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A New Geophysical Method for Monitoring Emplacement of Subsurface Barriers

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Abstract

Visualizing subsurface structures is an old and venerable problem. Many geophysical methods have been developed to meet the challenge and some of these have already been applied to visualizing placement of subsurface barriers. Unfortunately, none of these methods have yet demonstrated the ability to yield detailed structure or to reliably evaluate their performance.

Electrical resistance tomography (ERT) is a relatively new geophysical technology which has already proven useful for imaging many underground process. In this paper we discuss how this method may have the capability for high resolution imaging of barriers.

This paper describes the state of ERT technology, summarizing its capabilities as well as its limitations. Then we will demonstrate how the method might be used by showing relevant case histories of high resolution images of subsurface processes. Three dimensional images can be generated which might map barrier boundaries or delineate missed zones. The high speed data acquisition and image reconstruction may even make possible near real time information to guide barrier construction or augmentation.

Introduction

The goal of this paper is not to document our experience using electrical resistance tomography (ERT) to monitor the emplacement or to verify the integrity of a subsurface barrier, for the technique has not yet been used for either purpose. Rather, our goal is to document the capabilities of ERT with particular emphasis on how these capabilities could be used for such purposes. To accomplish this, we will summarize the results of two recent experiments in which fluids have been introduced into the subsurface and their movement and eventual distribution mapped in some detail using ERT. Using these examples we will point out the lessons which might be applicable for using ERT to map subsurface barriers and for verifying their performance.

We will describe two applications of ERT to mapping subsurface fluid movement, one application in the vadose zone and one in saturated soil, to demonstrate the versatility of the method for both cases. The first example will be the imaging of a dense non aqueous phase liquid (DNAPL) as it is added to a sandy aquifer and particularly as it moves along a clay barrier. The second example will be the imaging of a light non aqueous phase liquid (LNAPL) as it settles onto and spreads along a saturated aquifer.

Electrical resistance tomography (ERT) is a technique for reconstruction of subsurface electrical resistivity distribution. The result of such a reconstruction is a 2 or 3 dimensional map of the electrical resistance distribution underground made from a series of voltage and current measurements from buried electrodes.

To do ERT surveys we place a number of electrodes in boreholes and/or at the ground surface to sample the subsurface impedance distribution using an automatic data collection and switching system. A few hundred 4 electrode electrical impedance measurements are collected using of these electrodes. These data are processed to produce electrical tomographs using state of the art data inversion algorithms.

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The inversion algorithm solves both the forward and inverse problems. The forward problem is solved using a finite element technique. The objective of the inverse routine is to minimize the misfit between the forward modeling data and the field data, and a stabilizing functional of the parameters. The stabilizing functional is the solution's roughness. This means that the inverse procedure tries to find the smoothest resistivity model which fits the field data to a prescribed tolerance. For additional details, the reader is referred to LaBrecque et al. (1996).

DNAPL field experiment

The experiment was conducted in a double wall steel tank 10 meters square and 5 m deep at the Oregon Graduate Institute of Science and Technology in Beaverton, Oregon. This tank allowed for a safe release of perchloroethylene (PCE) into a soil section constructed of sand and clay. Two layers of powdered bentonite were included as barriers. The tank was saturated with 4 ohm m pore water to within about 25 cm of the surface. Four electrode arrays were used to generate two dimensional (2D) images in three planes; L1, L2, L3 and L4. Each array contained 10 lead electrodes spaced evenly between 50 cm and 275 cm depth. One hundred eighty nine liters (50 gallons) of PCE was released at a single point on the surface approximately midway between arrays L2 and L3. The release rate averaged about 2.0 liters/hr.

Both bentonite layers are clearly imaged (see lower right panel in Figure 1), the upper layer extending only part way across the tank. They are also clearly not uniform; the blochyness of the layers reflects the difficulties installing these structures in the tank as well as imperfections in the inverse process. However, ERT gives a detailed sectional view of variability in these confining layers which is impossible to achieve with conventional logging or even surface radar methods. This result is an example of the capabilities of ERT to delineate in cross section the shape and extent of a hydraulic barrier.

