus differing from single point data obtained from down hole logs. In this method, microtremor noise…excites surface waves, are recorded by a linear array of vertical refraction geophones. These noise records are transformed into slowness–frequency (p-f) space, and a dispersion curve picked along a minimum-velocity envelope. Modeling the dispersion curve produces a depth–velocity sounding …[using] both ambient noise and sweeps from the vibroseis". Figure 9 illustrates the ReMi data analysis process:

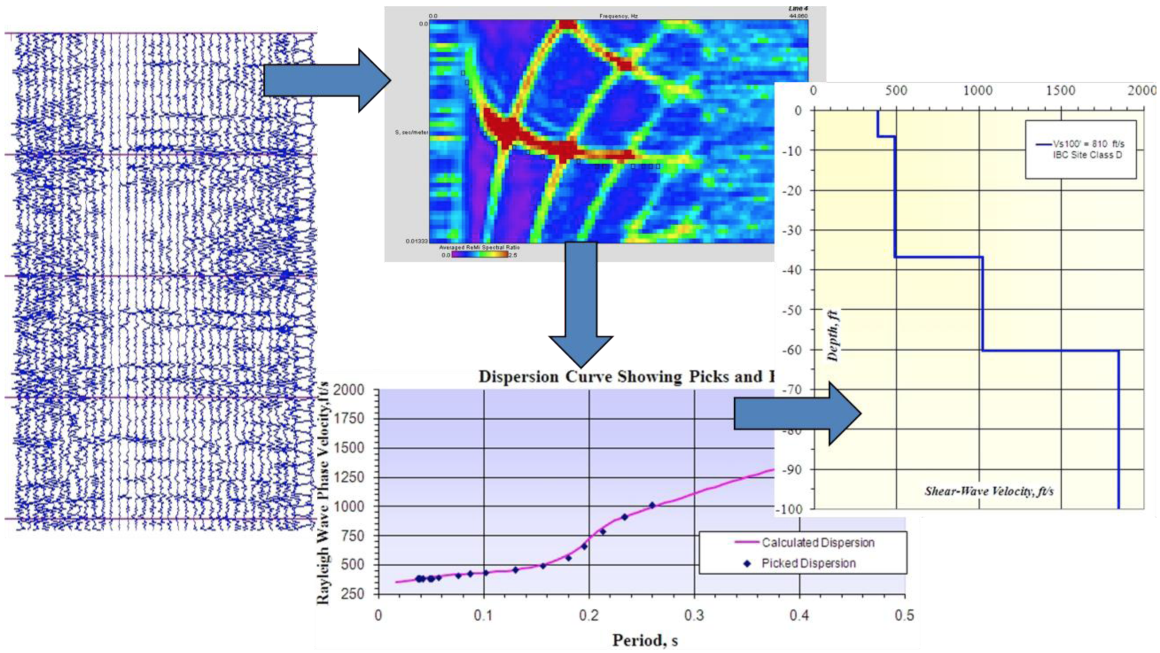

Figure 9. The ReMi data analysis process. Raw seismic data gathers (left -- from multiple geophone sets along a line) using either noise or data recorded during vibroseis operation, are then transformed into a slowness (inverse velocity) frequency diagram (middle) which is then used to produce to produce a velocity-depth curve (bottom) which is then used to interpret a depth-velocity model (right).

By computing a series of one-dimensional soundings and models along the survey line and interpolating the results, a map of lateral velocity changes can be produced as a cross sectional diagram. Again, from the optim report: "…Typically, the depth of penetration of the recorded wave field is half the array length. To resolve the velocity profile with sufficient sampling of low frequency waves to characterize the deep structure, the recommended array length is 2.5 times the estimated target depth. To image the velocity profile beneath Deployment 1 Line …to 600 m depth successfully with adequate resolution, data from overlapping subsets of instruments spanning 800 m to 1000 m were analyzed. This ensured definition of both the bottom of the cavity and the velocity structure beneath." In the data analysis, Optim found that better and more realistic results were obtained by analyzing Love wave phases rather than Rayeigh wave phases, with maximum consistency between results for deployment 1 and deployment 2.

