

# Evaluating Brine Deposits Using Borehole Magnetic Resonance

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## SUMMARY

Brine mining is an important source of elements such as potassium, iodine, lithium, and bromine that occur in solution in groundwater, typically in shallow brines occurring beneath saline or dry lakes or in deep brines in sedimentary basins. Where feasible, brine mining is an attractive alternative to conventional mining due to lower surface and environmental impact and lower OPEX than conventional mining operations.

As with any resource, evaluating brine deposits requires developing an understanding of how much resource is present and how it can be most economically produced. How much resource is present is a function of the bulk aquifer volume, the specific yield, and the brine composition, while the primary subsurface control on economic production is hydraulic conductivity, which dictates the rate at which the brine can be produced to surface. Specific yield and hydraulic conductivity are analogous to the free fluid volume and permeability quantities that are of interest in oil and gas resource assessment.

Borehole magnetic resonance has been applied in the oil and gas industry for the evaluation of bound and free fluid volumes and permeability for over twenty years. These same methodologies are equally applicable in the evaluation of brine deposits, however the hypersaline brines that are targets for commercial development cause highly conductive borehole environments that can be extremely challenging for magnetic resonance measurements. Nevertheless, use of borehole magnetic resonance measurements to help evaluate a sulphate of potash brine deposit currently under assessment shows that such measurements can be employed successfully in these environments.

**Key words:** brine mining, hydrogeology, magnetic resonance, well logging.

## INTRODUCTION

Hypersaline brines are an important source of elements such as potassium, iodine, lithium, and bromine. Extraction of such elements from hypersaline brines involves producing the brines to the surface, and then extracting the elements of interest through evaporation or other methods. Therefore, evaluating a hypersaline brine resource involves characterising both the storage and flow properties of the aquifer containing these brines.

Although the JORC Code (JORC, 2012) does not specifically address resource and reserve assessment of brine deposits, the Association of Mining and Exploration Companies (AMEC) has prepared draft guidelines for such assessment (AMEC, 2017). The AMEC draft guidelines are based largely on Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Best Practice Guidelines (CIM, 2012) designed for use with NI43-101 (CIM, 2011). Both AMEC and CIM guidelines emphasise the need for hydrogeological characterisation of brine deposits, with recommendations that total porosity, specific yield, permeability (hydraulic conductivity), transmissivity, storativity, and diffusivity all be evaluated and reported, with key parameters preferably determined using two independent methods.

For a brine deposit, resources are defined by the product of aquifer volume, producible water volume or specific yield, and element concentration in the brine. In defining reserves, the brine abstraction scheme dictates the achievable production schedule of the proposed development, which in turn controls the produced brine volumes. In terms of rock properties, abstraction rates are controlled by hydraulic conductivity and transmissivity. Therefore, key aquifer rock properties that need to be characterised are specific yield and hydraulic conductivity.

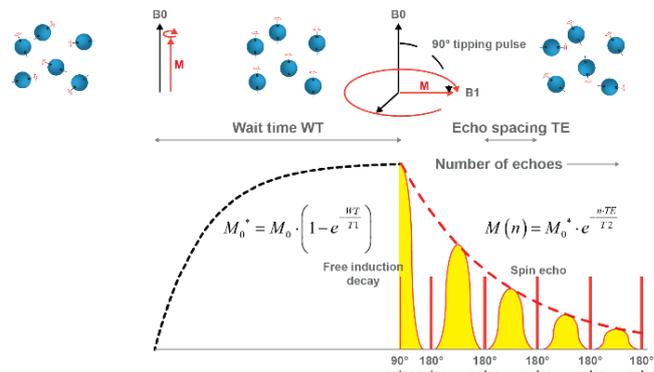
Hydrogeological parameters such as specific yield and hydraulic conductivity are typically determined using a variety of well testing methods, although well tests have greatest sensitivity to flow properties such as hydraulic conductivity. Measurements on core samples can also be used to characterise such hydrogeological parameters, although core data can be challenging to acquire in the relatively unconsolidated sediments associated with many brine deposits. Core analysis provides characterisation of small, discrete samples of an aquifer. While well tests sample a larger aquifer volume, they also provide only discrete measurements of aquifer properties. Borehole geophysical measurements, which can provide continuous data over entire aquifer intervals, are usually only used