The other panels in Figure 1 show the reconstructions after a pixel by pixel subtraction of the background image and therefore show only changes in resistivity distribution. At 3.5 hours the changes were quite small but the most significant feature is located below the release point--a resistive anomaly arching around the end of the upper clay. This anomaly probably forms as the resistive PCE displaces the more conductive pore water. Other small anomalies in this image are probably from unrelated but natural changes in the pore water conductivity and from data noise.

About 21 hours and 42 liters into the release the anomaly has grown large enough to extend from the release point, arch around the upper clay and reach down to just touch the lower confining layer. Apparently, most of the PCE continues to spill over the edge of the upper layer with little residing on top. Reflecting the dynamic nature of the system, the same small unrelated anomalies are still present and now a few others are forming. The weak disconnected features forming along the top of the lower clay may be small accumulations of PCE even at this early stage.

By August 18, at 45 hours, the anomaly begins to spread horizontally along the top of the lower clay as might be expected of the plume as more PCE reaches that layer. The appendage pointing up to the right in plane L2-L3 is not expected and we cannot explain its presence.

The release ended Sunday at noon, August, 20 after 189 liters (50 gallons) was released. On Monday, August 21 the tomographs show a different picture from that 3 days earlier. Only a small remnant is left of the arching anomaly from the surface and around the upper clay. This is understandable if it represented the downward moving PCE which by this time has mostly drained and been replaced by water. However, now a resistive anomaly almost 2 m long sits at the top of the lower clay layer, centered directly below the edge of the upper layer. From this tomograph we conclude that the bulk of the PCE has drained from the sands and is pooled on the lower layer. A 2 m diameter pool of 6 cm uniform thickness would accommodate the volume released and so the anomalies are consistent with a PCE pool at this location. Imaging the PCE movement and eventual fate is an example of how ERT might be used to verify the integrity of a hydraulic barrier, the PCE acting as a fluid tracer added to the system to see if it can breech the barrier.

Difference images were constructed for 4, 16 and 25 days after the release ended. In these images there are two clear trends. First, the anomaly associated with the free product plume breaks apart into separate pieces and each part becomes weaker with time. One explanation is that the free product is moving into topographically lower regions of the clay surface which are out of the image plane. The second trend is that anomalies unrelated to the PCE release are becoming more important. Especially prominent are those at the top right in the image planes. These may be due to the addition of fresh pore water to the tank as a result of heavy rains during the experiment.

LNAPL field experiment

This experiment was conducted in another double wall steel tank, similar to that described for the DNAPL experiment, at the Oregon Graduate Institute. In this case one hundred gallons of unleaded gasoline was released at a single point on the surface approximately midway between ERT arrays named L2 and L3. The release rate was 80 ml/m. The phreatic surface was held at 90 cm depth during the entire experiment.

ERT data was collected each day between planes L1-L2, L2-L3, L3-L4 and between L5-L3, L3-L6 (so that L3 is in common with both set of planes) during the release, and three times after the release ended. The baseline images at 1 Hz are shown in the top panel in Figure 2. The other panels shows those reconstructions after pixel by pixel subtraction of the background images from subsequent images. (Plane L3-L4 did not always converge.) These difference images show only changes in resistivity distribution.

On September 12 about 18 hours and 86.4 liters into the release, clearly shows a 10 to 40 ohm m resistive anomaly forming directly above the water table in L2-L3 and L5-L3-L6. Notice, however, that it is not uniform or even continuous. In fact, the largest resistivity changes are not directly beneath the release point but rather in plane L3-L5. We believe these anomalies are an indirect indicator of the LNAPL (Daily *et al.*, 1995) moving into a soil of heterogeneous permeability. There are several mechanisms which might be responsible for the resistivity changes associated with the LNAPL. First, is a spatial redistribution of the pore water in the capillary fringe as a result of changes in the pore water suction potential when the water-air boundary is replaced by a water-gasoline boundary. Second, is a displacement of capillary water by increased hydrostatic pressure as the gasoline enters the pore space. What ever the mechanism, we see a similar effect as was observed in the 1992 gasoline release at OGI (Daily *et al.*, 1995) and believe that the anomalies in Figure 2 are caused by the same mechanism as seen in the earlier data.

