MAPPING STRUCTURAL PATHWAYS FOR DNAPL TRANSPORT IN KARST USING INDUCED POLARIZATION

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ABSTRACT

A capped landfill in central Tennessee lies atop regolith, thought to be some 20 meters thick, which overlies limestone bedrock with extensive karst weathering. Fractures and joints are pervasive in bedrock, following three well-defined trends. Trichloroethene (TCE) has been detected in an offsite spring, and the State wanted to drill and sample a deep structure beneath the landfill to maximize the chances of finding this dense contaminant. An induced polarization (IP) survey in an agreed-to test section of the landfill produced a 3D map of subtle linear anomalies, interpreted as structures and karst development. The structures are enhanced beneath thicker parts of the landfill. Successive depth slices show that the enhancement effect progresses from broad areas beneath the landfill to narrower, deeper, linear zones downgradient from it. We hypothesize that an IP effect occurs because of clays within the structures, but also that migrating conductive leachate preferentially "lights up" these structures to IP, providing an indirect map of contaminant migration pathways. Seven boreholes were drilled on and off IP anomalies: nominal depths to bedrock (24 to 35 meters) were observed away from the IP-defined structures, but deep bedrock (>99 meters in one case) occurred within pockets of high IP response. These results were used to site two monitoring wells for which TCE data will be forthcoming.

INTRODUCTION

Bedrock imaging is an established tradition in geophysics. Nearly every conceivable technique has been applied to the task, from simple VLF and EM to 3D seismics. One of the most common methods for bedrock mapping is DC resistivity, especially for the 0 to 10 meter depth range traditionally missed by reflection seismics — though the past decade has brought vast improvements in shallow seismic capabilities.

Resistivity's "big brother" — induced polarization — is less commonly used. In the past, this has been understandable because DC equipment has been cheaper and simpler to operate than spectral instruments, but the gap between DC and AC instrumentation has been gradually narrowing. Because polarization provides an extra interpretational parameter, in certain applications IP's somewhat higher cost is worth the added technical proficiency. One example of such an application is mapping bedrock structure in karst.

In karst domains, the advantage of IP over resistivity is that solution features may contain weathered clays, which tend to be polarizable. Such features also tend to be conductive, and thus detectable by resistivity alone — but polarization helps discriminate between conductors like clays from conductors produced by groundwater and some soil-type changes.

The advantage of the polarization parameter increases further in landfill investigations like the one discussed in this paper. Other studies have shown that landfill materials produce a polarizing effect and that certain contaminants enhance the IP response in the presence of clays.

PROJECT GEOLOGY AND OBJECTIVES

The Dickson County Landfill is northwest of the city of Dickson, 20 km west of Nashville, Tennessee. The 6-hectare, Class I county landfill received municipal wastes from 1968 until shortly before it was capped in 2001. Two adjacent parcels contain a demolition landfill and a city dump, both roughly as large as the county landfill.

Like many other landfills in carbonate environments, the Dickson County Landfill is positioned over karst terrain. Bedrock is the Saint Louis Limestone, whose top is severely weathered to a thick overburden of regolith. The Saint Louis contains fractures and extensive solution features.

In 1994, the dense chlorinated solvent TCE was detected in a surface water sample at Sullivan Spring, 0.7 km northwest of the landfill. TCE was also detected in two drinking water wells southeast of the landfill. Drilling by the U.S. Geological Survey (USGS) at the northwest boundary of the landfill in 1995 showed bedrock elevations between 222 and 229 meters, and groundwater elevations from 229 to 236 meters. The data indicate a northwesterly hydrological gradient, placing Sullivan Spring in a downgradient position with respect to the landfill. However, all five wells installed on the downgradient perimeter of the landfill returned non-detections in all volatile organic compounds analyzed. Dye-trace tests also failed to recover dye in the spring. Either the landfill is not the TCE source, or the wells have not intercepted the migration pathways.

Because the landfill is a large place to look for narrow and complex structural pathways, the State agreed to identify a smaller zone of investigation, which available evidence suggested would be the most likely source of contamination. In this effort, two facts are relevant: drainages tend to have structural control, and local hydrological gradients tend to follow topography. Based on these considerations, the State selected a 91x300 meter (2.8 hectare) test strip along what was formerly a natural drainage, running along a linear topographic low between the County Landfill and the Dickson City Dump. The State's opinion was that any structure controlling the drainage might be a more likely pathway to move or trap TCE.

