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Magnetic Resonance Sounding Survey Data Collected in the North Platte, Twin Platte, and South Platte Natural Resource Districts, Western Nebraska, Fall 2012

Open-File Report 2014–1138

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The authors also thank Michaela Johnson for assistance with map preparation. Lyndsay Ball and Christopher Hobza provided valuable and thorough reviews of this report.

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Tables

Datum, Abbreviations, and Definitions of Symbols and Terms

Horizontal coordinate information is referenced to North American Datum (NAD83), projected into Universal Transverse Mercator Zone 13.

Acronyms

NRD	natural resource district
MRS	magnetic resonance sounding
sNMR	surface nuclear magnetic resonance
Tx/Rx	transmitter/receiver
XML	extensible markup language
XSL	extensible stylesheet language

Definitions for Magnetic Resonance Sounding Terminology

Larmor frequency	frequency at which hydrogen in water precesses
pulse delay	the time between two pulses in a T1 recovery (phase-cycled pseudo-saturation) measurement
pulse duration	length of each transmitter pulse
pulse moment	the strength of the transmitter pulse moment within a single measurement (amplitude multiplied by duration)
T1 measurement	an MRS technique which uses two transmitter pulses with a prescribed pulse delay
turn	in the context of a transmitter or receiver antenna, a turn refers to the number of overlapping wire loops that constitute the antenna.

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By M. Andy Kass, Benjamin R. Bloss, Trevor P. Irons, James C. Cannia, and Jared D. Abraham

Abstract

This report is a release of digital data and associated survey descriptions from a series of magnetic resonance soundings (MRS, also known as surface nuclear magnetic resonance) that was conducted during October and November of 2012 in areas of western Nebraska as part of a cooperative hydrologic study by the North Platte Natural Resource District (NRD), South Platte NRD, Twin Platte NRD, the Nebraska Environmental Trust, and the U.S. Geological Survey (USGS). The objective of the study was to delineate the base-of-aquifer and refine the understanding of the hydrologic properties in the aquifer system. The MRS technique non-invasively measures water content in the subsurface, which makes it a useful tool for hydrologic investigations in the near surface (up to depths of approximately 150 meters). In total, 14 MRS production-level soundings were acquired by the USGS over an area of approximately 10,600 square kilometers. The data are presented here in digital format, along with acquisition information, survey and site descriptions, and metadata.

Introduction

Magnetic resonance soundings (MRS), also known as surface nuclear magnetic-resonance (sNMR) soundings, have proven to be a useful tool for characterizing aquifer properties (Legchenko and others, 2006; Plata and Rubio, 2008). The MRS method is the only geophysical method that directly detects groundwater, which makes it an ideal technique for near-surface aquifer characterization.

In the fall of 2012, the U.S. Geological Survey, in cooperation with the North Platte (NPNRD), Twin Platte (TPNRD), and South Platte Natural Resource Districts (SPNRD), the Nebraska Environmental Trust and the Univeristy of Nebraska Conservation and Survey Division collected MRS data in western Nebraska in the fall of 2012 to improve the understanding of aquifer properties within the study area. The added hydrological property information provided by the MRS data when coupled with previous studies can improve accuracy and precision of current (2014) and future groundwater models which are the basis of many water-management decisions. As these groundwater models drive

policy decisions such as aquifer recharge locations, the additional information provided by these surveys has a direct impact on the water usage of the region.

Purpose and Scope

This report presents digital data and associated survey descriptions from 14 MRS datasets at 11 locations that were collected during October and November of 2012 in areas of western Nebraska (fig. 1). The digital data are in NGX.n format (appendix 1), which includes the processed data in MATLAB format, as well as XML (extensible markup language) files containing survey parameters such as location, loop geometry, and magnetic field intensity.

The data presented in this report expand upon previous MRS hydrologic investigations in central Nebraska (Irons and others, 2012) with additional MRS surveys in the western part of Nebraska. These surveys consisted of a particular type of MRS datasets called T1 measurements (phase-cycled pseudo-saturation recovery) (Walbrecker and others, 2011) that were used to investigate hydrologic parameters in the near-surface aquifer system ("production" data), as well as experimental loop geometries and survey designs (not discussed in this report). This report details the survey design parameters, processing techniques, and data results from the MRS production data.

