MRS: NEW GEOPHYSICAL TECHNIQUE FOR GW WORK: (2) EXPLOITATION FOR GW INVESTIGATIONS

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MRS DATA EXPLOITATION

MRS data acquisition and data inversion typically provide water content and NMR decay time constant as a function of depth. Such empirical data set with its inversion results is displayed at Figure 8 for the case of Waalwijk-1.

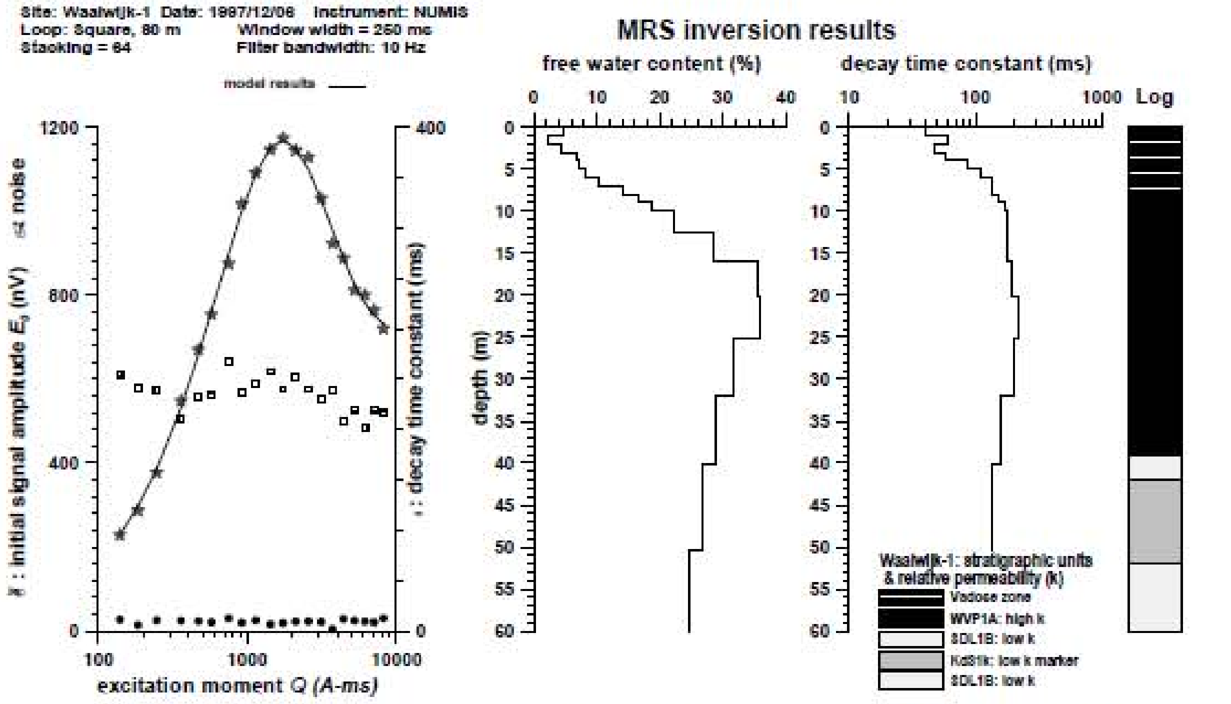

Figure 8: *MRS data set & inversion; Waalwijk-1, Netherlands: from left to right (1) MRS data summary, field [- E_0, - T_2^*, - noise] & model [—] vs. Q, (2 & 3) MRS inversion results: water content & decay time constant vs. depth, (4) Lithological log inferred from three nearest boreholes; in this model, the WVP1A unit has a higher permeability than the SDL1B and Kd31k units. (Item 4, TNO, 1998).*