The problem thus came down to looking for narrow solution structures over a relatively large area — one of the most favorable scenarios for using geophysics. Constraints of needing to image the 0 to 30 meter depth range, dealing with a relatively high surface conductivity, and working amidst small metal clips which hold erosion-control mats over the capped surface narrowed the choice of technique to two: reflection seismics and induced polarization. Seismic, of course, has a distinct edge in terms of structural resolution, but IP is more suited to examining polarizable structural fill material, such as clays or leachate. We decided to lead off the work with IP, then bring in seismic if required to pick drill targets.

SURVEY DESIGN

We targeted the top 30 meters, based upon the apparently nominal 20-meter depths to bedrock noted in the USGS wells. A multiple-line dipole-dipole array with a=15 meters was chosen to meet competing requirements of resolution and penetration. Nine lines of data were obtained, spaced 7.5 to 15 meters apart. Copper-braided electrodes were shallowly buried every 7.6 meters and attached to multiconductor seismic-style cable, which connected to a nearby recording truck.

The Zonge Engineering Zeta system was used to speed data collection. A computer-controlled multiplexer sequenced signal input and output. Transmitted signals were 0.5 Hz time domain. Received signals were measured by a GDP-32 16-channel receiver. All functions were under control of a laptop computer.

INTERPRETATION

Data were smooth modeled, incorporating the effects of topography. Gridded modeling results were converted to multiple constant-elevation slices; three are shown in Figure 1. The landfill (upper part of colored zones in Figure 1) has a conductive-polarizable imprint, which trends to more resistive and less polarizable material with depth. It is not clear at this time whether the landfill effect is due to the buried materials per se or to leachate.

Beneath the landfill effects (238 m and 226 m slices in Figure 1), complex structure not unexpected of karst is suggested. There is reasonable coherence in the full data set (not shown) from one depth slice to the next, although part of this coherency is an unremarkable consequence of the physics of the measurements and algorithm used in smooth modeling. We interpret three linear trends, labeled A, B, and C in Figure 1, which fit the full data set fairly well. As shown in Figure 2, geophysical trends A and B have equivalences in fracture-trace analyses of nearby outcrop; geophysical trend C does not. Oddly, the dominant trend actually observed in the outcrop is not apparent in the geophysics data within the limited study area.

As one progresses deeper in the full data set, the conductive-polarizable landfill effect appears to “creep” toward the geophysically inferred structures at mid-depths, becoming isolated as pockets in those structures at depth. We can envision several explanations for this, but our chief hypothesis is that leachate is polarizable, and that it moves via local hydrological gradient to the south, encounters the structures, then sinks and spreads within the structures. From an environmental standpoint, if this is true, structures would thus represent an important contaminant transport path. From a geophysicist’s standpoint, leachate “lights up” the structures to the IP survey, making them easier targets. Alternatively, the creeping effect may be a confluence of unrelated effects of shallow landfill-induced variations and clay effects in structures at depth. However, in either case, IP appears to have identified structural pathways relevant to contaminant migration.

The clustering of IP anomalies along apparent structures and at their intersections is significant. We interpret these features to be solution channels filled with polarizable weathered clay, with or without enhancement from leachate. The features were sufficiently defined that an in-field decision was made to not follow up with seismics, but to proceed directly with drilling confirmation.

Based on the geophysics, seven boreholes were installed, testing interpreted solution cavities as well as interpreted bedrock highs (Figure 1 shows the bedrock depths). Drilling showed that bedrock is surprisingly deep within the geophysical anomalies — as deep as 98 meters, or five times the typical depth in this area. Only the shallowest hole (24 meters) is roughly in line with the initial expectations.

We propose that the unexpectedly deep results were obtained because the geophysics has successfully located deep solution features into which the borings were placed. Although the IP survey’s maximum penetration is only about 30 meters based on starting assumptions, the correspondence between the IP results and the drilling is fairly good. Deeper bedrock was found along structural trend A and at structural intersections, and the deeper borings tend to occur in the strongest IP anomalies.

From an interpretational point of view, this encouraging result is shadowed by a difficult question of causality. Because bedrock is far deeper than IP’s depth of investigation over solution channels, all IP is investigating at those positions is weathered regolith far above the actual bedrock. So what is IP seeing? Are there residual structural manifestations in the regolith — fossilized structural remnants from earlier times when limestone occupied the space the regolith now dominates? If so, one could argue that clay or leachate infiltration into fossil porous structures explain the IP. However, we are skeptical that residual structural pathways could be preserved in the regolith. Lacking detailed and expensive geotechnical confirmation, we find the causal mechanism for our results elusive at this time.

