VISTACLARA INC.
NMR GEOPHYSICS

NMR Logging for Hydrogeologic Characterization of Lithium and Other Brine-based Mineral Resources

Introduction

Many critical mineral resources including lithium, uranium and potash are produced as brine groundwater resources. These critical minerals are typically found in highly saline groundwater in arid closed basins, and beneath dry lake beds. Production of brine-based mineral resources entails pumping mineral-rich brine from permeable brine aquifers and separating the minerals from water at the surface. The majority of the world's lithium stores are located in brine aquifers, and brine-based mining is presently the most economical way to produce lithium [1].

NMR logging tools were originally developed for oil and gas exploration where they have been used for more than 30 years to measure reservoir properties including total porosity, bound and mobile porosity, permeability and differentiation of oil, gas and water. In 2011, Vista Clara introduced Javelin®: the world's first small diameter NMR logging tools aimed at groundwater and environmental investigations.

In the 13 years since, Vista Clara has expanded our Javelin® NMR logging product line to include a wide range of wireline NMR logging tools (Javelin® Max, Slim, and Micro). Vista Clara also introduced the unique family of Dart™ person-portable NMR logging tools.

The key value that NMR logging tools provide in these applications are direct, continuous and high-resolution measurement of aquifer properties including total porosity, effective porosity and hydraulic conductivity.

This NMR-derived information on producible water volume, combined with the dissolved mineral concentration, can be used to define the size of the producible mineral resource. In addition, the NMR-derived hydraulic conductivity is highly useful for optimizing wellfield design and optimizing production.

NMR has key advantages over other geophysical logging methods, and these advantages are especially pronounced in brine and saline groundwater applications. Electrical resistivity measurements (E-logs or induction logs) are ambiguous in electrically conductive brines, whereas NMR logging tools are largely insensitive to the electrical properties of the subsurface and the salinity of groundwater itself.

Hence, in recent years, brine-based mining operations have adopted NMR logging as a key technology for exploration and development of brine-based mineral resources.

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Technical Advantages of Javelin® and Dart™ NMR logging tools for Brine-based Mineral Resource Investigations:

Javelin® and Dart™ NMR logging tools have specific features that make them especially well-suited to NMR logging in salt water and brine aquifers.

1. Robust and stable performance in highly electrically conductive groundwater.

Saltwater aquifers exhibit high electrical conductivity compared to freshwater aquifers. Elevated electrical conductivity can cause significant inductive loading of the NMR sensor coil via eddy current generation in the surrounding conductive sediments and water. This in turn leads to attenuation of the high-frequency B1 magnetic field in the sensitive regions of the NMR measurement, which in turn leads to errors in the NMR measured porosity. Javelin® and Dart™ NMR logging tools have specific design features that make them less susceptible to the effects of electrically conductive fluids than other available NMR logging tools:

• **Numax™ magnet/coil design.** The Javelin® and Dart™ probes utilize an innovative magnet/coil array called Numax™, which uses detection coils oriented perpendicular to the vertical axis of the tool. This design reduces the potential for generating undesirable circular eddy currents around the tool, compared to alternate magnet/coil designs that use axially-oriented detection coils [2].

• **Lower operating frequency.** The standard and high-resolution Javelin® and Dart™ tools operate at lower frequencies than competing NMR logging tools. The electrical "skin effect" of conductive fluids and bodies is frequency-dependent, and thus operating a lower frequency minimizes attenuation of the RF B1 magnetic fields in the NMR sensitive zone, improving the robustness and stability of the water content measurements in highly conductive brine.

• **Moderate Q-factors and proprietary Q-scaling technology.** Javelin® and Dart™ NMR tools use detection coils with moderate Q-factors that exhibit relatively small changes when immersed in electrically conductive fluids. Changes in coil Q-factor are continuously recorded during logging, and a proprietary algorithm is automatically applied to correct for changes in Q-factor, ensuring accurate water content measurement in all conductive fluid environments. Table 1 shows the measurement of water content before and after Q-scaling that is capable of compensating for signal loss in highly conductive media.

	Probe ID	Fresh Water	5% NaCl Brine	10% NaCl Brine
Before Q-scaling, no Salinity compensation	Dart DP140N	100%	94%	91%
	Javelin JPY238N	100%	92%	90%
Before Q-scaling, with Salinity compensation	Dart DP140N	100%	98%	95%
	Javelin JPY238N	100%	94%	94%
VC proprietary Q-scaling, no Salinity compensation	Dart DP140N	NA	94%	98%
	Javelin JPY238N	NA	96%	98%
VC proprietary Q-scaling, with Salinity compensation	Dart DP140N	NA	96%	102%
	Javelin JPY238N	NA	98%	102%

Table 1: Experimentally measured water content for Dart and Javelin probes calibrated in fresh water and then immersed in 5% and 10% NaCl brine solutions.

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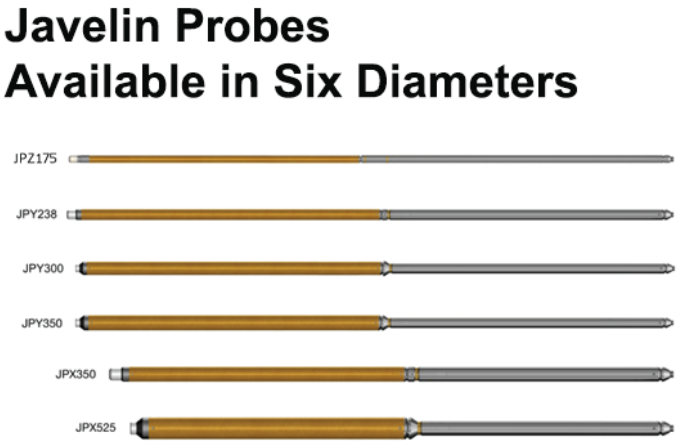
2. Ability to operate in a wide variety of borehole sizes.