Description of Study Area

The study area is in the panhandle of Nebraska and includes parts of the North Platte, South Platte, and southwest portion of the Twin Platte Natural Resource Districts (fig. 1). Major drainages in the study area include the North Platte River, South Platte River, and Lodgepole Creek. Agriculture is the dominant land use in the study area. Crops in valleys typically are irrigated with either surface water or groundwater (Luckey and Cannia, 2006). Dry-land crops and rangeland are the predominant land use in the upland areas. Crops in the upland areas typically are irrigated by water from the High Plains aquifer (Luckey and Cannia, 2006).

The hydrogeology of the study area has been described by many earlier investigators, including Darton (1903a, b); Wenzel and others (1946); Bjorklund (1957); Lowry (1966); Smith (1969); Smith and Souders (1971, 1975); Swinehart and others (1985); Barrash (1986); Souders (1986); Sibray and Zhang (1994); Verstraeten and others (1995); Steele and others (2002); and Steele and others (2007). Cannia and others (2006) created a hydrostratigraphic framework and characterized underlying aquifers of the study area and surrounding areas. This framework was used in recently published groundwater-flow models (Luckey and Cannia, 2006; Carney, 2008), which include all or parts of the study area.

The youngest aquifers in the study area are composed of Quaternary alluvial and eolian deposits, which occur primarily in the modern stream valleys and adjacent uplands, respectively. The alluvial aquifers consist of relatively coarse-grained sand and gravel and yield large quantities of water to wells (Luckey and Cannia, 2006). Depth to water is generally shallow in modern valleys, ranging from land surface to more than 30 meters. In the North Platte River valley, east of Mitchell, Nebr., and the South Platte River valley, the base of the aquifer is formed by Oligocene-age Brule Formation of the White River Group. West of Mitchell, the deepest parts of the North Platte River channels are eroded into undifferentiated Cretaceous-age sedimentary rocks. In the Lodgepole Creek valley, the Quaternary alluvial aquifer can be found overlying the Miocene-age Ogallala Formation as well as the Brule.

The Miocene-age Ogallala Formation is the principal member of the High Plains aquifer. It is the youngest Tertiary-age aquifer in the study area and consists of interbedded sandstone, gravel, silt, and clay. The Ogallala is the primary aquifer in the Cheyenne Tablelands (Steele and others, 2007) and other upland areas (fig. 1) in the study area (Carney, 2008). The maximum thickness of the Ogallala Formation exceeds 180 m in the study area and few wells have been drilled to the base of the formation. The depth to water ranges from more than 60 meters in the Cheyenne Tablelands to about land surface in the Lodgepole Creek valley. Well yields in the Ogallala Formation are highly variable and depend on local heterogeneities, but are generally suitable for irrigation (Steele and others, 2007; Abraham and others, 2012).

The Brule forms the base of the aquifer for much of the study area but can locally serve as an aquifer where it is fractured and saturated. Fractures in the upper part of the Brule Formation are horizontal to subhorizontal (Barrash, 1986). Typically, the fractures have very limited extent within the North Platte River and Lodgepole Creek valleys (Lowry, 1966). These fractured zones can provide large quantities of water to wells when hydraulically connected to streams or other aquifers (Barrash, 1986). In most areas, the lower part of the Brule Formation is a thick sequence of low-permeability, interbedded brown siltstone and mudstone. Localized sandstone and sand- and gravel-filled channel deposits can occur within the Brule Formation and can yield water to wells (Steele, 2007). Table 1 contains general descriptions for each hydrogeologic unit in the study area, along with the soundings that investigated those particular units.

Magnetic Resonance Sounding Survey Data

Overview of Methods and Measurements

The principles and applications of the MRS method are summarized by Weichman, Lavely, and Ritzwoller (2000), Legchenko and others (2006), Plata and Rubio (2008), and Walbrecker, Hertrich, and Green (2009). Briefly, hydrogen atoms in water will preferentially align their precession axis with the Earth’s magnetic field, which results in a weak net magnetization. The MRS method works by tipping this axis using a controlled electromagnetic source and measuring the change in magnetic field flux as a

time series at the surface as the atoms return to their original precession. This results in a measured (approximately exponential or multi-exponential) 'decay' of the MRS signal. The exponential decay is modulated by the precession of the Larmor frequency, resulting in a decaying, oscillating time series. The characteristics of this signal depend on the water content, bulk electrical conductivity of the ground and water, and matrix-pore geometry. By controlling the properties of the inducing electromagnetic signal, varying depths to and properties of an aquifer can be investigated.