On the morning of September 13 about 189 liters had been released, half the total planned release volume. Now the LNAPL anomaly is much stronger, especially in L5-L3-L6 where the resistivity has changed more than 50 ohm m. However, there is little change in the distribution which implies that the preferred paths initially established by the plume are not substantially altered with continued flow. This pattern continues on September 14th (not shown) as the release continues.

Then, after about 378 liters (100 gallons), the release ended at 1400 hours on September 15th. The images of that date in Figure 2 were taken between 1700 and 2000 hours on that date and the LNAPL anomaly is noticeably smaller in magnitude implying a relaxation of the plume--perhaps draining of LNAPL out of the image planes. On the 16th of September (not shown), the LNAPL anomaly continues to weaken. In part of L2-L3 it has all but disappeared although in plane L3-L6 changes are imperceptibly small. This heterogeneous behavior suggests complex movement of the plume even in this relatively simple geologic setting.

Summary and Conclusions

These results are intended to demonstrate the capabilities and limitations of ERT to provide detailed images of subsurface fluid movement, especially where it is possible to compare baseline data with that taken after the structure is placed, as would be the case for monitoring barrier emplacement. We have found that such difference imaging is very powerful for high resolution and high sensitivity imaging (see also, Ramirez *et al.*, 1996; Ramirez *et al.*, 1993; Daily and Ramirez, 1995). Both examples were of electrically insulating fluids. Barrier materials may be either electrically insulating or conducting, but the insulating cases described here are the more difficult to image and so show the worst case. The DNAPL experiment also demonstrates the capabilities of ERT to provide images of subsurface barriers, in this case bentonite layers in a sandy soil.