Exploration boreholes and production wells for brine-based mineral extraction are drilled with a wide range of diameters and completed using a wide range of casing methods. At the small end of the range are 3-inch core holes, and 2-inch PVC-cased wells constructed in 7- to-8-inch borings.

At the large end of the range are 17-inch diameter open hole pilot wells, and 6- to 12-inch PVC- or fiberglass-cased wells constructed in 14- to 18-inch borings. Javelin® NMR logging tools are available in a wide range of diameters to cover the entire range of lithium exploration and production wells as shown below. All Javelin tools have multi-frequency operation enabling each tool to operate in a larger range of borehole and well diameters compared to any single-frequency NMR logging tool.



Javelin Probe ID	Borehole Diameter (inches)	
	Min	Max
JPZ175D	2	4
JPZ175A	2	6
JPZ175E	2	8
JPY238N	3	9
JPY238T	3	11
JPY300N	4	13
JPY350N	4	13
JPZ525N	6	18

Figure 1: Left: illustration of Javelin NMR logging tools available in 6 different diameters to suit the widest range of borehole diameters. Right: table of the range of borehole diameters that each Javelin probe can effectively log.

Dart™ tools are the world's only person-portable and direct push/CPT deployable NMR logging tools. Dart's unique capabilities enable low-impact NMR investigations in shallow brine resource investigations, including single person logging of 1.5-inch and 2.0-inch PVC cased wells, and open boreholes as small as 1.5 inches in diameter.

Dart tools can also be deployed directly via direct push or CPT machines, including via lightweight drilling technology appropriate for drilling small and shallow boreholes in low-density dry lakebed sediments where heavy drilling machinery and vehicle-based geophysical logging is not possible (Figure 2).

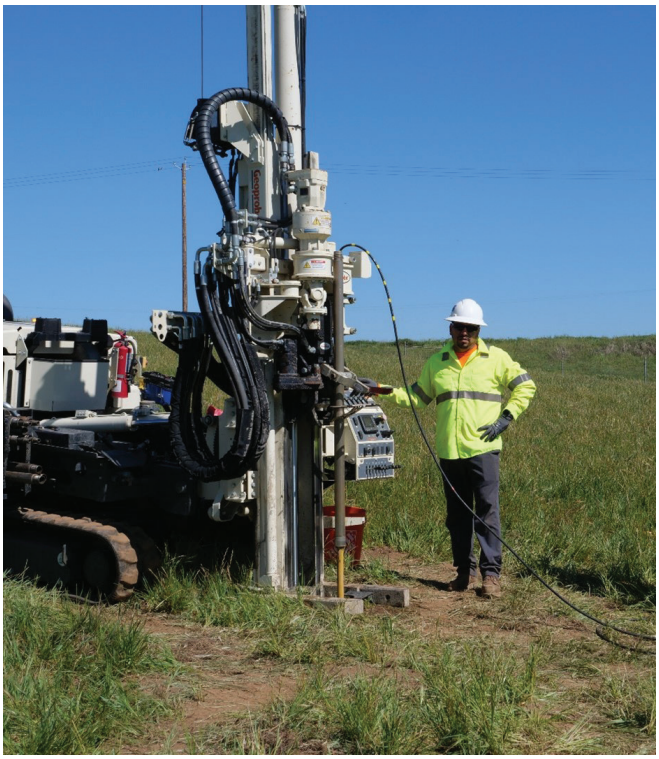


Figure 2: Dart™ NMR probe deployed by direct push machinery.

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3. Multi-frequency operation:

All Javelin® and Dart™ tools incorporate multi-frequency operation, which enables simultaneous collection of independent NMR data at multiple diameters of investigation – at no cost in logging speed or vertical resolution. This is like performing multiple logs with different single frequency NMR logging tools. This capability gives each tool the ability to obtain the highest possible SNR when all the NMR measurement shells are in the undisturbed formation, as shown in Figure 3. In cases where only the outermost shells are beyond the disturbed zone, only those shells can be used for measurements.

In comparison to a single frequency NMR probe, the multi-frequency operation of Javelin and Dart probes provides an opportunity to determine the radial variability in the formation or borehole, offering the potential to provide information about borehole or drilling conditions. This capability can be used to identify zones with washouts or invasion of drilling mud into the formation. In the example in Figure 4, increased bound water content was detected in the inner shell, compared to the outer shell. This enabled the correct interpretation of inadvertent detection of drilling mud in the borehole, and exclusion of the inner shell data from the interpretation.

A single frequency NMR logging tool offers no such means for identifying drilling mud in the open borehole or in large pores, and could result in a misinterpretation as capillary bound water in a low permeability formation, which would result in a diametrically wrong interpretation of a formation that has large pore spaces and high permeability.

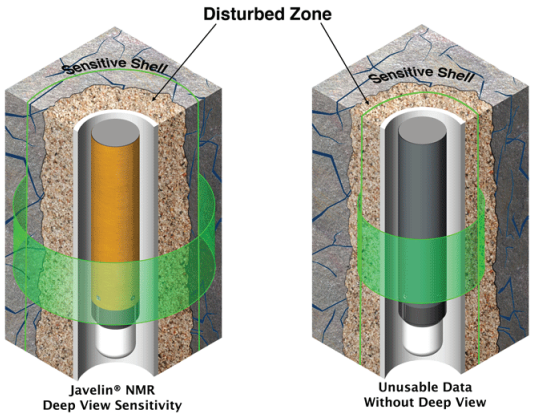

Figure 3: Multiple NMR Measurement Shells with deep view sensitivity enable data acquisition from areas beyond the disturbed zone that results from drilling processes.