qualitatively for applications such as lithology identification, and stratigraphic correlation. This is due to the lack of sensitivity of most borehole geophysics methods to pore geometry, which controls properties such as specific yield and hydraulic conductivity. Borehole magnetic resonance, which is a measurement sensitive to both pore volume and pore geometry, has been used in the oil and gas industry for over twenty years to evaluate storage and flow properties of hydrocarbon reservoirs, and is seeing increasing application in hydrogeological characterisation.

## BOREHOLE MAGNETIC RESONANCE

Borehole magnetic resonance (BMR) takes advantage of interactions between hydrogen nuclei and applied (electro)magnetic fields. Hydrogen nuclei possess both angular momentum and a magnetic moment; simplistically they behave like magnets spinning around their magnetic axes. The rate at which the nuclei spin is a function of the magnetic field strength they are exposed to. In a volume of water, or other hydrogen-containing fluids, the magnetic fields of the various hydrogen nuclei in the different fluid molecules will be randomly oriented. If an external magnetic field is introduced, these nuclei will align themselves with the external magnetic field, or polarise. If the effect of this external magnetic field is then removed, the nuclei will over time dephase, until they are again randomly oriented.

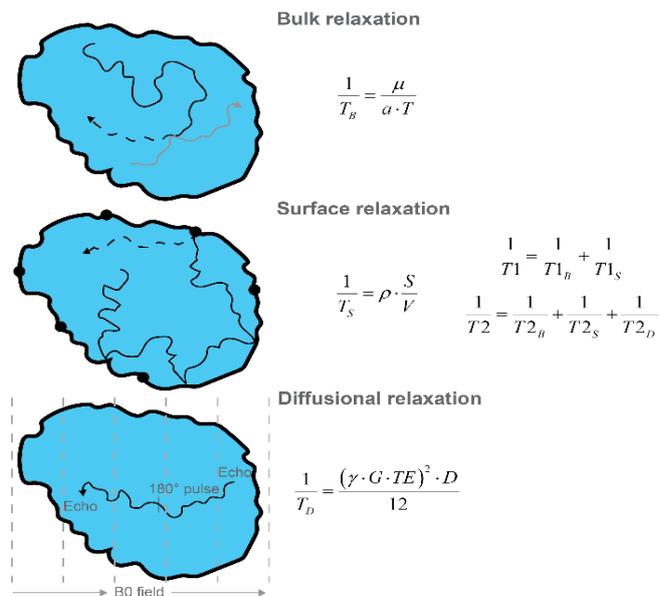
A magnetic resonance measurement consists of two steps (Figure 1). In the first step, an external magnetic field  $B_0$  is introduced for a certain period, the wait time or polarisation time. During this period, the hydrogen nuclei align with the  $B_0$  field. In the second step, the effect of the external magnetic field is removed. In practice, this is done by applying an electromagnetic pulse at a frequency in resonance with the spin rate of the hydrogen nuclei, tipping the nuclei through  $90^\circ$  into the secondary  $B_1$  field plane. As well as effectively removing the influence of the  $B_0$  field, this also results in the tipped hydrogen nuclei rotating around the  $B_0$  direction and perpendicular to their magnetic axes, or precessing. The precessing hydrogen nuclei generate an oscillating electromagnetic field that can be detected. This rotation rate is governed by the initial spin rate of the nuclei, which is governed in turn by the  $B_0$  field strength.



