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A series of confusing measurements in the search for water

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SUMMARY

A mine development in the high Andes of north-western Argentina requires a supply of fresh water for various uses, the largest being mineral processing. Complementary survey techniques in a gravel basin have provided vastly different and sometimes contradictory results. Mapping of the basin geometry proceeded via downhole resistivity logging, moving loop ground EM, and galvanic resistivity. The expected layering of low resistivity gravel fill over high resistivity basement rock, which was demonstrated by prior downhole logging, was turned on its head by surface electrical and EM surveys. Furthermore, subsequent borehole resistivity logs, which do not reach bedrock, support the increase of conductivity with depth, while water sampling indicates this is not due to greater salinity. Surface nuclear magnetic resonance was trialled for the direct detection of the upper part of the water table. The majority of these data were contaminated by mysterious noise sources in an area hundreds of kilometres from the nearest atmospheric activity, and fifty kilometres from the closest settlement. False negative readings appear to be common. The most recent drilling, demonstrating much deeper gravel than previously drilled or imagined, may explain an inability to image the bottom, but the reason for the deep conductivity remains a mystery.

Key words: water, hydrogeophysics, nuclear magnetic resonance, electromagnetics, Argentina, Taca Taca.

INTRODUCTION

In the high Andes, the scarcity of water is a major impediment to the development of mineral resources. First Quantum Minerals Ltd. has a copper porphyry development project in north-western Argentina (Figure 1) that will not proceed until sufficient water resources are defined to last for the approximately 30-year life of mine. Abundant hypersaline water is available, but sufficient fresh water is required to dilute this source until suitable for mineral processing. Fresh water is also required for general human use. Approximately 500 litres/s will be necessary. Gravel-filled basins surrounding the deposit were targeted for fresh water sources. One such basin, the Vega de Arizaro, was deemed prospective in light of surrounding topography, a small salar (salt lake) exhibiting local recharge, and proximity to the deposit (Figure 2).

Prior to any investigation of water resources, a standard initial model was expected for any geophysical response – conductive gravel basin fill over resistive crystalline bedrock. The outcropping hills surrounding the basin are largely felsic volcanics and intrusions, with some mafic lava flows. Weathering is limited in this very arid environment. The geophysical model was supported by a single initial downhole resistivity log. As new data were collected, the initial model was upended by moving-loop ground EM and galvanic resistivity soundings that both showed resistivity decreasing with depth. Follow-up drilling upslope of the initial hole intersected bedrock at much greater depth than expected, suggesting unusual bedrock topography that is higher at the centre of the basin. Downhole resistivity logs in the new holes returned profiles that either remain constant with depth or corroborate the decrease in resistivity with depth. To crown the perplexing results in this project, surface nuclear magnetic resonance, carried out to detect the top of the water table and pore volumes, was plagued by mysterious noise sources in an area hundreds of kilometres from the nearest cloud and 50 km from the nearest settlement. The majority of readings were either unusable or show very little water signal, although prior and subsequent drilling confirms this is false.

Figure 1. Location of the Taca Taca deposit.

METHOD AND RESULTS

Given the initial geophysical model, electrical and electromagnetic methods were deemed appropriate for defining potential water resources. This included moving-loop ground EM (MLEM), surface and downhole galvanic resistivity, and surface nuclear magnetic resonance (NMR). The NMR and MLEM followed one another along the same profile lines, with the complementary objectives of using the NMR to detect the water table and volume of pore water in the top 70-80 m, and the MLEM to map the overall depth of gravels. From these two datasets, a volume of water was to be modelled in the basin. Prior to starting any surface surveying,

a single downhole resistivity log in water exploration hole T23 provided the confidence to proceed with the geophysical assumptions. The gravels average 50 Ω·m and there is a jump to many hundreds of Ω·m in the bedrock for all different electrode spacings in the log (Figure 3). The transition depth from gravels to bedrock at 124 m in the geology log corresponds to this resistivity jump.

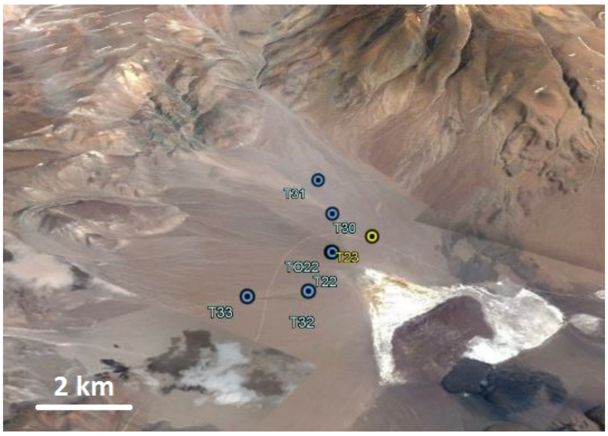

Figure 2. Google Earth image of water bore collars in the Vega de Arizaro, with a small salar (salt lake) at the bottom of the valley. T23, in yellow, is the site of the initial resistivity log.

