Multi-Frequency EM Surveys Help Identify Possible Near-Surface Migration Pathways in Areas Surrounding a CO_2 Injection Well: San Juan Basin, New Mexico, USA

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Introduction

Approximately 70 line-kilometers of multi-frequency EM data were collected over a carbon sequestration pilot site in the north-central part of the San Juan basin. The study was conducted as part of for the Southwest Regional Partnership (SWP) on Carbon Sequestration's San Juan Basin Fruitland Coal pilot test. The project was funded by the U.S. Department of Energy and was managed by the National Energy Technology Laboratory (NETL). The efforts reported on here were undertaken as part of the NETL Phase II Regional Partnership activities. The pilot test was undertaken in collaboration with ConocoPhillips as a joint enhanced coalbed methane recovery test and demonstration of CO_2 sequestration in deep, unmineable coal seams. The SWP conducted the pilot in the Upper Cretaceous High Rate Fruitland production fairway southwest of the northwest trending basin hinge. CO_2 injection began July 30th of 2008 and continued through August 14th of 2009. During the 12 month injection period approximately 319 MMCF, equivalent to nearly 18,407 short tons of CO_2 were injected into the Fruitland coals. The EM data were collected to locate flow paths in the near-surface sandstone that caps the site mesa that would vent CO_2 if it were to escape from the Fruitland coal injection zone. The Fruitland coals are located between 3000 and 3200 feet beneath the surface in the area.

An earlier model Aeroquest Sensortech (formerly Geophex) GEM-2 terrain conductivity meter was used to acquire the data. Data were collected at 4 frequencies: 45,030Hz, 16,890Hz, 4,110 Hz and 1,050 Hz At the time, the GEM-2 instrument did not have built-in stepping mode frequency transmission. In this study, data were initially collected using simultaneous transmission of all 4 frequencies. Data were re-acquired in select areas using only two simultaneous transmission frequencies: one high and one low. The survey was run twice to obtain observations at all four frequencies. In this case, transmission power at individual frequencies was higher and the recorded data had higher signal-to-noise ratio. Inverse models developed from both data sets using Interpex Limited IX1D v3 software contain noticeable differences. Inverse models developed from data recorded using only two transmission frequencies provided more continuous (less noisy) views of subsurface conductivity layering.

Background Geology of the Site

Approximately 70 line kilometers of EM data were collected over the pilot site to locate flow paths in the near-surface sandstone that caps the site mesa. The major purpose for acquiring the EM data was to locate high porosity, high-permeability near-surface zones that might vent upward migrating CO_2 and facilitate atmospheric return.

CO_2 was injected into the upper Cretaceous Fruitland coals at the site. There are three major coal seams in the injection zone. The upper and middle coals are both approximately 20 feet thick (6.1 meters) and the lower coal is close to 30 feet thick (9.1 meters). The CO_2 injection well is located on a mesa in the north central part of the San Juan Basin (Figure 1). The ground elevation at the injection well is 6321 feet (1927 meters) above sea level. Bedrock geology in the area consists primarily of nearly flat lying