Information acquired through MRS surveys allows, under suitable conditions, not only detection and positive identification of water bearing layers but also, the determination of their vertical geometry, i.e. depth and thickness, their free water content i.e. the amount of water free to move under realistic hydraulic gradients and an estimate of key parameters such as hydraulic conductivity, *K*, and transmissivity T (Legtchenko et al., 2004). For a given lithology/mineralogy, the longer the NMR decay rate, the coarser the water bearing pore-size below the water table. This important observation was first explained by Korringa et al. (1962) in their "KST" model. Later, Kenyon et al. (1989) showed empirical observations, which confirmed this model. In fact, the relationship between NMR decay rate and pore-size allows, through decay rate spectra analysis, the determination of pore-size distribution. Figure 9 is a pictorial diagram of the in-situ pore-size estimation process by NMR: the smaller the pore, the fastest the relaxation of the precessing $^1H^+$ nuclei through repeated contacts with the solid grain surface. Figure 10, described in the next section, is a reminder that magnetic effect may interfere if the measuring scheme is too simple. Finally Figure 11 is a summary of the classical study by Kenyon et al. (1989) on the empirical demonstration of the direct relationship between pore-size and NMR decay time.

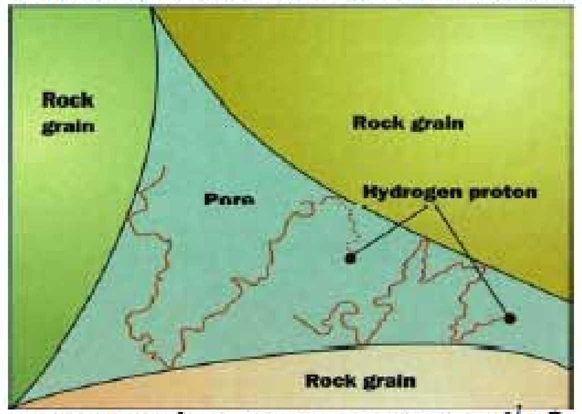

Figure 9: *Schematic representation of $^1H^+$ nuclei free precession within a rock's pore (after Kenyon and Gubelin, 1995)*

