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## Results of geophysical monitoring over a “leaking” natural analogue site in Italy

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### Abstract

CO<sub>2</sub> storage in the subsurface is becoming more and more attractive as a means to reduce CO<sub>2</sub> emissions to the atmosphere and hence minimize human-induced global warming. The ability to monitor and verify these CO<sub>2</sub> storage reservoirs is a key element for further implementation of other storage sites. Since the current sites fortunately do not appear to “leak” CO<sub>2</sub>, it is difficult to test the most suitable monitoring techniques for their ability to detect CO<sub>2</sub> migration pathways. In this study different monitoring methods have been evaluated at a site in the Latera caldera (central Italy) where natural, thermo-metamorphically produced CO<sub>2</sub> finds its way to the surface. The aim of the study is to identify which monitoring methods can detect the migrating CO<sub>2</sub> and to gain understanding of the preferential migration pathways of the CO<sub>2</sub>. Different geophysical monitoring techniques have been deployed at a small, 200 x 500 m study area located in the centre of the caldera: 2D reflection seismics (testing different sources), 2D refraction seismics, multi-channel analysis of surface wave (MASW), ground penetrating radar (GPR), micro-gravity, magnetometer, self-potential (SP), 2D and 3D geo-electrical measurements and electro-magnetic (EM31 and EM34) measurements. Furthermore CO<sub>2</sub> flux measurements were performed in a dense grid over the study area, and a limited number of soil gas samples collected along two profiles, to “ground-truth” the geophysical results. In general a good correlation has been observed between the different methods and the presence of CO<sub>2</sub>. Geophysical responses, especially those of the reflection seismic and magnetometer data, change markedly from one side of the proposed main fault to the other, probably linked to a sharp geological boundary. The observed fractures on the seismic data seem to correspond with the preferred migration pathways of the CO<sub>2</sub>. The GPR and resistivity measurements detect strong variations in conductivity induced by the presence of the CO<sub>2</sub> up to about 2 and 20 meters depth, respectively, as supported by the soil gas and flux measurements.

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## 1. Introduction

CO<sub>2</sub> storage in the subsurface is becoming more and more attractive as a means to reduce CO<sub>2</sub> emissions to the atmosphere and hence minimize human-induced global warming. Large scale demonstration projects such as Sleipner, Weyburn and K12B have already demonstrated the feasibility of the concept, and various monitoring methods indicate the secure containment of the CO<sub>2</sub> in the reservoirs. The ability to monitor and verify these CO<sub>2</sub> storage reservoirs is a key element for further implementation of other storage sites. Since the current sites fortunately do not appear to “leak” CO<sub>2</sub>, it is difficult to test the most suitable monitoring techniques for their ability to detect CO<sub>2</sub> migration pathways. In this study, different monitoring methods have been evaluated over a site where natural, thermo-metamorphically produced CO<sub>2</sub> finds its way to the surface. The aim of the study is to assess the capability of various geophysical methods to identify CO<sub>2</sub> migration pathways and to identify if any of these are capable of detecting the migrating CO<sub>2</sub> itself.

The study area is located in the west-central part of the Italian peninsula, about 100 km north of Rome within the now extinct LATERA caldera. Despite the fact that the area is heavily affected by both regional faults and local collapse structures, deep drilling in the area has shown that some CO<sub>2</sub> is still trapped in areas where the overlying flysch rocks are still intact. CO<sub>2</sub> is being continuously produced, however, a portion of it does migrate along the numerous faults and is released to the atmosphere from gas vents. The occurrence of these gas-transmitting faults represent an excellent natural test site to study the application of various geophysical tools to better understand CO<sub>2</sub> leakage and migration.

A small study area of approximately 500 x 200 meters, located in the centre of the caldera, clearly shows a change in vegetation at the locations where CO<sub>2</sub> (and limited H<sub>2</sub>S) is reaching the surface. Small bubbles can even be observed along an interval of a narrow creek that crosses the survey grid. Different geophysical monitoring techniques have been deployed at this site: 2D reflection seismics (testing MiniGun, PWD and MiniVib sources), 2D refraction seismics, multi-channel analysis of surface wave (MASW), ground penetrating radar (GPR), micro-gravity, magnetometer, self-potential (SP), 2D and 3D geo-electrical measurements and electro-magnetic (EM31 and EM34) measurements. Furthermore CO<sub>2</sub> flux measurements were performed in a dense grid over the study area, and a limited number of soil gas samples collected along two profiles, to “ground-truth” the geophysical results.