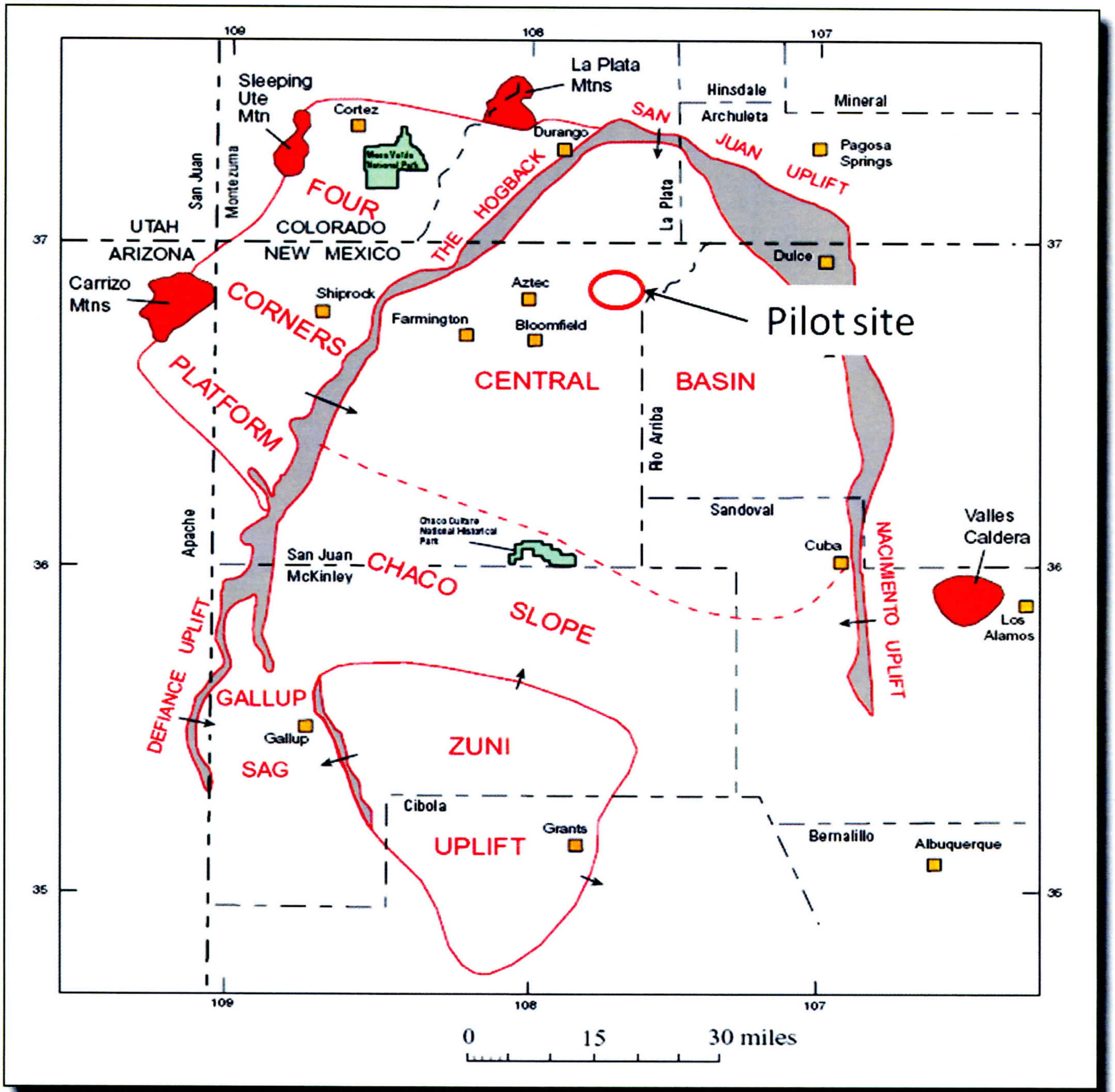

Figure 1. The location of the pilot site is shown in general with reference to the outline of the San Juan Basin located in the northwestern corner of New Mexico. The northern most edge of the basin extends into the southwest corner of Colorado (Taken from Fassett, 2000).

tan conglomeritic sandstone and shale of the Cuba Mesa Member of the basal Eocene age San Jose Formation (approximately 54 My age). The mesa is covered in places by colluvium of varying thickness. Exposures along the mesa rim are dominated by a series of sandstone and shale layers. The mesa is underlain by a thick (~11 meter (36 foot)) sandstone (Figure 2). A thin shale (1.2 meters (4feet) thick) lies at the base of the sandstone (Figure 3). This pattern of alternating sandstone and shale intervals is prevalent throughout the area (Figure 4). Evidence of active drainage during wetter periods as well as seep and spring activity are notable along the flanks of the mesas in the region.

A photo from beneath the edge of the mesa near the canyon head (Figure 4) provides perspective on the scale of the intervals being investigated using the GEM-2. The massive sandstone is approximately 11 meters thick; it is underlain by a weaker shale interval that measures approximately 1 – 2 meters thick in the area. The canyons in the regoin appear to develop primarily through groundwater sapping. The process is common throughout the area and was initially observed along the perimeter of the mesa to the southwest. Massive sandstone layers form the resistant mesa floor and the prominent benches along the canyon wall (Figures 3 and 4) are underlain by seeps in places. The underlying shales are preferentially eroded. Rock falls often point up-slope to seeps beneath the lip of massive sands that cap the mesa and form benches along mesa flanks. Headword erosion occurs in this fashion, widening and extending headward canyon development.

The view down the length of one of these canyons (Figure 4) reveals about 60 meters (200 feet) of the section underlying the site mesa. The EM survey was undertaken to provide information about conductivity variations within the upper 10 to 12 meters (33 to 40 feet) of section capping the mesa.

Figure 2. The CO_2 injection well is located in middle-left of the photo. The massive sandstone underlying the site is exposed in a canyon-head south of the injection well.

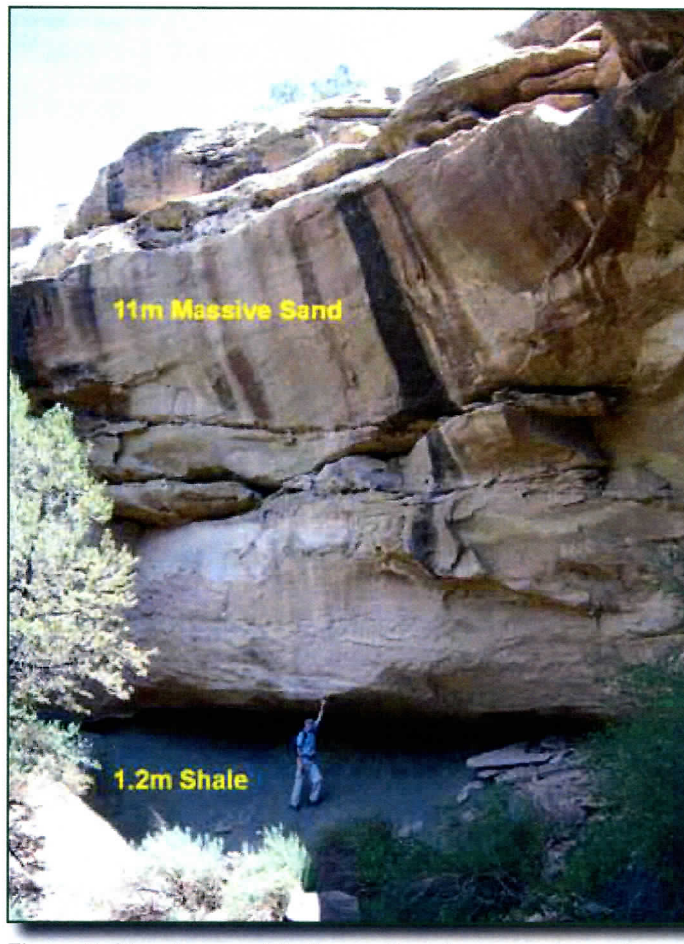

Figure 3. Massive sand that caps the site mesa. A weathered shale zone is observed at the base. Preferential erosion of the shale undercuts the sandstone layer.

EM Survey Method

The Aeroquest Sensortech (formerly Geophex) GEM-2 multi-frequency terrain conductivity meter was used to evaluate the EM response of the site at several transmission frequencies. Recordings were made at 45,030Hz, 16,890Hz, 4,110 Hz and 1,050 Hz The high frequency (45,030 Hz) response (Figure 5) reveals a complex pattern of conductivity variation through the area. Data in some areas of the survey were collected at different times. To evaluate changes that might be associated with differences in recent precipitation and water saturation of near-surface intervals, surveys incorporated overlap and in some cases were repeated to determine if significant differences in EM response occurred through time. Anomaly amplitudes were observed to vary with time; however, similar, nearly identical patterns were observed in the terrain conductivity response.