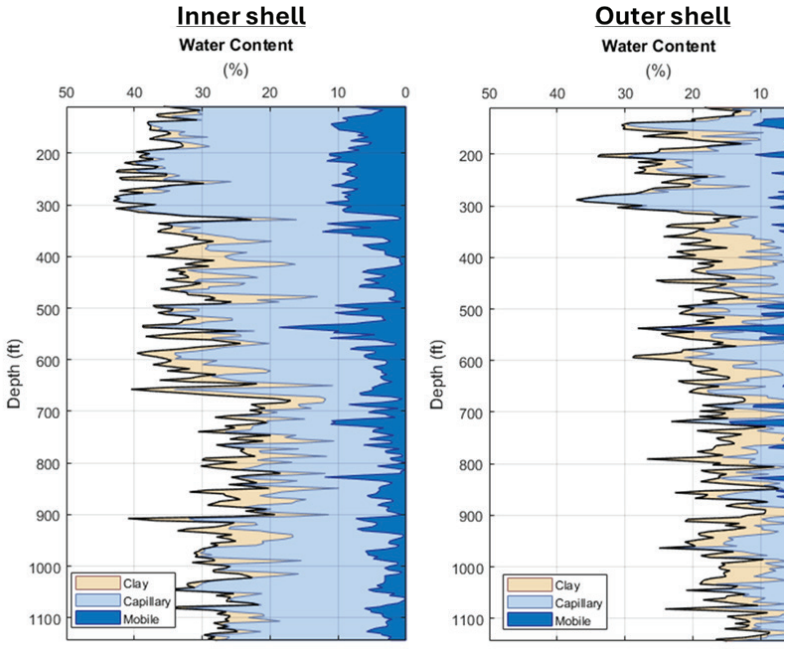

Figure 4: The multi-frequency NMR logging tool allows radial profiling to identify detection of drilling mud in the open borehole, and the invasion of drilling mud into the formation. Left:In this example the innermost shell is not fully in the native formation, and some inadvertent detection of drilling mud in the borehole leads to inaccurate overestimation of porosity and capillary-bound water in the formation. Right: The absence of excessive capillary bound water in the outermost indicates that the NMR data in the innermost shell is compromised by detection of drilling mud in the borehole, hence the inner shell was excluded from the final interpreted NMR log. This capability is not available when using a single-frequency NMR logging tool.

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4. Reduced susceptibility to electromagnetic noise.

Javelin® and Dart™ tools operate exclusively below the AM broadcast band and incorporate proprietary Numax™ electronics to provide greatly increased suppression of electromagnetic interference (EMI).

Conducted EMI originates in the power source used to run the logging equipment or in other electronics connected to the system (e.g., winch motors and controllers, laptop power supplies, and computer monitors).

Radiated EMI originates from the environment (e.g., thunderstorms) and nearby cultural sources (e.g., pumps, machinery, and RF transmissions). If uncorrected, EMI from these sources can contaminate the NMR signal, generating spurious features in logs and lowering confidence in the results.

The Numax sensor electronics package significantly reduces the impact of these external EMI sources. The EMI suppression effects are most pronounced when logging near the surface, above the water table, or in dry boreholes. A real world example of the power of Numax noise suppression electronics is shown in Figure 5.

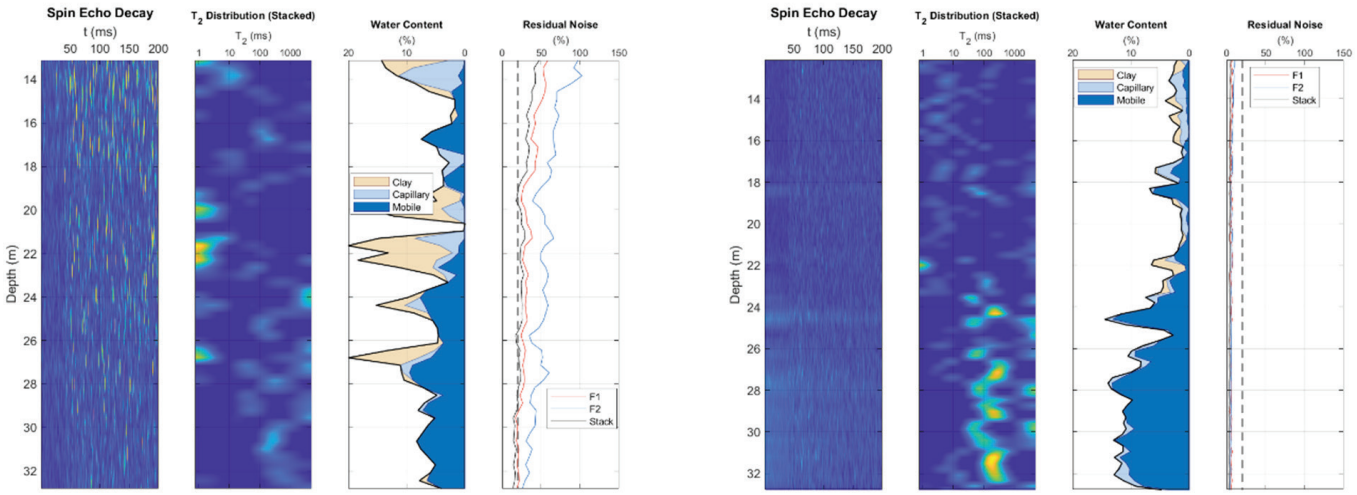

Figure 5: Demonstration of Numax™ noise suppression technology. Two Javelin NMR logs collected in the same section of borehole on the same day, one without the Numax configuration (left) and one with the Numax configuration (right). Residual Noise levels from EMI interference are greatly decreased with the Numax configuration, resulting in a reduction of spurious artifacts in the log, particularly in bound water content.