**Figure 1: Making a magnetic resonance measurement. Spinning hydrogen nuclei polarise under the influence of an external magnetic field  $B_0$ , and dephase when the influence of this magnetic field is removed; this is achieved by tipping the nuclei through  $90^\circ$  into the  $B_1$  plane using a resonant frequency electromagnetic pulse. While rotating in the  $B_1$  plane, the hydrogen nuclei in turn generate an oscillating electromagnetic signal that is measured. Polarisation and dephasing are quasi-exponential processes characterised by time constants  $T_1$  and  $T_2$ .**

When all the hydrogen nuclei are precessing in alignment, a peak electromagnetic signal is generated. However, due to local heterogeneities in the  $B_0$  field, nuclei will precess at different rates and hence quickly dephase, causing a reduction in the net electromagnetic signal. This process, known as free induction decay, is an experimental artefact and is reversible. Applying an appropriate electromagnetic pulse will tip the nuclei by  $180^\circ$ , effectively reversing the direction of rotation. This will bring the faster and slower precessing nuclei back into alignment, causing a new peak signal, or spin echo, to be generated. By applying a series of  $180^\circ$  pulses at a regular interval, or echo spacing, the precessing nuclei can be continually refocused.

While this is taking place, the hydrogen nuclei are also undergoing irreversible dephasing; this has the effect of moving the axis of rotation of the nuclei out of the  $B_0$  direction so that they no longer contribute to the measured signal. Therefore, over time the amplitude of the spin echoes reduces as nuclei undergo irreversible dephasing. Both polarisation and dephasing of the hydrogen nuclei are quasi-exponential processes, with the rate of polarisation described by the longitudinal relaxation time  $T_1$  and the rate of dephasing described by the transverse relaxation time  $T_2$ . The rates at which polarisation and dephasing take place are controlled by interactions between the magnetic fields of the hydrogen nuclei and other local magnetic fields (Figure 2); this includes interactions with the magnetic fields of other hydrogen nuclei in the fluids, known as bulk relaxation, and interactions with magnetic fields generated by paramagnetic atoms such as iron and manganese that may occur in the minerals bounding fluid-containing pores in a rock, known as surface relaxation. Another contributor to dephasing is diffusional relaxation, which takes place when fluid molecules move to areas of differing magnetic field strength during a magnetic resonance measurement, and are therefore not refocused successfully by



**Figure 2: Polarisation (longitudinal relaxation) and dephasing (transverse relaxation) involve two processes, bulk and surface relaxation, occurring in parallel. Dephasing is additionally influenced by diffusional relaxation.**

applied 180° pulses. Each of these relaxation mechanisms operates in parallel, and so the overall relaxation rate is dominated by the fastest mechanism.

## HYDROGEOLOGICAL APPLICATIONS OF BOREHOLE MAGNETIC RESONANCE

For the case of water in a porous medium such as a rock, surface relaxation is the primary mechanism driving polarisation and dephasing of hydrogen nuclei. Surface relaxation involves interactions between the magnetic fields of individual hydrogen nuclei and the magnetic fields generated by paramagnetic atoms such as iron and manganese. Such atoms occur as part of the chemical structure of the rock matrix, and so as fluid molecules move around within pores in a rock, the hydrogen atoms in these molecules may interact with such atoms occurring close to the surfaces of the pores. For a pore of a given volume, the higher its surface area the more likely it is that molecules will approach the pore walls and interact, so the surface-to-volume ratio of a pore is a major control on the rate of surface relaxation. There is also a direct correlation between surface-to-volume ratio and pore size, so the rate of surface relaxation reflects pore size in a rock. For a rock with a range of different pore sizes, a range of relaxation rates will be observed. The signal amplitude related to each relaxation rate indicates the pore volume of the associated pores.

The T2 distribution, or distribution of signal amplitudes related with different transverse relaxation rates, is the fundamental output of a borehole magnetic resonance measurement, concisely summarising the results of the measurement (Figure 3). Signal amplitudes are calibrated to a water reference, so the amplitude related with each relaxation rate is a direct measure of the amount of water, or pore volume, associated with that relaxation rate (pore size). The first hydrogeological property that can be determined from the T2 distribution is the total water content or total porosity, this is simply the sum of amplitudes of each element in the distribution. This porosity is derived directly from the magnetic resonance measurement itself and is independent of any lithology effects.

As well as looking at the sum of amplitudes of all the elements in the T2 distribution, it is useful to look at the sum of amplitudes of the elements within a range of T2 values, corresponding to a range of pore sizes. This can be used to determine the water volume that is free to move, the specific yield, and the water volume held in place in the rock by capillary forces, the specific retention. The T2 values used to separate bound and free fluid are well defined for typical lithologies, or can be determined from core measurements.