EM surveys were carried out along east-west lines spaced at 10 meter intervals across the site. Line-of-site navigation along individual lines was not possible in the area. Real-time GPS positioning was used to track measurement locations. A hand held GPS unit along with guidance from a field assistant in foresight or backsight locations was used to maintain profile location during individual line surveys.

In its original configuration, the GEM-2 was set up to transmit all selected frequencies simultaneously. In this configuration the transmitter power is divided between selected frequencies and reduces transmitted power at individual frequencies. To increase transmission power, the surveys were repeated in selected areas. In the repeat surveys, transmission was limited to two frequencies (one high and one low) to enhance transmitted signal strength and improve depth of penetration. This required that the area had to be surveyed twice to obtain coverage at the four frequencies acquired in the earlier surveys. In the following discussions we present comparisons to illustrate differences in EM response. Differences are particularly noticeable at lower frequency. We also present inverse models along a profile line developed using Interpex Limited IX1D v3 software. The inverse models provide insights into the conductivity variations as a function of depth and spatial location at the site. They also illustrate the improvement in data quality obtained by limiting transmission to a couple frequencies.

Figure 4. View out along the mesa edge reveals an alternating sequence of sandstones and shale layers underlying the CO_2 well site.

Results

Comparison of the lowest frequency (1,015 Hz) quadrature components (Figure 6) reveals that both data sets are chaotic in appearance. The data collected using only two transmitted frequencies (Figure 6B) has smaller range (approximately 0 to 400 ppm of the primary field). Whereas the data collected using four simultaneously recorded frequencies (Figure 6A) has much greater variability (300 to -3000 ppm) with values mostly in the negative.

Coherent patterns begin to appear in the 4,110Hz data over the area (Figure 7). The low conductivity area noted in the regional 45,030Hz view (Figure 5) is not revealed in the 4,110Hz data acquired initially (Figure 7A). The earlier (2007) data reveal a very noisy low frequency response which contributed large errors to the EM inversions. The recent (2008) survey provides more coherent views (Figure 7B) of induced EM fields at the 4kHz frequency and suggests that lower error inversions will be possible.

The 16,890 Hz data continues to reveal improvements in signal-to-noise ratio when the number of simultaneously recorded frequencies is reduced (Figure 8). Features in the 16,890 Hz data set, recorded with only one additional frequency (Figure 8B), are more coherent and well defined.

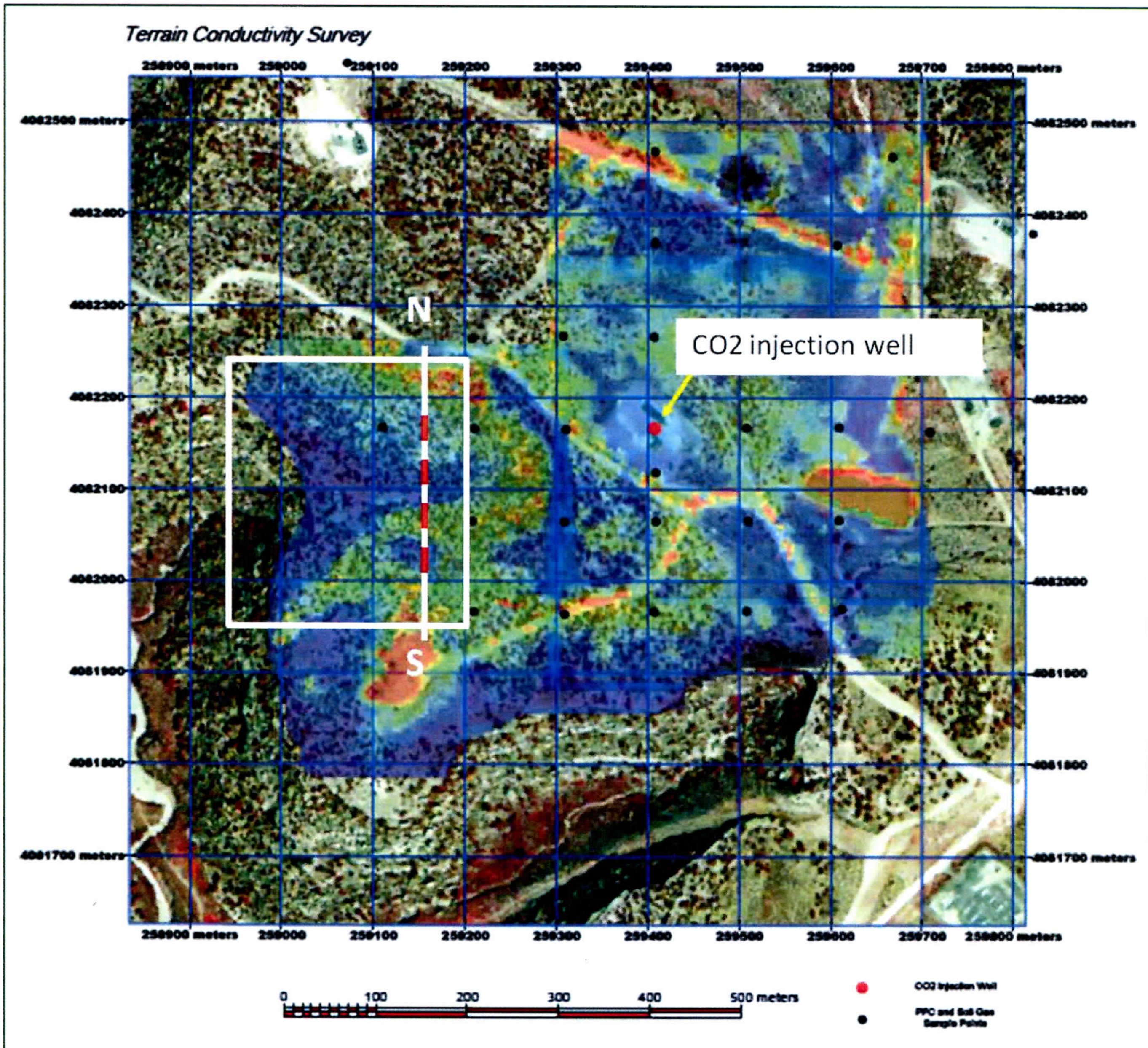

Figure 5. The GEM-2 45,030 Hz response is superimposed on a QuickBird view of the site mesa. Data collected in the area outlined by the white square are examined in detail. The bluer areas correspond to low conductivity and the green to red responses to higher conductivity.

