GROUNDWATER PATHWAY MAPPING USING AIRBORNE GEOPHYSICS: TWO CASE STUDIES

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Abstract
The application of airborne geophysics to groundwater pathway mapping is detailed at two military sites in the USA. The first case involves DNAPL contamination at Camp Crowder, Missouri resulting from rocket component testing. Contaminants percolate through a cherty residuum into a karst aquifer and towards contaminated wells via unknown pathways. The importance of an integrated approach is stressed. This study employed well logs, photo-geologic analysis, airborne electromagnetic and magnetic surveys, seismic profiling, and two-dimensional electrical resistivity imaging. The results provided a three-dimensional regional image of the bedrock topography that has been confirmed with follow-up bore holes. The second case was also designed to map bedrock topography with airborne electromagnetics at Fort Detrick, Maryland, but in a much shallower setting. The use of a priori knowledge to set airborne system parameters is emphasized. The use of routine, but seemingly unnecessary technologies as part of a general screening process led to a surprising result, which called into question several years of ground geophysical interpretation.

Introduction
Camp Crowder, a Missouri Army National Guard training facility located south of Neosho, Missouri, is part of the Pool's Prairie NPL site. This facility was used for rocket engine and components testing for many years. Resulting DNAPL contamination found within the soil and groundwater is suspected of migrating off-post through conduit and fracture systems within the underlying karst bedrock. Dye tracer studies have confirmed groundwater movement towards the contaminated wells, though the actual route of migration is not known. The overburden is dominantly a cherty residuum, through which the surface water and contaminants percolate into the underlying karst aquifer. An integrated approach using photo-geologic analysis, airborne electromagnetic surveys, seismic profiling, and two-dimensional electrical resistivity imaging (2D-ERI) was conducted to map subsurface changes associated with this complex karst system.

Each of the various data sets provides a unique and valuable input to the interpretation process. The integration approach was to start with point data from bore holes, expanding to local surveys with surface geophysics, then continuing to a regional survey with airborne geophysics. The regional data were then used to locate other potential sites for higher resolution ground surveys, followed by directed drilling and treatment.

Fort Detrick is an active U.S. Army base in Frederick, Maryland. The objective at this site was to map basement topography for ground water pathways. An airborne electromagnetic survey was planned to complement ground-based resistivity surveys, and to form a basis for tying ground surveys into a regional context. A magnetometer survey was unnecessary for this objective as there were no ferrous objects or targets in the otherwise open field. Since it could be flown with minimal additional effort, however, it was included in the airborne work plan. The resulting magnetic map showed an intricate network of underground pipes covering the entire survey area that were being misinterpreted as geologic features in the resistivity surveys.

Camp Crowder
The geology at Camp Crowder is dominated by a highly weathered cherty residuum at surface, with a continuous transition to competent limestone at depth. The depth to competent bedrock is highly variable, making ground water pathways unpredictable, although there is a shallow regional dip to the

northeast. Drilling encountered DNAPLs in the immediate vicinity of the Engine Test Area (ETA) and the Component Test Area (CTA) (Figure 1). Dye trace experiments showed that some pathways led to springs in the next valley over on the northeast side of the base. Drilling also revealed the irregular bedrock topography and directed the station spacing for the ground geophysical surveys. The resistivity and seismic surveys were able to provide a basis for interpolating between holes and model a profile of bedrock depth that is relatively unaffected by smaller irregularities (Figure 2).