The following sections provide examples of

Javelin and Dart NMR logging tools in brine mineral resources.

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Sociedad Química y Minera (Chile - Lithium)

Sociedad Química y Minera (SQM) is currently the world's second largest producer of lithium and is possibly the first organization to use NMR logging to estimate lithium brine mineral reserves and optimize exploration and production for lithium brine resources. SQM operates a large lithium brine extraction and processing facility at the Salar de Atacama (Figure 6). Salar de Atacama is the Earth's largest and purest active source of lithium and accounts for 27% of the Earth's known lithium reserves [3].

SQM pioneered the use of NMR logging to estimate the producible porosity of brine aquifers and to combine the NMR-derived producible porosity with measurements of dissolved lithium content to estimate the lithium resource size.

SQM has been using Javelin® NMR logging tools since 2016 to log exploration, production and monitoring wells throughout the Salar de Atacama in northern Chile. As of April 2023, SQM has performed Javelin™ NMR and/or additional logs in at least 566 boreholes in the Salar de Atacama, totaling over 50,000 vertical meters of NMR measurements [4].

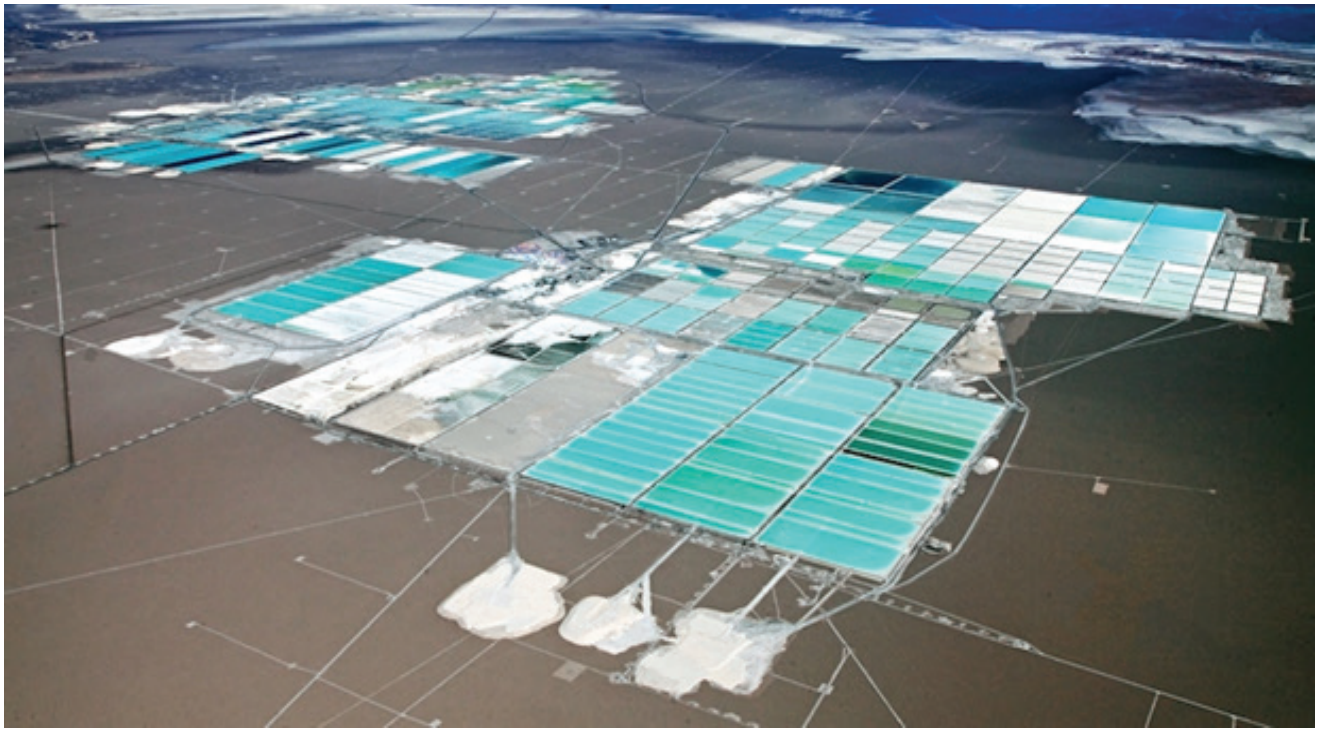

Figure 6: Evaporation ponds in the Salar de Atacama, in Northern Chile. (Image courtesy of SQM.)

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Sociedad Química y Minera (Chile - Lithium) (continued)

Today SQM owns and operates several Javelin™ NMR tools at the Salar de Atacama. These include 1.75-inch diameter Javelin tools that are used to log 2-inch PVC-cased monitoring wells (Figure 7), and 2.38-inch Javelin tools that are used to log open holes prior to installation of casing, and to log 3-inch and 4- inch diameter PVC-cased monitoring wells. The NMR data from these tools are used for lithium resource estimation, optimization of well construction, and optimization of production.

Figure 8 shows an example of an NMR log acquired by SQM using a Javelin® JP238 probe in a 3-inch PVC-cased monitoring well in Salar de Atacama. This example illustrates the information content provided by the NMR log, including the continuous high-resolution estimate of the producible (mobile) water content throughout the log, the dual porosity (mix of matrix water and fracture water) in the halite formation from 10-44m, and the clay-rich formation from 45-72m.

Figure 7: SQM personnel deploying a Javelin JP175 NMR logging tool in a 2-inch diameter PVC-cased monitoring well.