Field data were collected by using a large (tens of meters in diameter) loop of wire that was lain flat on the ground surface as the transmitter (Tx); the electomagnetic signal from this transmitter tips the hydrogen atoms. Often, the same loop was used as the receiver (Rx) after the transmitter signal was stopped. Additionally, one or more loops were deployed to characterize ambient electromagnetic- noise signals for removal during processing.

In this study, a T1 pulse measurement was used at each sounding location. A transmitter pulse at the Larmor Frequency—the frequency at which hydrogen precesses as a function of the ambient magnetic field—is followed by a second pulse (out of phase by π radians) at a prescribed delay, between 10 milliseconds and 2 seconds (called a pulse delay). The MRS decays were measured after each pulse. A single pulse delay with varying pulse amplitudes constitutes one sounding, whereas many soundings with varying pulse delays constitutes one T1 measurement. Multiple-pulse amplitudes allow the instrument to probe different depths (Irons and others, 2012).

The chosen delay times were a function of survey conditions and hydrologic parameters and often were modified concurrently as data were collected and as conditions warranted. This sequence of pulse moments was stacked between 20 and 40 times depending on the ambient electromagnetic-noise level present (for example, from vehicles, electric fences and power lines) at the particular sounding location. A single antenna consisted of one or more coincident loops (or 'turns'), resulting in a higher transmitter moment. Table 2 contains locations, loop geometry, and pulse delay parameters for each sounding.

Survey Design

Survey locations (fig. 1) were based on three factors: (1) the need to sample the many lithologies in the various aquifers of each of the three Natural Resource Districts; (2) proximity to boreholes, preferably those that had associated data from aquifer tests to calibrate results of subsequent numerical interpretation; and (3) site access.

The transmitter and receiver antenna (Tx/Rx) parameters were chosen as a function of site access, expected hydrologic parameters, and field conditions. They each consisted of a loop of wire in either a figure-eight or square configuration. Generally, a square configuration has greater depth of investigation, whereas a figure-eight configuration has superior noise-cancelling ability. For this study, a typical survey configuration consisted of an array containing one transmitter/receiver loop and,

situated some distance away (three to four times the loop diameter at least), at least one noise reference loop to record ambient electromagnetic-noise signals.

GMR Instrument

The data were acquired with a Vista Clara, Inc., GMR MRS instrument, which used up to eight coincident transmitter/receiver channels. In this configuration, one channel constitutes a transmitter/receiver pair, whereas the other channels correspond to noise-measurement loops. The instrument was deployed as specified by the manufacturer and used two DC/DC (direct current) voltage converters for added power. When more than four channels were used, the four-channel expansion module was attached allowing for up to eight channels. The instrument was tuned using the supplied tuning module, which modifies the capacitance of the system such that the transmitter resonates at or close to the Larmor frequency. In addition, an auxiliary tuning module for finerloop tuning (quarter-farad) was used when necessary due to loop geometry and ambient magnetic fields. Figure 3 shows the instrument deployed in the rear of a vehicle, with one transmitter/receiver loop and seven additional receiver loops; figure 4 shows a schematic diagram of standard instrument setup.

Ancillary Measurements

Horizontal and vertical data were collected with a Garmin Montana 650 handheld Global Positioning System (GPS) unit. Loops were laid out using tape measures, and the corners or centers of the loops were measured by GPS. These data are reported in North American Datum of 1983 (NAD 83), projected onto the Universal Transverse Mercator (UTM grid,), zone 13N.

The background magnetic-field strength was measured at the beginning of each survey at the transmitter location using a GEM Overhauser magnetometer. Multiple measurements taken over the course of several minutes were averaged, and the average value is presented in the data files (appendix 1).

When possible, ambient air temperature was estimated and recorded, as there is a slight dependence on temperature in the MRS response. However, this dependence is minor and only has significance during detailed numerical interpretation later.