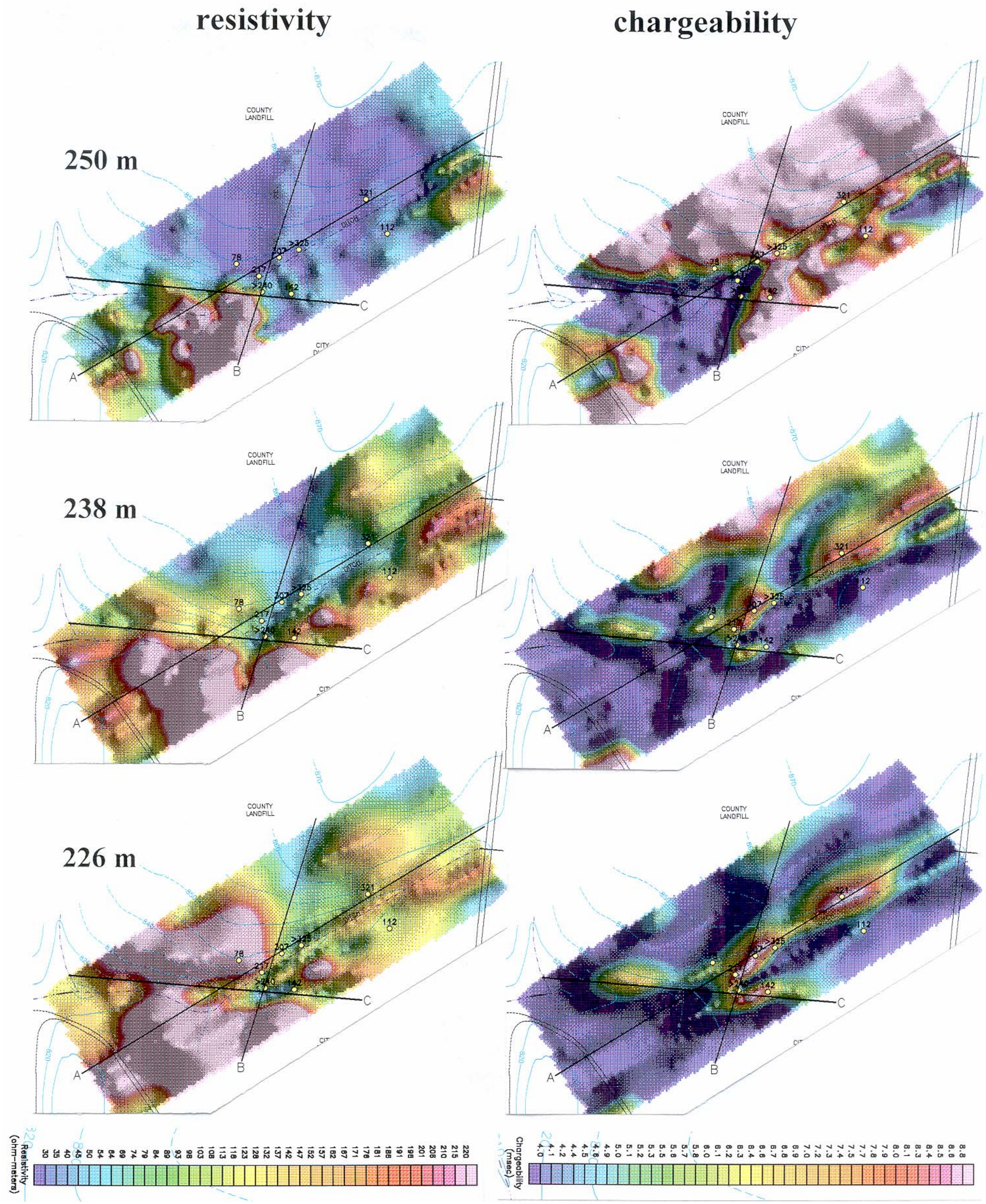

Figure 1: Modeled data at three elevation slices; surface elevation lies between 250 and 260 meters. Yellow dots are borings drilled after the geophysics; adjacent numbers are depth to bedrock in the borings. Interpreted structural trends A, B, and C may have a slight southerly dip.

