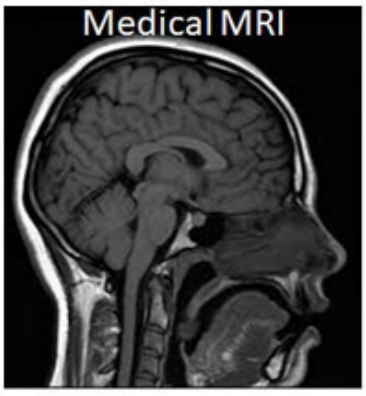
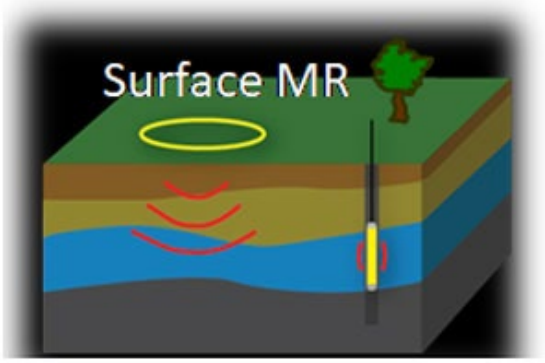
GMR: Superior Technology for Surface Magnetic Resonance Measurements of Hydrogeologic properties

Prepared by Vista Clara, Inc

1 Introduction

Surface magnetic resonance is a powerful geophysical method that provides direct, non-invasive detection and imaging of groundwater. However, the ability to obtain reliable and accurate results requires sophisticated instrumentation and software. Choosing the wrong instrument can result in unreliable data, lost investment, and potentially physical injury to the users or bystanders. Professionals in hydrogeology need to carefully weigh key design features in order to choose the most powerful, capable, and accurate instrument to characterize groundwater systems with confidence and safety.





Surface magnetic resonance is based on the same physics as medical MRI. Medical MRI measures hydrogen in biological tissues to diagnose injury or disease. Surface magnetic resonance measures hydrogen in groundwater to measure groundwater aquifer properties.

1.1 The Surface Magnetic Resonance Method

Surface magnetic resonance (also known as surface NMR, proton magnetic resonance and magnetic resonance sounding) is a powerful ground-based geophysical method used to non-invasively detect and measure groundwater. Magnetic resonance measurements are directly sensitive to both the presence of water and its interaction with grain surfaces, enabling us to differentiate water that is bound in small pores (*bound water*) from water that is stored in large pores (*mobile water*). Surface magnetic resonance measurements can also provide unambiguous estimates of hydrogeologic properties, including hydraulic conductivity and specific yield. Finally, surface magnetic resonance is a very cost-effective method for groundwater investigation compared to drilling.

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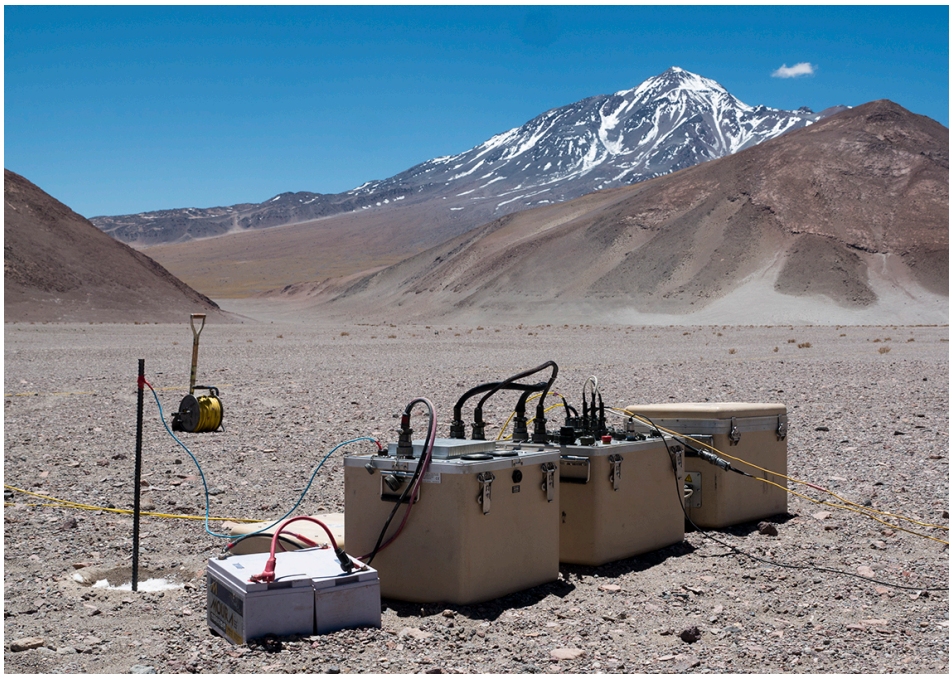
1.2 The Critical Requirements of Surface Magnetic Resonance Equipment