The pore size information summarised in the T2 distribution can also be used to estimate permeability. Two main approaches have been employed for permeability estimation from magnetic resonance data. The first approach builds on a range of empirical relationships between porosity, permeability, and irreducible water saturation that have developed over the years; the most common equation of this form is the Timur-Coates permeability equation  $k_{Timur-Coates} = 10000 \cdot a \cdot n^b \cdot \left(\frac{S_y}{S_r}\right)^c$ , where  $k_{Timur-Coates}$  is the permeability estimated from the Timur-Coates equation (mD),  $n$  is the porosity (1),  $S_y$  is the specific yield (1),  $S_r$  is the specific retention (1), and  $a$ ,  $b$ , and  $c$  are constants with typical values of 1 (mD), 4 (1), and 2 (1). The second approach is based on Kozeny-Carmen-type models, with average pore size information coming from the logarithmic or geometric average of the T2 distribution; the most common equation of this form is the SDR permeability equation  $k_{SDR} = a \cdot n^b \cdot T2_{LM}^c$ , where  $k_{SDR}$  is the permeability estimated from the SDR equation (mD),  $T2_{LM}$  is the logarithmic mean value of the T2 distribution (ms), and  $a$ ,  $b$ , and  $c$  are constants with typical values of 4 (mD/ms<sup>2</sup>), 4 (1), and 2 (1). Dlubac *et al.* (2013) reviews the origins of these equations, and discusses the application of borehole magnetic resonance-based permeability estimates in aquifer characterisation.

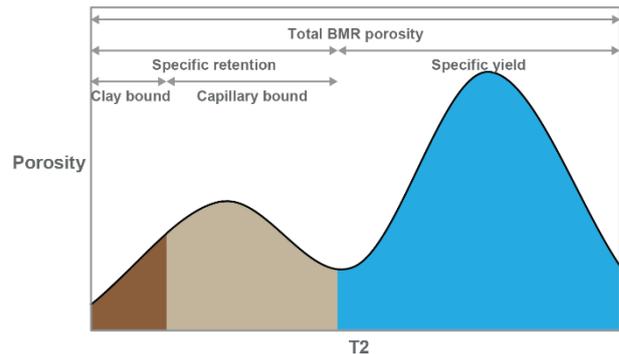
Hydraulic conductivity  $K$  (m/sec) can then be derived from permeability as  $K = \frac{9.869233E-10 \cdot k \cdot \rho \cdot g}{\mu}$ , where  $k$  is the permeability (mD),  $\rho$  is water density (g/cm<sup>3</sup>),  $g$  is the acceleration due to gravity (9.80665 m/s<sup>2</sup>), and  $\mu$  is the dynamic viscosity (cP). Transmissivity  $T$  (m<sup>2</sup>/s) can further be derived from hydraulic conductivity as  $T = K \cdot b$  where  $b$  is thickness (m).

Therefore, due to the sensitivity of magnetic resonance measurements to both pore volume and pore size, a range of storage and flow properties characterising hydrogeological behaviour can be estimated from such data.

## CHALLENGES ASSOCIATED WITH BOREHOLE MAGNETIC RESONANCE IN HYPERSALINE BRINES

Borehole magnetic resonance measurements involve both transmitting and receiving electromagnetic signals. These two functions are almost always achieved using the same physical RF antenna. The signal-to-noise ratio of the receiver is directly related to the Q of the antenna. Typical borehole magnetic resonance tools use a high Q receiver system to maximise noise rejection. However, a high Q design also has implications when transmitting the electromagnetic pulses that firstly tip and then refocus hydrogen nuclei.

In hypersaline environments, the conductive borehole environment increases the current draw on the antenna, as well as potentially slightly altering the resonant frequency of the tool. With a high Q antenna, the effect of this can be dramatic. Current draw can exceed



**Figure 3: The T2 distribution reflects the volumes of fluid occupying different pore sizes. Integrating amplitudes over the full T2 distribution gives the total porosity, while integrating amplitudes over a range of T2 values allows subdivision into different fluid types based on pore size, such as specific yield and specific retention.**

power supply capacity, which can lead to damaged tool electronics. For these reasons, conventional borehole magnetic resonance tools such as have been employed in the oil and gas industry are limited in their application in saline borehole environments.