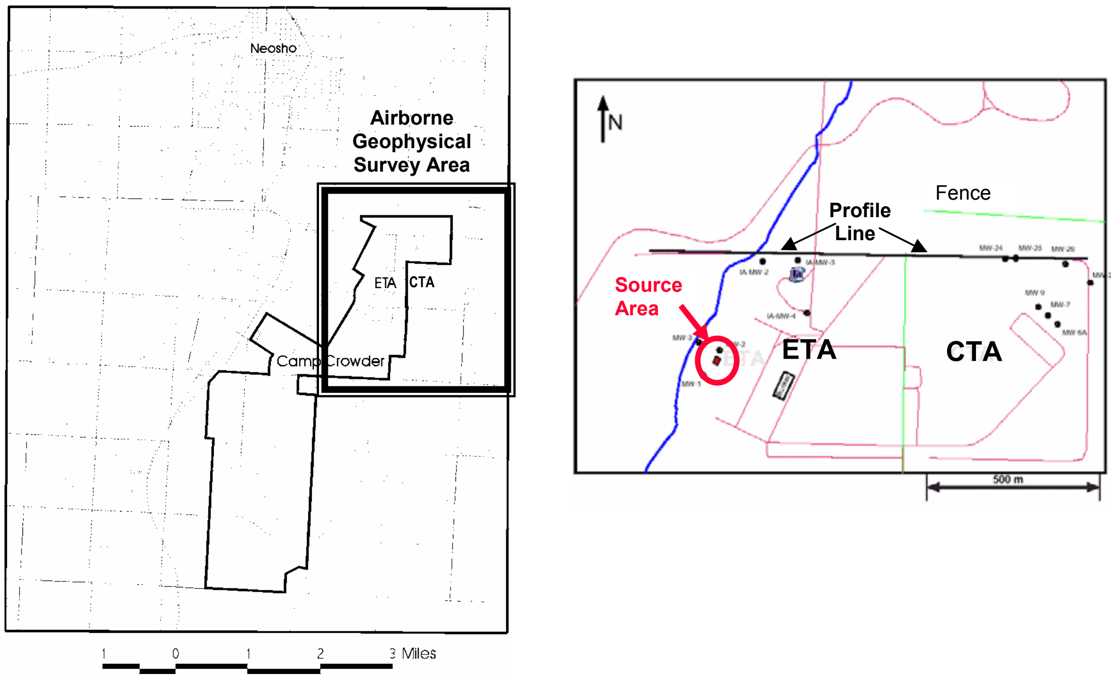

Figure 1: Map of Neosho and Camp Crowder, Missouri. Inset box is airborne geophysical survey area. Blow up area is ETA/CTA area only, with surface geophysical survey lines and drill sites.

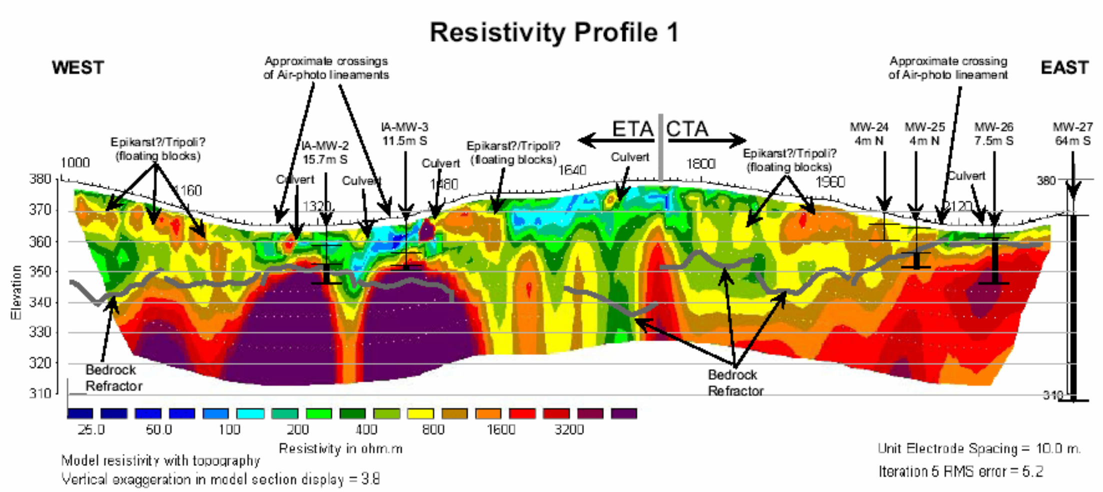

Figure 2: Surface geophysical survey results along profile 1 (as shown in Figure 1). Drilling results, seismic refractor, photo-geologic lineaments and various man-made artifacts are shown over resistivity cross-section.