Advanced engineering solutions are required to meet the requirements for successful surface magnetic resonance measurements. If a surface magnetic resonance system is not adequately engineered to address these challenges, the acquired data will be unusable or will lead to incorrect conclusions, resulting in wasted time, wasted money and damaged reputations.

The requirements of the surface magnetic resonance measurement impose many significant challenges for the engineering and design of the instrumentation, including:

(1) Extremely high power, including very high stored energy, is required to energize groundwater to depths greater than 100 m.
(2) The extremely small signal amplitude, on the order of 10s of nanovolts, requires sensitive electronics and the ability to reject environmental noise from powerlines, industry, and storms.
(3) Magnetic geology can alter the groundwater response leading to errors in interpretation that must be overcome with advanced pulse sequences and modelling.
(4) Recorded signals can be very short requiring a very short dead-time between high-voltage (kV) transmit mode and low-voltage (nV) receive mode.
(5) The complex nature of magnetic resonance quantum spin dynamics requires sophisticated physics modelling, advanced pulse sequences, and precise digital timing.

Most importantly, given the high voltages and currents involved in these measurements, safety engineering solutions must be designed to protect the operator and bystanders.



The GMR instrument in the field.

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2. Safety Engineering and Risks of Unsafe Equipment

Safety is the first concern regarding any field-deployed system, especially those that involve a high voltage operating environment. *If a surface magnetic resonance system does not incorporate the highest levels of safety engineering, the results can be catastrophic, including electrocution, arc flashing, and fatal injury.*

Businesses, government agencies, and universities do everything in their power to avoid injury incidents as well as the liability and financial consequences that can result from a tragedy. There are documented cases of users and bystanders being injured by unsafe surface magnetic resonance equipment delivered by other manufactures. It is, therefore, important to understand the purpose and function of GMR's extensive safety features.

2.1 Risk of Shock and Fatal Electrocution

Stored and transmitted energy levels. Modern surface magnetic resonance equipment can store 10s of thousands of Joules of energy on their bus voltage storage capacitors, at hundreds of volts of potential. When transmitting normally, surface magnetic resonance equipment can generate up to 800 amps of current through the surface cables cables and interconnect cables/connectors and can generate up to 6000 volts between the terminals of the transmitting coil and tuning unit. This level of electrical energy, if discharged accidentally or contacted through any part of a person, can cause devastating physical damage to the equipment and severe injury, blindness and potentially death to a person.

The GMR 6000-V transmitter unit.

Electrocution. An obvious personal hazard is electrocution. Hazards include any person creating a short circuit between two stored high voltage DC energy elements or making contact between a high voltage AC voltage on say a surface cable, and any lower potential such as the chassis or earth ground.

Arc Flash. Arc flash is an often-overlooked hazard whereby a sudden or accidental discharge of stored energy between two contacts causes an explosion which can cause metal components to turn into a very high temperature plasma. The resulting explosive event can cause blindness, severe burns and even death[1][2].