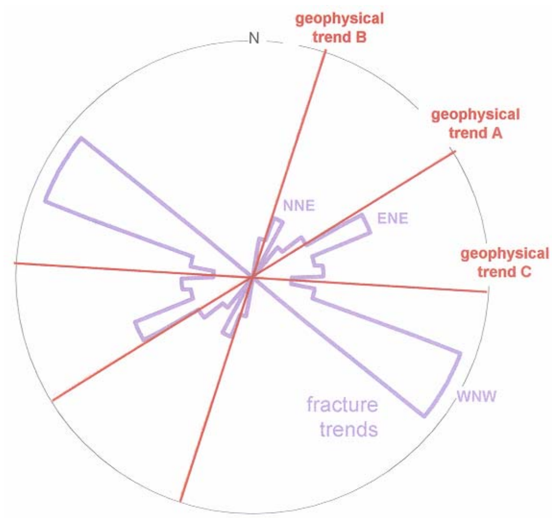

Figure 2: Trends of fracture traces and the three interpreted geophysical structures.

Nevertheless, we found the drilling results sufficiently encouraging to target the deepest interpreted cavity for a pair of shallow and deep monitoring wells. The deep well actually never tagged bedrock because, at 99 meters, the driller ran out of casing. The well was screened at 79 to 97 meters below grade; the adjacent shallow well was screened at 9 to 45 meters. Sampling is pending as this paper is being submitted.

GENERATING A USEFUL IMAGE OF THE DATA

One of the interesting conundrums in modeling is something along the lines of "there's no free lunch." Traditional modeling generates hard-edged contacts, suggesting unrealistic accuracy to non-specialists; smooth modeling does a better job in this regard, but frustrates geologists wishing to draw their pens across definable contacts. So the question inevitably arises: how do we represent the data in a way that is intuitive yet not misleading, once the images are out of our hands in some boardroom far away, populated by business people rather than scientists?

The answer is sometimes a 3D representation, but for an odd reason. A 3D data set, resident in the computer, adds another order of magnitude of value to a project, which one might suppose adds an equivalent value to imaging the data. This is quite the case in a virtual reality simulation. But when we represent 3D on a flat page, we get only an impression of 3D, not actual 3D — you cannot turn the image and look into it from all angles, and a side of an object obscures its interior. This is another lesson with the no-free-lunch flavor. But this "loss" of information tends to work in the geophysicists' favor because such a plot preserves the essence of an interpretation without allowing the viewer to make unwarranted measurements of spatial positions or amplitudes. In effect, a well-designed 3D representation gets across the big-picture meaning of a project without over-representing the meaning of the data.

In this project, we wanted to obtain such a 3D representation, but were faced with an additional challenge. Neither the resistivity or chargeability parameter defines a geologic feature in a direct sense, for both are influenced by conductive landfill material, leachate, and possibly changes in groundwater saturation. A direct image of either produces unsatisfactory results. Having already interpreted the data, we sought an image that would reflect that interpretation, while preserving some semblance of objectivity in how the image is generated.

We could have produced a 3D image of IP directly, but it would show solid pods instead of cavity-like surfaces, and the pods would be masked by a landfill-induced IP high near the surface. An imperfect but, we think, helpful solution is a "negative IP image" of chargeability, shown in Figure 3. This approach rests on the fact that chargeability decreases rapidly with depth, but remains elevated over polarizable cavities. Hence, if we plot a pseudo-elevation surface at which IP decreases to, say, less than 6 msec, we would expect cavity-like depressions over solution features — a representation that makes intuitive sense to the viewer. The choice of the threshold value is entirely arbitrary; we selected a value (6 msec) which best reflects our interpretation, yet does not distort the capabilities of the technique.

The resulting image is an effective way to communicate the findings, especially to non-technical decision makers. Because the negative IP image is not a geologic interface, but only a very imperfect and derivative analog of it, the image should not be over-sold. Pseudosections and elevation slices provide much more representative views of the data results and limitations.