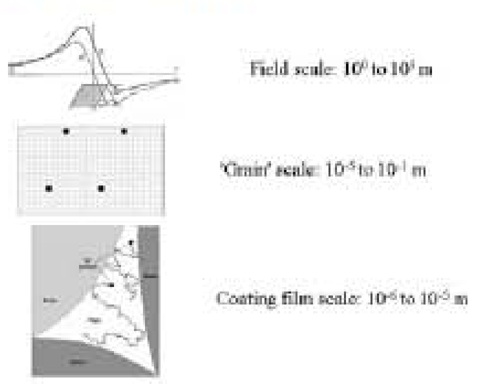

Figure 10: *Magnetic gradients at various scales of concern to MRS*

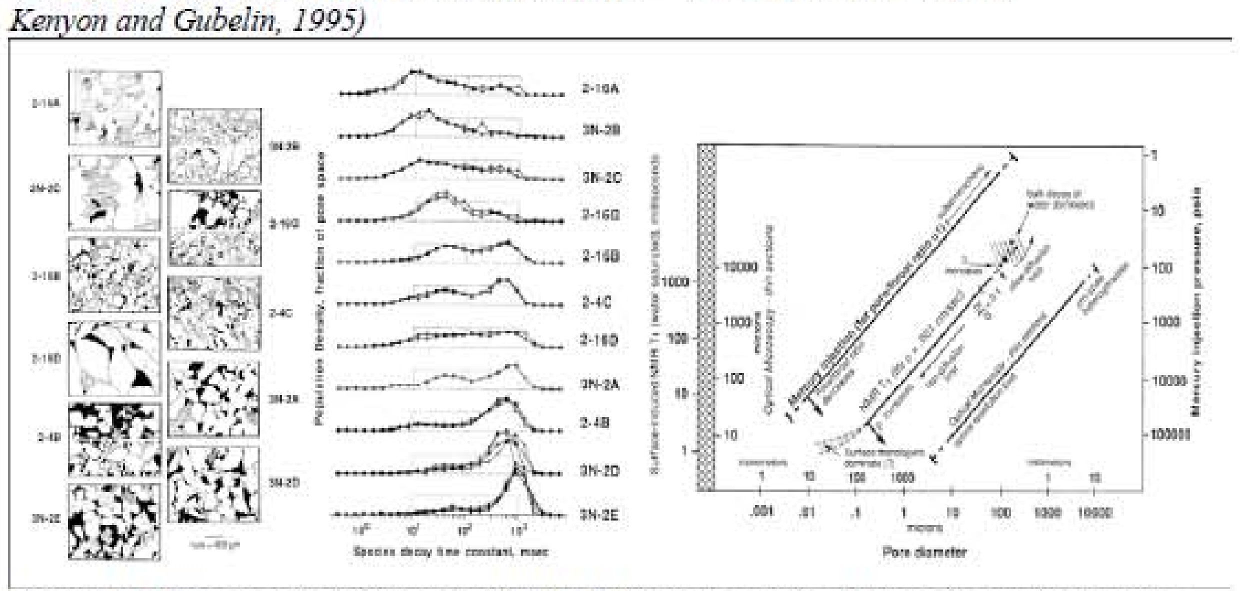

Figure 11: *Pore-size distribution and NMR. Left: micrographs of 11 rock samples; centre: corresponding NMR T1 spectra; right: correlation pore-size vs NMR T1, optical microscopy and mercury injection. The NMR and mercury injection curves are graphically offset for clarity (Kenyon et al. 1989).*

Because of the close link between pore-size, throat size, hydraulic permeability and hydraulic conductivity, NMR logs can reliably supply flow properties information. MRS, which is less advanced than its borehole-logging counterpart, is less reliable in environments where magnetic minerals are present. Also in most cases, MRS supplies an average decay rate instead of a decay rate spectrum. Above the water table, in particular at depths below GPR reach, MRS can supply information difficult to acquire non-invasively, such as water content and water film thickness or water drop size (Roy and Lubczynski, 2005). However, the exploitation of MRS in the vadoze zone still needs calibration. For GW resources assessment, there are four items of main concern: recharge, aquifer storage & flow properties estimation and quality of GW. These items/tasks are usually done through a combination of techniques including pumping and recovery tests, other hydrogeological methods, numerical model methods including 1D and distributed models. MRS is most likely to play an increasingly significant role in such resource mapping and quantification strategy.

MRS CAPABILITIES AND LIMITATIONS

Following a little over a decade of tests and evaluations, the users' perspective is that MRS is highly appropriate for GW work due to (1) its inherent selectivity for $^1H^+$ and therefore in the near surface for GW, (2) its performance as a non-invasive sounding tool, i.e. information as a function of depth, (3) the relevance of its inverted parameters to characterize aquifers and aquitards: θ_{MRS} and T_d. MRS is mostly used in a sounding mode, i.e. 1D, and the most readily available information is the one related to water quantity (θ_{MRS}) as a function of depth for both the vadoze and the saturated zone. Its hydrogeological significance needs careful considerations e.g. Lubczynski and Roy (2005). *K* and T calibrations have progressed significantly and lithology dependent factors have already been evaluated e.g. Vouillamoz (2003). An example of the use of signal decay spectral analysis is shown in Figure 12. Such technique is currently limited to MRS data sets with high S/N. In this Figure 12, the water content is resolved into 3 components of pore-size: "fine", "medium" and "coarse". The figure also shows an alternate way of displaying the MRS data set summary: the excitation moment *Q* is displayed along the Y-axis to stress the relationship (sounding parameter) between *Q* and depth. On the other hand, the MRS technique is sensitive to ambient noise: MRS cannot be acquired near power lines, industrial installations nor during magnetic storms. The current implementation of the technique is not yet compatible with all geological settings: magnetic materials and some stratigraphic combination of aquifers and conductive layers may generate 'masking' effects e.g. Roy and Lubczynski (2003). Figure 10, schematize sources of magnetic gradient of concern to MRS; magnetic gradients, if not accounted for, can shorten the measured NMR decay rate beyond the MRS instrument aperture window and thus may become insensitive to water in some magnetic rocks (Roy et al., 2008). Also some geological structures, e.g. conductive shear zone in an otherwise resistive environment, may channel natural and cultural noise lowering the S/N ratio of the acquired MRS data set.

