Airborne Geophysical Solutions for Geotechnical Challenges

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SUMMARY

Assessing geological risk is a significant part of infrastructure planning and managing project cost overruns and delays are persistent challenges for engineers and project managers. Risks can be difficult to control given the high cost of detailed ground investigation programs using traditional approaches (i.e. geotechnical drillings). Airborne electromagnetic surveys (AEM) are increasingly being used to mitigate geological uncertainty and save time and money.

The SkyTEM method of airborne time-domain electromagnetics is flown with helicopters (HTEM) and is an innovative and advanced technology capable of mapping the top 500 metres of the Earth in fine detail and in 3 dimensions. SkyTEM technology and data help geological organizations and government agencies on all seven continents unearth a wealth of geological information. HTEM data can be of substantial value to pre-engineering and construction projects and in this White Paper we give examples of the applicability of HTEM surveys to geotechnical engineering. The case studies selected provide examples of how and why engineers and others use SkyTEM data as a critical input for decision making. The high-resolution images available from SkyTEM are used to quickly develop a geological model and are used with available ground truth data to adjust, update and improve the geological interpretation and selection of appropriate sites for development. Coverage of large and/or remote areas requires only a few days. Airborne electromagnetic surveys (AEM) have been used routinely for mineral and oil and gas exploration since the 1950s. See "Airborne Electromagnetic Systems - 50 years of development." See https://www.tandfonline.com/doi/abs/10.1071/EG998001.

INTRODUCTION

As the human populations grow so does the infrastructure we build to accommodate people. Civil engineering is called upon to build bigger and bigger structures while geotechnical engineers must constantly develop new techniques to ensure the underlying ground will support those structures. The conventional approach to infrastructure pre-studies involves the use of geotechnical drillings and other ground-based techniques. The advantage is generally highly accurate point information however drillings and the application of ground-based techniques are time-consuming and costly. They can also often be challenging or impossible to carry out at locations with limited access. Consequentially, information may be scattered with significant gaps in data coverage which requires interpolating between data points and the introduction of risk to decision making. On the grounds that conventional approach's have limitations, helicopter-borne time-domain electromagnetics ("HTEM") is increasingly employed as a tool to complement existing methods in large scope pre-studies.

HTEM is a highly cost-efficient technique for rapid mapping of large land stretches and coast lines without being constrained by access to the ground. The method maps changes in ground electrical conductivity (or it's inverse, resistivity) from the surface down to several hundred metres, virtually continuously along each line of flight. Variances in the conductivity of earth materials can be correlated with different characteristics of rock and soil and HTEM data can be used to interpret geological settings to update geological and hydrogeological models. HTEM data can be employed to interpolate lithological information between boreholes and soundings where information may be deficient. Interpretation is reinforced with available borehole information. From a practical point, it is advantageous to perform HTEM as one of the first of the earth science disciplines since results can guide further subsurface investigations and ground follow up, including strategic targeting of new boreholes. Some studies and experience suggest that up to 50% of geotechnical drillings can be reduced if HTEM is carried out prior to commencing drilling programs. One limitation of HTEM must be mentioned, that is, HTEM data are significantly distorted when collected within 100-200 m of electrical installations such as powerlines. It is therefore not feasible to employ HTEM in urban areas or close to these installations.

HTEM SOLUTIONS TO THE GRAND CHALLENGES OF CIVIL ENGINEERING

An expert task force assembled by the ASCE TCCIT (Technical Council on Computing and Information Technology) Data Sensing and Analysis (DSA) Committee identified several grand challenges the civil engineering community faces today that can be addressed with remote sensing techniques and data analysis. https://www.asce.org/computing-and-it/news/20141014-civil-engineering-grand-challenges--opportunities-for-data-sensing,-information-analysis,-and-knowledge-discovery/. As outlined in Table 1 below HTEM data can be of substantial value to pre-engineering and construction projects and this White Paper presents several real world examples of how and where HTEM data was used to quickly and economically reduce risk.

Challenge	HTEM solution
Improving construction productivity	Reduction and/or optimal placement of boreholes, scan vast areas quickly, no "boots on the ground"
Enhancing construction site safety	Identification of ground fractures and faults
Rising sea levels	Depth and breadth of saline intrusion along coast lines, bathymetric measurements
Enhancing disaster management through infrastructure resilience	Slope stability studies, depth to bedrock, quick clays
Estimating level of soil erosion	Annual surveys to measure changes in overburden thickness and shoreline erosion
Monitoring the health of infrastructure	Pipeline leaks, cathodic protection assessment, characterization of man-made earth works
Managing groundwater	Aquifer volume, fresh and brackish water, identification of areas for groundwater recharge and water banking.

Table 1: HTEM solutions to geotechnical challenges

IMAGINE IF…….

Imagine if you could map the earth in fine detail to a depth of 500 m, quickly and economically. It is possible and here's how it came to be. In Denmark, as in much of the world, the supply of drinking water is based entirely on groundwater resources. In the 1990s the Danish Environmental Protection Agency decided that before land could be slated for urban development it had to first be examined to determine if aquifers were present in the area in order to protect them from potentially harmful human activities. To make sound decisions on how to protect this critical resource it was important to base decisions on accurate and reliable information - in this case, spatially dense hydrogeological maps.

Ground based methods to map the subsurface produced highly accurate 3D data sets but were slow and difficult to employ in hilly terrain or populated areas. A borehole drilling program was to costly and not feasible for mapping such a large area. Airborne geophysical systems at the time primarily served the mineral exploration and oil and gas industries and were not up to the task of concurrent resolution of the near surface and deep geology. You got one or the other but not both. They also did not have the low noise characteristic and sensitivity required to resolve subtle geological contrasts. An R&D team of leading geophysicists, hydrologists and scientists set out to develop an airborne method capable of mapping the earth in fine detail – from the very near surface to depths of about 500 m – the interval where the aquifers resided. They also set out to collect highly accurate noise free data that was robust enough to create advanced map products within a few days of being acquired.

With these specific aims in mind the first SkyTEM high resolution electromagnetic system was developed (see Figure 1). It was and still is breakthrough technology that has changed how we map the earth. SkyTEM's mapping abilities are recognized globally by engineers, scientists and others with a need to accurately map the subsurface and the SkyTEM method has been called upon to locate water on a Galapagos Island, characterize a pipeline construction route in Australia, study slope stability on Mt. St Helens, identify contaminant pathways, map saltwater intrusion along the shorelines of several continents and characterize a construction site prior to large infrastructure projects. These and many other examples can be found here https://skytem.com/downloads. Quest, a PBS channel science show, featured SkyTEM in a broadcast about mapping critical aquifers, the video can be watched at https://www.pbs.org/video/quest-skytem-aquifer.