The highest 45kHz frequency component has the shallowest depth of penetration and is fairly coherent in both surveys (Figure 9). Areas marked by lower response level are associated with well drained, mostly soil barren areas (blue areas in Figure 5).

A comparison of the quadrature components observed at all four frequencies recorded using the dual-frequency transmission reveal some consistency from frequency to frequency with exception of the lowest frequency (1,050 Hz) component. Much of the variability is expected to be associated with variations in the rock conductivity as a function of depth. Similar patterns of extracted conductivities (Figure 10) are also observed at each frequency.

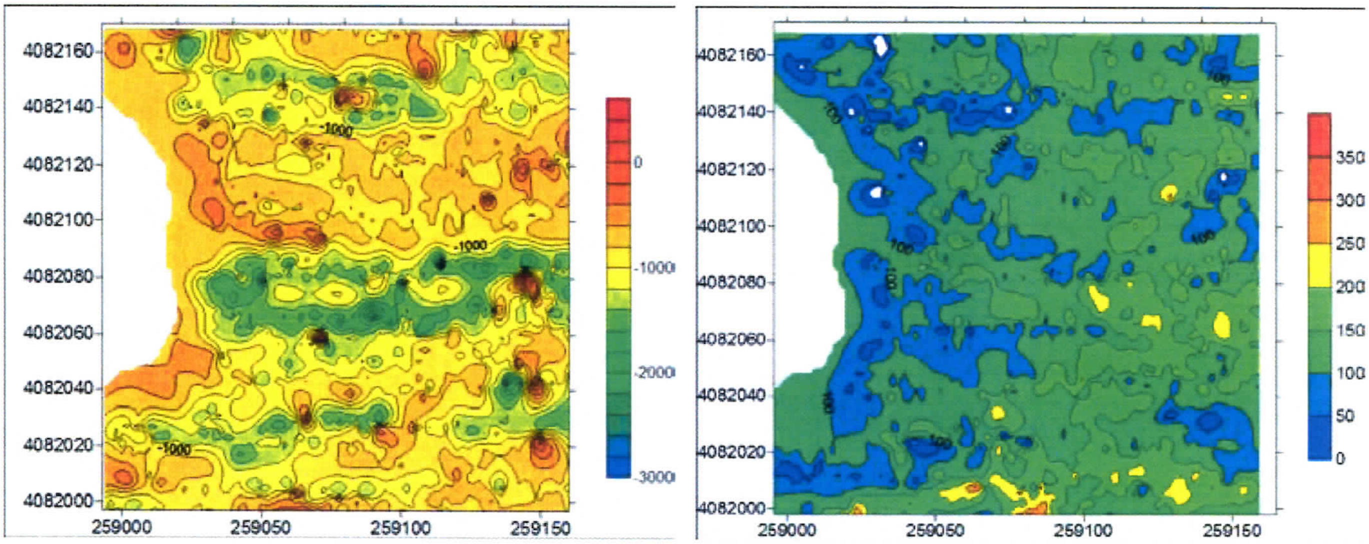

Figure 6. A) 1,015 Hz quadrature response observed in the earlier July 2007 survey. Four separate frequencies were collected simultaneously during this survey. B) The 1,015 Hz component collected in the later June 2008 survey was collected along with only one additional frequency component.

Inverse Model Study

Resistivity inversions of the four simultaneously recorded frequency responses (Figure 11) provide some insights into the near-surface resistivity distributions. The profile of soundings (Figure 11) was developed using Interpex Limited's IX1D v3 1D sounding inversion software. The modeled profile crosses the east end of the low conductivity channel-like feature that develops in this area and opens to the west

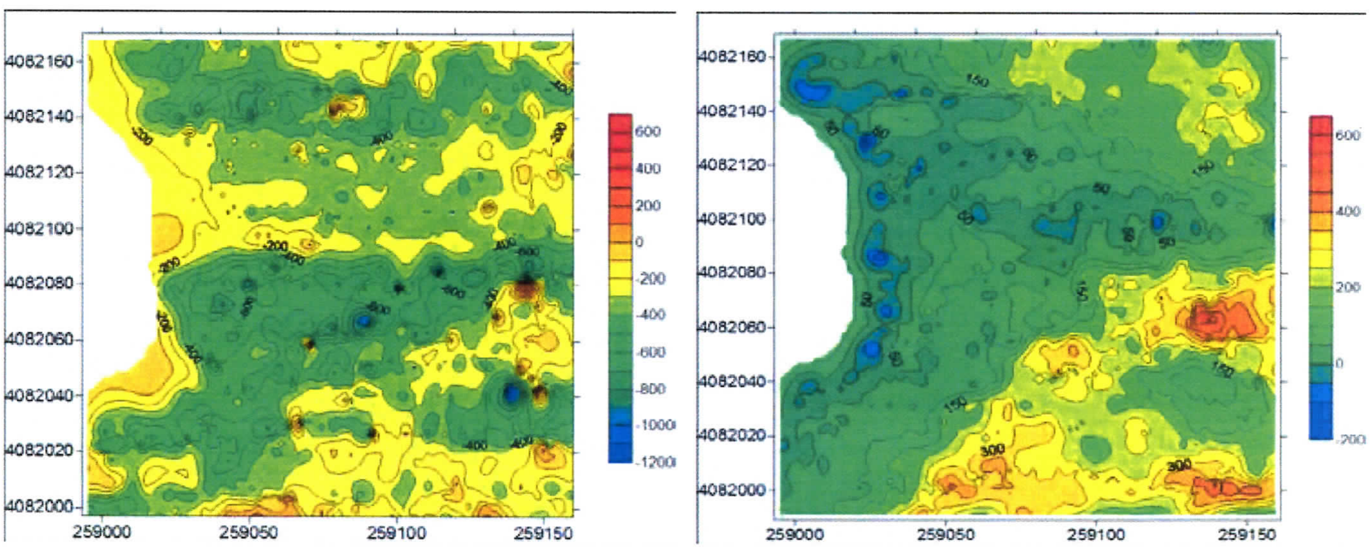

Figure 7. A) 4,110 Hz quadrature response observed in July 2007. Four separate frequencies were collected simultaneously during this survey. B) The 4,110 Hz component collected in the June 2008 survey was collected along with only one additional component.