This paper describes results obtained using the various monitoring techniques. First an introduction to the local geology is given. Then a short description of the various methods applied is provided followed by an interpretation of all the data and some recommendations for monitoring the shallow subsurface.

## 2. Local geology at Latera

The following is summarized in part from [1]. The Latera geothermal field is located in the west-central part of the Italian peninsula within the Latera caldera, a large, elliptical (10x8 km), NNE-SSW trending structure with several eruptive vents located both within and outside of the caldera (figure 1a). The field is thought to be the result of the “intrusion” of a hot Na-Cl brine into the local carbonate-hosted Ca-SO<sub>4</sub>-HCO<sub>3</sub> aquifer. Although studied since the early 1970s for geothermal energy (figure 1b), the area was well known long before that for the gas-rich springs and CO<sub>2</sub> -rich gas vents which suggested the presence of gas reservoirs at depth. The occurrence of the deep origin CO<sub>2</sub> that is migrating to the surface makes this site an ideal natural field laboratory (“natural analogue”) where gas migration mechanisms can be studied, monitoring technologies can be tested, and health, safety, and environmental impact can be assessed.

The local geology of the Latera area is dominated by five main units, although not all are visible in outcrop: a metamorphic basement, the “Tuscan” limestones, the “Ligurian” flysch, the volcanics and associated intrusive bodies, and the neo-autochthonous post-orogenic sediments. In addition travertine deposits, which are located SW of Latera and associated with CO<sub>2</sub> -rich springs, are not discussed here due to their distance from the zone of interest. This geological sequence is complicated by the tectonics of the area, with compressive phase thrusting and folding of the Tuscan and Ligurian units into place and tensional tectonics and volcanic collapse causing sub-vertical motion and the formation of grabens and calderas.

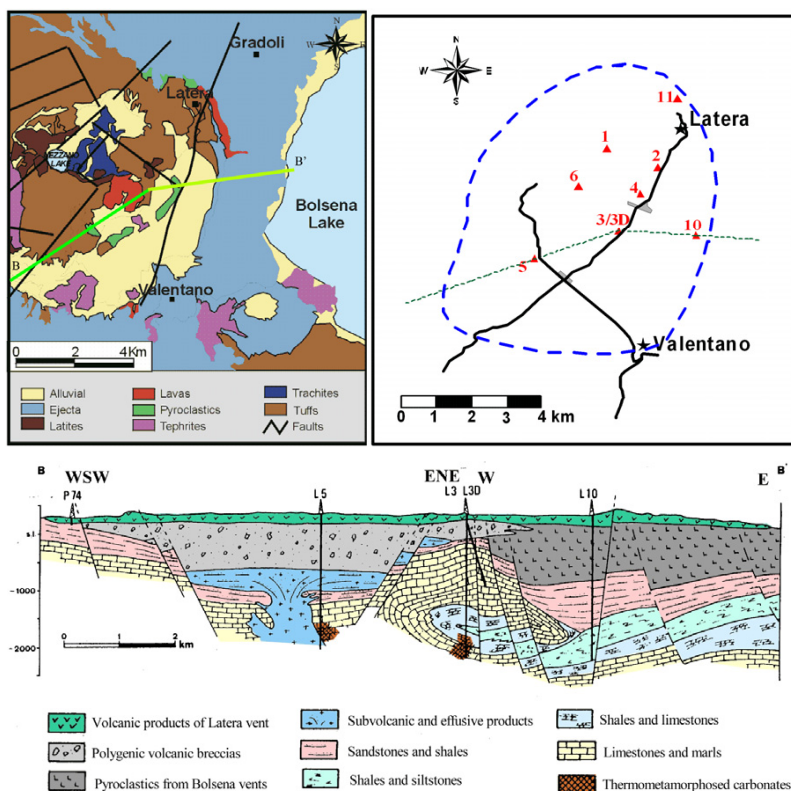


Figure 1 (a) Geological map of the Latera caldera. (b) Location map showing deep bore-holes (red triangles), main roads (black lines), caldera outline (blue dashed line) and towns (black stars) for reference. Note the location of the study area marked as a grey rectangle at the junction of the two main roads. (c) A geological cross-section from [2] based on deep well and geophysical data.