The National Science Foundation employed SkyTEM to map groundwater beneath Antarctic glaciers, the story from the Antarctic Sun is found here https://antarcticsun.usap.gov/science/4395. Scientists working on the Antarctic project noted the system's ability to map the hidden distribution of ice and water on the frozen continent and stated that the SkyTEM Method provided more knowledge about the subsurface of Antarctica than 40 years of drilling and traditional geological studies. To meet the Grand Challenges of geotechnical engineering SkyTEM technology is versatile and can be customized to suit a wide range of projects as outlined in the following case studies.

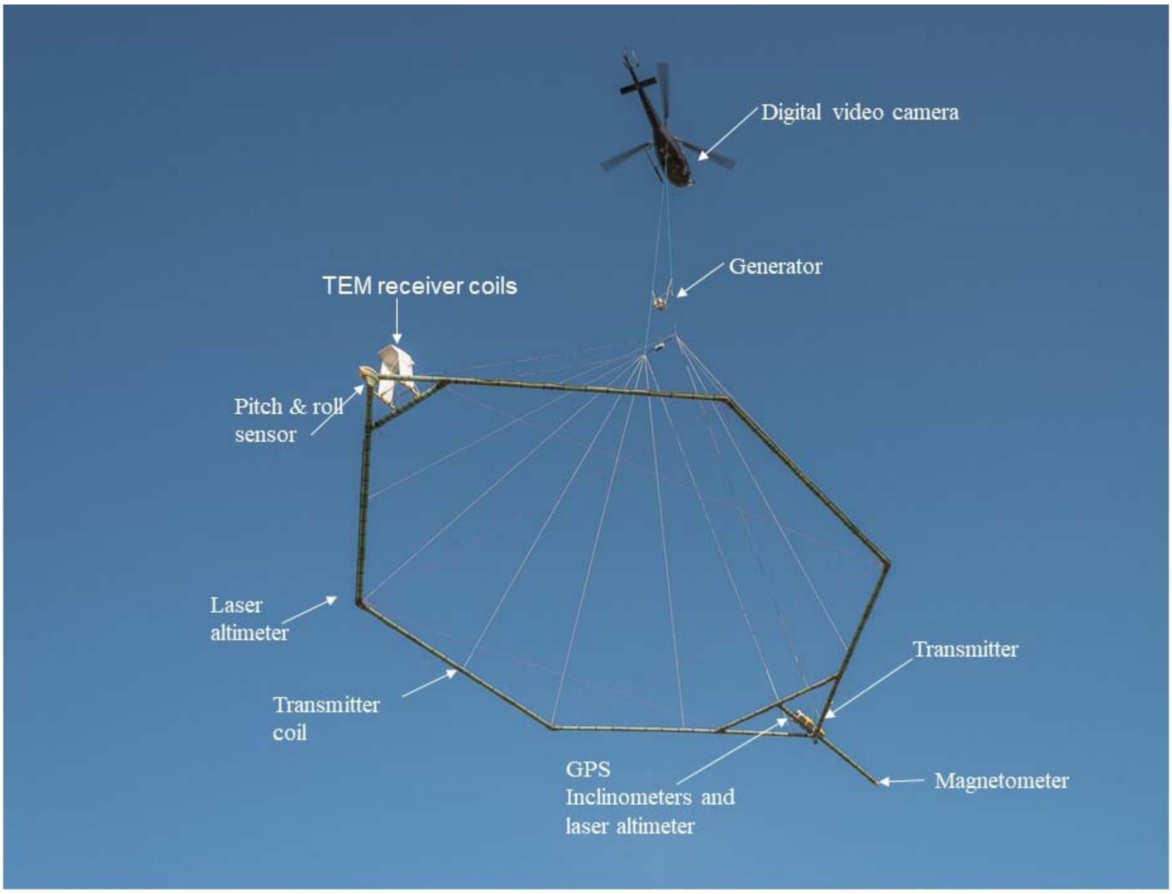

Figure 1:SkyTEM airborne system and instrumentation

LET'S GET GEOPHYSICAL (FROM WIKIPEDIA)

Exploration Geophysics uses physical methods (e.g., seismic, gravitational, magnetic, electrical and electromagnetic) at the surface of the Earth to measure the physical properties, that is, the relative electrical resistivity or conductivity of various earth materials, along with anomalies in those properties. Figure 2 below provides typical resistivity/conductivity values of various earth materials. Geophysics is most often used to detect or infer the presence and position of economically useful geological deposits, such as ore minerals; fossil fuels; geothermal reservoirs; and groundwater reservoirs. Geophysical techniques can be compared to computed tomography (CT) scans performed on the human body as they are non-invasive ways to diagnose or flesh out geological features and conditions. Geological features can be located, mapped, and characterized in three dimensions by detecting variations, or anomalies, and airborne geophysics has been an integral part of mineral and petroleum exploration programs since the 1950s (see https://library.seg.org/doi/abs/10.1190/1.1820341).

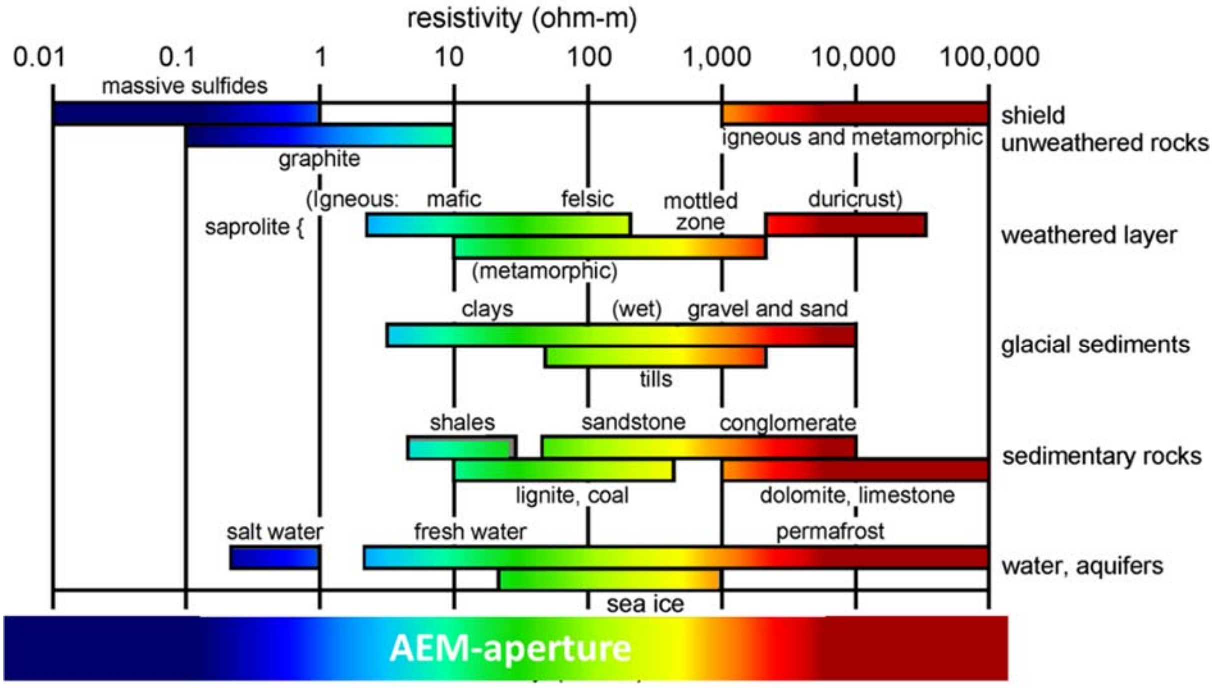

Figure 2: Representative chart (adapted from Palacky, 1987) illustrates very generally how the resistivities of important rock groups compare to each other. This type of figure is given in most texts on applied geophysics