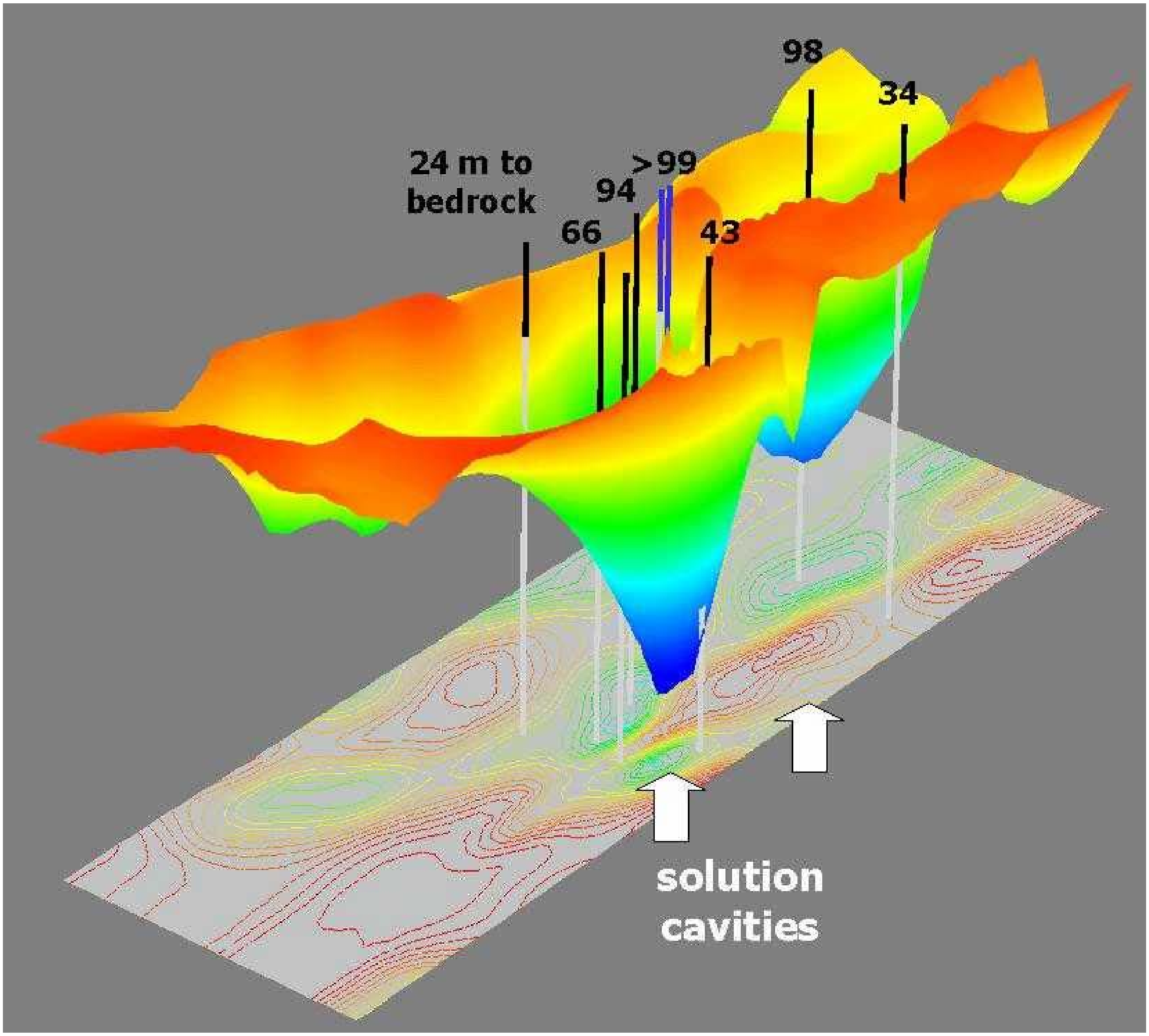

Figure 3: 3D representation of the IP data, an iso-chargeability surface we call "negative IP image".

CONCLUSIONS

We have interpreted structures which are in reasonable agreement with known bedrock fracture trends, and which contain IP anomalies we think arise either from clays within solution cavities or the migration of leachate to those cavities. The preliminary results were available in the field, permitting the geophysical team, the client, and the state regulator to confer and make on-the-spot decisions. This led to an important determination that we had tagged the most likely spot for contaminant accumulation, given the uncertainties inherent in karst. Accordingly, fewer borings and wells were required to test a "worst-case" scenario. Drilling has substantially confirmed the results, and the state regulator involved in the project was extremely pleased with the approach and results. Based upon reasonable assumptions, geophysics saved $134,000 in drilling costs within the test area, and arguably ten times that amount if a traditional hunt-and-peck drilling strategy had been followed across the entire site.

While IP was a significant success with regard to a landfill contamination issue at this site, the larger picture is that IP may be a prime tool for karst investigations in general. We note that acquisition of the resistivity parameter alone, as is common in the industry, would have been insufficient at this site. Given the fact that karst targets involve clays, that clays tend to be polarizable, and that high-production IP equipment is readily available, we suggest that IP is generally preferable to DC resistivity for appropriate karst investigations.