Data Processing

The recorded data were processed using the GMR-QC (version 2.1.1) processing program developed by Vista Clara, Inc. First, the time-series records are truncated to the length of interest (recorded as truncation length in the data files, appendix 1), which was primarily held constant at 500

milliseconds (mS) in these surveys, and band-pass filtered (where all frequencies outside of a window around the frequency of interest are eliminated). A truncation length of 500 mS provides an optimal tradeoff between having the shortest record possible (to avoid ambient electromagnetic-noise signal contamination) while still recording the longest expected decay. Filter parameters are given in table 2. The software then uses the time-series data from noise-reference loops—assumed to be devoid of MRS signal and containing only ambient electromagnetic noise signals—to compute a transfer function to remove correlated signals from the MRS data (Haykin, 1991; Walsh, 2008). Pulse moments corrupted with broadband noise (usually due to a noise spike during the record) with insufficient improvement after filtering are discarded. These resulting data are ready for analysis and further numerical interpretation techniques at this stage.

Digital Data

Digital data are presented in the folders described in table 3. The following describes the digital data in each subfolder. (*http://pubs.usgs.gov/ofr/2014/1138/GIS_data*)

Geographic Information System Data

The Geographic Information System (GIS) folder contains the locations of each sounding in Environmental Systems Research Institute (Esri) shape files. This directory includes a single *.shp file containing the sounding locations as well as projection information (*.prj file).

Geophysical Data

The data files consist of processed data compliant with NGX.n specifications. Each sounding is contained within a separate directory and contains a NGX.n data file in the format of a MATLAB workspace (as provided by Vista Clara, Inc.) for each pulse delay and a NGX.n header file (*.ngxn file extension) containing metadata, which is based on the XML 1.0 file format. An extensible stylesheet language (XSL) style sheet is included in each directory for convenient viewing of the header information. The header file is best viewed in Internet Explorer 9 or Mozilla Firefox 30; however any XML reader or text reader is sufficient to access the information.

Each sounding location contains the processed time-series data for pulse two for each sounding. The first pulse record for the longest offset (a proxy for a free induction decay measurement) is also included, except for sounding location 'LAT,' where the pulse one data file became corrupted during acquisition and was unrecoverable.

Summary

This report summarizes the acquisition and processing of magnetic resonance soundings (MRS) conducted during 2012 in areas of western Nebraska and contains a release of the digital data. The survey investigated a variety of geologic units in the region, focusing on the primary aquifer systems. The T1 MRS and ancillary data are presented in NGX.n format and include the MRS sounding data, positioning information, and magnetic field values.

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Appendix 1

The NGX.n file format specification is a specific file format for magnetic resonance sounding (MRS) survey data. A single dataset consists of a MATLAB workspace and an NGX.n header file. All survey parameters, such as locations and ambient magnetic field as well as all data are contained in these two files.

The workspace file, containing the data, consists of the parameters shown in table 1-1. The file, containing a *.mat extension, can be opened with MATLAB, Octave, R, or Python with the SciPy library.

The header file (with extension *.ngxn), which contains survey and ancillary information, is based on the XML (extensible markup language) 1.0 format. An XSL (extensible style sheet language) style sheet is included for convenient viewing with Mozilla Firefox (tested with version 25.0 in Ubuntu 12.04), Internet Explorer (tested with version 9, Windows 7), and Safari (tested with version 5.1 in OSX 10.7.5). The file also can be read with any text-editor software. A complete description of the NGX.n file format is available at *http://ngx.lemmasoftware.org*.