The information on the depth and conductivity profiles from the ground surveys were used to determine the necessary parameters for an airborne electromagnetic survey on a regional scale. This was flown by Fugro Airborne Surveys with their five-frequency coplanar coil system with supplementary Cs magnetometer. In addition, photo-geologic analysis was conducted to map surface lineaments on a regional scale.

Multi-frequency inversion of the airborne data was performed by ORNL and correlated with the surface geophysics and well logs. Matching the change in conductivity to the bedrock interface produced a regional map of bedrock topography and residuum thickness. Potential pathways were traced from the ETA source area outward in several directions (Figure 3). Follow-on ground surveys and drilling have verified the depth estimates from the airborne data and presence of new pools of DNAPLs in bedrock troughs.

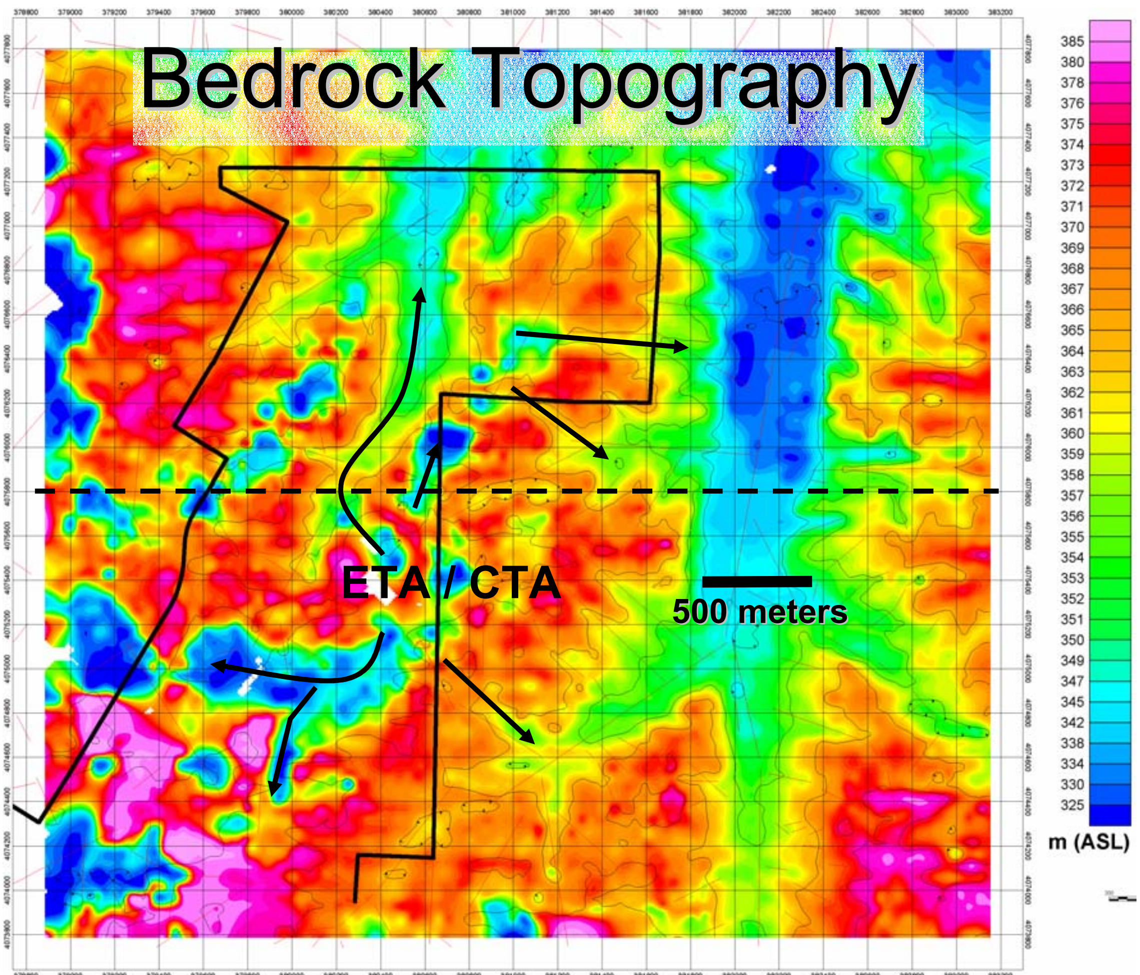

Figure 3: Bedrock topography map from airborne electromagnetic survey. Map covers area indicated as airborne survey in Figure 1. Camp Crowder boundary is shown in solid black. Dashed black line indicates airborne survey line used to correlate with the surface survey line from Figure 2. Potential contaminant pathways from the ETA site are shown as black arrows. Surface topography and photo-geologic lineaments are shown in grey.