In analyzing the dispersion curves (bottom plots in Fig. 9), these observations were made by Optim: "…the dispersion curves over the [anomaly] are flat in shape compared to those away from the [anomaly], which trend steeply straight down.

Flattening of the curve at mid frequencies above the cavity necessitated the presence of a low velocity body at depths greater than 200 m. While the dispersion curves above [the anomaly] are clear, those away from the [anomaly] are weak. This may be due to the fact that the surrounding stratigraphy includes alternating layers of strong and weak volcanic deposits. The strong layers are likely to inhibit the propagation of waves due to the high velocities. However, above the cavity, the explosion is likely to have caused a high degree of fracturing and destruction of these weak and strong layers. The resultant low velocity zone of the cavity allows channeling of high energy waves at higher frequencies, enhancing the dispersion curve. The channeling of waves through the low velocity [anomaly] produces both a change in shape of the shear-wave dispersion and enhances high frequency energy content. Together, these attributes aid the detection of the [anomaly]…".

The ReMi interpretation of these data from U20ak is an iterative, forward-modeling process: initial constraints are put on the model, based on estimated depths of the cavity, the top of the rubble chimney, and seismic velocity values for the geologic units. The models are then run and compared to the data processed as above (basically going from the bottom plot of Fig. 9 to the right-hand plot). As for many geophysical methods, this modeling process is non-unique; e.g. different models will fit the same set of data. General practice is to accept the simplest model that best fits all other information as well as the data that is being analyzed. The key is not to "over parameterize" the process – model as few layers as needed consistent with the data. Both Rayeigh and Love wave phases were analyzed, but it became clear that only the Love waves were sensitive to the velocity contrast due to the chimney. In the modeling process, it soon became clear that there was a low Love wave velocity zone in region of the cavity and rubble zone at U20ak, the key to the modeling was how best to constrain the vertical and lateral extent of this low velocity zone.

Figures 10 and 11 show two end members of the velocity modeling illustrating a range of possible configurations of the low velocity zone, which undoubtedly is a velocity anomaly due to the presence of the cavity and rubble chimney resulting from the UNE. The range here represents the trade-off between determination of the velocities within anomaly and defining its shape. In this case, the base of the anomaly was fixed at 615 m – this is about 10 m below the emplacement point for the UNE and probably about 20 above the base of the explosion cavity. Velocities in the matrix rock match those observed by modeling segments of the survey line away from the rubble chimney. The model was kept simple (thinner layers of tuff units cannot be resolved anyway, and modeling the effects of the anomaly is more straightforward with a simple model).

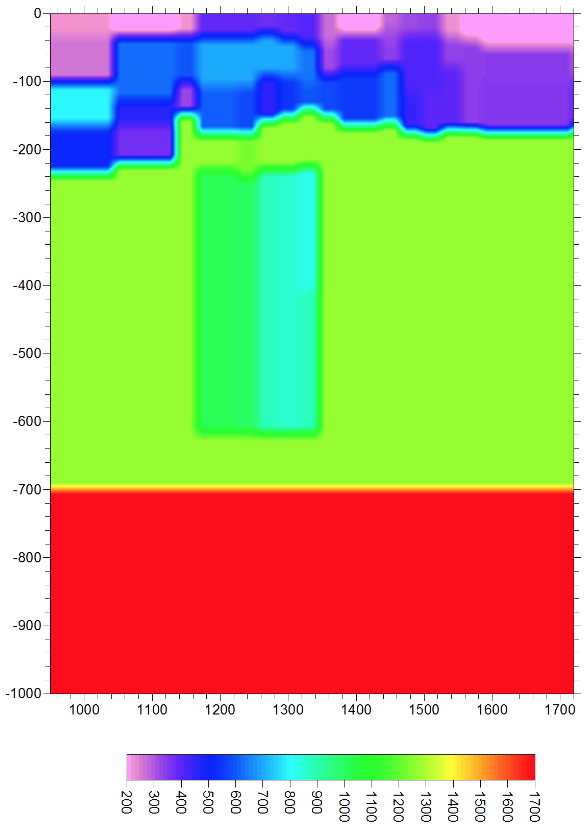

Figure 10. Two-dimension representation of the shear wave velocity in the vicinity of U20ak. Velocities within the low velocity zone were developed by fixing the base of the zone at 615 m depth and fixing the upper extent to 220 to 240 m.