(figures 5 and 10 D). Recorded in-phase components were nearly always negative. These observations could not be matched in the computer inversions and were typically masked during the modeling process. The results reveal shallow low resistivity (red) areas that are usually associated with thickened soil cover. These low resistivity zones are generally restricted to the upper two to three meters of the inverse model consistent with soil cover observations in the field. Although low resistivity is invariably associated with soil covered zones, the converse is not necessarily the case: some areas covered by a thick blanket of soil often have high resistivity response.

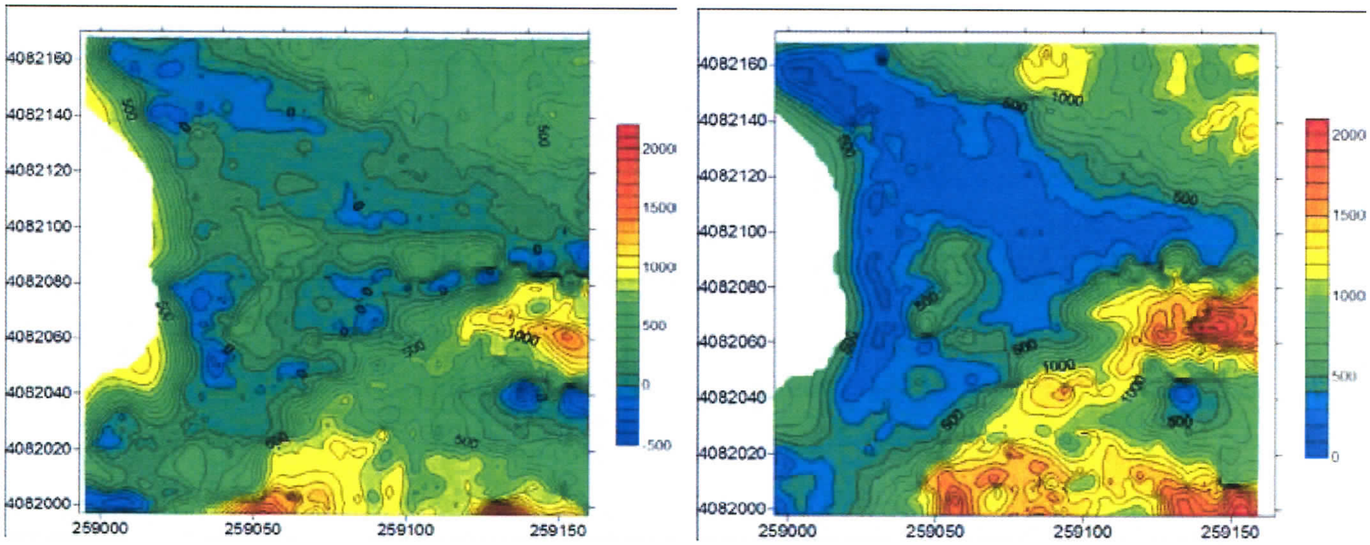

Figure 8. A) 16,890 Hz quadrature response observed in July 2007. Four separate frequencies were collected simultaneously during this survey. B) The 16,890 Hz component collected in the June 2008 survey was collected along with only one additional component.

The deeper section shows considerable local lateral variability. The inverse models lack coherence from point to point along the profile. The high resistivity surface feature near the center of the profile appears to have a high resistivity root; however, the presence of significant local variability limits certainty in this interpretation. The inverse models provide a glimpse of subsurface conditions in the area, but low signal to noise ratio, especially in the deeper parts of the model limit confidence in possible interpretations.

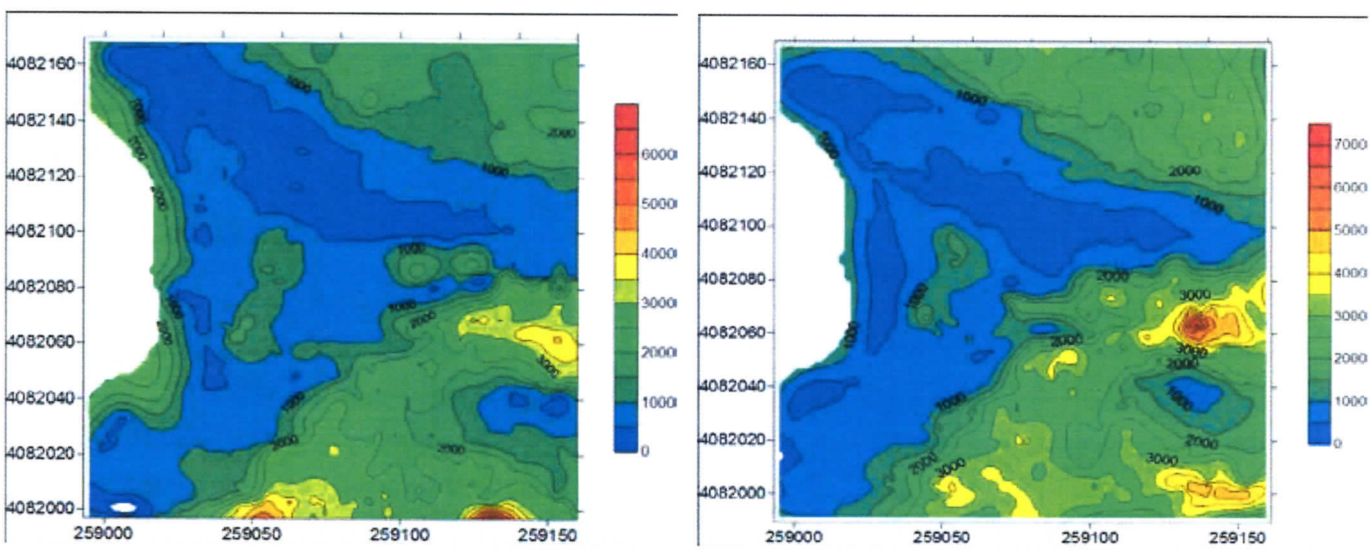

Figure 9. A) 45,030 Hz quadrature response observed in July 2007. Four separate frequencies were collected simultaneously during this survey. B) The 45,030 Hz component collected in the June 2008 survey was collected along with only one additional component.