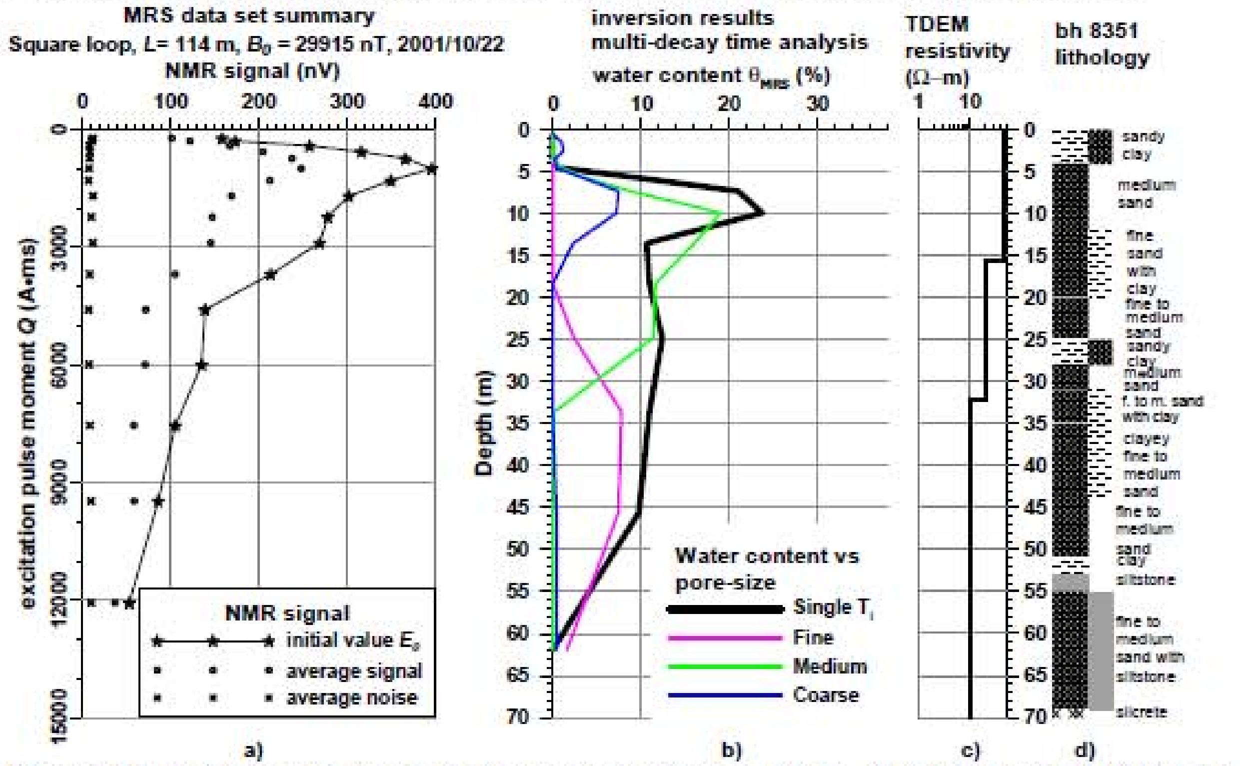

Figure 12: *MRS investigation on a paleo-channel near Maun, Botswana, site BH8351; a) data set summary, b) MRS inversion results with multi-decay time analysis, c) TDEM resistivity, d) BH 8351 lithology (after Mangisi, 2004; Roy and Lubczynski, 2005)*