The deep borehole data are summarized [2] in a cross-section (figure 1c) which transects the caldera from the SW to the centre to the E (figure 1a). A number of points should be highlighted in regards to the cross-section: i) the extent of the caldera, shown by the small increase in elevation; ii) the shallow occurrence of the carbonate basement (i.e. Tuscan Nappe) in well Latera3, interpreted as a recumbent synclinal fold whose axis trends NNE and verges to the east; iii) deeper occurrence of the carbonates in well Latera5, interpreted as a caldera collapse structure bounded by normal faults; and iv) thermo-metamorphosed rocks in both wells Latera 3 and 5. Although the distribution in the borehole cores cannot be disputed, it must be remembered that the cross-section above is based on data from only 3 wells (plus geophysical data) and thus it should not be taken as the only interpretation. For example the repeating sequence observed in Latera3 could also be explained by thrust faults striking approximately N-S, while others have interpreted it as the eastern wall of an old caldera collapse [3]. Regardless of its origin this structure separates two distinctly different stratigraphies, with syenite intrusions, carbonates and a thick sequence of volcanic breccias to the west and a thick series of lavas and pyroclastics to the east.

In terms of structures formed by sub-vertical motion, the collapse structures associated with the various stages of local Mt. Vulsini volcanism are particularly important. It has been proposed that three caldera collapses occurred in the Latera area [3], beginning with a small Latera collapse, followed by the larger Bolsena caldera formation (now Bolsena Lake) and finally by a second Latera collapse structure which completely consumed the first. The sub-vertical faults associated with these calderas have either remained open for fluid flow (resulting in springs or gas vents on surface) or have become sealed by fault gouge or secondary mineral precipitation (thereby isolating entire blocks and creating heat/water convection cells). As the geophysical techniques applied here penetrate up to a

maximum of a few hundred metres, the main lithological units that will be investigated are the volcanics and the overlying alluvium. Whereas some more detailed information is available for the volcanic rocks, unfortunately no such information is available for the alluvium in the area of the study site (including, most importantly, its thickness).

### 3. Local topography of the studied area

Two differential GPS topographic surveys were conducted over the survey area. The merged results from the two surveys are shown in figure 2a. As can be seen the survey area ranges in elevation from about 398 to 405 m above sea level, with the highest points at the NW and SE extremes of the grid and the lowest within the small creek that crosses the centre of the grid. From this figure one can clearly see an irregularly-shaped area of low elevation in the centre of the grid to the NW of the creek. This area is clearly visible in the field (figure 2b) as a depression with no vegetation, where the exposed soil is grey, powdery and has points with precipitated secondary minerals. This area is presumed to form part of the main gas vent, in addition to gas bubbles that are released within the creek. Five approximately equidistant NW-SE trending study lines have been defined (numbered from 1 to 5 from SW to NE). The data from the merged grid was used to extract the elevation trends along each of the five study lines. This data was needed to correct some of the geophysical surveys, such as the resistivity profiles.

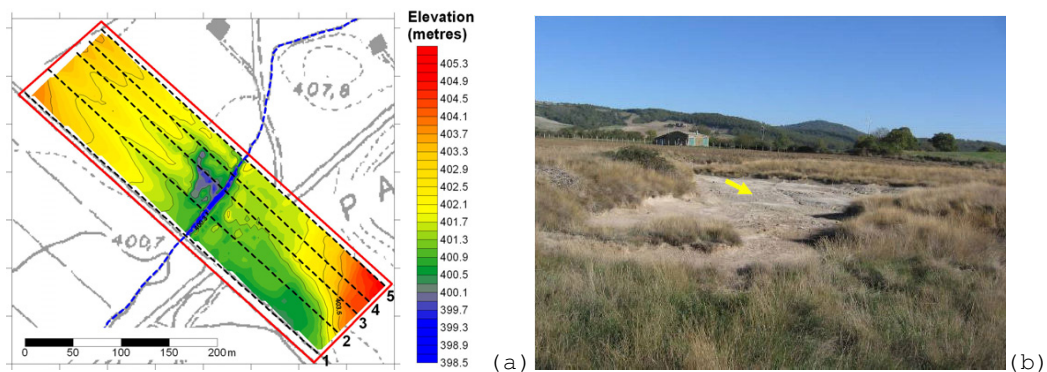


Figure 2 (a) Contour map showing the topography of the study area, created by merging the detailed and regional datasets and (b) a photo of the main gas vent with no vegetation around it.