There are certainly also some variations in velocity within the anomaly, since velocities in the rubble will be lower, but mimic, velocities in the surrounding rock. The lateral resolution of the model is fixed by the geophone spacing on the survey lines to 30 m; the lateral extent of the anomaly in the model is about 150 m. This agrees well with the estimated diameter of the cavity and rubble chimney of about 120 m. Vertical resolution is not constrained as well as the lateral resolution, because the model is developed by interpolating a series of vertical soundings.

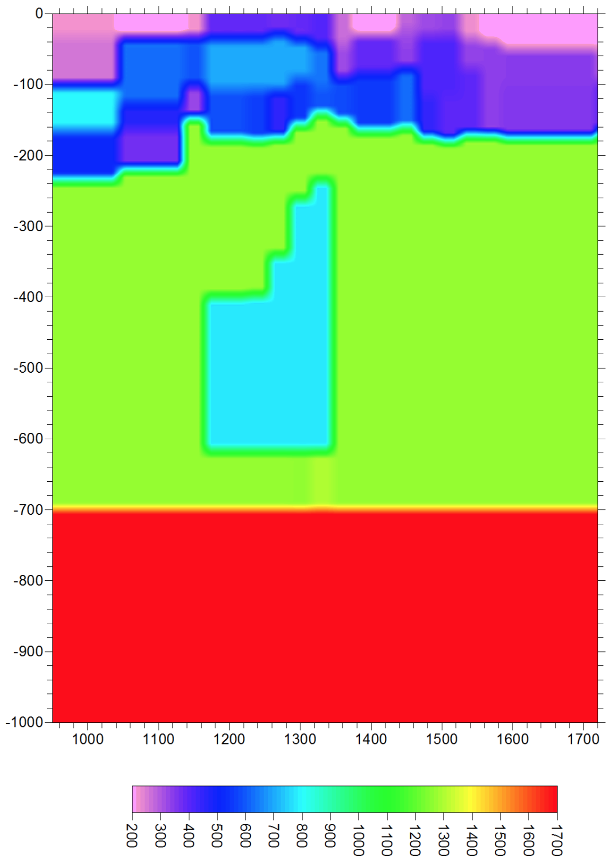

Figure 11. Two-dimension representation of the shear wave velocity in the vicinity of U20ak. Velocities within the low velocity zone were developed by fixing the base of the zone at 615 m depth and fixing seismic velocity within the zone to 817 m/s, contrasting to a velocity of about 1300 m/s in the surrounding undisturbed rock.

The data collected from the active seismic survey were also analyzed by personnel at the University of Nevada, Reno, (Louie, 2013) with reflection processing methods. Results are shown in Fig. 12. From the report by Louie: "None of the multicomponent source or receiver combinations showed first arrivals that could be easily picked, or any clearly prominent reflections or conversions. However, P-P reflection brute stacks of Deployment 1 Line 1 did show some reflections near the [U20ak] cavity, as well as terminations and possible diffractions at the edges of the rubble chimney. We subsequently produced SH-SH and P-SV reflection brute stacks of the same line that showed somewhat stronger reflections from the cavity, as well as from the volcanic stratigraphy. SH to SH reflections appear in the VsT transverse vibrator component recorded by the geophone Y component for Deployment 1 Line 1. We hypothesize that we are observing P to SV conversions in the VP vibrator component recorded by the geophone X component for Deployment 1 Line 1. While these multicomponent reflections are apparently correlated with blast and stratigraphic features, they are not unique and therefore not diagnostic of the blast effects."