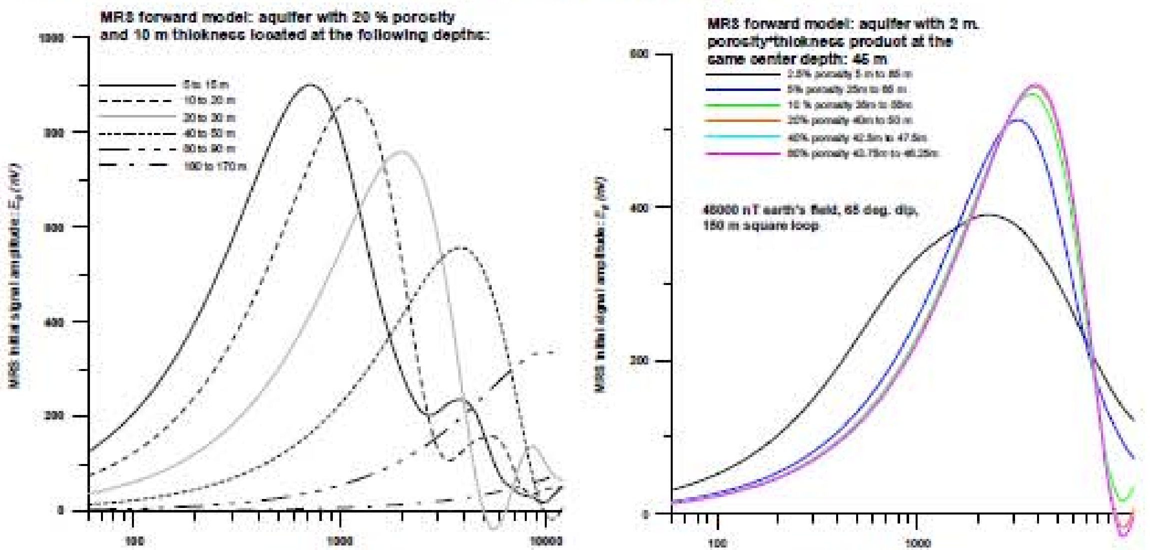

Figure 13: *MRS forward models: left – depth vs. Q relationship; right: MRS equivalence when depth*thickness ≈ or < loop size: L*