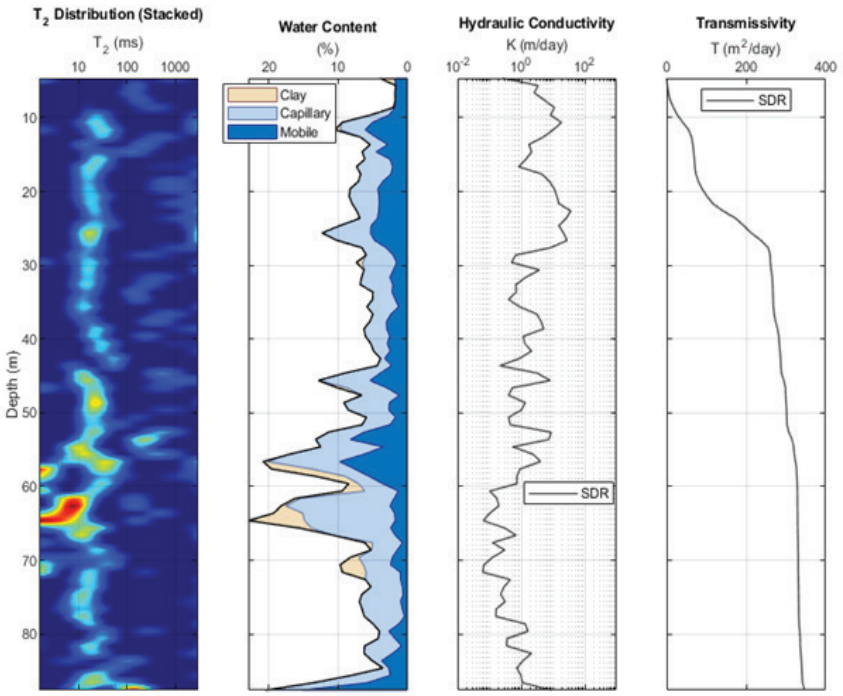

Figure 8: Javelin NMR log of a mixed formation of halite, gypsum and clay in the Salar de Atacama.

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Andina Perforaciones and Conhidro (Argentina – Lithium and Freshwater Resources)

Andina Perforaciones and Conhidro are a team of private companies that perform well drilling and hydrogeological consulting on groundwater development projects in Argentina. Andina Perforaciones performs the well drilling and installation, and Conhidro provides all of the technical and scientific support for the wells, from prospecting through geophysical methods, geological control of drilling and final evaluation of the well with pumping tests.

Andina Perforaciones and Conhidro have actively participated in most of the Lithium projects that are being developed in the Northwest of Argentina within what is known as the Lithium Triangle that covers the countries of Argentina, Chile and Bolivia. Since 2021, Conhidro has used Vista Clara's Javelin® Max system to determine the most productive zones within pilot wells based on NMR-estimated effective porosity and hydraulic conductivity.

Conhidro's use of the Javelin® Max has enabled their customers to reduce costs and risks associated with exploration, well construction and production management.

Figure 9 shows a Conhidro-acquired Javelin® NMR log of a lithium resource exploration borehole drilled under a salt flat in northern Argentina. This log was acquired using a Javelin® Max NMR logging system with JPX525 three-frequency probe, with a maximum diameter of investigation of 21 inches.

This NMR log identifies varying detritic and evaporitic sections with depth, with the majority of potential production estimated to be in the lower half of the well (as indicated by the NMR-derived transmissivity curve).