SKYTEM SYSTEMS

SkyTEM airborne geophysical survey systems deliver truly innovative and unique technology capable of delivering accurate and finely detailed images from the very near surface to depth (See Figure 3). Systems are quickly configurable to match project-specific goals and targets. SkyTEM *FAST* systems can acquire over 1,000 line-kilometers of high-resolution data per day and are aerodynamically engineered for challenging weather and terrain conditions.

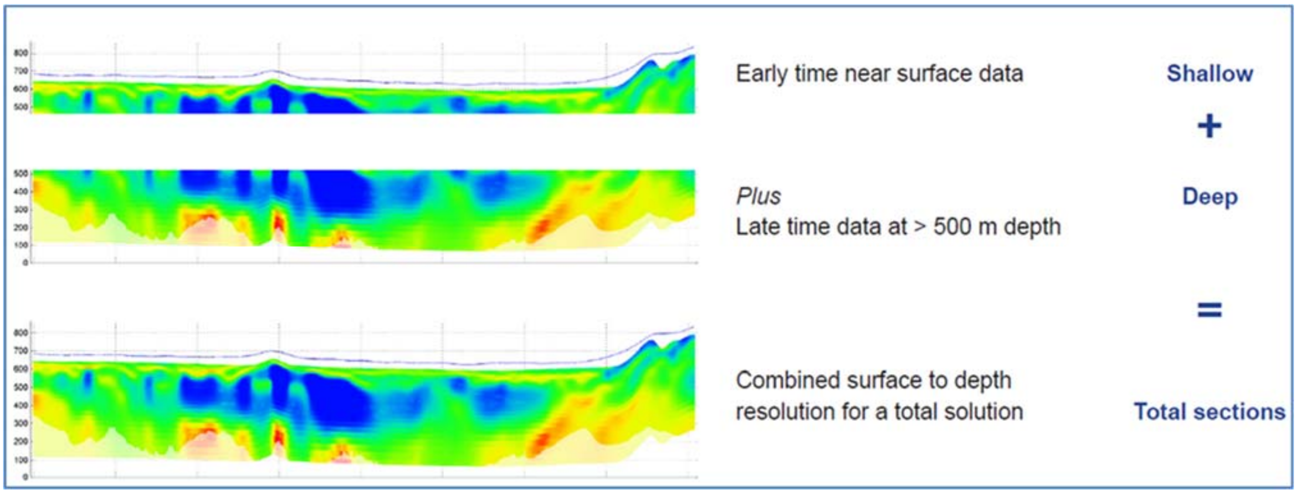

Figure 3: Resistivity data - concurrent mapping of near surface and data at depth with SkyTEM system

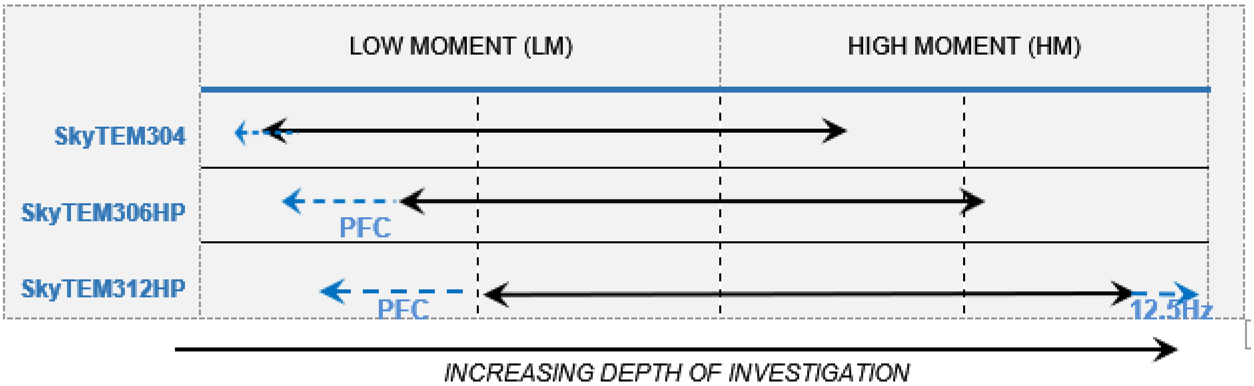

Table 2: SkyTEM choice of system for varying mapping requirements

SkyTEM304 – The trendsetting SkyTEM pioneer

SkyTEM304 has been employed worldwide since 2004 for a wide range of applications including mineral, oil and gas exploration, geotechnical engineering solutions and most of the globally acclaimed SkyTEM water mapping projects. SkyTEM304 is the only system proven to deliver accurate data from the top few meters to depths of up to 350 m.

SkyTEM306 HP – Detailed near surface exploration

The SkyTEM306 HP (High Power) collects both near surface and deep data and can be configured in FAST mode, featuring an aerodynamically superior system reducing acquisition costs by flying at speeds of up to 150 km/h.

SkyTEM312 HP – Deep exploration

Optimized for exploration at increased depth the system can be configured in FAST mode, as well as High Power (HP) with a peak moment up to 1,000,000 NIA.

A more thorough description of all SkyTEM systems with their specifications are found here https://skytem.com/tem-systems/

CASE STUDIES

ROCK TUNNEL PRE-INVESTIGATIONS – MAPPING POTENTIAL WEAKNESS ZONES	
Location	Zambia, Africa
Date	2016
Client	Norwegian Geotechnical Institute (NGI)
Challenges	• Pre-engineering for hydropower tunnel • Map overburden thickness • Map geological faults • Large remote area with few services
Solution	• SkyTEM304 for high resolution of the near surface as well as to a depth of 350 m. • Quick data collection and delivery

SN Power, a global hydropower company, and the Norwegian Geotechnical Institute (NGI) applied SkyTEM to characterize rock mass along three proposed hydropower tunnel routes 150 kilometers NE of Lusaka, the capital of Zambia. The focus of the airborne electromagnetic (AEM) survey was to 1) determine thickness of the weathered layer (overburden) and 2) map potential weakness zones along the tunnel alignments to decrease the overall project risk in terms of finances and scheduling. The main reasons for selecting the AEM method were based on the need to survey a large area and complete the data collection within a short time without mobilizing a large team to the site.