Moving-loop Ground EM

MLEM soundings were planned to map the depth of more conductive gravels and provide the volume of potential aquifer above the bedrock. A loop of 200 x 200 m was combined with a Geonics EM-37 transmitter producing 20 A of current and a PROTEM 20-channel receiver. Data were recorded at both 25 and 2.5 Hz, both of which contributed to 1D layered inversions. The results of the soundings are overwhelmingly opposite to what was expected: a more resistive near-surface gives way to ever increasing conductivity with depth, as shown in the example of Figure 4. While the model curves are calculated to greater than 600 m, below this depth they appear completely unconstrained.

Confusion over the EM results increased with the opposite trend in resistivity below 100 m occurring between the borehole log for T23 (Figure 3) and the EM sounding taken at the same spot (Figure 5). At this point, faced with the inability to trace a bedrock boundary, a new approach was initiated with overburden modelling using only the 25 Hz data, ignoring the elevated late-time responses. Model data was calculated to fit an overburden plate to the first 9 MLEM channels using the Maxwell™ overburden plate algorithm (ElectroMagnetic Imaging Technology). This early-time model data alone was then inverted using EMAX conductivity-depth imaging software by Fullagar Geophysics Pty Ltd. This workflow effectively reverses the resistivity transition from surface to depth, as shown in Figure 6 for one section. Top of basement surfaces were created using various resistivity thresholds, and a 50 Ω·m surface provides the closest match to the bedrock intersection of T23, the only existing hole entering bedrock at the time. It is unclear whether T22, drilled in the same campaign, finished in bedrock or still in gravel at 192 m.

The next stage involved drilling more exploratory holes, which were only partly influenced by the geophysics so far modelled. One of the objectives of the new drill program was to test gravel depths and water levels upslope of T23, where the EM model now indicated shallow gravel and the NMR results were mostly negative (c.f. blue drill collars in Figure 2). The string of confusion continued when these upslope holes drilled much deeper gravel than the 124 m in T23: 326 m in T30, 298 m in T31, 289 m in T32, and 265 m in T33. This now suggests that the top of bedrock gets deeper away from the salar that sits in the low point of the basin, a topography that does not follow expected bedrock slopes under the gravel.