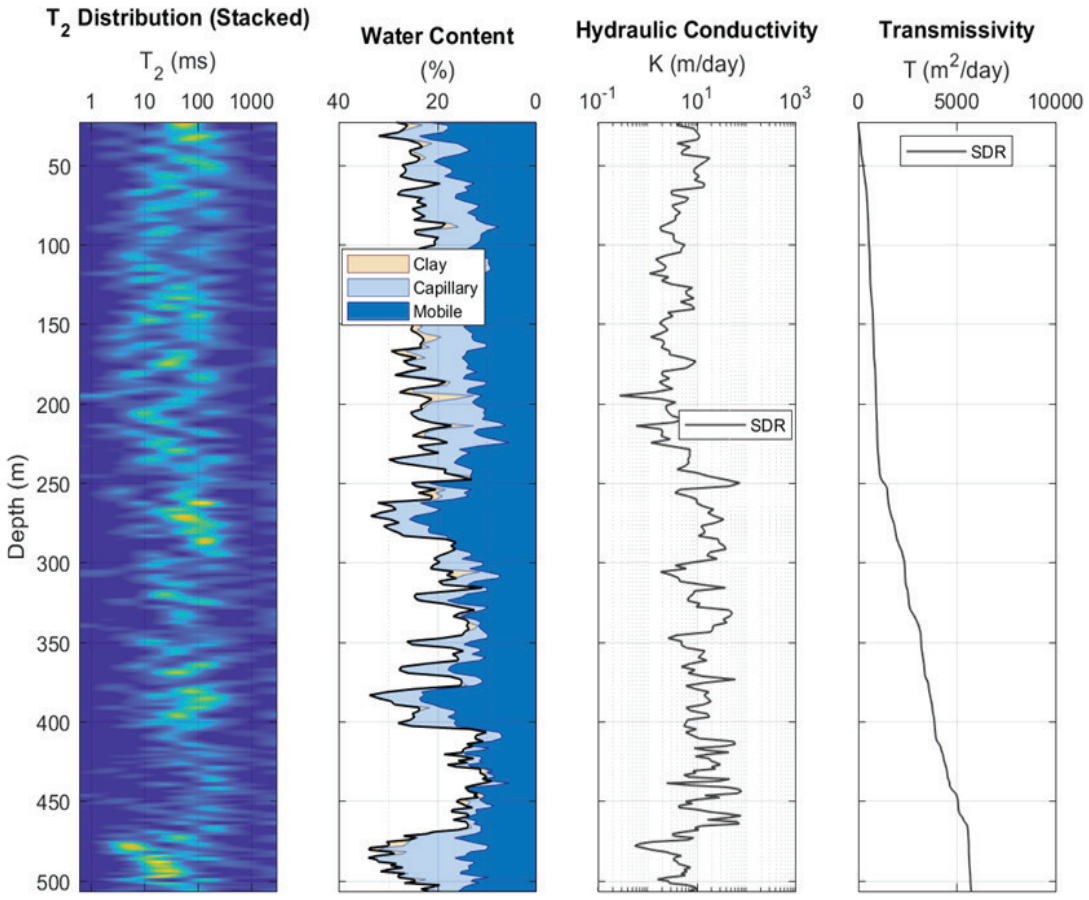

Figure 9: Javelin NMR log of a lithium resource exploration well in Argentina, 2022. This well was drilled by Andina Perforaciones and the NMR log was acquired by Conhidro using a Javelin Max with JPX525 probe.

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Andina Perforaciones and Conhidro (Continued)

Conhidro is also applying their Javelin® Max NMR tool for exploration and development of fresh groundwater resources. Figure 10 shows a Conhidro-acquired Javelin® Max NMR log of a well in the semi-arid Chaco Plain area of Argentina. The purpose of this well was to provide drinking water to an indigenous community. This area has the particularity that there is brackish water from the surface to depths of 300 meters, and from there, layers of sand with fresh water appear.

The Javelin® NMR log in this example clearly highlights two freshwater aquifer units between 300 and 400m, and the Javelin® NMR log was used to determine the optimal well-screen location, which resulted in a successful and productive water supply well for an indigenous community.

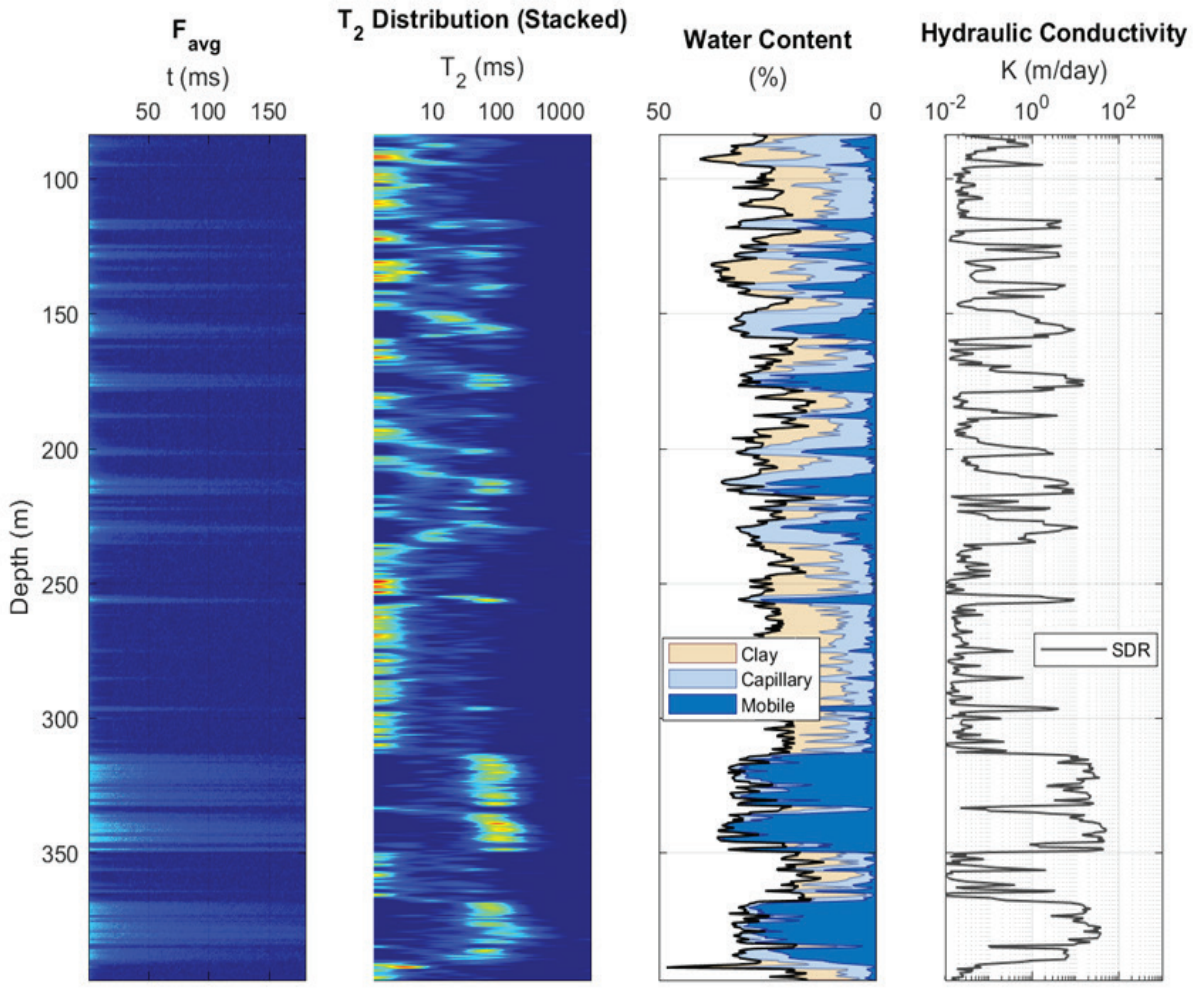

Figure 10: NMR log acquired by Conhidro, using a Javelin® Max with JPX525 probe, in the Chaco Plain region of Argentina. This area has an unusual distribution of brackish water in the upper 300m, and productive freshwater-bearing sand aquifers below 300m. The Javelin® log in this example clearly highlights two freshwater aquifer units between 300 and 400m, and the Javelin® NMR log was used to determine the optimal well-screen location, which resulted in a successful and productive water supply well for an indigenous community.