The field area was resurveyed as noted above. Selected areas were resurveyed in two passes: one, using transmission frequencies of 16,890 Hz and 1,050 Hz; and a second pass using frequencies of 45,030 Hz and 4,110Hz Inverse models were developed following the same procedures used with the earlier four-frequency data. A slightly smaller portion of the line was modeled (see dashed red line in Figure 5). The results (Figure 12) have much better spatial coherence from sounding to sounding. The inverse models suggest that the subsurface can be divided roughly into three layers. The base of the model extends approximately 8 meters beneath the surface.

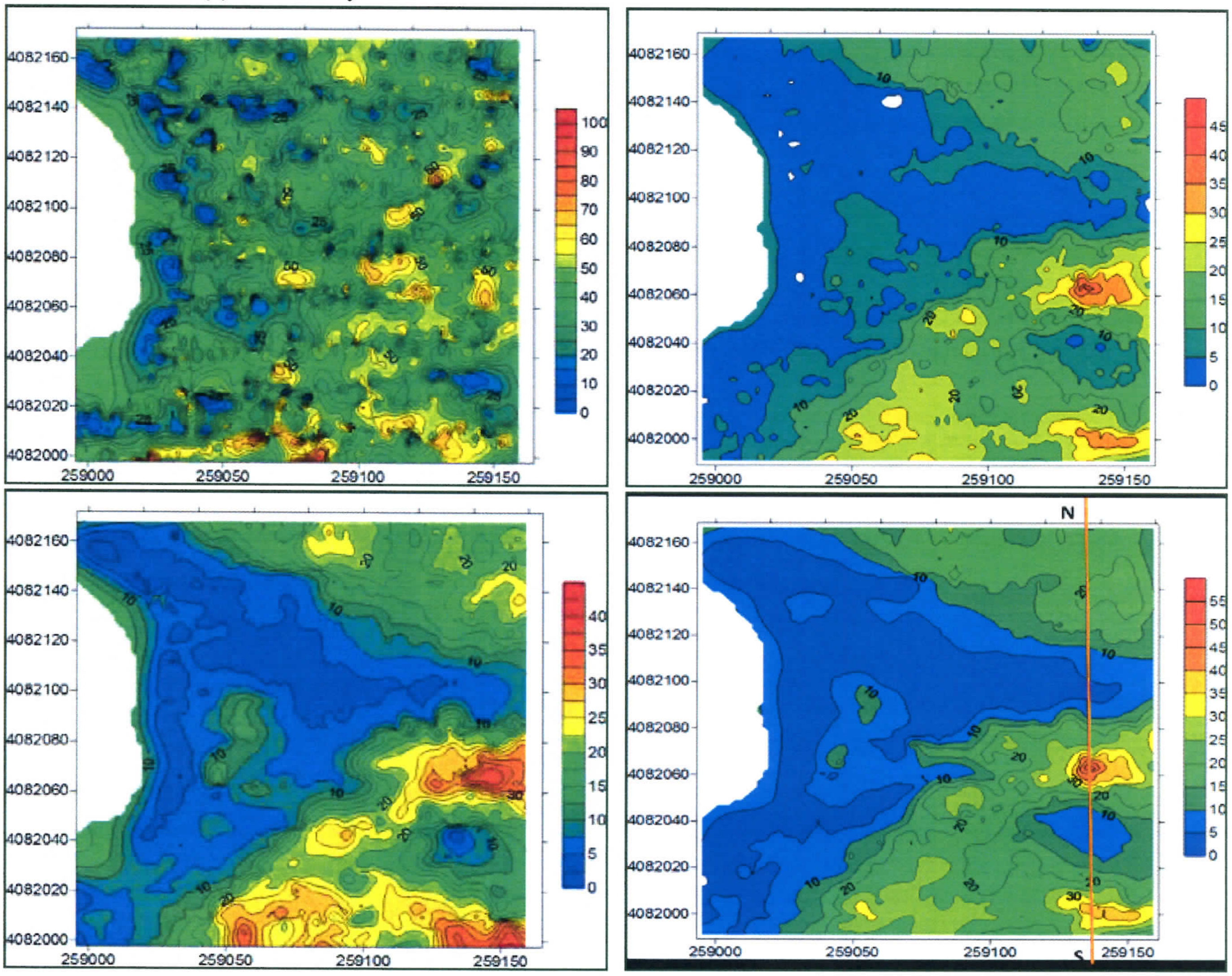

Figure 10. Conductivities extracted at each frequency. A) 1,050 Hz' B) 4,110 Hz; C) 16,890 Hz; and D) 45,030Hz An inverse model was computed along the NS profile line (orange line) shown in D.

The comparison reveals improved signal-to-noise ratio in the model derived from data in which ground response was measured using only two transmission frequencies and illustrates improvements in the quality of the inversions obtained using the revised approach to data acquisition.

The high resistivity area that opens to the west (Figure 5 and Figure 10D) and extends to the edge of the mesa appears to consist of a headward conduit that extends from the surface down into higher resistivity less conductive areas of the sandstone that caps the mesa. Increased resistivity is interrupted by a 2-m thick zone of lower resistivity that extends from depths of about 3m to 5m subsurface.