Figure 4: Map showing location of the Muchinga Waterway (right) and Mulungushi (left)

Flight lines were flown over the two tunnel alignments as shown in Figure 4 - the Muchinga Waterway to the east and the Mulungushi Waterway to the west, separated by about 35 km. The eastern Muchinga project is divided into two segments - Up Stream (U/S) in the North and Down Stream (D/S) in the South. The survey was flown using the SkyTEM304 system that provided the required combination of depth of investigation (DOI) and high resolution of the near surface. 10 to 20 parallel lines with a flight line spacing of 100 m were flown along each of the tunnel alignments for a total of 354 line-km flown over three separate blocks, in two days.

Figure 5 shows in plan view the average resistivity of a layer comprised between altitude 940 and 960 m - the altitude of the transfer tunnel for Muchinga D/S. The blue colors indicate resistive material typical for intact bedrock whereas red to yellow indicate conductive material that could be weathered rocks, weakness zones and sediments. It is unlikely the planned tunnel (shown as the white line) will encounter major weakness zones such as the area identified in the north. This conductive zone is probably due to the NNW-SSE trending fault (previously mapped). The lower resistivity zone mapped in the south is most likely a quartzite vein which may extend deeper than previously mapped. The processed data from the AEM survey was useful for visualization of the existing sub-surface geological conditions. Specifically, high resistivity areas (competent bedrock) can be distinguished from low resistivity areas (incompetent weathered rock). Based on the resistivity maps, recommendations for ground-based investigations and locations for a strategically sited borehole were suggested. The weathered layer depth derived from AEM was used to find ideal quarry sites for sand and gravel.

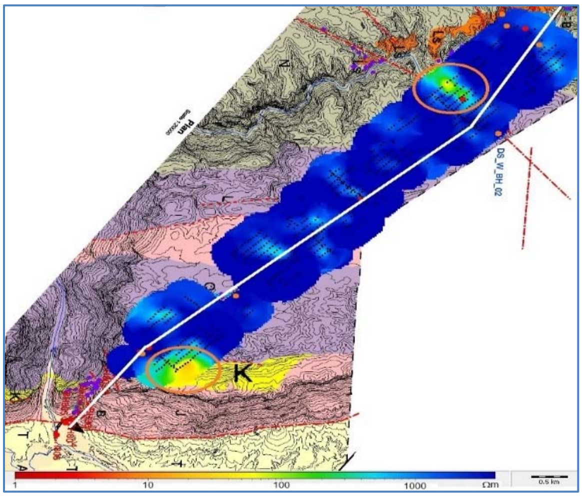

Figure 5: Muchinga D/S – Average resistivity at the elevation of the transfer tunnel. The planned transfer tunnel is shown as a white line. The geological map is presented in the background. Black dots represent the coverage of the inverted AEM data, the gaps are due to coupling in the voltage data and the steep topography. Two conductive zones (circled) may indicate weathered rocks and weakness zones. The southern anomaly is related to a quartz vein (marked as "K" and shown in yellow colour on geological map). The northern one is related to a NNW-SSE oriented fault that was previously mapped (marked with a red dashed line).

Along the Mulungushi alignment the vertical resistivity section (Figure 6) shows two potentially major weakness zones, shown in yellow that were previously not known. The location of these anomalies was valuable to the project as ground investigation could then target these zones that could have easily been missed as there is no surface evidence for these structures.

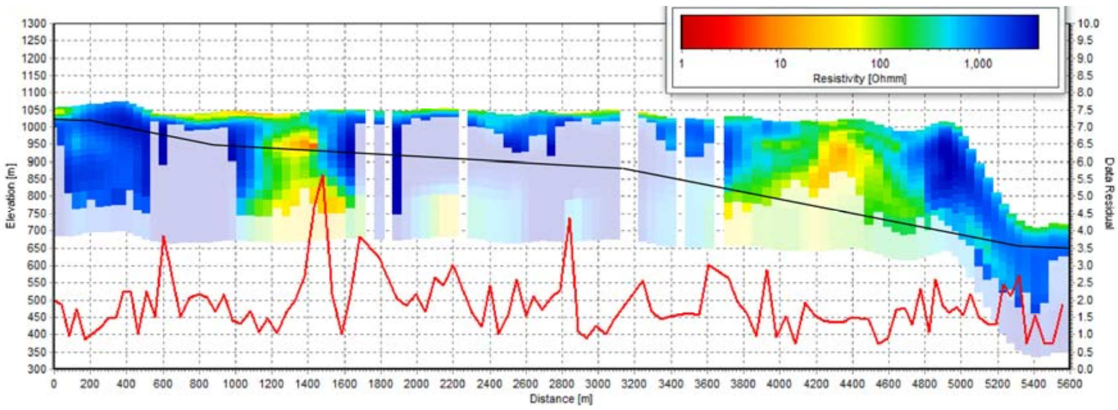

Figure 6: AEM resistivity model along Mulungushi alignment (tunnel indicated as black line) showing two low resistivity zones along the planned tunnel.

ROAD TUNNEL PRE-INVESTIGATION – MANAGEMENT OF RISK

Location	Bhutan, Eastern Himalayas
Date	2014
Client	Norwegian Geotechnical Institute (NGI)
Challenges	Pre-engineering feasibility study in extremely rugged and inaccessible terrain • Determine overburden thickness and identify potential weakness zones
Solution	• AEM to collect data in inaccessible terrain • SkyTEM304 for high resolution of the near surface as well as to a depth of 350 m.

In 2014 The Department of Geology and Mines (DGM) of Bhutan and the Norwegian Geotechnical Institute (NGI) co-operated on a project titled "Management of risks caused by natural hazards for new infrastructure development in Bhutan". More on this project can be found in the book "Geotechnics for Sustainable Infrastructure Development" found here https://link.springer.com/book/10.1007/978-981-15-2184-3.

DGM in co-operation with the Department of Roads contracted NGI to perform a feasibility study of a road tunnel between Thimpu, the capital city, and Wangdu. One of the tasks of the project was to assess the design and construction feasibility of a road tunnel that would provide a safer alternative to hazardous existing roads. The tunnel would shorten the main travel route between the two main towns (70 km) by approximately half and reduce the driving time to about one third. The AEM method was chosen for the pre-investigation with the objective to quantify the weathering thickness and obtain potential indications of weakness zones along the tunnel corridor.

The survey area was at high altitudes in the Himalayas making it impossible to carry out geotechnical investigations on land over the proposed tunnel length. Maneuvering the helicopter was challenging due to lower air density and the rugged topography, and gusty winds made it difficult to tow the instrument under the helicopter. After a reconnaissance flight it was deemed unlikely the entire area could be densely covered by an AEM survey within the project's time and budget constraints and areas with the highest priority were covered.