Figures

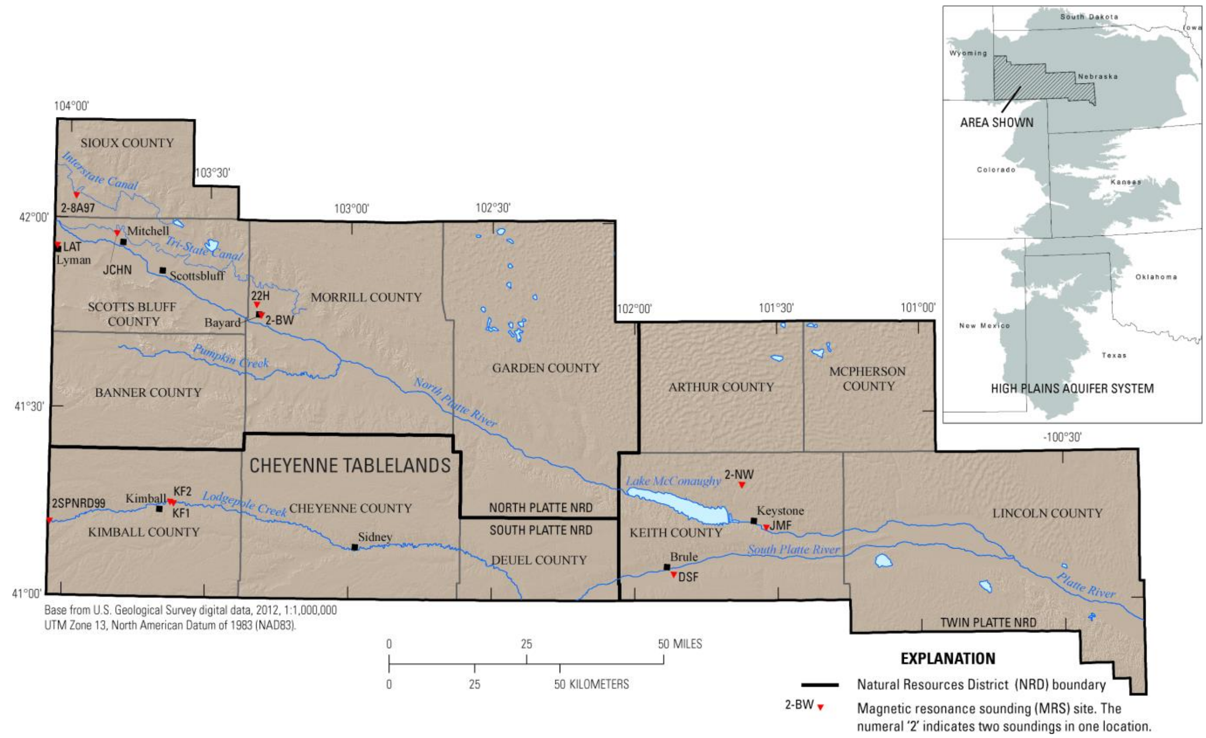


Figure 1. Magnetic resonance sounding locations.