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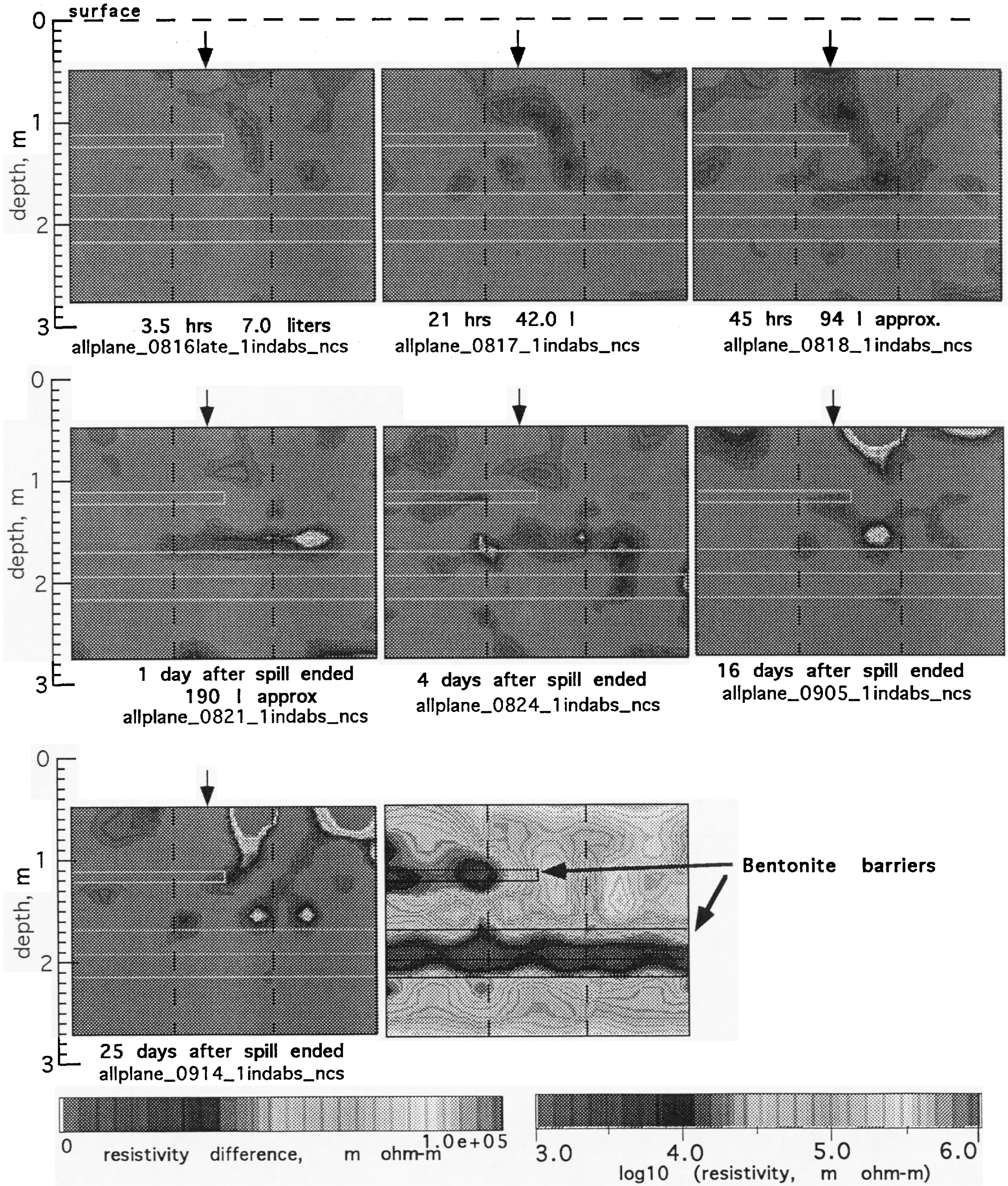
Figure Captions.

Figure 1. ERT of the DNAPL data at 1 Hz showing the baseline image and difference images or changes in resistivity between the baseline and subsequent times during the release. The arrow shows the DNAPL release point in plane L2-L3. The left color bar is for the difference images while the right color bar is for the baseline image.

Figure 2. ERT results for LNAPL data acquired at 1 Hz. The first row are baseline images taken on 09/11, before the release started. The arrow shows the LNAPL release point in plane L2-L3 and the dashed line is the location of the water table. Below the baseline data are difference images taken during the gasoline release.