The survey totaling 158 line-kms was flown with the SkyTEM304 system delivering enough depth penetration to map the top of the bedrock as well as high resolution characterization of near surface. The nominal terrain clearance for the towed system is usually 30 m, with an increase over forests, power lines, or any other obstacles. Due to the topography and wind the instrument altitude varied considerably (between 30 and 400 m) with a mean around 110 m. The data quality, although quite variable within the survey area, was still adequate for analyzing the priority areas.

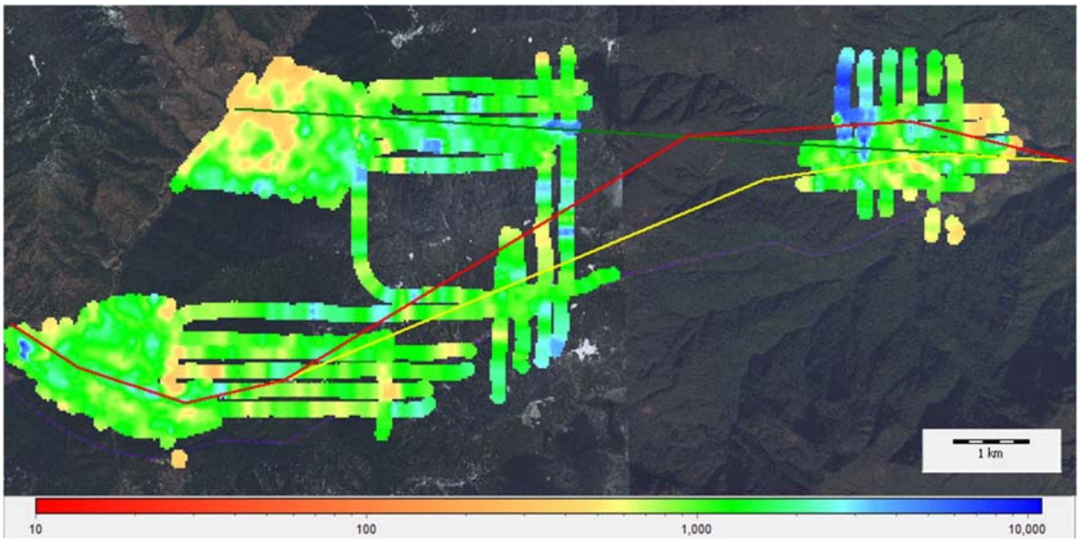

Figure 7: Average resistivity in a layer from 0 to 25 m depth below surface, for the entire survey area

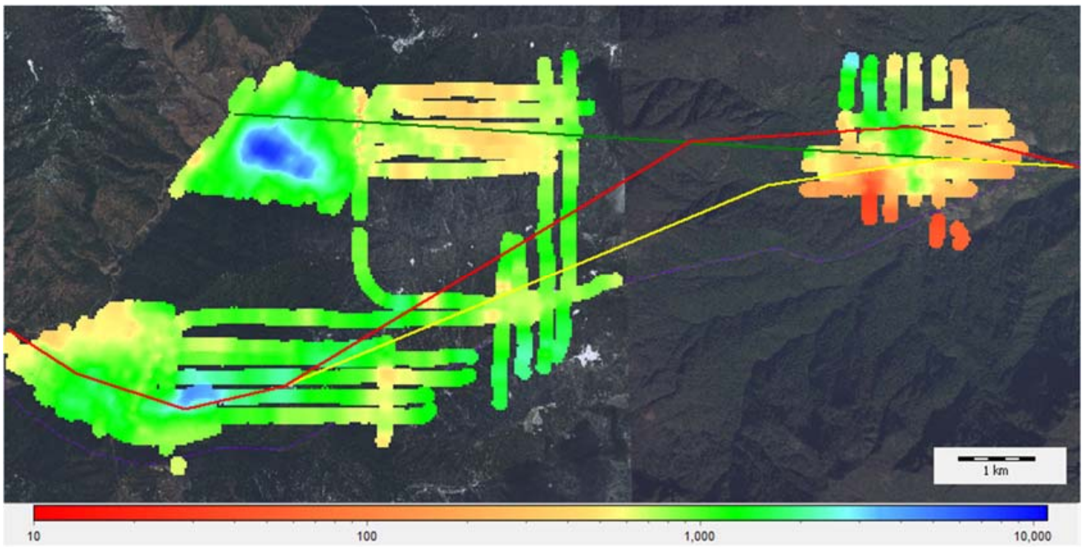

Figure 8: Average resistivity in a layer from 300 to 350 m depth below surface, for the entire survey area

Two example resistivity maps of geological interest are shown in Figures 7 and 8. Figure 7 presents the mean resistivity map from the surface to 25 m depth and is intended for the portals design. Figure 8 presents the mean resistivity map between 300 and 350 m depth and is intended for the tunnel design. The green to blue colors indicate resistive material typical for intact bedrock whereas red to yellow indicate conductive material that could be weathered rocks or weakness zones. Three tunnel alignments are drawn on the resistivity maps. Green was the proposed route, red and yellow are potential alternate locations for the western portal and tunnel.

As expected, near surface resistivity are lower in the valleys than at the peaks due to weathered material in the valleys. Deep weathering is indicated by the yellow colours in the NW (Figure 7), confirmed by prior geological knowledge. The highest surface resistivity is found near steep cliffs close to the eastern portal. On average, the near surface resistivity is quite high (above 500 Ωm).

At depth (Figure 8) we observe a region of lower resistivity (yellow color) 1.5 to 3 km east of the NW portal and a region of very low resistivity (red color) in the SE of the eastern portal. This conductive anomaly may correspond to a weakness zone that should be investigated further.

An alignment shown by the red line is proposed based on the SkyTEM data. It was chosen to follow the resistive regions in the AEM model and avoid the eastern conductive body. The deep conductive anomaly located SW of the eastern portal is a concern and is scheduled for follow up with dedicated ground investigations. The survey results were perceived as very valuable to DGM as the complete survey costs were comparable to one single deep drilling in these topographic conditions.

PIPELINE ROUTE – RISK ASSESSMENT	
Location	South east Queensland, Australia
Date	2011
Client	Queensland Gas Company
Challenges	• Pre-engineering feasibility study in flooded and inaccessible terrain • Identify areas of shallow bedrock where blasting or re-routing of pipeline would be required
Solution	• AEM to collect data in inaccessible terrain • Quick delivery of data • SkyTEM304 for high resolution of the near surface

The record rainfall and severe flooding in South East Queensland, Australia, in early 2011 wreaked havoc in at least 70 towns and affected hundreds of thousands of people. In addition, business and industry suffered and many important resource infrastructure projects experienced significant delays. Queensland Gas Company's Curtis LNG (QCLNG) Project was one such project. Operating under a tight deadline the project was under increasing pressure to deliver the project under worsening conditions.