### 4. Data acquisition

**Soil gas and CO<sub>2</sub> flux:** Individual soil gas samples were collected at depths ranging between 60–80 cm along two of the main study lines. Field analyses were conducted for CO<sub>2</sub>, H<sub>2</sub>S and H<sub>2</sub> by directly attaching a Draeger gas analyser. Samples were also collected for laboratory analysis, first for helium on a mass spectrometer and then for major and hydrocarbon gases on two gas chromatographs. CO<sub>2</sub> flux was measured using the closed-circuit, accumulation-chamber technique (e.g. [4]) over a regular grid covering the entire study area and having a 10 m sample spacing. Areas with highly anomalous flux values were observed in the central portion of the grid. These values range from 50 to 2500 g m<sup>-2</sup> d<sup>-1</sup>, with two points having a flux >6000 g m<sup>-2</sup> d<sup>-1</sup>, compared to background flux rates of approximately 10–30 g m<sup>-2</sup> d<sup>-1</sup> (caused by biological soil respiration). These results indicate that while this entire interval is a zone of gas release, gas flow rates are spatially variable and that enhanced flow occurs along preferential pathways. The high density sampling at the edge of the anomalous zone clearly defines the rapid increase in flux and concentration over a small distance, with, for example, CO<sub>2</sub> flux increasing from 100 to 400 g m<sup>-2</sup> d<sup>-1</sup> over 2 metres and CO<sub>2</sub> concentration increasing from 20 to 80% over 4 metres at one location. The majority of the anomalies are located in the central part of the grid, around the depression and between the creek and the road to Latera. In addition high values are also observed in the area to the south-east of the road and along a NW-SE

trending anomaly in the south-eastern part of the grid. The main anomaly trend appears to be almost N-S, with the highest anomalies occurring predominantly as isolated spots that highlight the channeled flow of the gas.

**Ground Penetrating Radar (GPR):** More than 5000 metres of GPR profiles (250 MHz antennas) were conducted over the study site, most within a detailed pseudo-3D grid to the east of the road intersection plus transects along two of the main study lines. The two long profiles show a correspondence between high CO<sub>2</sub> flux and an apparent deeper penetration of the radar signal which is manifest by irregular reflectors deeper in the time section. This observation is in good agreement with GPR surveys conducted on other gas vents in the caldera [5], which was interpreted as being due to the complex interaction of up-rising CO<sub>2</sub>, plant growth/health, and surface water content. In the detailed pseudo-3D grid (127, 30m-long lines spaced 1 m apart) a map of the 0-4ns average amplitude shows a number of anomalous areas. Some of these anomalies can be correlated with high CO<sub>2</sub> flux and areas of CO<sub>2</sub>-impacted vegetation, again related to CO<sub>2</sub>-water-vegetation interactions. Correlation within this grid was not as clear, however, as that observed in a previous study on a single isolated vent located about 3 km to the north of this site [5], likely due to the fact that this new site is more complex.

**Micro-gravity:** A single horizontal profile was conducted along line 1, perpendicular to the creek, with measurements performed every 10 m over an entire length of 420 m. The gravity profile shows a residual gravity minimum, which has been interpreted as a paleo-incision of the creek, filled with less dense sediments. It is interesting to note, however, that this minimum (i.e. negative values) falls within the interval of anomalous soil-gas CO<sub>2</sub> and CO<sub>2</sub> flux values, implying that the gravity minimum may also be, in part, linked to the gas emanation itself.

**Magnetometer:** One horizontal profile was performed with a magnetometer, along part of the central study line 3. A clear contrast appears between the NW and SE parts of the study area, divided by the creek, which is undoubtedly linked with a geological change that is also observed in the seismic imaging. But no clear correlation with CO<sub>2</sub> vents has been observed.

**Seismic data:** Both refraction and reflection seismics (2D) were acquired over the study area. For the refraction seismic data the first arrivals of the P waves were analysed on all seismic traces available, which allowed a complete reconstruction of the Time-Distance trend registered on the geophones for each shot. By using a type of tomographic processing, a P-wave velocity field model was iteratively constructed which best approximates the diagram of the Time-Distance diagram in this field. Seismic wave velocity values range from a minimum of 0.3 km/s to a maximum of 2.1 km/s. A lowering of the volcanic rocks in the central part of the area by around 20 m and the presence of a thicker interval of overlying, low-velocity sediments is postulated. This seems to correspond with the observed reflector on the GPR-data in the central part.