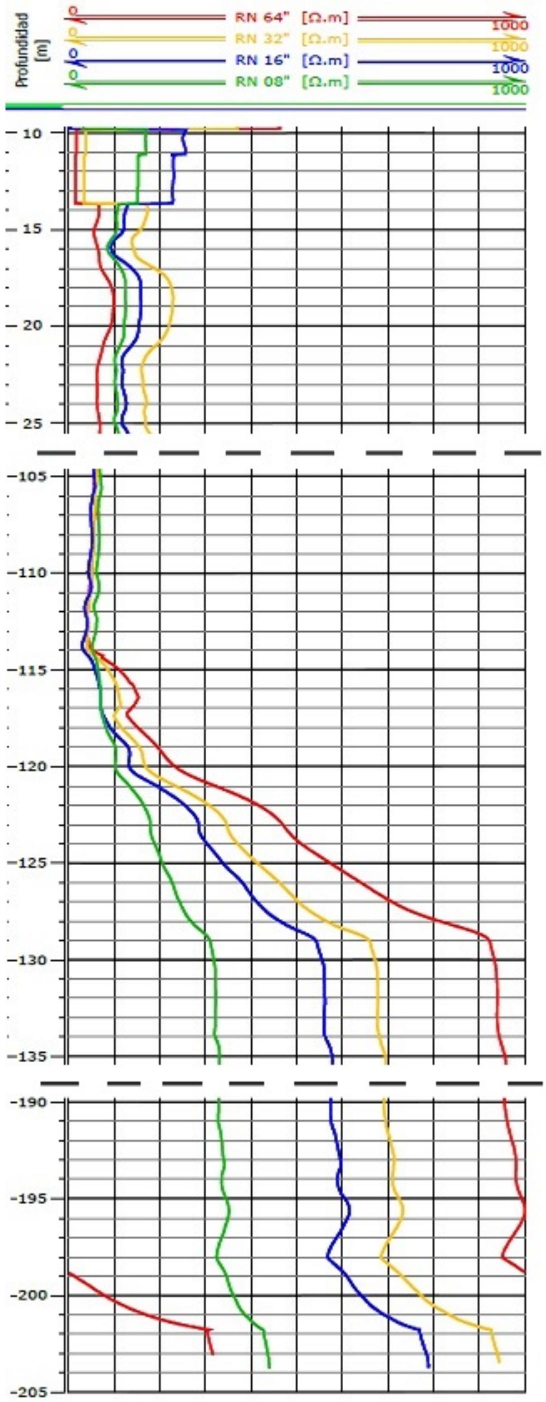

Figure 3. Downhole resistivity log for T23 (discontinuous depth scale), showing the expected change from conductive gravels up to ~120 m depth to resistive bedrock below.

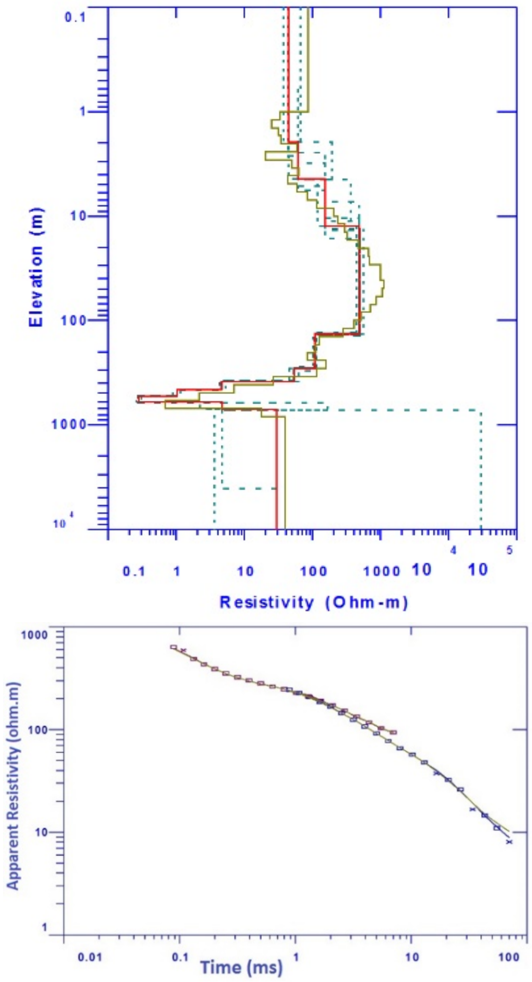

Figure 4. Typical EM sounding showing decrease of resistivity with depth. (Top) Multiple equivalent 1D resistivity models fitting (bottom) 25 Hz (red) and 2. 5 Hz (blue) sounding curves.

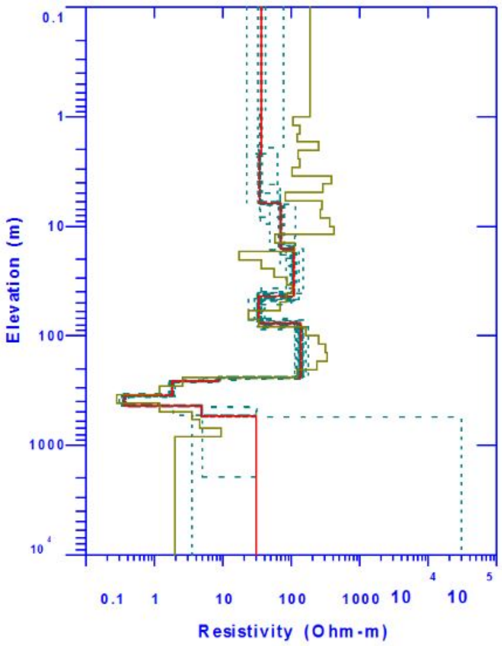

Figure 5. Equivalent 1D resistivity models for an EM sounding at the site of borehole T23, showing the opposite trend to the borehole log below 100 m (c.f. Figure 3).

Downhole resistivity logs in the new drill holes produced an about-face relative to the log of T23, showing, like the ground EM, profiles of decreasing resistivity with depth (Figure 7). This, combined with the deeper than expected gravels, has caused a rethink of the validity of the original ground EM soundings. It is quite possible that the signal reflects this increasing conductivity at depth and does not see resistive basement out of reach below. Analysis of the water sampled from the boreholes does not indicate an increase in salinity with depth, therefore the source of the deep conductive zones must be from the rock mass.