A key component of the project was characterization of the corridor, which was delayed by the floods and resulting land access issues. It was decided to conduct an AEM survey of the corridor that, while not providing the same level of detail as ground investigations, was able to provide QGC with early information showing shallow bedrock months ahead of when the same information could have been obtained via traditional means. With the survey program completed in 6 days of surveying and preliminary results (shown below) delivered within 48 hours of acquisition, the airborne solution was crucial to meeting the projects deadline and engineering objectives.

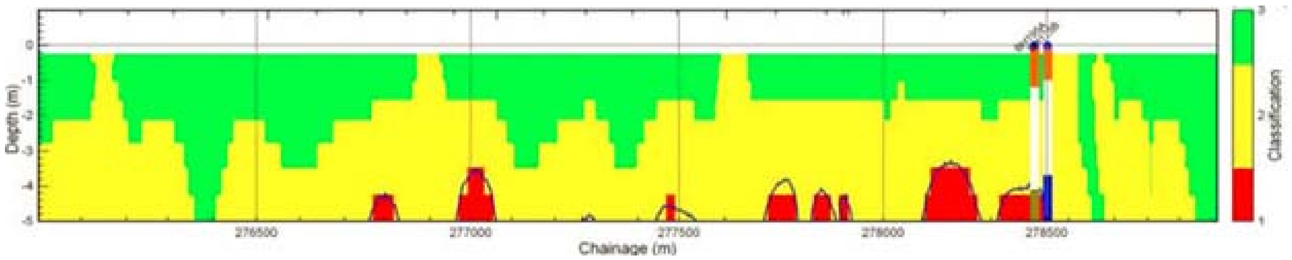

Figure 9: Vertical profile of the top few metres showing risk of shallow bedrock (red = high risk, green = low risk)

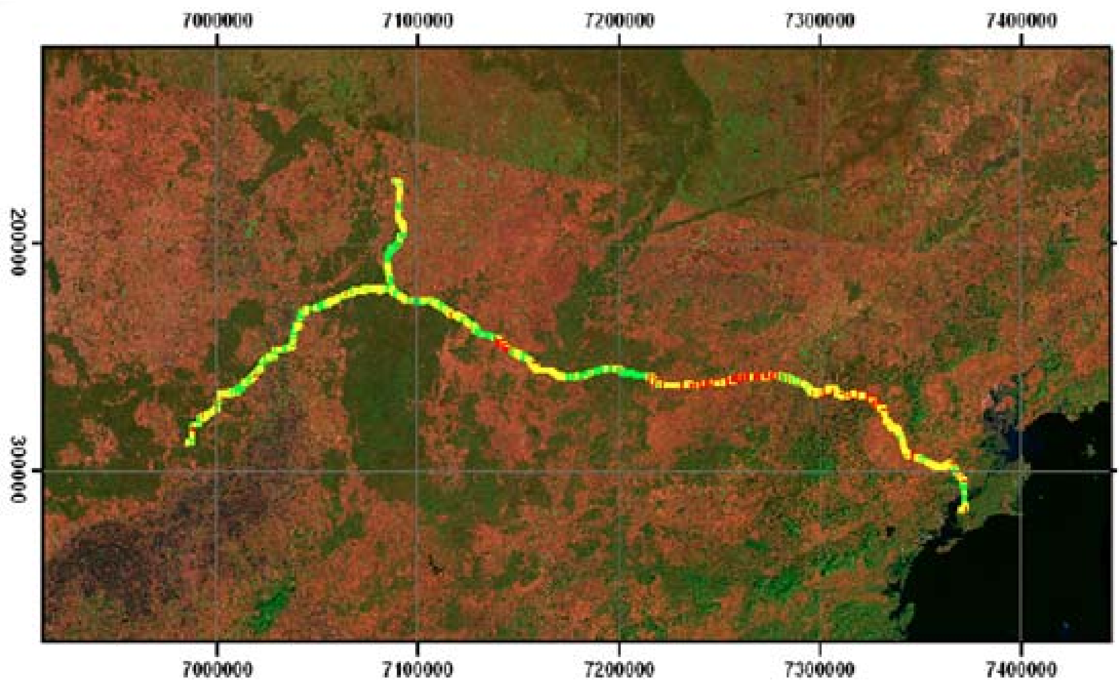

Figure 10: Plan view showing shallow bedrock risk assessment

A vertical profile along a segment of a flight line is shown in Figure 9. The result from the survey was a simple map and GIS dataset of the pipeline route, colored by risk of shallow bedrock - red = high risk, green = low risk (Figure 10). This allowed QGC to quickly perform early-stage de-risking and assess priority areas to focus on for site investigations and deliver the project ahead of schedule.

MAPPING WATER, LOCATION OF ENGINEERING MATERIALS AND IDENTIFICATION OF POTENTIAL GEO-HAZARDS	
Location	Horn River Basin, British Columbia, Canada
Date	2011
Client	Geoscience BC and four partner oil and gas companies.
Objective	• Map groundwater resources • Map the near surface
Solution	• AEM to quickly collect data over a large area • SkyTEM304 for high resolution of the near surface
Bonus: Interpretation of the AEM data also revealed	• Artesian water and prediction of further water flow • Identification of potential drilling hazards • Detection of near surface coarse materials for engineering applications

Approximately 2,400-line km of SkyTEM304 AEM data were collected over the Horn River Basin in April 2011. The objective of the AEM survey initially was to delineate possible sources of near surface groundwater thought to be contained in quaternary paleochannels. During the interpretive process the resistivity data indicated several interesting geological features and anomalies. A paper describing this work in more detail can be found here https://geoconvention.com/2014-abstract-archive/.

Figure 11 shows a vertical profile along a 14-kilometer segment of a flight line. Below the weathered top layer, the resistivity model shows considerable and significant detail. A thin, continuous conductive layer (red) is seen throughout the property at a depth ranging from 15-25m. This layer is thought to represent a thin lacustrine clay horizon which has the potential to be an aquitard. Below this clay cap, over most of the property, a relatively resistive and variable thickness layer is imaged below (green). Below this layer the model resistivity drops to relatively low values (< 10 Ωm) before the depth of investigation of the system is reached. The layers below the clay cap are interpreted to represent water charged quaternary paleochannels overlying a basal quaternary clay fill. In this case the paleochannel is filled with water as evidenced by Well d-66-f that has artesian water flow from the quaternary, however, based on a blowout from drilling into trapped gas in a contiguous property during the survey, the AEM data can also be used to identify areas where the clay caps trap significant accumulations of shallow gas and present a potential drilling hazard. It was also found that the highly resistive areas at surface (blue) contained aggregate deposits that could be used for various engineering applications such as road and drill pad construction. The entire data set is available for download at http://www.geosciencebc.com/reports/gbcr-2012-04/