The reflection seismic data is generally of poor quality. Imaging with seismic data in volcanic terrains is often not straightforward because of the lack of clear layering and the scattering effect of the volcanic rocks. The penetration of the seismic data is about 1000 meters. The main aim of acquiring the seismic data in this project was to detect possible faults and corresponding migration pathways for the CO<sub>2</sub>. In general the quality of the seismic data improves drastically towards the north, starting from the observed boundary between the low velocity and high velocity shallow subsurface (i.e. in the vicinity of the creek). A clear change in character of the seismic data can be observed on the shorter of the two profiles.

**Electro-magnetic (EM) measurements:** A total of 202 measurements with a 10 m coil spacing were done with both horizontal and vertical coil orientations along the five NW-SE oriented study lines. The direction of the 10 m dipole were done inline. After a quick evaluation of the data acquired along the survey lines, an additional set of 94 measurements was acquired in and around the anomalous areas. The EM measurements clearly show a low resistivity (high conductivity) anomaly in the center of the area, coinciding with high CO<sub>2</sub> fluxes. Many vertical dipoles show anomalies with negative conductivity in the EM34 measurements. More precisely, a consistent increase in resistivity with maximum penetration depth for EM measurements done with the vertical loop (V) is observed. This indicates a small lateral structure perpendicular to the measuring line, coinciding with the seismically observed boundary. Although the values near these negative conductivities cannot be used for generating depth profiles, they can be used for interpreting small lateral conductive zones, like a fault with CO<sub>2</sub>. For measurements done with the horizontal loop (H) no such consistent trend has been observed.

**Geo-electrical (GE) surveys and spectral induced polarization (SIP):** Both 2D and 3D resistivity measurements as well as spectral induced polarization measurements were carried out over the area. All three 2D resistivity profiles show a distinct low resistivity zone (3-20 Ohm-m) at the location of the CO<sub>2</sub> gas vent compared to surrounding values (up to 125 Ohm-m). The zone is larger and more pronounced in the southern profiles (lines 1 and

3) than in the northern profile (line 5). The start of the low resistivity zone corresponds well with the transition observed on the seismic data. Similar anomalies are observed in the SIP measurements

A significant amount of gas in the saturated sediments of the superficial aquifer would be expected to result in an increase in electrical resistivity. The low resistivity anomaly is therefore thought to be a secondary effect that is probably related to the CO<sub>2</sub> gas vent. The possible causes, ranked in order of likelihood are:

- mineralized local groundwater associated with the CO<sub>2</sub> gas vent;
- mineralized sediment in a local fault;
- deeper thermal conductive groundwater that finds its way up following the same route as the CO<sub>2</sub>.

The third possibility is less likely because the temperature of the local surface water with the CO<sub>2</sub> bubbles is not high (around 8 °C). In order to more-accurately determine the origin of the increased conductivity in this interval, detailed temperature and chemical analyses could be performed on groundwater samples from both inside and outside the gas vent area. These samples are less influenced by evaporation and rain than surface water. Another prominent feature on the profiles is the shallow low resistive zone towards the end of lines 1 and 3 in the NW-corner of the area. This zone does not seem to be connected to the CO<sub>2</sub> rich zone nor are there anomalies in this area in the other datasets, and thus this area is interpreted as being covered by a more conductive (clayey) sediment.

**Self potential (SP):** The self potential is the potential measured using a constant reference that is supposed to be outside the anomalous zone being surveyed. In our case, we chose the NW corner of the cultivated field as a reference. A 400 m long profile was acquired in the field, using the same locations as the electrodes used for the SIP. A relatively good electrical contact was observed (i.e. good measurement repeatability) even in the central hard dry zone. Nevertheless, the data were a bit noisy and it was necessary to apply a moving average window to smooth the curve. A –50 mV anomaly is measured, clearly above the noise level, centered on the CO<sub>2</sub> vent. This position corresponds to the very conductive body observed in the electrical tomography, EM and resistivity measurements. The SP profile has a shape that is well correlated with this conductive anomaly, with an abrupt north face and a smooth face toward the south.