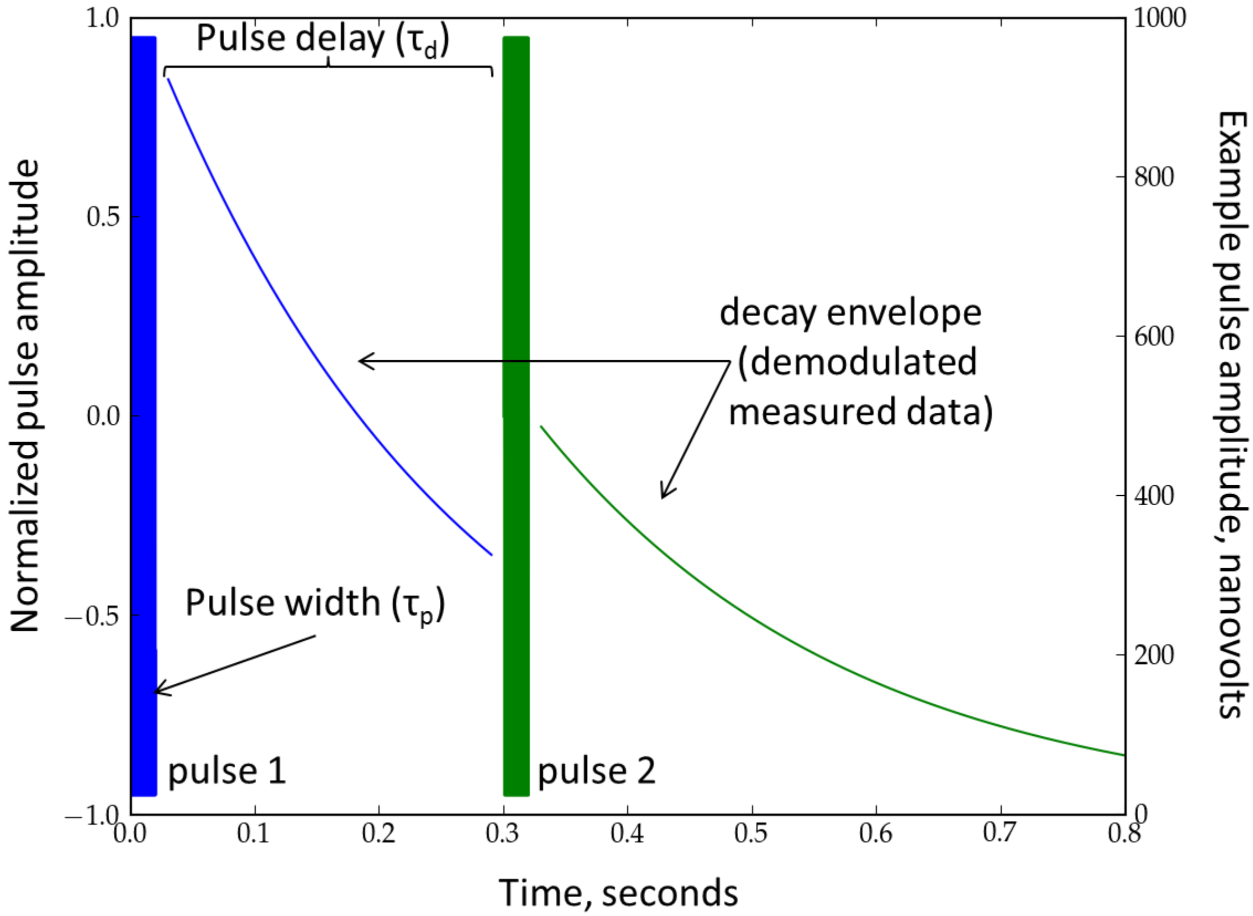


Figure 2. Schematic T1 pulse sequence.

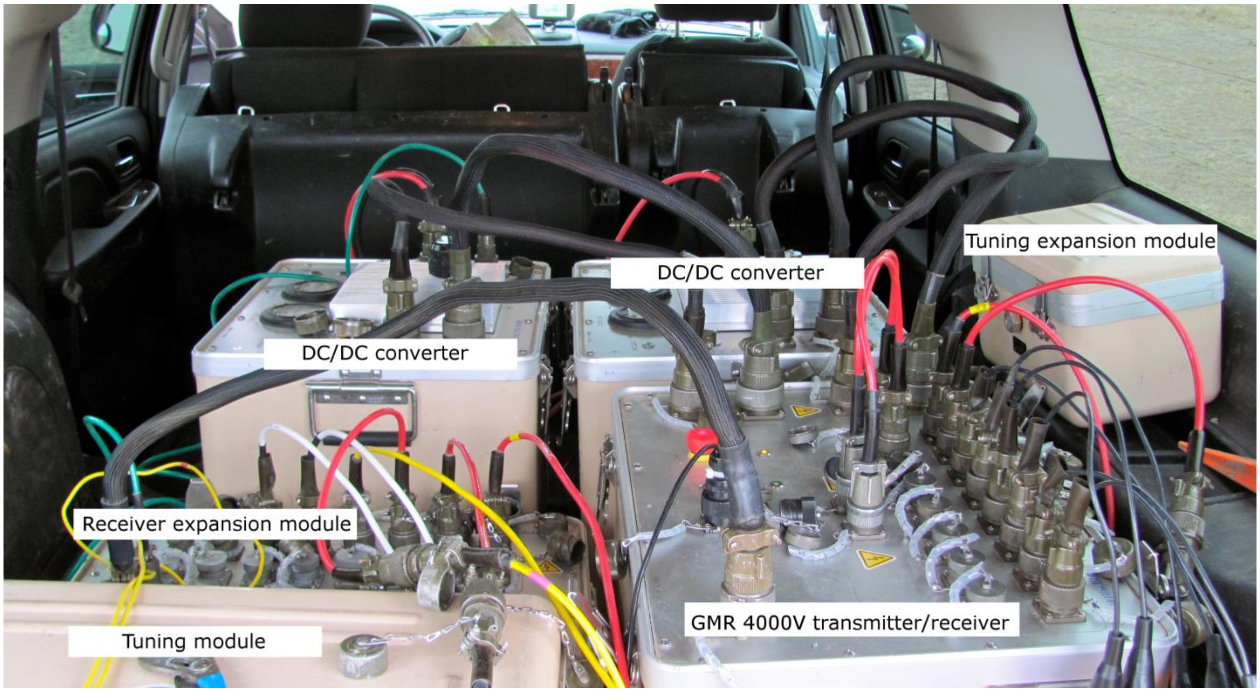
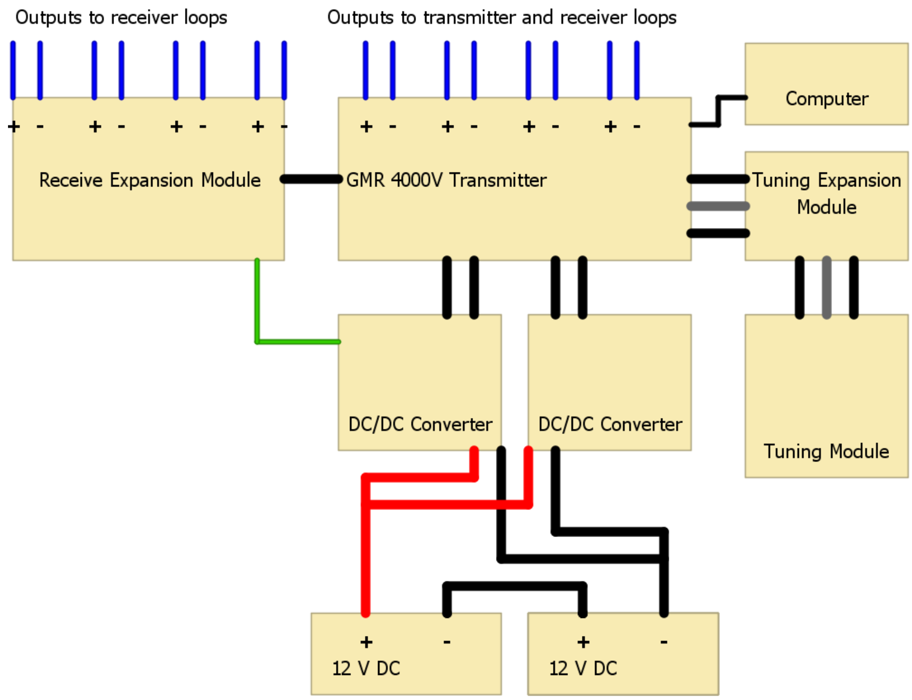