Surface-based geophysical surveys were used to map the character of the overburden and underlying bedrock and provide ground truth connections between the drilling and airborne results. Seismic refraction data proved best in resolving the top of the competent bedrock (below the weathering layer), whereas the resistivity data imaged the top of the weathered horizon (transition from low-to-high resistivity) and coarser grained intervals within the overburden. In many instances, lineaments interpreted from aerial photographs coincide with disruptions observed in the ground-based geophysics. Interpretation of the surface geophysical data suggests that a mantle of friable, heavily fractured, and/or weathered rock overlies the competent bedrock and may act as a zone for contaminant storage, and for migration over short distances.

Airborne multi-frequency electromagnetic mapping provided a regional view of the site. Conductivity inversion of the data correlated well with the surface geophysical data and indicated that the mantle of friable material extended farther than originally anticipated. Derived bedrock topography indicates that the contaminant source area is situated on a transition zone between deep and shallow residuum, with paths and pools leading in several directions.

Fort Detrick

A similar approach was proposed for Fort Detrick. Ground geophysical surveys were followed by photo-geologic analysis and an airborne geophysical survey in order to tie results together on a regional scale. The site was much smaller and crowded by residential neighborhoods (Figure 4). Only about 200ac in Block B were amenable to flyover with the towed electromagnetic system. The depth to bedrock was shallower than at Camp Crowder, requiring a higher frequency electromagnetic system provided to ORNL by the USGS. A low altitude magnetometer survey was also flown to take fullest advantage of the helicopter mobilization and covered portions of Block A in addition to Block B. Block B featured an open field with a road on the south side and a landfill on the north side. The electromagnetic results showed the landfill as a conductive high, and a low conductivity area that was potentially related to a nearby depression (Figure 5). The magnetometer results, however, clearly showed a surprising network of underground pipes (Figure 5) belonging to an abandoned and apparently forgotten air sampling system. The center of this network correlated exactly with the center of the conductivity low seen in the electromagnetic data, indicating that the network was sufficiently well connected to distribute the transmitter power over a considerable distance.