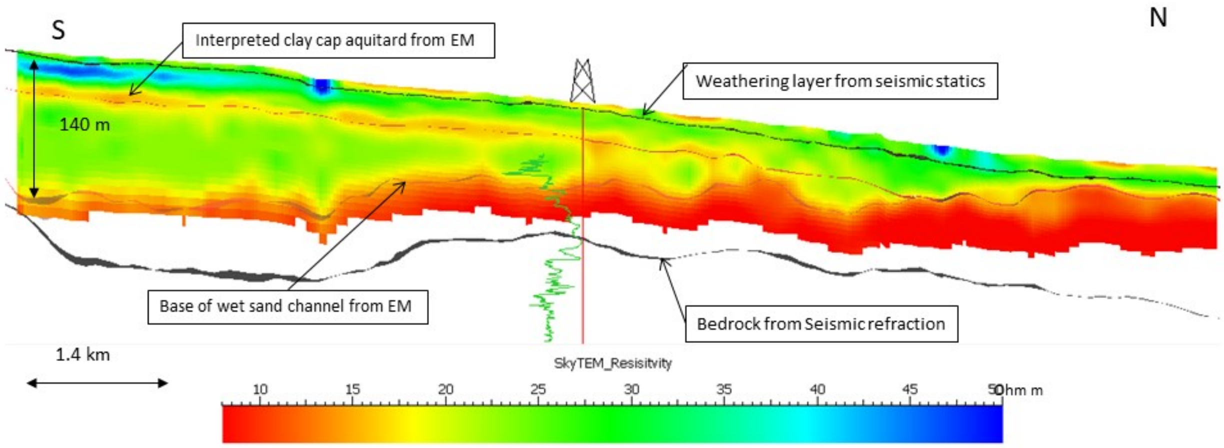

Figure 11: North-South section showing an integrated interpretation of SkyTEM inverted resistivity model and seismic data

INFRASTRUCTURE PLANNING – AVOIDING POTENTIAL DISASTER	
Location	Kevitsa, Finland
Date	2011
Client	First Quantum Minerals
Objective	Map depth to bedrock for pre-construction of infrastructure
Solution	SkyTEM304 for high resolution of the near surface

In 2011 First Quantum Minerals (FQM) applied SkyTEM304 at the Kevitsa mine site located in northern Finland. To process a planned increase of mined nickel and copper FQM's objective was to find shallow intact bedrock for construction of a crusher. Overburden needed to be excavated down to the bedrock and to save on costs FQM searched for a location where the depth to bedrock depth was less than 10 meters. Site geology at the mine was characterized by bedrock overlain by quaternary till, varying in thickness between a few metres up 50 metres. In some areas, the upper part of the bedrock is fractured or weathered, which renders it highly unsuitable for placement of the crusher.

Boreholes at the site were unevenly distributed and had been carried out over many years by different contractors, so quality of the borehole interpretations varied. Also, normal practice drilling boreholes on this site was to stop once hard rock was encountered which could potentially result in false characterization of a weathered layer as competent bedrock. A location for the crusher close to mine infrastructure was selected based on sparse borehole information that implied an overburden thickness of less than 5 metres. FQM ascribed a significant uncertainty to the depth of the bedrock and decided to commission SkyTEM to carry out an airborne survey of the site.

The AEM survey indicated the depth to bedrock was more than 20 metres and not 5 metres as estimated based on the boreholes. Figure 12 shows depth to bedrock in brown/green colours derived from the SkyTEM resistivity data. The red circle is the site where the crusher was to be placed initially. Given the significant capital investment to be made in mine site infrastructure several geotechnical drillings were carried out based on the AEM survey. The depth to bedrock determined from these boreholes showed a good correlation with the results from the AEM survey as shown as white circles in figure 12. The crusher site was moved to the area delineated by the blue circle shown.

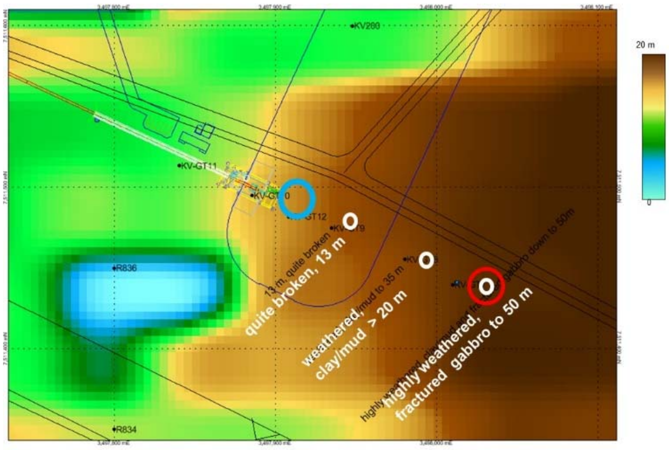

Figure 1: Results of geotechnical drillings plotted on top of the AEM generated Depth to Bedrock

Characterizing depth to bedrock from sparse geotechnical drilling can be risky and the consequences of faulty characterization can range from frustrating to disastrous. With a reliable conductivity contrast AEM mapping offers an inexpensive method to reduce uncertainty beyond what geological mapping can do. The success of the project was based on the availability of petrophysical statistics to tune the EM modelling, and ultimately, on the use of the modelling to guide further drilling to the satisfaction of the engineering team. Chris Wijns, FQM's Group Geophysicist stated that the AEM survey saved FQM a large sum of money because the original location "would have been disastrous" (Wijns 2016). A paper on this work, "*Airborne EM for mine infrastructure planning*", by Chris Wijns can be found at https://www.publish.csiro.au/EG/EG16033

WATER AND MINE OPERATIONS – AVOID IT OR EXPLOIT IT	
Location	Republic of Sudan, Africa
Date	2017
Client	Orca Gold Inc
Objective	Locate reliable sources of water
Solution	SkyTEM312Fast

Orca Gold Inc. (Orca), a Vancouver based company with exploration properties in Africa, determined that their gold project in the Sudan was uneconomic without a reliable source of water. Effectively, one tonne of water would be required to process one tonne of ore. Ground geophysical methods and exploratory boreholes in the immediate area of the mine indicated that available water contained in a sandstone formation was limited in size and reliability, had high salinity content and would require costly reagent treatment before it could be used. Construction of a pipeline from the Nile was too expensive, and it was concluded that development of the mine would be economically unfeasible.

Orca and their hydrogeological consultant, GCS Water & Environmental Consultants, decided to employ SkyTEM with two specific objectives. The first was to re-explore an area with a previously identified aquifer to the north to determine if it could be expanded. The second was to explore an area to the west of the prospect and within a radius where water could be economically piped to the mine site. This area was selected because it contained two pump tested wells that had surprisingly high yields despite what was thought to be known of the hydrology. A SkyTEM312*FAST* AEM system was commissioned to collect the data.