Figure 3. GMR instrument deployed with one transmitter/receiver coil and seven additional receiver coils.

***A*. Instrument deployment.**



***B*. Field deployment.**

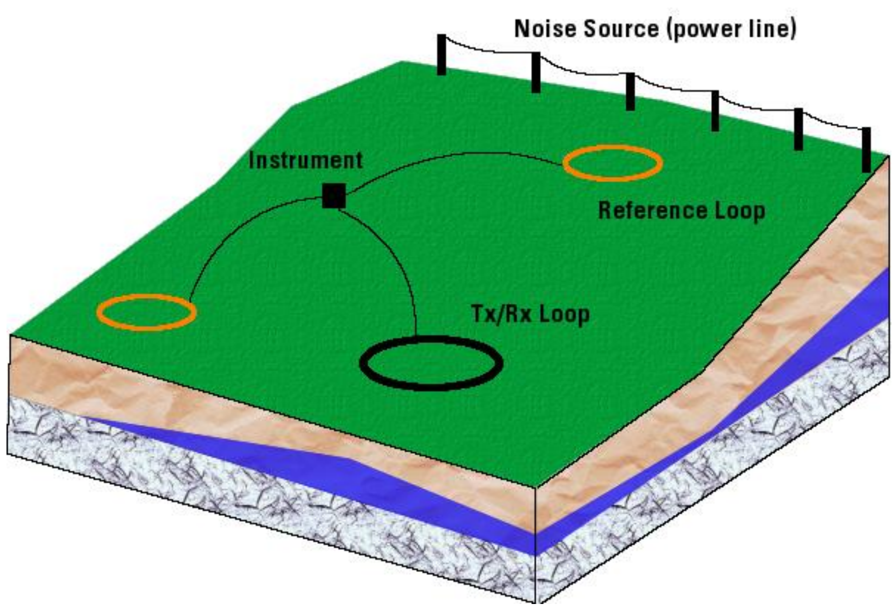


Figure 4. Schematic representation of *A*, instrument deployment and *B*, field deployment.

Tables

Table 1. Principal hydrogeologic units of the study area and corresponding locations of Magnetic Resonance Sounding (MRS) data.