[1] https://www.e-hazard.com/learn/arc-flash-videos/arc-flash-100a-disconnect.php
[2] https://www.youtube.com/watch?time_continue=4&v=cah15Pg_XaY&feature=emb_logo

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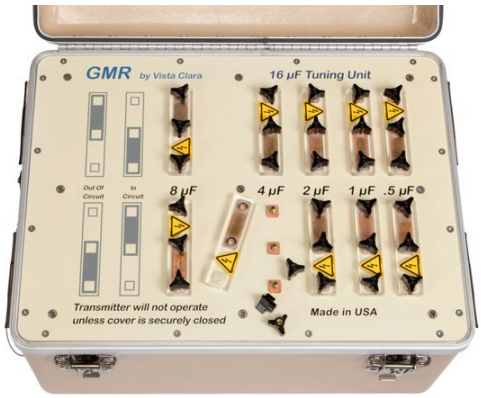
2 Essential Features Mitigate Electrical Risks to Operators & Bystanders

Professional system-level safety engineering. Field operators need surface magnetic resonance equipment that has been professionally inspected by independent, licensed 3rd party safety engineering and compliance professionals. All of Vista Clara's products, including GMR, are reviewed through the initial design and product engineering stages by independent, 3rd party safety engineering compliance professionals. This level of safety engineering has required significant investment, but it makes Vista Clara's GMR instruments among the safest available in the world.



The GMR tuning unit has multiple layers of safety engineering including no-touch bus bars and a safety interlock circuit that prevents the system from operating if the tuning unit lid is not securely closed.

"No-touch" electrical contacts. A known rule of safety around high-voltage (HV) is that an operator should **never** be required to touch an uninsulated or exposed electrical contact with their hands or fingers. The failsafe way to prevent this is to supply surface magnetic resonance equipment with high-voltage and environmentally rated mating connectors that prevent the need for the operator to touch the electrical contacts. It is incredible but unfortunately true that some manufacturers continue to supply surface magnetic resonance equipment that requires operators to touch the primary current and voltage carrying conductors ***with both hands*** to make necessary connections to field cables. Vista Cara's GMR product family uses 100% environmentally and voltage/current rated no-touch contact connectors for all cables and interconnects. These connectors are expensive compared to the use of exposed lugs and wing nuts, but it protects your operators and bystanders from unnecessary electrical hazards and makes their job easier at the same time.

The GMR no-touch contact connector.

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Automatic Fast- and Slow-Bleed Energy Dissipation. To maximize user safety, surface magnetic resonance equipment should incorporate both fast-and slow-bleed energy dissipation resistors on the high voltage bus capacitors. The fast bleed function should engage automatically whenever the main system power is off. The slow bleed function should be permanently installed on each high voltage storage capacitor so that if the system control is ever lost, the capacitors will still discharge. Beware of surface magnetic resonance equipment that uses software-controlled pulses to discharge the stored energy through the surface coil. This method is unreliable and may expose the user to unseen stored energy hazards especially if the main system power or USB connection is interrupted, or if the software crashes. Vista Clara knows of at least one documented case where a user experienced a dangerous arc flash when making connections on a competitor system that was not properly discharged.

The GMR safety features.

Unambiguous "always on" indicators of bus voltage and power state. Users need unambiguous visual indicators of two primary conditions where the system is energized and potentially hazardous: (1) when the transmitter is powered on and capable of transmitting, (2) when the DC bus capacitors have any significant stored energy on them. Even when the system power is off, stored energy on the DC bus capacitors can discharge through misuse of the system or attachment/detachment of connectors. GMR instruments have *three levels of visual hazard indicators* that provide for unambiguous warning of electrical energy hazards in all instances:

(1) Bright amber warning lights on the Transmitter and DC Converter top panels that are illuminated when the system is either

a) powered on and capable of transmitting, or

b) powered off but still has more than 5 volts of charge on the internal DC capacitor bus.