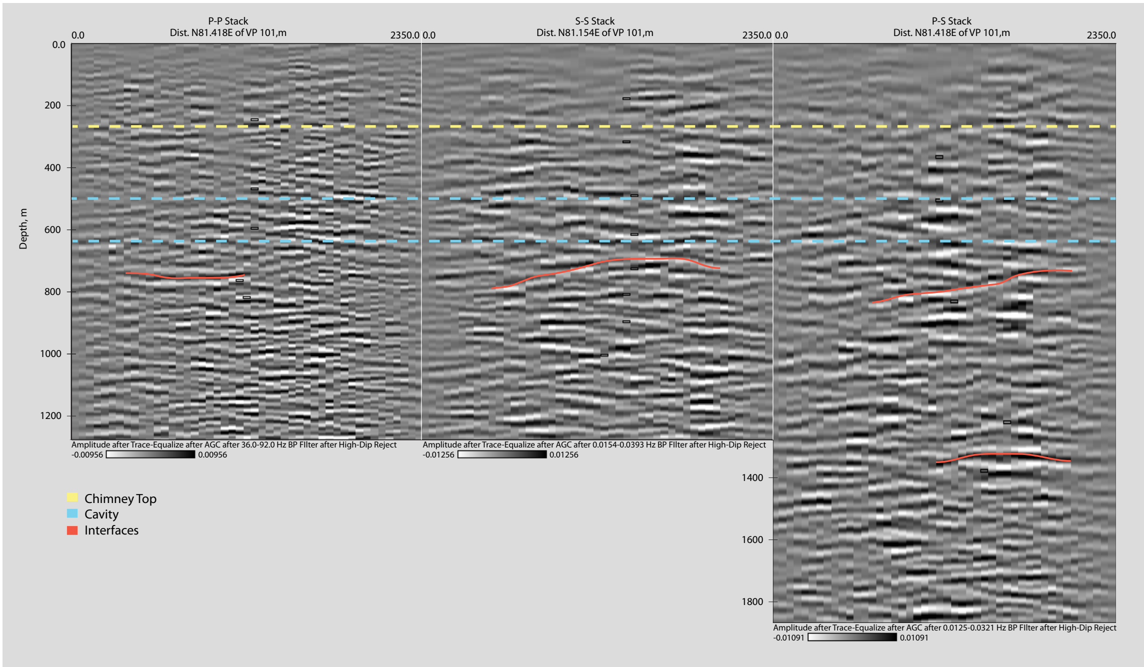

Figure 12. Plot of all three trial multicomponent CMP stacks with test and geological-feature depths marked. Left stack: P-P; center stack: SH-SH; right: P-SH. The yellow dashed line marks the presumed depth of the top of the rubble chimney; the dashed blue lines mark the depths of the top and bottom of the explosion cavity. The red curves at about 750 m depth mark possible geometries seen in the stacks for the bottom of the Paintbrush lavas and the top of the underlying ash-flow tuffs.

Summary of Active Seismic Survey Results

Both refraction microtremor (ReMi) and reflection analysis methods were used to interpret data collected over the U20ak UNE site. The ReMi results revealed a shear wave velocity anomaly in the vicinity of the expected rubble chimney zone. The lateral resolution of the anomaly (150 m wide) is better than the vertical resolution, which is affected by the trade-off between the vertical extent and the velocity within the anomaly. The reflection processing revealed some possible reflections at depths of the top and bottom of the rubble zone as well as some lateral discontinuities, but these are not easily distinguished from the background reflections. The field data collection for the survey took an experienced crew of five people seven days to accomplish. The data analysis process took longer, including time to assemble and do initial processing of the data collected.

It is clear from this exercise that standard seismic reflection processing methods would probably not be successful in imaging the rubble zone from the UNE in the layer tuff geology typical of this part of Nevada, although being able to apply an active source directly over the target may have improved the results. The ReMi method, however, is encouraging in that it does reveal a velocity anomaly related to the rubble zone of the UNE. In this case, the resolution of the anomaly is probably sufficient to use the ReMi results to define a drilling target for a slant borehole to intersect the rubble zone. A more robust source of seismic energy (producing both compressional and shear waves) would certainly improve the results of the ReMi method and possibly reflection processing, but the modest vibrational source used here is more representative of what will be used during an OSI under the CTBT.

The data set acquired for this project is quite extensive because of the longer records recorded for ReMi processing. The data that have been processed to date represent an initial cut at analysis. The nature of the data set is such that it can be used for several different approaches to analysis that are the focus of further studies.

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