Galvanic Resistivity

Given the counterintuitive ground EM results, and prior to the most recent drilling, an independent model was provided by some galvanic resistivity soundings collected in Schlumberger arrays. The majority of these also show a steady decrease of resistivity with depth (Figure 8). It is unlikely that galvanic currents, input with a transmitter of maximum 1260 V, would penetrate as deeply as the inductive EM currents, and therefore the soundings would not generally sense bedrock. The correspondence with the EM reinforces the hypothesis that gravel is deep, but the source of the conductivity at depth remains conjecture. In a twist to the story, the vertical electric sounding taken beside T23 appears to corroborate the borehole log that set the initial geophysical model – the resistivity model jumps in amplitude from 45 Ω·m to about 250 Ω·m at 120 m below surface (Figure 9). This is remarkably consistent with the borehole log in both amplitudes and depth. Ignoring the EM sounding at this site, this suggests that bedrock may indeed be shallower here than in all other drill holes.

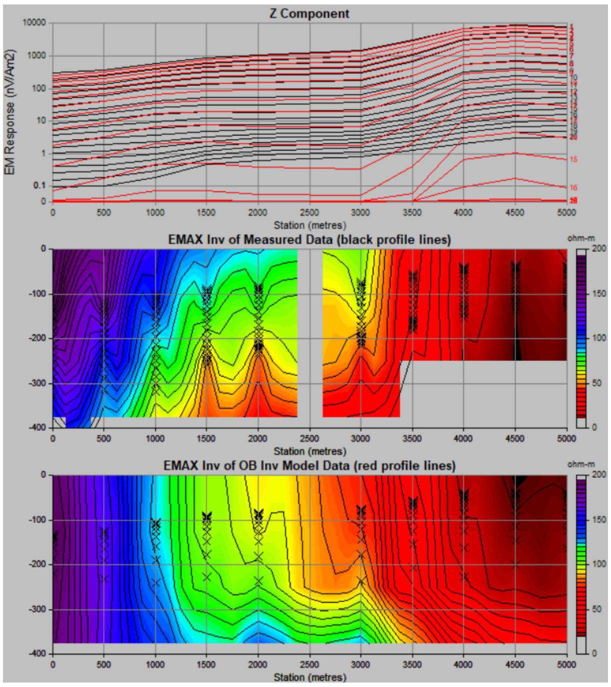

Figure 6. (Top) Maxwell overburden modelling to fit the first nine time channels of the MLEM data. Black profiles are the measured data and red profiles are the model data. (Middle) EMAX inversion of the original measured data and (bottom) EMAX inversion of the model data.

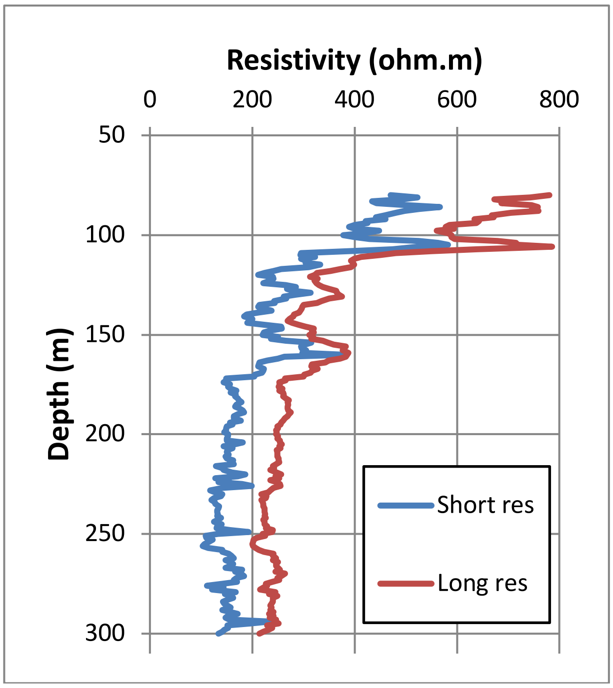

Figure 7. Downhole resistivity log (short and long electrode spacing) for T31.