High resistivity (low conductivity) is interpreted to represent zones of higher porosity and permeability. At the surface these areas are generally clear of colluvium. To the east toward the interior of the mesa, soil cover is scoured by narrow channels that funnel runoff out to the mesa rim. The mesa rim is generally characterized by a high resistivity (low conductivity) border that extends several tens of meters into the interior of the mesa (see Figure 5). The lower resistivity (green to red) areas generally correspond to areas of variable soil thickness across the surface of the mesa. Areas covered by soil are more likely to retain moisture from infrequent rain and snow fall. Total annual precipitation in the region is approximately 8 inches. Soil covered areas are also likely to inhibit evapotransportation of water from the underlying sandstone. Based on the inverse models we suggest that resistivity increases with depth and that the EM response is largely controlled by intervals within about 8 meters of the surface.

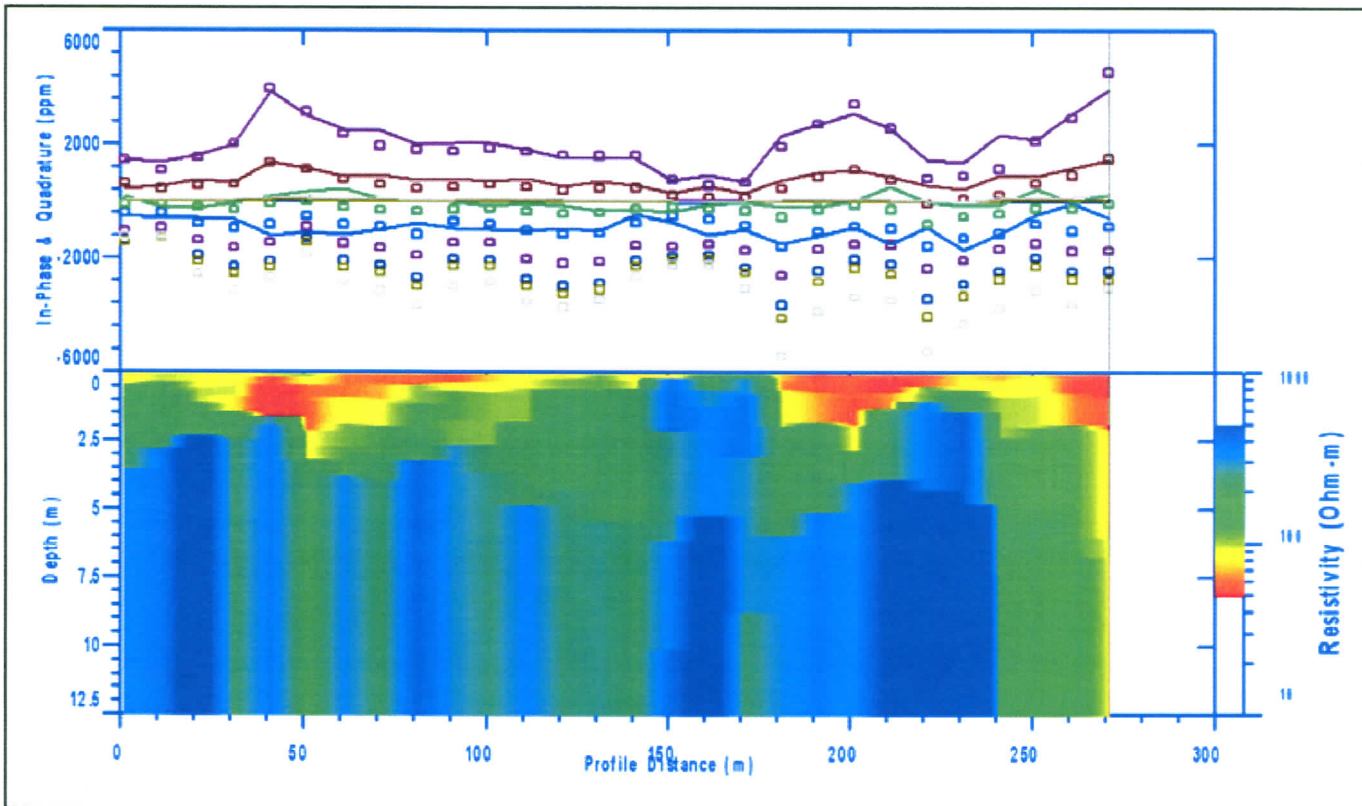

Figure 11. Inverse models portrayed in profile view. Models were developed from GEM-2 soundings made using 4 simultaneously transmitted frequencies. See Figure 5 for line location.

Summary

Approximately 70 line kilometers of EM data were collected over the Southwest Regional Partnership (SWP) Fruitland Coal Phase II pilot test site to locate flow paths in the near-surface sandstone that caps the site mesa. Identification of high porosity/permeability near-surface flow paths provides useful information to those engaged in monitoring, verification and accounting (MVA) efforts on carbon sequestration sites. This information can be used to help place tracer and soil-gas monitoring stations in areas where CO2 leakage, if it happened to occur, might re-enter Earth's atmosphere. It was felt that the quickest and most inexpensive way to identify near-surface migration pathways was to conduct terrain conductivity surveys. Data were collected using the Aeroquest Sensortech (Geophex) GEM-2 broadband EMI sensor. The instrument allows one to observe ground response simultaneously at multiple frequencies. Data are collected at a walking pace and locations are tracked using on-board GPS. In this study we present results of the site survey and evaluate different approaches to data acquisition.

The number of transmitted frequencies and transmission power are important factors to consider when conducting the broadband EM survey. In the earlier model GEM-2, the temptation was to use several frequencies in a single pass. However, as the number of transmission frequencies increased, the transmission power at individual frequencies decreased since all frequencies were transmitted simultaneously. This reduced overall signal-to-noise ratio, particularly at lower frequency. Two overcome these limitations, surveys were repeated using only two transmission frequencies to improve transmission power and signal-to-noise ratio. The initial surveys were made using simultaneous acquisition of data at four frequencies: 1,050 Hz, 4,110 Hz, 16,890 Hz and 45,030Hz Repeat surveys were then made using only two frequencies. Two passes were required to obtain the same set of measurements at all four frequencies: one pass using transmissions at 1,050 Hz And 16,890 Hz, and a second pass using frequencies of 4,110Hz and 45,030 Hz.