A low Q tool design is more resilient to changes in operating frequency, and the impact of being off resonance is reduced. Unexpectedly high current draws are also avoided with such a system, which enables such tools to operate in high conductivity environments without being damaged. The tool used in this work was developed specifically for applications that require a low Q, including hypersaline and iron-rich environments.

### APPLICATIONS OF BOREHOLE MAGNETIC RESONANCE IN BRINE DEPOSIT EVALUATION

Figure 4 displays an example of borehole magnetic resonance data acquired in a borehole drilled to evaluate a potential sulphate of potash ( $K_2SO_4$ ) deposit. Track 1 displays the natural gamma ray radioactivity, which reflects variations in mineralogy, primarily clay content, in this clastic aquifer. Track 2 presents the total BMR porosity, representing the total water content in the aquifer, which is subdivided into specific yield and specific retention fractions in Track 3. Track 4 contains hydraulic conductivity derived from Timur-Coates permeability, and Track 5 displays the measured T2 distribution. Overall, very good quality data has been acquired in this

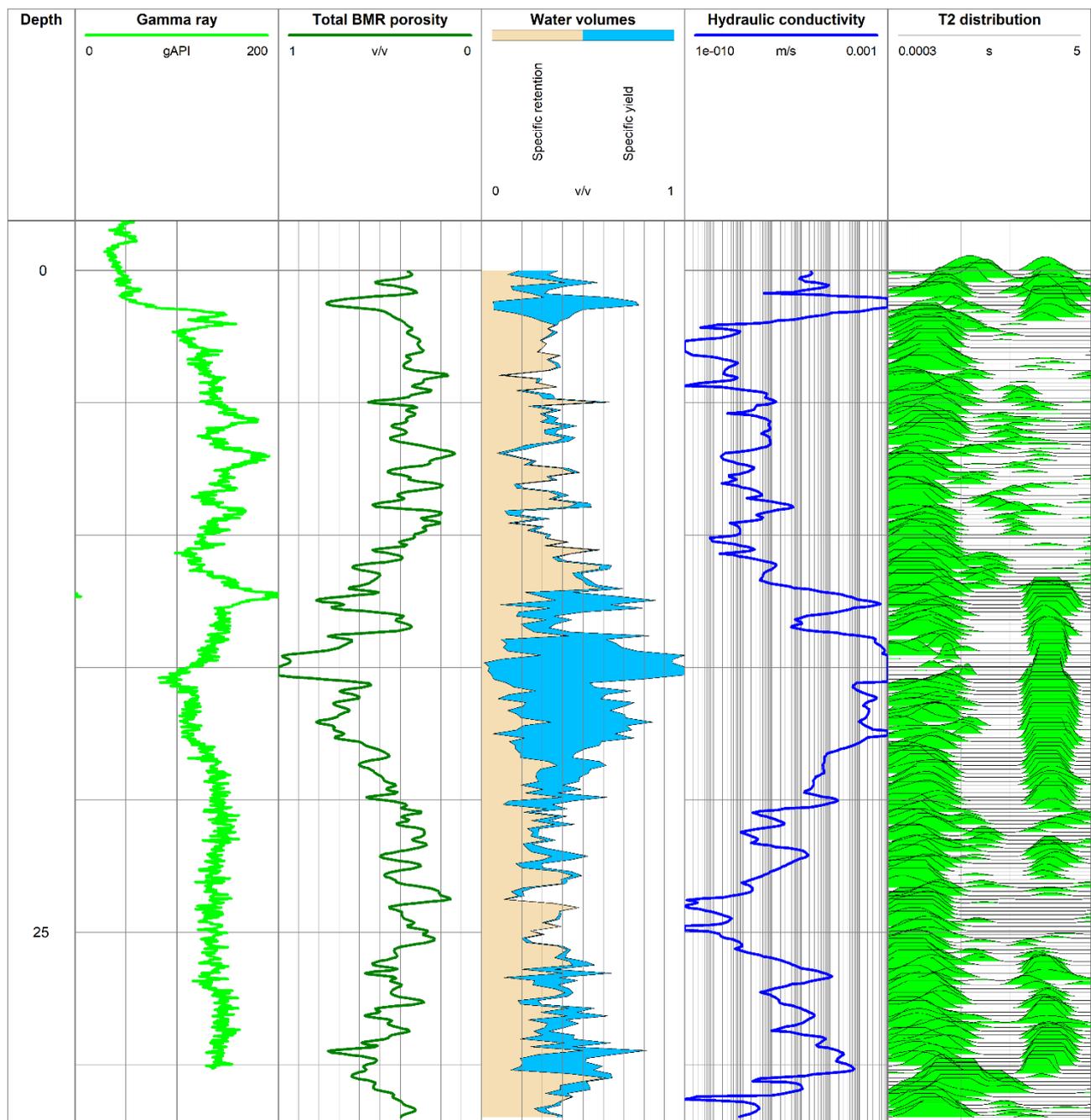


Figure 4: Borehole magnetic resonance evaluation of a potential brine deposit. Key hydrogeological parameters derived from borehole magnetic resonance data are specific yield in Track 3 and hydraulic conductivity in Track 4.

borehole, and other boreholes drilled to evaluate this deposit, and the tool has operated successfully in this hypersaline environment. The tool fully captured all the signal, even when frequency shifts occurred due to loading of the antenna in the high conductivity borehole environment. Current draw was kept within operating limits of the power supply and there was no detected drop in power supply voltage during pulse sequences.

This example does illustrate one additional challenge with evaluation of brine deposits, which can influence all potential evaluation methods. Due to the generally unconsolidated nature of the shallow aquifers associated with many brine deposits, particularly those hosted in dominantly clastic aquifer rocks, significant borehole enlargement is commonly observed. The borehole magnetic resonance log presented in Figure 4 was acquired through PVC casing due to concerns about borehole stability, so no caliper measurement is