**TEM and VES:** Both Time-domain EM and Vertical Electrical Sounding have been applied over the main CO<sub>2</sub> vent. The coincident 25-25 m TEM sounding provides precise shallow information that indicates that the conductive body is a tabular structure (more or less with the same size as the loop size). The coincident 100-100 m TEM sounding provides more regional information that shows that the conductive body below the CO<sub>2</sub> vent is small compared to the investigated volume. A good correlation is observed with the previous VES sounding (SW of the TEM soundings).

## 5. Interpretation in a 3D integrated data model

An integrated 3D data model was created to interpret the data. Figure 3 shows different snapshots taken from this integrated model. Figure 3a shows three of the inverted resistivity lines. The view of the plot is oriented towards the North-East. A high conductivity (low resistivity) zone in blue can be identified in the central part of the area. This trend is clearly picked out on the 20 Ohm-m isosurface (figure 3b). Figures 3c and d demonstrate the strong correlation between the high conductivity and respectively the CO<sub>2</sub> flux data (figure 3c) and the EM data (figure 3d). Towards the NW the transition from low resistivity to high resistivity corresponds exactly to a change in character on the shorter of the two seismic lines, as displayed in figure 3e (with 20 Ohm-m isosurface) and figure 3f (without isosurface). Gently-dipping continuous reflections can be seen on the NW part of this line, whereas in the SE part the seismic energy seems much more scattered with lower amplitudes and no coherent reflections. The boundary between these two zones defines a SE dipping surface. Tomographic inversion results of the refraction survey (not displayed here), also define this boundary, indicating a shallow low velocity zone SE of the transition and a shallow higher velocity trend towards the NW. Laterally the same transition can be observed on the EM data (figure 3d) and on the SP data (displayed as the “filled” central line in figures 3g,h) with a high conductivity (low resistivity) in the central part, as well as on the magnetic data (displayed as a solid line in figures 3g,h). This zone corresponds exactly with the zone of anomalously high CO<sub>2</sub> flux (figures 3c-h) and concentration measurements. The highest CO<sub>2</sub> fluxes coincide with the transition zone. Our interpretation of the sharp transition corresponds to a non-sealing normal fault, probably dipping towards the SE (figures 3g,h). Towards the SE antithetic faults are to be expected allowing flow pathways for the CO<sub>2</sub>. Again this corresponds well with the observed conductivity, with the low seismic velocities and most importantly with the observed flux measurements. The interpreted main fault is

plotted in figures 3g,h (in yellow). Towards the NW a shallow conductive zone can be observed both on the GE data (figure 3a) and on the EM data (figure 3b), picked out well on the 20 Ohm-m isosurface, however no anomalous CO<sub>2</sub> fluxes have been measured in this area. This conductive zone is very shallow, in contrast to the central part of the area, and thus is interpreted as a clay layer. Overall it can be concluded that all data show a good correlation with the measured CO<sub>2</sub> fluxes at the surface and are consistent with each other.

## 6. Discussion and conclusions

In this study different monitoring methods have been evaluated over a site where natural, thermo-metamorphically produced CO<sub>2</sub> finds its way to the surface, with the aim of identifying which monitoring methods best image the gas migration pathways and which, if any, can detect the migrating CO<sub>2</sub> itself. The two field campaigns in Latera (Italy) took place in October 2006 and October 2007 both under good weather conditions. In general there is a good correlation between the different methods and the presence of CO<sub>2</sub>. ERT, EM and SP data in particular show a strong correlation with measured fluxes of CO<sub>2</sub>, as does GPR. These seem to detect the variations in conductivity induced by the CO<sub>2</sub> up to about 10 meters depth. However the observed increase in conductivity associated with the CO<sub>2</sub> is likely to be a secondary effect (dissolution and acid-rock interaction) not directly related to the gas itself; this needs to be investigated further. Seismic data extends to 1000m depth, but is generally of poor quality and interpretation is not well-constrained. However, a distinct change in character is observed that coincides with the margin of the surface CO<sub>2</sub> fluxes. This is interpreted as a faulted boundary, thought likely to be the main migration pathways towards the surface for the CO<sub>2</sub>. A repeat survey of the different methods is envisaged in a different follow-up project to investigate repeatability aspects of the various methods and possible seasonal changes affecting the CO<sub>2</sub> fluxes.