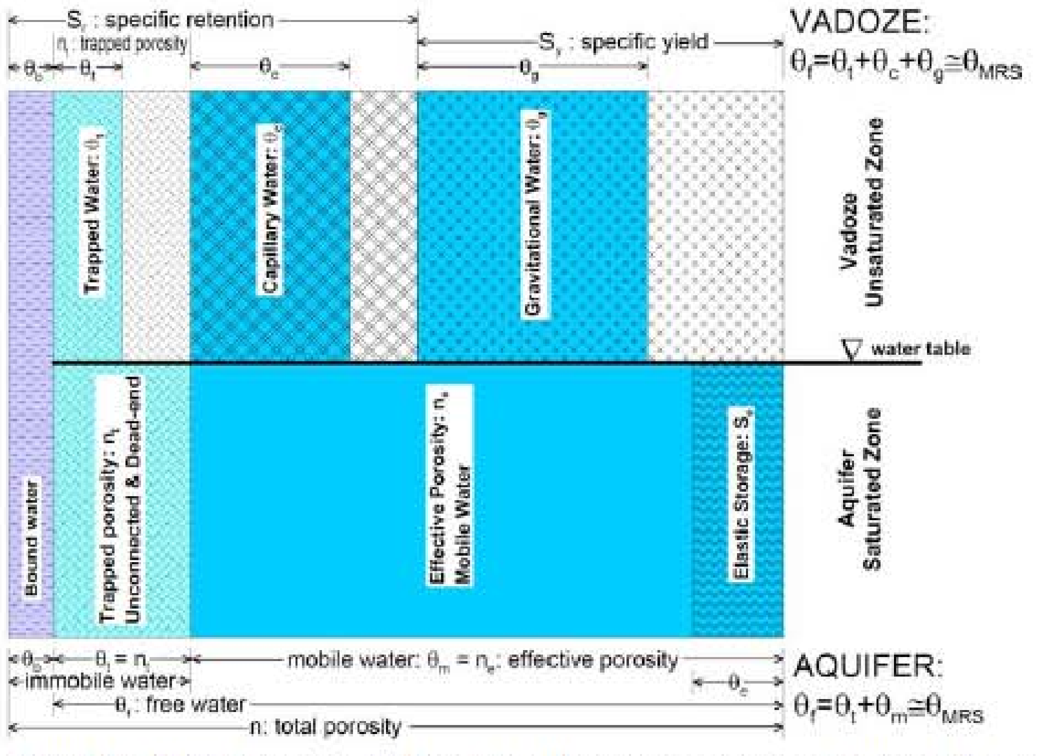

Figure 14: *MRS water content θ_{MRS} and GW storage parameters (after Lubczynski & Roy, 2005)*

Figure 13 illustrates two aspects of the aquifer storage quantification. The left part of the figure clearly shows, through modeling results, the depth discrimination of a 20% porosity 10 m thick aquifer from a mean depth of 10 to 165 m using the excitation moment *Q* as the sounding parameter. The right part of the figure illustrates a limitation familiar to geophysicists working with electrical techniques: the equivalence limitation. For a porosity*thickness product of 2 m with a mean depth of burial at 45 m, using a 150 m loop size easily resolve an 80 m thick aquifer but will only determine the porosity*thickness product when the thickness is reduced to less than 5 m under the modeled conditions specified in Figure 13. Contrary to most other non-invasive geophysical technique, MRS can discriminate to some extent the kind of water detected. In summary MRS detects mostly free water but Figure 14 goes into much finer details about such discrimination both from the saturated and unsaturated zone. Finally, one of the most difficult discrimination from a geophysical perspective is the separation between the specific yield and the specific retention of the vadoze zone. This is highly dependent on rock grain-size distribution and rock surface properties. Figure 15 is a reminder about empirical observations on that aspect. MRS is not yet calibrated to fully perform such discrimination but progress is ongoing.

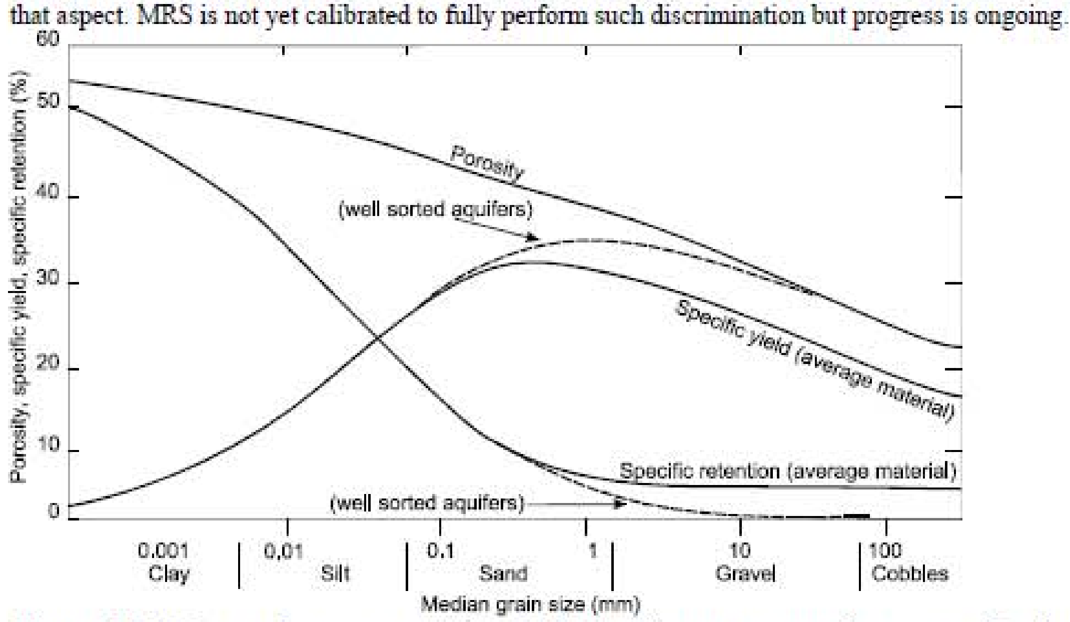

Figure 15: *Relation between specific yield, specific retention and porosity (Stephens et al. 1998)*