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Agrimin (Australia – Potash)

Agrimin Limited (Agrimin) is developing a greenfield potash fertilizer operation at Lake Mackay, in Western Australia. Lake Mackay is estimated to be the world's largest undeveloped sulphate of potash (SOP) brine deposit.

This very shallow brine-based resource is being developed in an innovative way, through low-cost drainage trench technology, as illustrated in Figure 11.

Figure 11: On-lake development of test production trenches used for brine resource extraction at Agrimin's Lake Mackay production facility.

In 2018-2020, as part of the initial exploration project, Agrimin used Vista Clara's Dart™ and Javelin® portable NMR logging tools to evaluate the brine-based potash resources in the shallow subsurface beneath the dry Lake Mackay. The availability of the single-person-portable Dart™ NMR logging system was critical to this project, because the low density sediments on the surface of the dry lakebed are not able to support typical drilling equipment and typical geophysical well logging vehicles. Instead, Agrimin employed special-purpose lightweight drilling equipment to install shallow (~5m deep) 2-inch PVC monitoring wells, and used the person-portable Dart™ system to collect the NMR logs in most of these wells.

Figure 12 shows a photo of the all-terrain vehicles that were used to move the Dart™ equipment to well sites across Lake Mackay, and a Dart™ control unit on the back of a towed equipment trailer.

Figure 12: Photo of Vista Clara Dart™ equipment being used by Agrimin to log shallow 2-inch PVC cased monitoring wells on the dry bed of Lake Mackay, Western Australia. The lightweight Dart™ tool was essential to getting in-situ NMR data in this environment, as the low-density sediments of the lakebed would not support typical drilling and geophysical logging vehicles.

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Agrimin (Australia – Potash) (Continued)

The Dart™ NMR measurements were utilized to estimate total porosity and specific yield, and provided similar results to those estimated from core samples, at much lower cost, and without the ambiguities associated with disturbance and loss of sample.

The benefit of using NMR is that it can provide a continuous log of mobile porosity enabling quantitative estimation of the brine-based mineral resource. Moreover, in addition to observations of lithology from core samples, the NMR log provides high-resolution site characterization information including sediment classification and estimates of hydraulic conductivity that can significantly improve groundwater flow model [5].

Figure 13 shows an example Dart™ NMR log of a 2-inch PVC-cased monitoring well at Lake Mackay The NMR log at this location indicates a primary production zone at depths between 1 and 3m with effective porosity of 28-34% and average hydraulic conductivity of about 10m/day. At this location, there are mostly fine sediments with low permeability below 3m.