Figure 1


surface
0
1
2
3
depth, m
3.5 hrs 7.0 liters
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21 hrs 42.0 l
allplane_0817_1indabs_ncs
45 hrs 94 l approx.
allplane_0818_1indabs_ncs
1 day after spill ended
190 l approx
allplane_0821_1indabs_ncs
4 days after spill ended
allplane_0824_1indabs_ncs
16 days after spill ended
allplane_0905_1indabs_ncs
25 days after spill ended
allplane_0914_1indabs_ncs
Bentonite barriers
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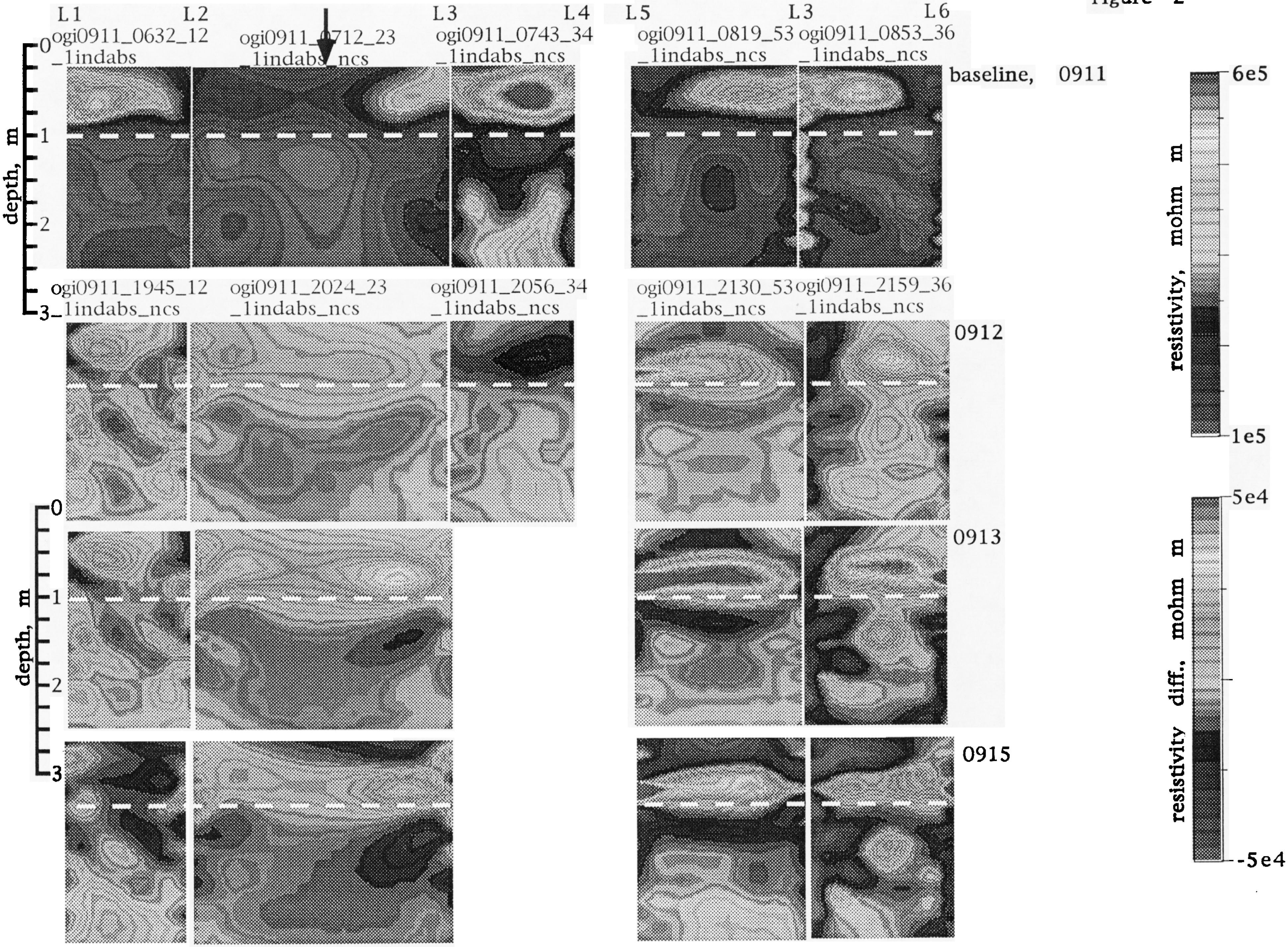
1.0e+05
resistivity difference, m ohm-m
3.0
4.0
5.0
6.0
log10 (resistivity, m ohm-m)



L1 L2 L3 L4 L5 L3 L6
ogi0911_0632_12 _1indabs
ogi0911_0712_23 _1indabs_ncs
ogi0911_0743_34 _1indabs_ncs
ogi0911_0819_53 _1indabs_ncs
ogi0911_0853_36 _1indabs_ncs
baseline, 0911
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ogi0911_2056_34 _1indabs_ncs
ogi0911_2130_53 _1indabs_ncs
ogi0911_2159_36 _1indabs_ncs
0912
0913
0915
depth, m
0 1 2 3
resistivity, mohm m
6e5
1e5
resistivity diff., mohm m
5e4
-5e4

Figure 2

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