MRS ON-GOING R&D

Typical research and development directions involve S/N improvements, 2D & 3D capability and a widening of the NMR signal aperture window. Important progresses are made with respect to the application of the Spin Echo (SE) mode for magnetically disturbed sites and the hydrogeological control and calibration of the technique (Figure 16). After suitable development along several R&D directions, one can expect better ground penetration, higher GW selectivity and higher relevance of inverted parameters than e.g. GPR, possibly with less spatial resolution. However, it is most likely that the optimal use of the MRS technique will be tightly integrated with other geophysical techniques to supply the most relevant information in a rapid and cost-effective way. Currently, the technology is available from France and Russia with other implementations being developed to my knowledge at least in Germany and USA. Active working groups in MRS are located in various parts of the world including in Australia, China, France, Germany, India, Netherlands, Russia, Spain, USA etc. Four international workshops have allowed users and designers to share their experience and knowledge on the technique (Berlin 1999, Orléans 2003, Madrid 2006 and Grenoble 2009).

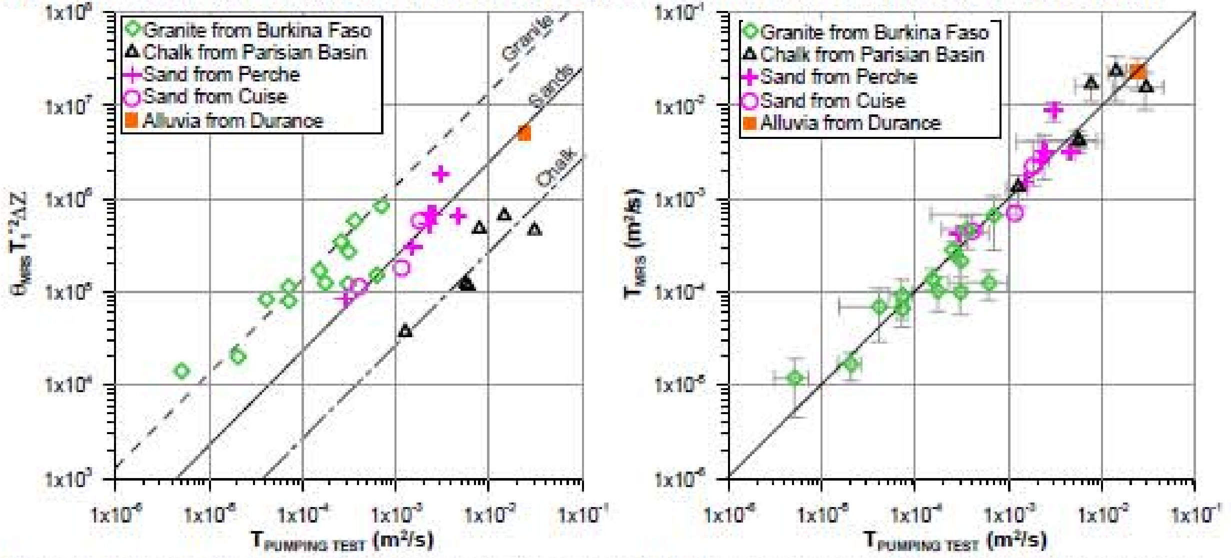

Figure 16: *Calibration of MRS results in terms of hydraulic parameters: (left) T from pump tests versus MRS T-estimator: $\theta_{MRS}T_1^{*2}\Delta Z$ showing lithology dependence (broadly classified as granites, sands and chalks), (right) MRS-T calibration after integration of lithology-dependent factor (Vouillamoz, 2003).*

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