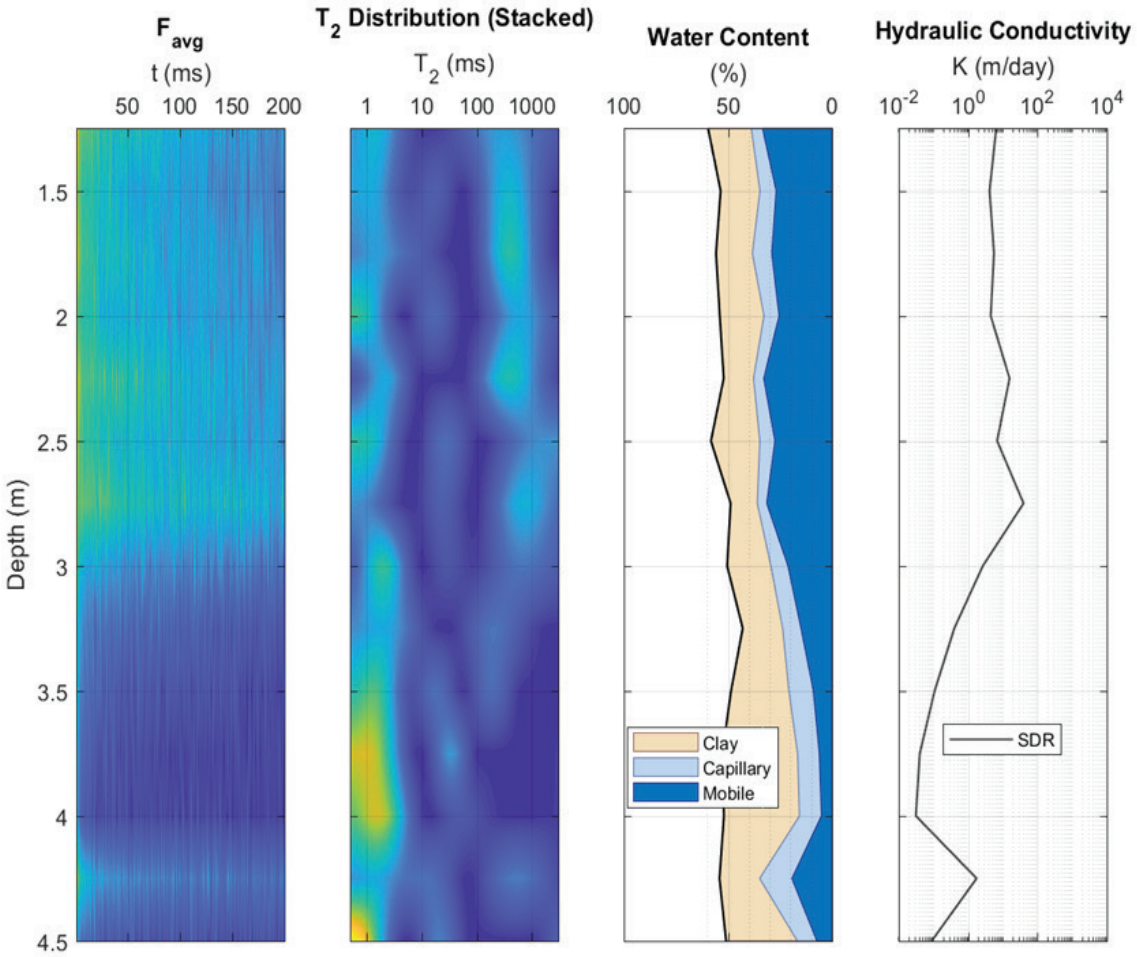

Figure 13: Dart NMR log of a shallow 2 inch PVC-cased well installed on the dry lakebed of Lake Mackay. The NMR logging data from this portion of the study were used to define the 3D lateral and vertical variability of mobile water and hydraulic conductivity. These NMR-derived parameters were used to estimate the brine-based mineral resource size and to optimize the design of the drainage trenches and production facilities.

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Agrimin (Australia – Potash) (Continued)

In a second phase of the project, Agrimin used Vista Clara's Javelin 1.75-inch diameter NMR probe to log five monitoring wells located approximately 15 km south of Lake Mackay and approximately 25 km southeast of the process plant [6] (see Figure 14). This area is being evaluated as a wellfield to supply water to the Lake Mackay Sulphate of Potash (SOP) project.

Figure 14: Javelin® NMR logging system with 1.75 inch diameter NMR probe, logging a 2 inch PVC-cased well in the proposed water supply wellfield for the Agrimin Lake Mackay Sulphate of Potash project.

The results of the NMR logging were used to develop a groundwater model at this site, to inform an environmental risk assessment of the proposed wellfield, and more recently to compile a H3 Hydrogeological assessment to support primary EPA approvals for the project.

The NMR logging results from one representative well (MWP-15) are shown in Figure 15. This NMR log identifies a favorable groundwater production zone from 60-85m, and a potential confining unit from 30-40m.

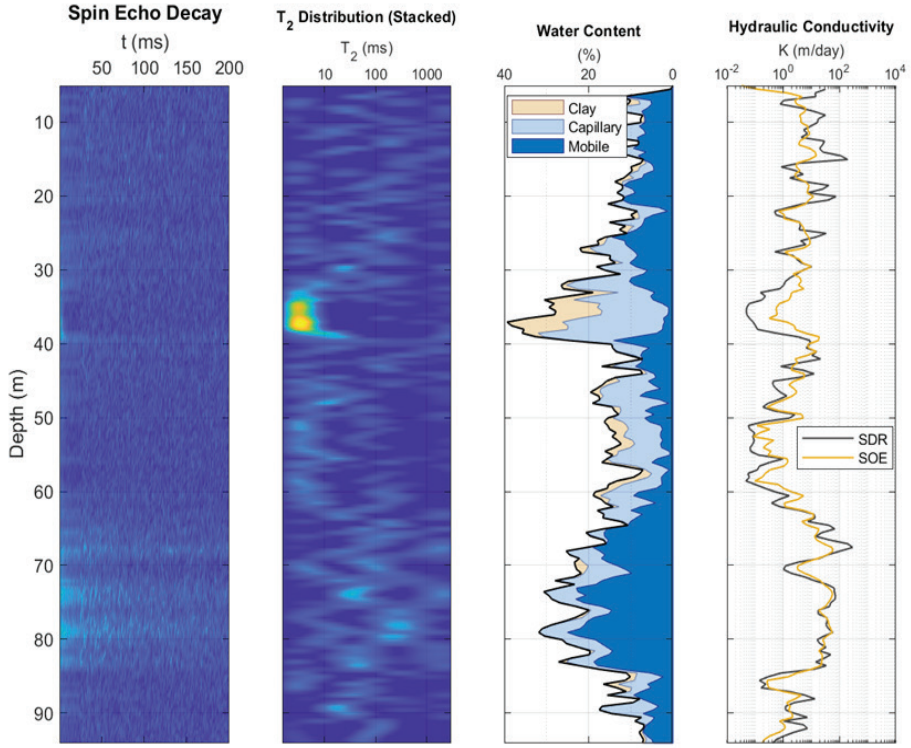

Figure 15: Javelin® NMR log of well MWP-6, at Agrimin's Lake Mackay water supply wellfield. This NMR log indicates a favorable groundwater production zone from 60-85m and a low permeability confining layer from 30-40m.

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Summary

Vista Clara's Javelin® and Dart™ NMR logging technologies have been successfully employed in a wide range of brine-based mineral resource development projects in the Americas and Australia.

Javelin® and Dart™ logging systems continue to be used successfully for exploration and production of numerous brine-based minerals, including lithium, potassium and uranium.

NMR logging measurements are especially valuable for brine-based groundwater investigations because the NMR data provide high-resolution, continuous measurements of the hydrogeological properties of primary interest: effective porosity and hydraulic conductivity, and the NMR measurements are generally insensitive to the electrical properties of the subsurface.

Javelin® and Dart™ tools have specific design features that enable stable, reliable and high-quality NMR measurements in near surface brine aquifer environments.

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[5] Agrimin Hydrogeological Fieldwork Update

[6] MACKAY POTASH PROJECT DETAILED HYDROGEOLOGICAL ASSESSMENT (H3 LEVEL): SIDE BOREFIELD

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