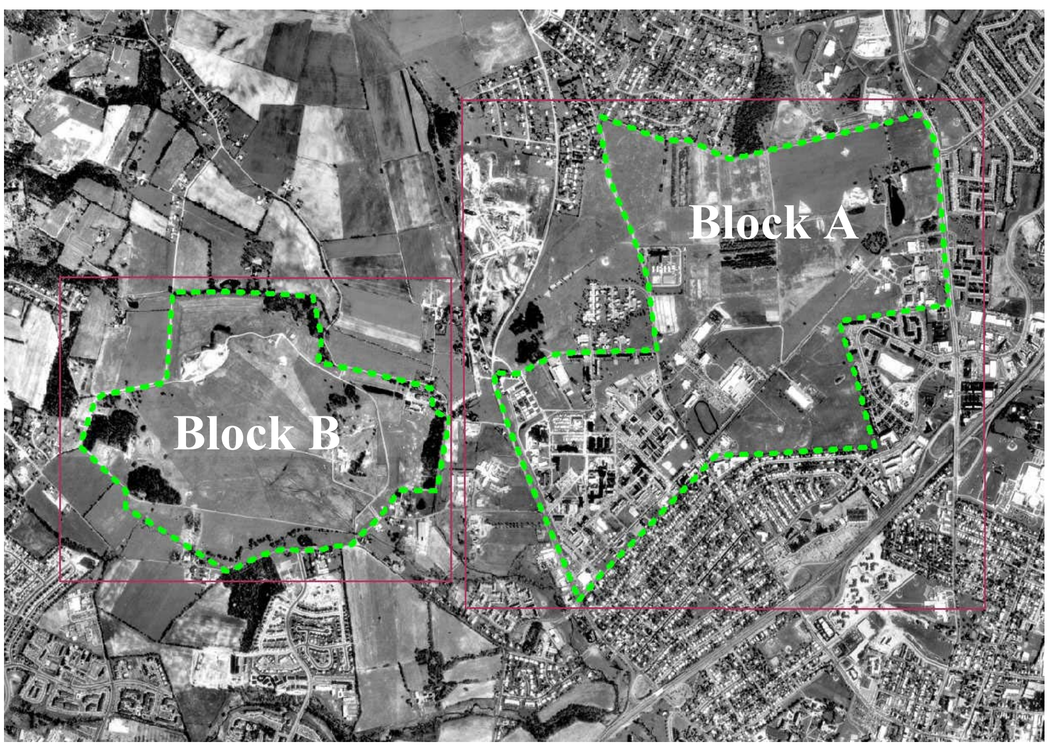

Figure 4: Aerial photograph of Fort Detrick, Maryland with base boundaries outlined in green.

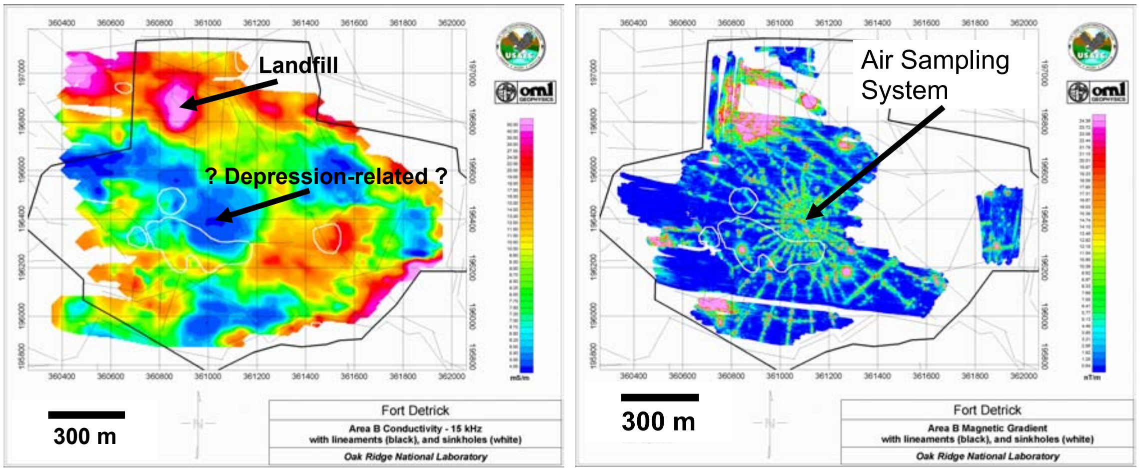

Figure 5: Apparent conductivity (left) from 15kHz airborne electromagnetic survey, and magnetic analytic signal (right) from low altitude magnetometer survey. The center of the air sampling system corresponds to the center of the conductivity low. Photo-geologic lineaments are superimposed in grey, interpreted depressions and sinkholes in white.

Conclusions

The integrated approach to regional or large scale investigations has proven extremely effective. A survey sequence that transitions from well logging to surface to airborne surveys and back down in reverse order allows large areas to be cost-effectively covered with complete tie in between the various techniques. Each stage of the project provides new information that is critical to the success of the next stage either as ground truth and calibration on the way up, or as direction towards new targets on the way back down.

The integrated approach also includes the use of potentially redundant techniques where financially practical. In these projects the magnetometer survey was included as a low-cost addition. At Camp Crowder nothing unusual was found, but at Camp Detrick the magnetometer data had a significant impact on the interpretation of the airborne electromagnetic data, as well as years of previous ground data. In areas with a long history of cultural activity, a wide suite of reconnaissance techniques should be employed to verify the background conditions.

Acknowledgements

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