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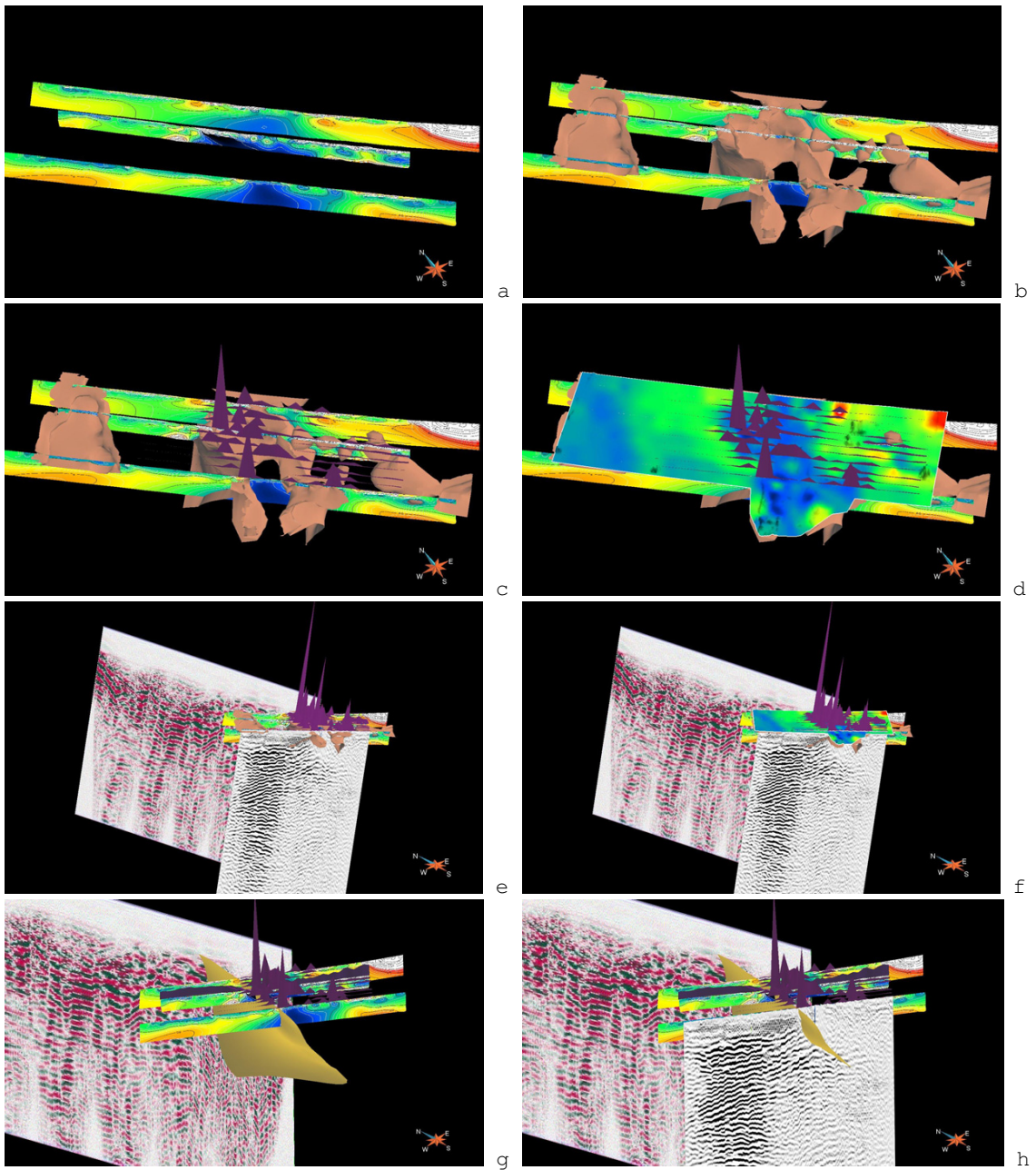


Figure 3: Snapshots of the 3D integrated data model. (a) 3 GE profiles showing the low resistivity anomaly coinciding with the main gas vent (b) Iso-surface of the 20 Ohm anomaly. (c) Gas fluxes are coinciding with the low resistivity area. (d) Correspondence with the EM measurements over a 3D grid. (e) Seismic line showing a clear change in character at the Northern boundary of the GE anomaly. (f) Correspondence with the EM measurements over a 3D grid. (g) and (h) give a perspective on all the data showing the interpretation of a major fault. Furthermore the SP measurements (“filled” central line) and the magnetic measurements (solid central line) show the same delineation as observed on the seismic, EM and flux data.