Preliminary results from the north area re-enforced the ground geophysics and borehole results that indicated water was present but not in quantities sufficient to support mine operations. New targets were identified but were small and did not appear to be economic or were high risk for further exploration. Interpretation of the AEM resistivity data from the west area however, identified potential economic zones, and the first boreholes were targeted on the highest conductivity zones. These produced some water but not in usable quantities. Interpretations of the geology were adjusted, and the drills were moved to moderate conductivity targets with a down-dip. This approach quickly proved very successful with a series of boreholes proving high yields of low-salinity water.

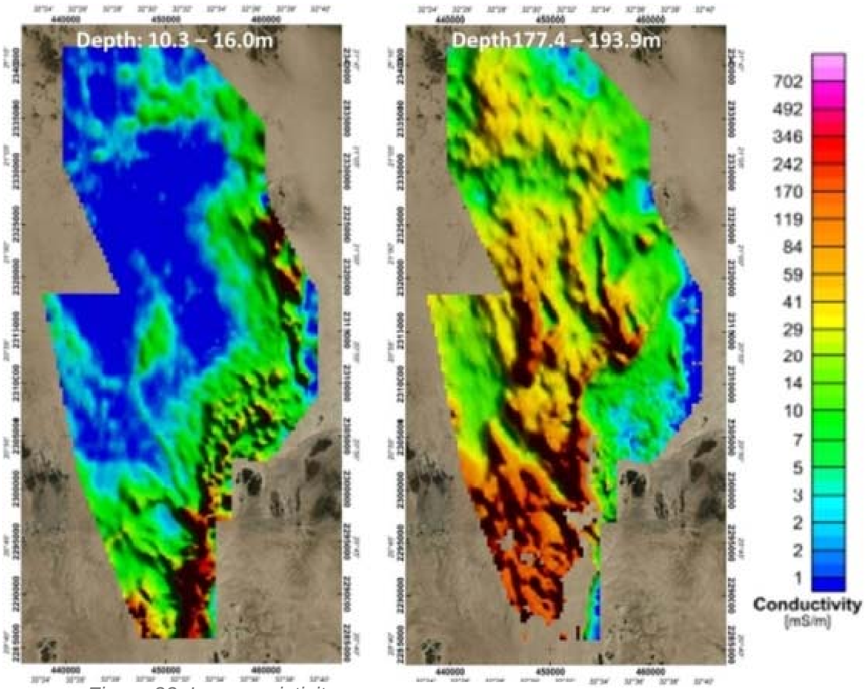

Figure 23: Layer resistivity maps

The current interpretation of the West area is that conductivities above the water table are uniformly low (shown as the cool colours in the left panel of the Layer Resistivity Maps in Figure 13). Good aquifer material is associated with moderate to high conductivity (10-50 mS/m) and the area was interpreted to have a well-defined layer with low clay content and fresh water. Lower than 10 mS/m is likely to be unfractured granitoid basement or dry sediment above the water table. Above 50-100 mS/m is likely to be clay-rich sediments with poor aquifer properties, saline water, or conductive andesite basement. After evaluation of the yields and quantities of water produced in the area Orca was able to announce their decision to proceed to a definitive feasibility study based on increased throughput made possible by the new water discovery that reduces unit process operating cost, leading to a material increase in the "in-pit" resources.

CONCLUDING OBSERVATIONS

Earth's surface is the only habitat available to humans, and understanding the processes by which our habitat has been created and the ways in which it changes is important to determining the causes of environmental degradation, to restoring what is degraded, and to guiding decisions toward a sustainable future. We have the technological ability to monitor closely the response of landscapes to climate change and human activities, as well as to interactions with other Earth surface processes. Based on the case studies provided here recommendations can be given for the application of AEM-surveys for geotechnical projects:

- AEM should be the first ground investigation step. Drilling locations can then be planned efficiently based upon AEM results.
- Subsequently drilling results should be incorporated in AEM data interpretation and visualization leading to a combined geological model (e.g. bedrock topography)
- AEM is better suited for regional-scale projects rather than isolated projects because costs can be relatively high for small surveys.
- Survey extent is limited by the presence of power lines and urban infrastructure.
- Adequate lead time is recommended, especially for more remote areas. Time is also needed for logistics planning and for contingencies such as visa or work permit delays. The need for good flying conditions can limit survey work to certain seasons, depending on location.

We thank Dr. Andi Pfaffhuber, Norwegian Geotechnical Institute for his ground-breaking applications of advanced airborne geophysical techniques and for allowing us to reprint material from his publications and reports.

SKYTEM PROVIDES A WIDE RANGE OF SUBSURFACE SOLUTIONS

Global scope

Our diverse and highly skilled workforce of geophysicist, engineers, technicians and project managers have managed and completed projects on all seven continents and are experienced in all aspects of geophysical data collection and safe operations. Our global coverage is complemented via partner companies that are strategically located to ensure availability of our technology and services.

Technology and emerging needs

The SkyTEM Method is not based on what others have done – and are still doing – rather, we engineered a truly innovative and unique technology capable of delivering accurate and finely detailed images from the very near surface to depth using airborne geophysical surveys. We focus on improving your ability to find, manage and develop resources and your ability to make timely decisions with confidence. We continue to develop the next generation of TDEM sensors, including the achievement of even greater depths of penetration and increasing our already high S/N ratio, via our on-going investment in R&D.

Environment and safety

We take great pride both as a company and as individuals in our contribution to the communities where we live and work. We operate always with great care for the environment and are proud of the many ways that our employees work to safeguard it.

Our work

We recognize that the world needs all the water, energy and mineral resources we can develop, and we work continuously to develop ways to map and manage these resources.

SkyTEM HQ in Denmark

THANKS A MILLION

On September 9, 2019 SkyTEM celebrated the acquisition of 1,000,000 kilometers of airborne time domain electro-magnetic data. That's equivalent to almost 25 trips around the world, and we mapped all of it with helicopters on all seven continents, safely and without incident or accident.

SkyTEM reached this point by attracting highly qualified and dedicated people to work in a culture of innovation and continuous improvement - and they engineered the best airborne geophysical mapping systems possible. The result is unparalleled technology available in a choice of systems suited for a wide variety of exploration objectives. As the success stories have spread, SkyTEM has also became recognized for their professionalism and focus on client needs. The 1,000,000 kilometre journey does not stop here - this milestone is only the beginning and SkyTEM is excited to continue advancing the technology, its influence and its solutions.

SkyTEM staff presented a Certificate of Appreciation to SLN in New Caledonia as we reached 1,000,000 kilometres of airborne geophysical data collected and delivered. Left to right are: Solvej Plenge Trautner (Project Manager SkyTEM), Pierre Pecheur (Pilot), Anne Raingeard (BRGM), Gwladys Lansun (SLN), Mohamed Kadar (SLN), David Nauss (Field Manager Devbrio/SkyTEM) and James Ball (Field Manager SkyTEM