System	Series	Unit age (Ma)	Geologic unit	Hydrogeologic characteristics	MRS sites (fig. 1)
Quaternary	Holocene and Pleistocene	Present to 1.8	Alluvium	Unconfined high-yielding water-bearing unit which is the principal aquifer in the North Platte River valley.	22H, 8A97, BW, DSF, JCHN, JMF, KF1, KF2, LAT
			Eolian sand	Generally fine sand, may be a source of water for livestock or domestic wells.	
Tertiary	Pliocene	2.5 to 4.0	Broadwater Formation	Coarse fluvial gravel and sand. Found in channel deposits north of the North Platte River valley.	
	Miocene	5.0 to 18.5	Ogallala Formation	Unconfined water-bearing units capable of high yields. Important aquifer in Cheyenne Tableland area. Not present in North Platte River and Pumpkin Creek valleys.	NW
	Miocene-Oligocene	19 to 23.5	Arikaree Group	Unconfined water-bearing unit in Cheyenne and Northern Tableland areas. Well yields are moderate.	
	Oligocene	30 to 33.7	Brule Formation	Upper Brule is an unconfined, fractured water-bearing unit, which may yield large volumes of water. Storativity is low except where overlain by saturated alluvium. Fractured Brule Formation only occurs in the North Platte River valley and Pumpkin Creek, and Lodgepole Creek valleys. Lower unfractured Brule Formation is not a source of water and serves as an aquatard.	2SPNRD99

Modified from Cannia and others, 2006 and Abraham and others, 2012.

Table 2. Sounding locations and transmitter/receiver geometry.

[Northing and Easting, in meters (m), Universal Transverse Mercator (UTM) projected coordinates, zone 13N, North American Datum of 1983 (NAD 83); Tx/Rx geometry, transmitter/receiver (Tx/Rx)loop configuration; Tx/Rx side length or diameter, length of a side of the square loop if configuration is indicated as a square and diameter of each loop if configuration is indicated as a figure-eight, in meters (m); Pulse delay, Pulse duration, and Truncation length, in milliseconds (mS)]

Soundings (fig.1)	Northing (m)	Easting (m)	Tx/Rx geometry	Tx/Rx side length or diameter (m)	Pulse delay (mS)	Pulse duration (mS)	Truncation length (mS)
22H	4626368	638506	Figure-8	46	100, 200, 300, 500	40	500
2SPNRD99	4561081	579635	Figure-8	46	300	10, 30	500
8A97	4656744	584624	Figure-8	44	100, 200, 300, 500	30, 40	300, 500
2-8A97	4656715	584618	Square	100	40; 100; 200; 300; 500; 1,000; 2,000	30	500
BW	4623427	639997	Figure-8, two-turn	33	100; 200; 300; 1,000	30	500
DSF	4551423	763532	Figure-8	44	100, 300, 500	30	500
JCHN	4646053	596941	Figure-8	44	300, 500	10, 30	500
JMF	4566237	790105	Figure-8	44	100, 300, 500	30	500
KF1	4567424	616200	Figure-8, two-turn	34	100, 300, 500	30	500
KF2	4567719	615152	Figure-8	44	100, 200, 300, 500	30	500
LAT	4641932	579560	Figure-8	45	100, 300	30	500
NW	4578479	782513	Square	50	100, 200, 300	30	500
2-NW	4578500	782482	Square	100	50, 100, 200, 300	30	500

Table 3. Organization of digital data and description of files and folders.

Folder	Description
GIS	Geographic information consisting of survey locations in shape-file format.
DATA	The digital data in NGX.n-compliant format[1].

[1]Detailed file-format description available at ngx.lemmasoftware.org.

Table1-1. NGX.n data file contents (*.mat file extension).

Variable	Contents
T_dead_time	Time between the end of the transmitter pulse and the beginning of the time-series record, in seconds.
T_pulse	Pulse width, in seconds.
coil_n_fid	Array containing the time series data for each pulse moment for channel 'n' (number of samples x number of pulse moments).
detect_frequency	Larmor Frequency, in Hertz (Hz).
fs	Sample rate, in Hz
interpulse_delay	Pulse delay, in seconds.
pulse_moment	Array of pulse moments used in Amp*seconds.
pulse_moment_phase	Phase of each pulse moment.
pulse_moment_voltage	Transmitter voltage for each pulse moment, in volts.
time_fid	Time of each sample, in seconds.

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