(2) Analog voltmeters on the top panel of the DC Converter (or transmitter in GMR Flex) that always indicate the exact voltage on both banks of bus capacitors.

Analog voltmeters on the top panel of the GMR DC converter.

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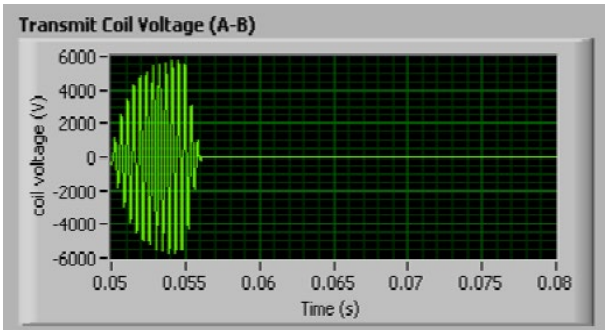
Surface magnetic resonance instruments that use software as the only basis for monitoring and reporting the charge status of internal capacitors are prone to software crash, USB or computer failure, and hence are not-fail safe and should not be considered for use.

Minimizing the time at High Stored Energy. Another means of enhancing electrical safety is to utilize data acquisition procedures that minimize the amount of time the system is idle with high voltage on the storage capacitors. The GMR instruments utilize advanced programming methods that collect full ranges of pulse moment data over repeated acquisition cycles, thereby minimizing the time that the system is in its high energy state. These acquisition cycles also end with the system in the lowest energy state after each completed measurement.

3 Reliable Data in Every Situation and Environment

Simple magnetic resonance systems can operate in "perfect" environments where groundwater is shallow, signals are big, noise is low, and the geology is non-magnetic. These "perfect" environments, however, are very uncommon in surface magnetic resonance. Instead, most applications of greatest interest are in challenging environments, where groundwater is deep, noise sources are nearby, and magnetic geology may be significant. In order to deliver accurate data with reliability in a wide range of environments, recently developed features should be considered a requirement by any customer.

Highest power and largest depth of investigation at all product levels. All of Vista Clara surface magnetic resonance instruments incorporate advanced H-bridge power conversion architectures that generate 2-times the output voltage and current from the same differential bus voltage, compared to competing manufacturers equipment. As an example, Dlugosch et al. (2011) show that the standard GMR instrument produces much higher current in the same 100 m surface loop than other systems (page 3, left column, lines 23-28). Higher voltage and current increase depth of investigation and improve detection and resolution of fast relaxing signals. The GMR family also offers an extra-high-voltage (XHV) version with 6000 V (12000 Vpp) and 800 A output, and the light-weight GMR Flex that output 2000 V (4000 Vpp) and 400A, rivaling competitor's full-sized equipment.



GMR transmitter coil voltage

Beware of competitors who only use Vpp as an output spec; "2000 Vpp" is a deceptive description of a product that produces a maximum coil voltage of 1000 V.

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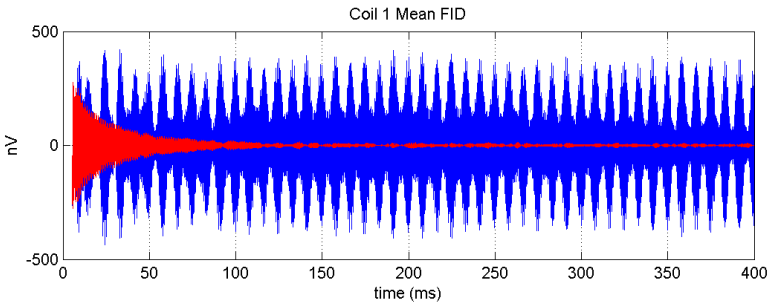
Shortest instrument dead time and its importance. A very-short instrument dead time (i.e. the time it takes to switch from transmit to receive mode) is crucial to acquire reliable data because it allows capturing the earliest part of an FID signal, where the SNR is highest. It also allows detection of faster-relaxing signals that are invisible to instruments with long dead times. GMR incorporates proprietary transmit/receive switching electronics that provide shortest dead times among all surface magnetic resonance equipment. The standard GMR has a dead time of less than 5 ms, and the GMR Flex has a dead time of less than 1 ms.