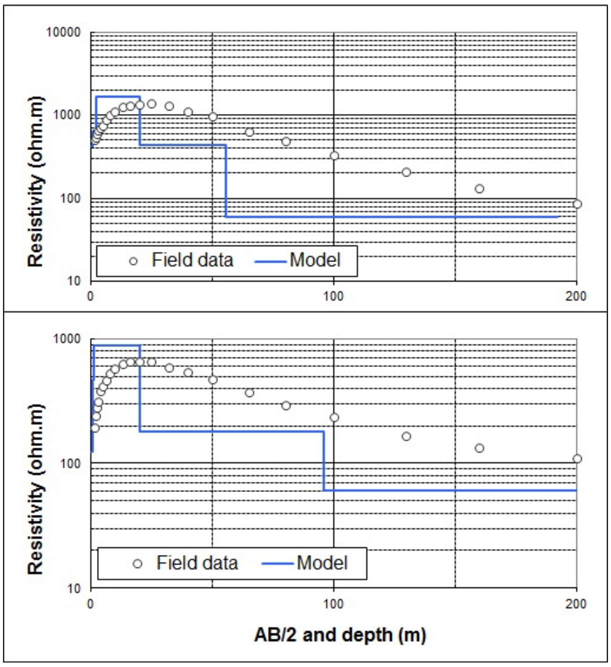

Figure 8. Two vertical electrical soundings showing typical marked decrease in resistivity with depth.

Nuclear Magnetic Resonance

Nuclear magnetic resonance is a technique to directly detect the presence and abundance of hydrogen atoms (Hertrich, 2008; Walsh, 2008). An external magnetic field, applied at a specific resonance frequency appropriate to the substance under investigation (in this case H), perturbs the atoms from their natural alignment or polarisation under the Earth's magnetic field. In the off-time, the relaxation of the nuclei occurs at the intrinsic Larmor frequency associated with the substance, and this is measured as an induced voltage in a coil. In surface NMR, the external magnetic field is produced with a loop, such that the survey progresses much like MLEM. The majority of the time, the abundance of hydrogen is directly related to the volume of water, and via the relaxation time of the signal, the technique can discriminate between bound water, e.g. in hydrated minerals like clays, and free water, which flows through permeable rock and can be extracted. Given the average 50 Ω·m resistivity of the gravels suggested by the original downhole resistivity log, the NMR at Taca Taca was expected to be effective for the top 80 m. The technique should detect the top of the water table and an idea of porosity away from the existing water bores. By assuming saturation from the top of the water table to the base of gravels (which would be mapped by the MLEM), one could calculate an approximate volume of contained water in the basin.

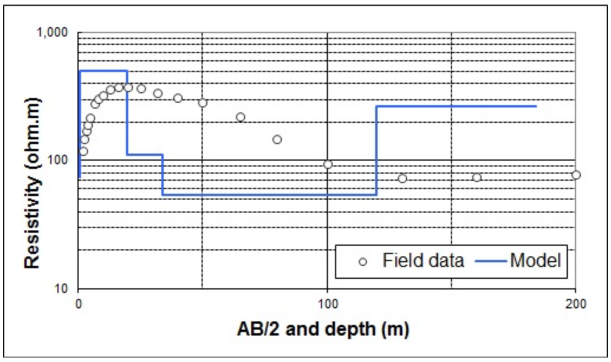

Figure 9. Vertical electrical sounding beside T23 showing atypical but logical higher resistivity at depth.

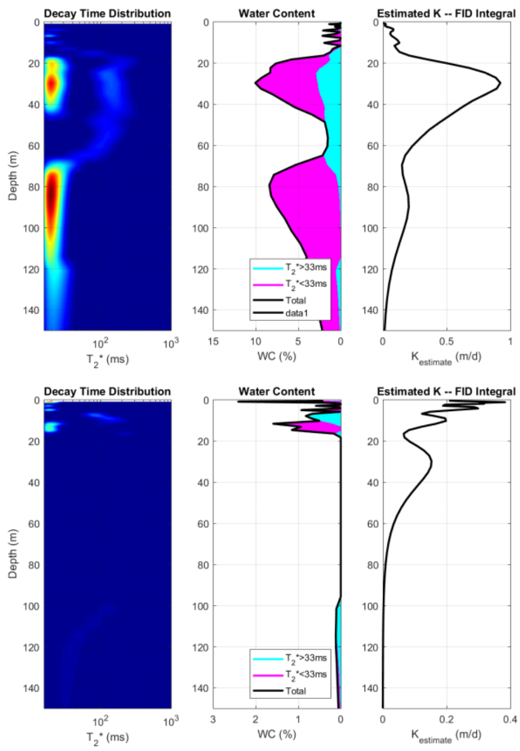

Figure 10. (Top) Good quality NMR data inverted for water content, and (bottom) poor quality sounding inverted and showing no water right beside the producing borehole T22. Pink areas under the 1D inversion curves relate to free water, and cyan areas reflect bound water.