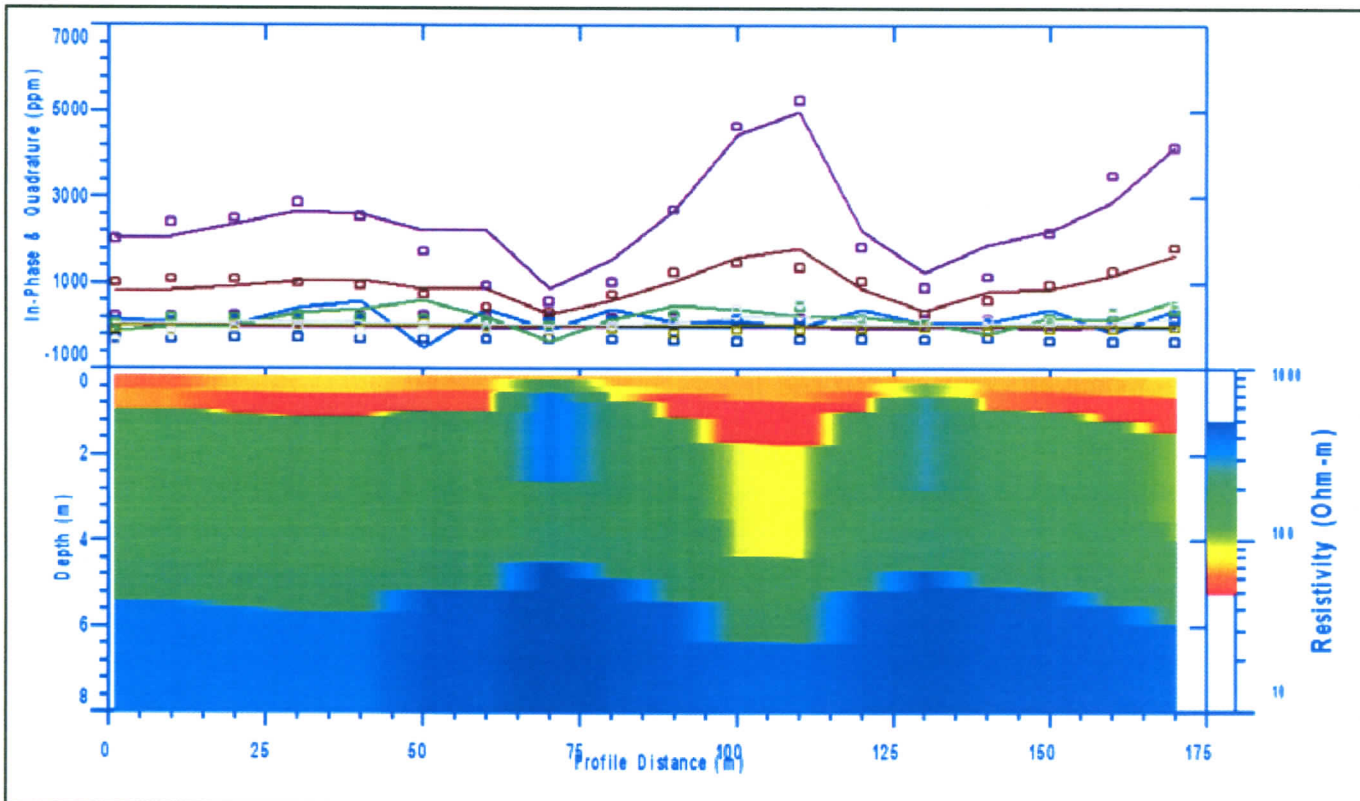

Figure 12. Layered inverse models developed along the north-south cross section. High resistivity (low conductivity) is denoted by the bluer colors; lower resistivity (high conductivity), by the orange to red colors.

Interpex Limited IX1D v3 sounding inversion software was used to derive inverse models of the GEM-2 data. Multifrequency soundings are modeled one-by-one and displayed in profile view. Inverse models derived from the initial data set contain considerable noise. Local spatial variability is significant between adjacent soundings. Models derived from data reacquired using only two transmission frequencies have much better signal-to-noise ratio.

Inverse models reveal continuous resistivity layering down to depths of about 8 meters beneath the surface. The models reveal the presence of a layered subsurface consisting of three layers that become increasingly resistive with depth (Figure 12). High resistivity (low conductivity) features in the area are interpreted as higher porosity, higher permeability conduits that facilitate drainage of precipitation and runoff through the sandstone to its base. Interpreted high permeability conduits extend from the surface down into the higher resistivity base of the layer. The sandstone lies on a relatively impermeable shale. Water accumulating at the base of the sandstone forms seeps in some areas and preferentially weathers the underlying shale. Eroded shale undercuts the sandstone. Unsupported sandstone edges begin to fracture and eventually collapse under their own weight.

Low conductivity channels (high resistivity or blue areas in Figures 11 & 12 are interpreted high permeability well drained areas in the sandstone that caps the site mesa. The rim of the mesa is characterized by a high resistivity well drained border that often extends 50 to 100 meters (~ 160 to 320 feet) into the interior of the mesa. High resistivity features are not limited to the mesa rim but are widely distributed across the mesa. The area in the vicinity of the injection well consists of a patchy distribution of low conductivity areas (Figure 5) considered to be dry and well-drained. High porosity/permeability areas are considered likely conduits for near-surface escape of any CO2 leakage that might migrate upwards through fracture zones and faults interpreted in 3D seismic coverage of the site. The low resistivity (red) areas are probably controlled by variable soil thickness across the surface of the mesa. The higher conductivity of these soil covered areas may be produced by increased water retention.

We note that newer models of the Aeroquest Sensortech GEM-2 EM sensor have been modified to incorporate step-mode operation. The newer configuration allows one to transmit each frequency at full transmission power. The requirement to repeat surveys using a smaller number of transmitted frequencies is no longer a requirement.

Acknowledgements

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