Wideband receive electronics and multi-channel noise adaptive cancellation. Vista Clara Inc. invented the technique of using multiple receive loops with adaptive signal processing to cancel noise in surface magnetic resonance data (Walsh, 2006). This noise cancellation technique is an important development in the surface MR field in the past 2 decades and has enabled the surface MR method to be used much more broadly worldwide. The effectiveness of the noise cancellation technique is highly dependent on the detection and reference channels having identical broadband frequency responses. It's also dependent on having a sophisticated and robust signal processing architecture. Instruments that utilize narrowband tuned receive coils, or a mixture of different tuned and untuned coils, are significantly limited in their ability to cancel space-time correlated noise due to different spectral mixing of noise sources in the different coils. GMR is the only system with up to 8 channels (Walsh, 2006).



An example of the effectiveness of GMR's sophisticated adaptive multi-channel noise cancellation process on data quality. Blue: single channel surface MR data before noise cancellation. Red: the same data after GMR's adaptive noise cancellation.

Magnetic resonance signals are phase-coherent; your instrumentation should be as well. Some manufactures offer "multi-channel" surface magnetic resonance equipment that does not even use a synchronized clock to ensure the different channels are sampled at the same time, or even at the same sample frequency. Faulty data sampling schemes reduce time-domain correlation between the channels and prevents effective noise cancellation. Some manufacturers' equipment reduces the data to low-fidelity in-phase and quadrature data, using outdated low bandwidth filtering and demodulation schemes. The data produced by such schemes provide no opportunity for wideband processing and analysis (Dlugosch et al., 2011).

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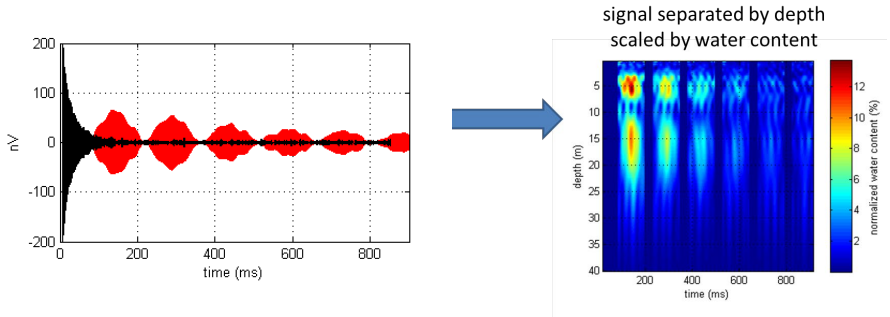
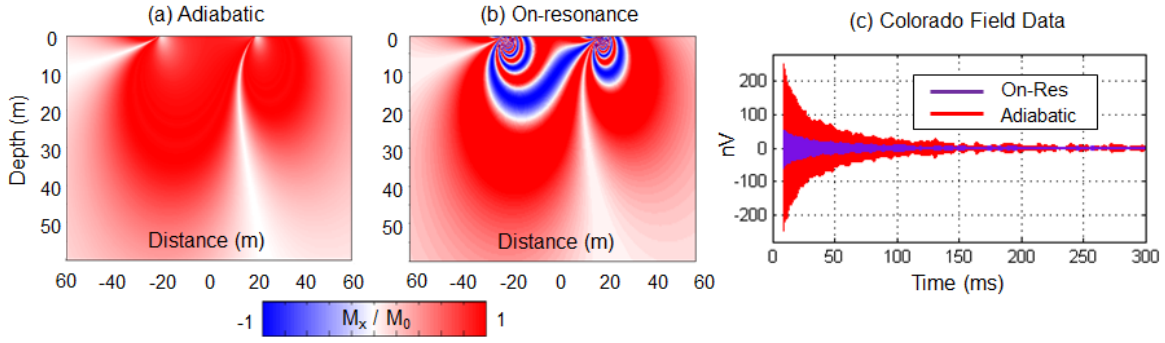
Magnetic Geology and the Means to Overcome it. In magnetic environments the FID signal undergoes additional relaxations and can no longer represent the true hydrogeology. Phase cycling on all pulse sequences enables detection of the true relaxation shape of the signal. The GMR instrument uses patented pulse sequences that are designed to unambiguously measure groundwater in magnetically-susceptible aquifer materials. These pulse sequences include Car-Purcel-Meiboom-Gill (CPMG) (same as below), Multiple Spin Echo with Phase Cycling (Elliot Grunewald et al., 2014) and Crush Recovery (Elliot Grunewald & Walsh, 2012). In addition, Vista Clara's software include linear off-resonance inversion capability to accurately assess significant variations of the earth's field in the ground.



Left: an example of FID (black) and CPMG (red) signals acquired at a site with magnetic geology using GMR. Right: GMR's high-resolution all-linear inversion maps magnetic resonance signals in depth while preserving wideband amplitude, phase and frequency information for enhanced pore-scale analysis.

Small Loops, Tiny Signals, and Instrumentation Noise. The GMR instruments incorporate ultra-low-noise wideband receive electronics that were designed and optimized for the surface magnetic resonance application. This is a very important feature in order to achieve high SNR, especially when using small surface loops for shallow groundwater investigations. In light of increasing the SNR, GMR also benefits from patented "*adiabatic*" pulse sequences (E. Grunewald et al., 2016) with ability to produce 3 times higher signal than the standard on-resonance pulse sequence.



An example of adiabatic (left) and on-resonance (center) profiles, and (right) a comparison of actual recorded surface magnetic resonance signals using the standard FID sequence (blue) and GMR adiabatic sequence (red).

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4 Equipment Engineered for Durability and Longevity

Vista Clara's surface magnetic resonance instruments are engineered to the highest standards to enable reliability and performance in the widest range of conditions. The GMR proprietary features include rugged power electronics shock mounted for protection and longevity. In addition, capacitors, switching amplifiers and switches are all significantly over-rated for temperature, voltage and current for longevity. These instrument features cost more than lesser-engineered products, but ensure the reliability of the GMR product line. Unreliable geophysical equipment actually costs the user much more in the long run, due to loss of productive field time and cancellation of groundwater surveys, due to failed or inoperable equipment.

GMR in the field. Top: Alaska USA (-15C), bottom: Western Australia (+48 C).

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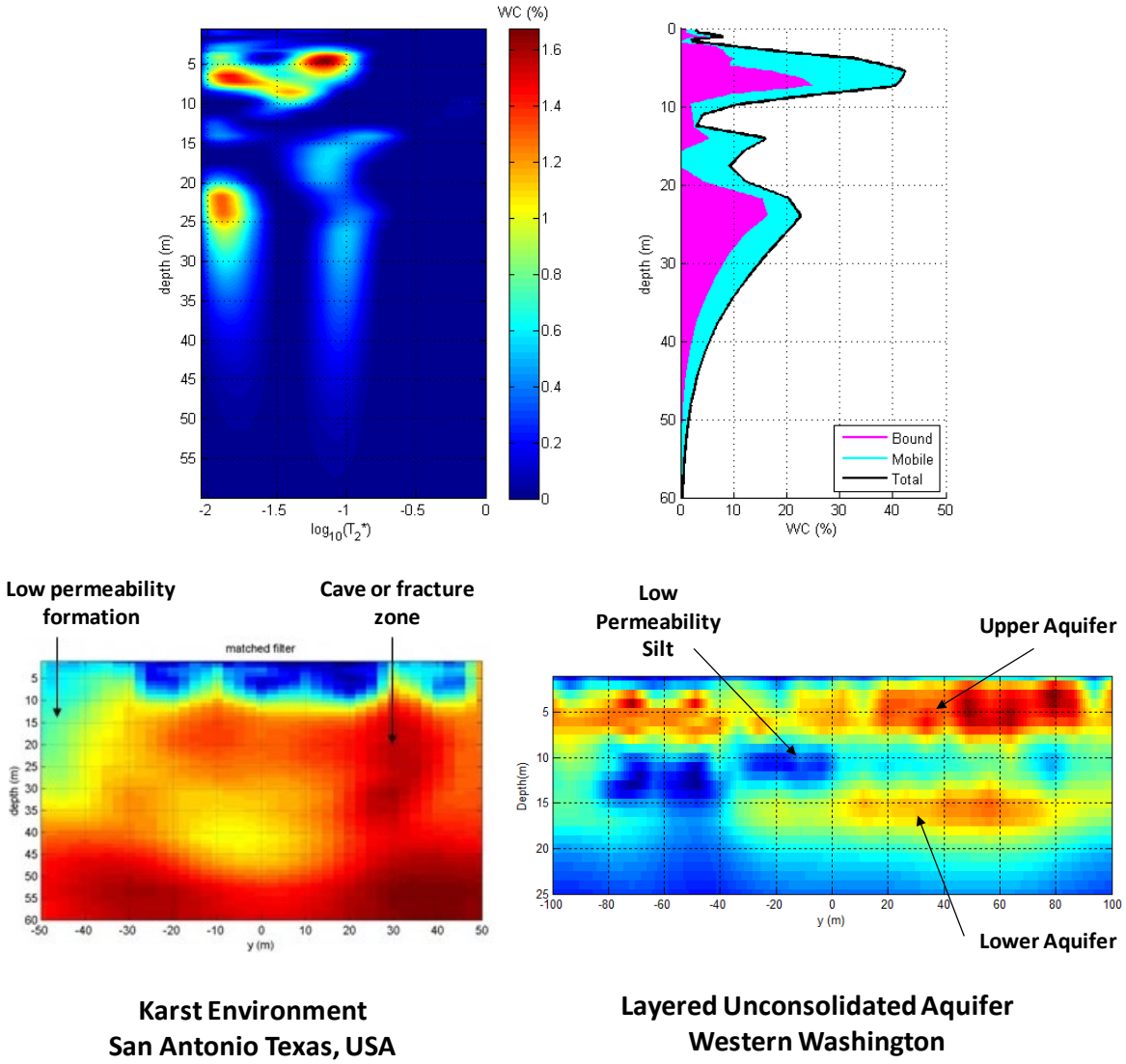
5 User-friendly Processing and Visualization

The users should be able to count on the manufacturer to provide the best available software tools to enable the effective processing and interpretation of the acquired data. The GMR processing and inversion software package includes:

- interactive QC software
- all linear inversion for highest resolution and preservation of coherent signal amplitude and phase content
- full spectrum visualization of relaxation distribution vs depth, and
- full 2D inversion software.

Users should steer clear of vendors who provide outdated freeware with their equipment or rely on unaffiliated academic organizations to support their customers software requirements.



Examples of 2D surface NMR results obtained from the GMR software.

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6 Conclusion

Surface magnetic resonance is powerful geophysical method for detection and characterization of groundwater. But the measurement is inherently difficult from engineering, application and interpretation points of view. The method demands more of the instrumentation and processing/ interpretation tools than any other geophysical method. Therefore, to get useful data "**safely**" and "**efficiently**" in the widest range of geological and cultural environments, and to get the most value out of your data, you need top of the line technology produced by a vendor that is 100% focused on magnetic resonance geophysics and the specific requirements of this powerful measurement.

7 Patents

The GMR instrument is protected by the following patents:

US 7,986,143 B2; US 8,451,004 B2; US 8,581,587 B2; US RE43,264 E; US 10,145,915 B2; EP 1 651 974 B1; US 9,599,688 B2; US 9,551,807 B2; US 9,588,068 B2; US 10,302,733 B2

8 References

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