The data collection was plagued by electromagnetic interference of unknown origin, with very high noise levels (>25 nV) obscuring any signal at many stations. While the sky

was cloudless for hundreds of km in all directions, sferics may travel well over a thousand km and could be the culprit. Wind levels were also high and very constant from 8h00 onwards every day, although there was no evidence in the data for specific frequencies related to wind-induced vibration of the loop or instruments. In the end, very few stations returned a positive signal for water, even in areas where this is demonstrably false (Figure 10, bottom). This may be partly due to the low magnitude of the geomagnetic field at Taca Taca, which, in conjunction with the low inclination, results in a signal only 25% the strength of what would be received in the central USA or Europe (Hertrich, 2008). The absence of a water signal even with low-noise data can sometimes be attributed to local magnetic anomalies that distort the IGRF. This changes the Larmor frequency to which the transmitter has been tuned, and therefore the excitation of the H atoms is less effective. Figure 11 shows, however, that there is little in the way of strong local magnetic anomalies in the NMR survey area, with a range of -20 to -100 nT. Given the gyromagnetic ratio of 0.0426 Hz/nT for H (calculated from Hertrich, 2008), a change of 100 nT translates to a change of only ~ 4 Hz in the Larmor frequency.

In the end, the NMR was adopted as a dataset with no false positives but admitting an unknown number of false negatives. It was not used with confidence to map the surface of the water table or the probable volume of saturated gravel.

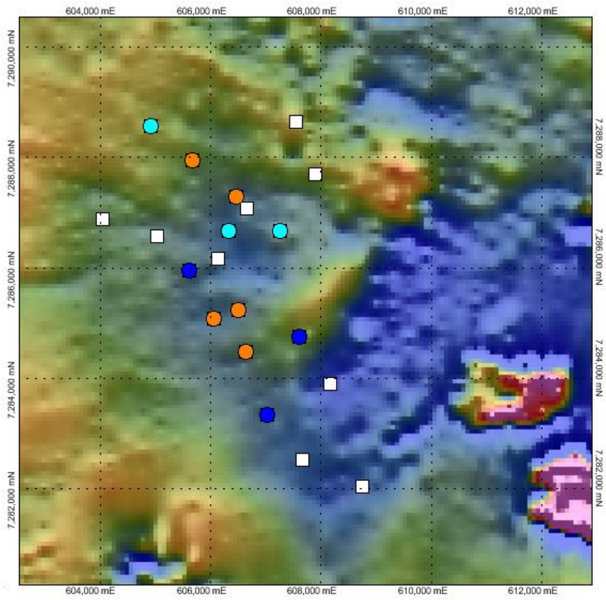

Figure 11. NMR stations over RTP magnetic field. There are no significant magnetic anomalies that would distort the geomagnetic field near NMR stations and affect the Larmor frequency used to perturb H atoms.

CONCLUSIONS

A series of contradictory and counterintuitive geophysical measurements has bewildered those involved in their interpretation during the effort to locate and define fresh water resources for a mine development in northwestern Argentina. Initially disconcerting MLEM results show conductivity increasing with depth and no clear contact with resistive basement, contrary to a prior borehole resistivity log. Following the MLEM, galvanic resistivity soundings reinforced this general depth profile in most places, highlighting the need to explain the phenomenon lithologically because there are no observations of increased salinity in the water sampled during drilling. More recent drill holes have extended the probable depth of gravels upslope of the basin centre. This complicates the assumed bedrock topography, but together with new borehole resistivity logs that corroborate the deep conductive zone, the deep gravel that was drilled explains the EM and resistivity data that do not detect basement. The positive aspect to a deeper basin away from the central salar is the possibility of a large water reservoir that can be pumped without drawing down the recharge into the salar. While not at the moment affecting the new interpretation of the gravel volume in the basin, the cause of the deep conductivity remains a mystery.

ACKNOWLEDGEMENTS

Vista Clara Inc. collected and inverted the NMR data, struggling and experimenting through the frustration of an apparently noisy environment. Quantec Geoscience Argentina S.A. carried out the MLEM surveys and provided 1D inversions. Nigel Cantwell of Resource Potentials Pty Ltd tried to creatively re-model the perplexing MLEM results. Mercoaguas collected both the surface and downhole galvanic resistivity data. All parties were privy to my frustration with the confounding results.

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