available to confirm hole size, however the porosity reading of 100% around 15 m depth suggests that the hole size is larger than the diameter of investigation of the borehole magnetic resonance tool, in this case 190 mm, and so the tool is sensing the enlarged fluid-filled borehole over this interval. Tools optimised for larger diameter of investigation will provide more robust data in such environments.

## CONCLUSIONS

Key hydrogeological parameters required for brine deposit resource and reserve definition are specific yield and hydraulic conductivity. These quantities are traditionally measured using well tests or on core samples; both are measurements of properties over discrete volumes of rock, and at very different scales. Borehole magnetic resonance is a continuous borehole geophysics measurement sensitive to both pore volume and pore geometry, so it can be used to estimate properties such as specific yield and hydraulic conductivity, and it is seeing increased application in hydrogeological studies. However, borehole magnetic resonance measurements can be adversely affected by high conductivity environments, which can exist in the presence of hypersaline brines. Such affects can be minimised or mitigated by appropriate tool design, and successful application of borehole magnetic resonance measurements for brine deposit evaluation has been demonstrated.

## REFERENCES

- AMEC, 2017, Guidelines for resource and reserve estimation for lithium and potash brines [online]: available from <https://www.amec.org.au/> (Association of Mining and Exploration Companies).
- CIM, 2011, National Instrument 43-101 – Standards of disclosure for mineral projects [online]: available from <http://web.cim.org/> (Canadian Institute of Mining, Metallurgy and Petroleum).
- CIM, 2012, Best practice guidelines for reporting of lithium brine resources and reserves [online]: available from <http://web.cim.org/> (Canadian Institute of Mining, Metallurgy and Petroleum).
- Dlubac, K., Knight, R., Song, Y.-Q., Bachman, N., Grau, B., Cannia, J., and Williams, J., 2013, Use of NMR logging to obtain estimates of hydraulic conductivity in the High Plains aquifer, Nebraska, USA: Water Resources Research, 49, 1871-1886.
- JORC, 2012, Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code) [online]: available from <http://www.jorc.org> (The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia).