Geological Survey of Ireland Research Programme
- Short Call 2015, Final Report -

Name of Lead Investigator	Dr. Ulrich Ofterdinger
Email	U.Ofterdinger@qub.ac.uk

Organisation name	Queen's University Belfast		
Organisation type:	☒HEI	☐Public Sector (other)	☐Private Sector

Project Title	Determining fractured bedrock aquifer parameters using Magnetic Resonance Sounding to better constrain numerical groundwater models in support of catchment scale water resource management
Contract No.	2015-sc-003

2. Project information:

Title of project	Determining fractured bedrock aquifer parameters using Magnetic Resonance Sounding to better constrain numerical groundwater models in support of catchment scale water resource management
Did you make any formal amendment to the project workplan / budget?	☒ yes ☐ no If yes, please specify: Within the overall budget framework, individual budget line items were amended as outlined in Section 3 below.

<u>Project Report (*max 1500 words, excluding figures and headings*)</u>:

(i) Objectives and scientific/engineering targets beyond the state of the art

The objectives of the proposed project were aimed at demonstrating the applicability of the Magnetic Resonance Sounding (MRS) method as a non-invasive tool for measuring key hydrogeological parameters in Irish fractured bedrock aquifers at relevant scales for catchment-based water resource management and modelling.

As reference,. the basics of the MRS method are provided in Legchenko and Valla (2002). Of particular interest with regard to the link between the MRS parameters and key aquifer parameters is the assessment of aquifer porosities (Vouillamoz et al., 2012), an important parameter when assessing groundwater contaminant transport processes.

The project was complete at two study sites previously characterised as part of the QUB Griffith Geoscience Award and as part of the EPA-funded QUB-UCD collaboration across Precambrian and Devonian-Carboniferous bedrock aquifers, respectively. The study site included the Gortinlieve site in Co. Donegal (Fig. 1) and the Kilmessan Quarry, Co. Meath.

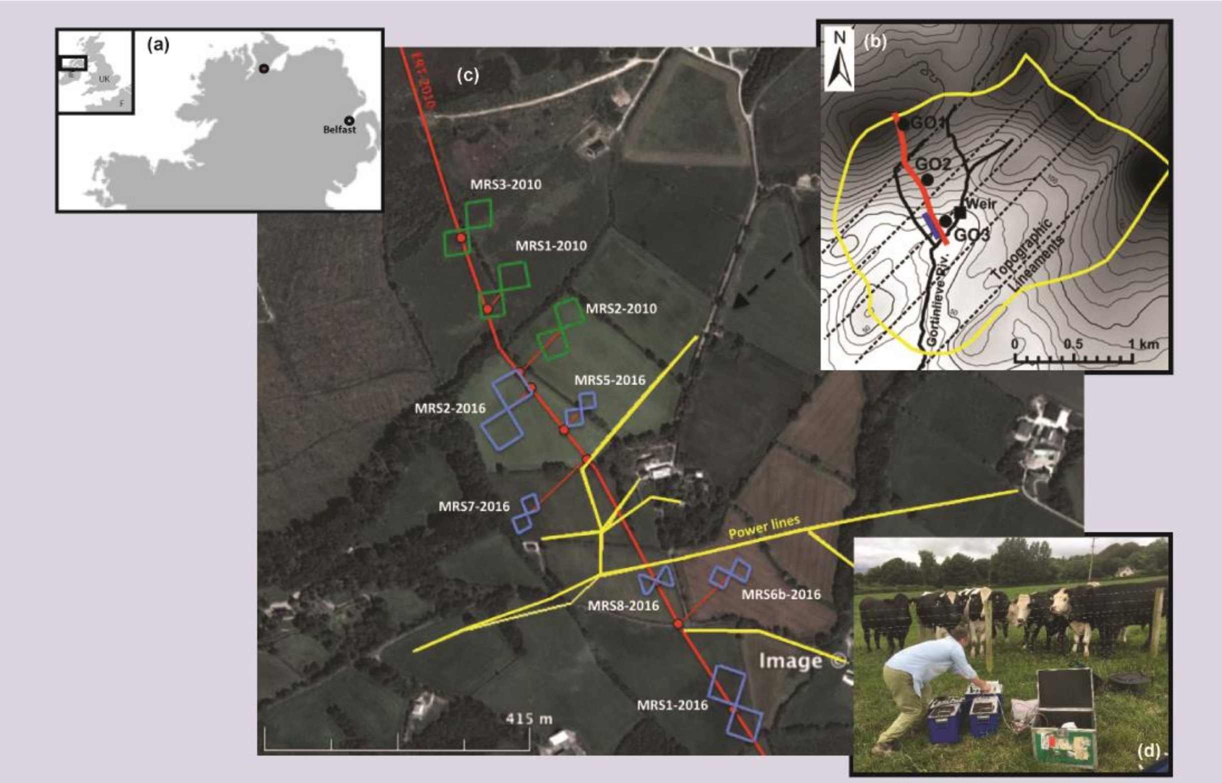

Figure 1: (a) Location of Study Site; (b) Physical Setting of Study Site - yellow line: catchment boundaries; black dots: monitored boreholes; red line: ERT profile; blue line: seismic profile; (c) Location of MRS stations (figure-eight loops) and ERT profile (red line); thin red lines show projections of MRS stations onto profile;yellow lines: electrical power lines (220V and high voltage lines); (d) Application of MRS in the field

At the Gortinlieve site, the project demonstrated the feasibility of the MRS method for determining aquifer effective porosities at the decametre scale. In combination with data from previously completed Electric Resistivity Tomography (ERT) surveys, the project was able to resolve the variation in aquifer porosities across the weathered and unweathered vertical profile of the Precambrian fractured bedrock units, thus combining the spatial resolution of structural bedrock geometry from the ERT data with the direct measurements of aquifer storage properties from the MRS survey. The MRS data with acceptable signal to noise ratios can be divided in three main groups (Figure 2).

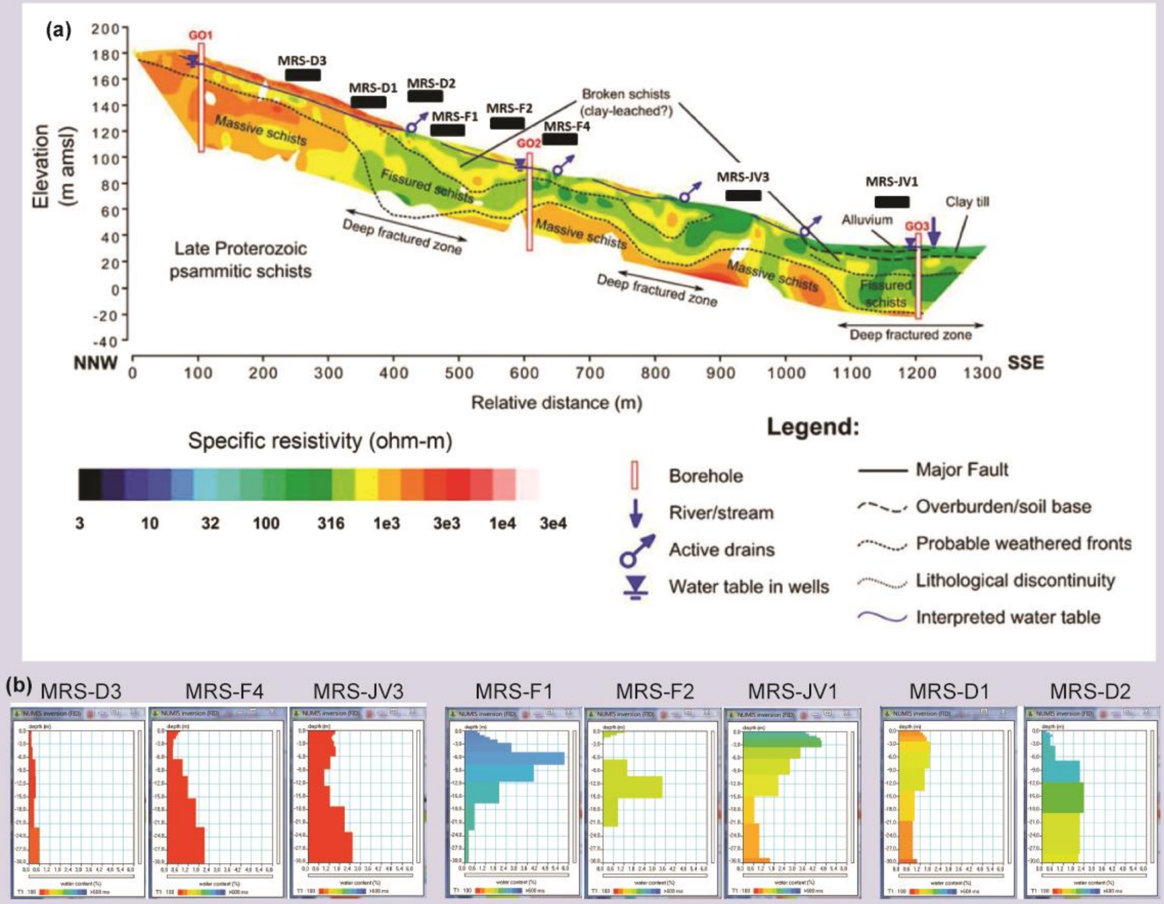

Figure 2: (a) Projected Locations of MRS stations on ERT profile; (b) Inversion of MRS data for Gortinlieve stations - MRS logs showing insignifcant/absent water (D3,F4,JV3); MRS logs revealing a significant weathered-rock aquifer (F1, F2, JV1); MRS logs reliably detecting water in the transitional zone between fresh hard rock and significant weathered-rock aquifer. (D1, D2).

Based on the estimated thickness of the weathered part of the bedrock units from the ERT data, the average water content across the weathered part of the aquifer was computed (Table 1).

Table 1: Summary of MRS estimation of the volume of water in the subsurface and conversion of the volume into an average water content using ERT estimate of the thickness of the weathered part of the aquifer.

Site Name	V_{min} (m^3/m^2)	$V_{regulariz}$ (m^3/m^2)	V_{max} (m^3/m^2)	DZ-ERT (m)	ERT Unit	W_{min} (%)	$W_{regulariz}$ (%)	W_{max} (%)	R_{mean} (ohm-m)
D1	0.42	0.46	0.52	40	broken+fissured	1.04	1.16	1.31	1000
D2	0.76	0.77	0.79	40	broken+fissured	1.89	1.93	1.99	800
D3	0.07	0.07	0.07	20	fissured	0.33	0.34	0.35	1000
F1	0.55	0.55	0.59	20	broken	2.74	2.75	2.94	500
F2	0.27	0.30	0.32	15	broken	1.81	2.00	2.16	1000
F4	0.22	0.23	0.25	20	fissured	1.08	1.14	1.23	500
JV1	0.45	0.48	0.51	20	alluv+till+broken/fissured?	3.02	3.22	3.37	150
JV3	0.20	0.22	0.23	30	fissured	1.02	1.11	1.14	550

The volume of water provided by the MRS inversion plotted vs. the thickness of the weathered bedrock aquifer from the ERT data shows some correlation, with MRS water volume increasing with increasing weathering (Figure 3a). The best correlation is obtained when considering the thickness of the broken and fissured zone together (R^2 of 0.75), which can be explained by the limited resolution of ERT and MRS.

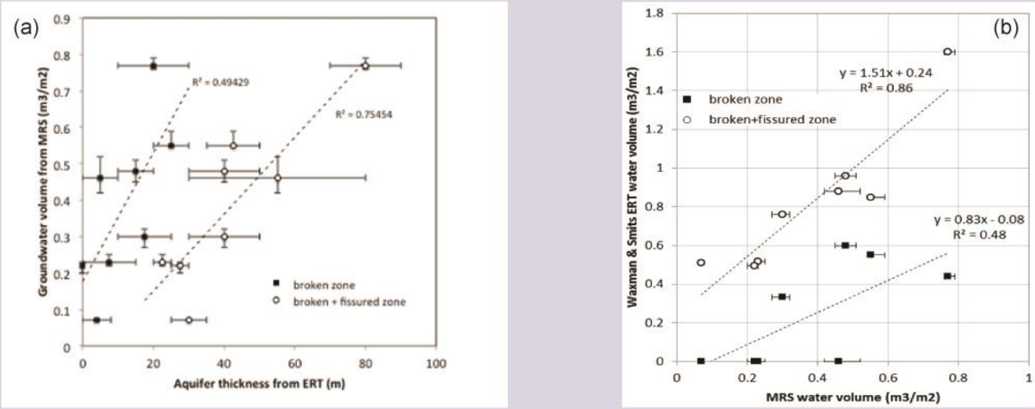

Figure 3: (a) MRS volume of water in the subsurface vs. thickness of the weathered zone aquifer from ERT considering broken zone and broken+fissured zone; (b) Comparison of MRS estimated water content with ERT-derived porosity.

The water volume calculated for ERT-derived porosities using the Waxman & Smith Model (*Comte et al. 2016*) is plotted against the MRS water volume in Figure 3b. Two scenarios are presented considering the total water-saturated zone above the deep fresh bedrock, (i) the highly weathered, or broken, and fissured zone together; and (ii) the broken zone only. Better correlation is obtained when considering broken (highly weathered) and fissured (poorly weathered) zone together. This can be explained by limited resolution of both ERT and MRS, which do not allow for an accurate resolution of different parts of the aquifer. The volume of water derived from the ERT data is systematically larger than that measured by MRS. It can be explained, at least partly, by the fact that the MRS method detects only mobile water and ERT is sensitive to both mobile and immobile water within the aquifer pore spaces. The derived aquifer porosities were successfully integrated into initial numerical groundwater flow models (Fig. 4) for catchment transects to better constrain the calibrated groundwater flow regime . Preliminary numerical model simulations have been carried out in dynamic steady-state (long-term transient simulations with time-invariant boundary conditions, i.e. recharge and river stage) incorporating aquifer heterogeneity distributed according to (1) pump test interpretation of hydraulic conductivities and (2) weathering spatial variations as consistently delineated by ERT and MRS.

Simulations show the major control of aquifer heterogeneity of hydraulic conductivities on flow patterns and groundwater pathways. Darcy fluxes (groundwater flow rates) are about 10 to 100 times higher in the transition zone as compared to the shallow bedrock, and over 1000 times higher as compared to the deep (unweathered) bedrock (Fig. 4b). Flow directions tend to have a dominant horizontal (parallel to topography) component in the transition zone, however the contribution of the vertical component increases with increasing depth (Fig. 4b,c&d). In dynamic steady state the distribution of aquifer porosity have insignificant influence on flow patterns and groundwater pathways. However it exerts a strong control on groundwater transit times in the aquifer (Fig. 4c&d). A homogeneous porosity value taken at 0.5% as a standard value for weathered/fractured aquifers in Northern Europe shows large transit times, up to 220,000 days (600 years), and long/deep pathways for the groundwater recharged uphill, which ultimately discharge in the main river downhill (Fig. 4c). Porosities distributed according to ERT and MRS results (3% in alluvium; 1% in the transition zone; 0.5% in the shallow bedrock and 0.1% in the deep bedrock) overall shows much shorter groundwater transit times of up to 50,000 days (137 years) for the longest/deepest flowpaths (because of the lower porosity than standard value of 0.5%) and longer flow paths in the transition zone (higher porosity than standard value) (Fig. 4d).

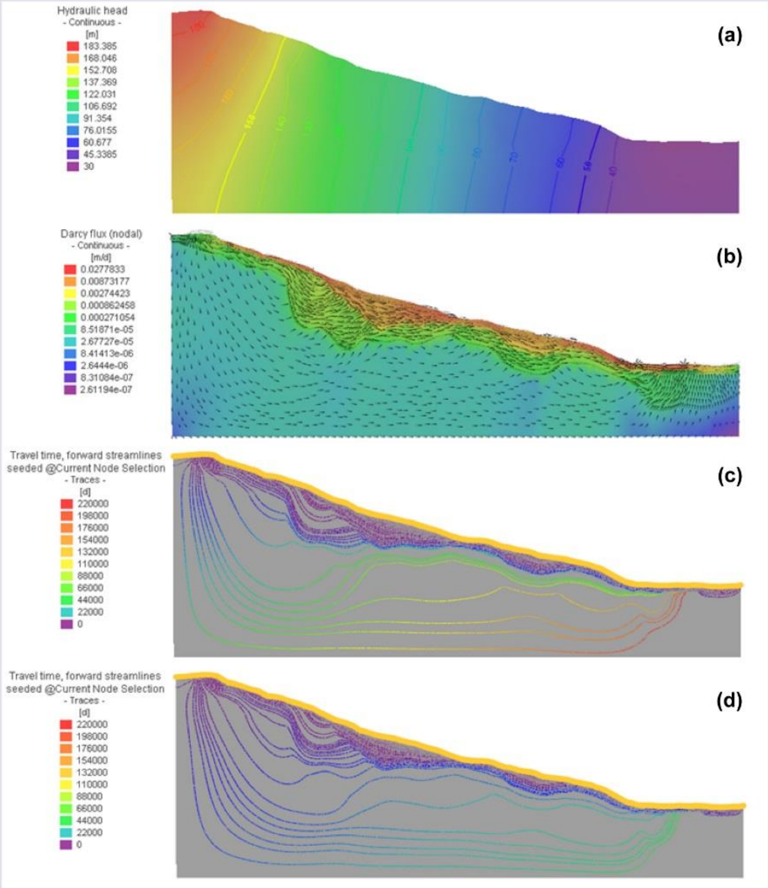

Figure 4: 2D finite element numerical groundwater model simulation in dynamic steady-state at the studied hillslope co-inciding with boreholes and ERT profile (preliminary results); (a) calculated groundwater head distribution; (b) Darcy flux distribution and flow vectors; (c) path-lines and transit time distribution for a homogeneous distribution of effective porosity (0.5%); (d) pathlines and transit time distribution for distributed effective porosity from joint application of ERT and MRS data (0.1 to 3%).

This has major implications on timescale of contaminant attenuation in groundwater. Numerical modelling activities are still ongoing. Further analysis will in particular explore and quantify the contribution of the spatial porosity data as provided by combining MRS and ERT to assist in resolving the flow dynamics in full transient conditions (i.e. seasonal recharge variations including wet and dry periods), for which aquifer storage parameters play an important role in regulating surface water flow and with regards to the response of groundwater resources to long-term change in climate and human activities.

The MRS soundings completed at Kilmessan Quarry were targeting a previously identified water bearing fracture zone within the fractured host rock (Figure 5). The soundings failed to resolve this discrete water bearing feature within the decametre-scale MRS investigation volume. However, the soundings were able to confirm the lower bound of signal resolution of the MRS method with high confidence due to the favourable signal-noise ratio at this location. Thus, while the site specific information on bedrock porosities was limited, these soundings provided high quality data for further method development.

Figure 5: (a) Location of Study Site; (b) Aerial Photograph of Quarry and inferred location of fault zone (dashed line); (c) Site View of MRS Survey within Quary (View SE along fault zone); (d) Site View of MRS Survey within Quarry (View NW along fault zone)

In summary, the MRS soundings completed as part of the project were able to successfully demonstrate the feasibility of the MRS method to measure aquifer porosities in Irish bedrock aquifers. In particular, determining aquifer parameters directly through MRS soundings in combination with using ERT data for a detailed resolution of aquifer geometries and stratigraphy proved a successful approach. This in turn provided key information at relevant scales to better constrain numerical groundwater flow models. This combined application of MRS and ERT in fractured bedrock environments has previously not been documented and thus the findings of this project and associated publications present a progress beyond the current state of the art.

(ii) Implementation (including reference to timelines, milestones, management)

The MRS field survey at the two study sites was complete within two weeks during Q2/3 2016 in collaboration between the project partners at IRD, QUB, UCD and UoA, including academic and junior research staff from the partner institutions. Collected MRS data were processed and inverted subsequent to the completed fieldwork and an internal project report summarising the data collection, processing and interpretation was completed by all partners during Q3 2016. Collected MRS data were integrated into initial numerical groundwater flow models during Q4 2016.

The MRS method and the subsequent project findings were presented at the Geological Society Conference in Belfast (June 2016) and at the October IAH Technical Discussion Meeting and the 2016 GSI Geoscience Conference (November 2016). A first paper manuscript has been developed by the project partners summarising the results of the field surveys and a second paper manuscript focussing on the outcomes of the numerical modelling study is currently in preparation (see Appendix 1). Furthermore, the project findings will be presented at the EGU 2017 General Assembly in Vienna (see Appendix 1).

No significant issues regarding the project implementation were encountered. However, due to unforeseen access restriction to Kilmessan Quarry during the field campaign the number of soundings that could be completed at this study site were less than originally anticipated.

(iii) Outputs (please use bullet points)

The project delivered a number of key outputs, including:

- Demonstration Project for the application of Magnetic Resonance Sounding (MRS) to measure aquifer parameters and their spatial variations in Irish hard rock aquifers;
- Demonstration Project for the combined and supplementary use of MRS and ERT data for characterising fractured bedrock environments
- Demonstration Project for the use of MRS data for better constraining numerical groundwater flow models;
- Training of Junior Research Staff in the application of the MRS method and integration of MRS data into modelling approaches;
- Presentation of MRS applications in Aquifer Characterisation to the wider community of Hydrogeology practitioners and researchers at Geological Society and IAH events (see Appendix 1);
- Preparation of Conference Presentations (Geological Society Belfast Conference, Geoscience 2016 event, EGU General Assembly 2017; see Appendix 1)
- Preparation of join paper manuscripts (see Appendix 1)

References

Comte, J-C., Cassidy, R., Caulfield, J., Nitsche, J., Ofterdinger, U., Wilson, C. (2016) Heterogeneity of groundwater storage properties in the critical zone of the Irish metamorphic basement from geophysical surveys and petrographic analyses, Abstract EGU2016-17468, EGU General Assembly 2016, Vienna, 17-22 April

Legchenko, A., and Valla, P. (2002) A review of the basic principles for proton magnetic resonance sounding measurements; *Journal of Applied Geophysics*, 50, 3-19, http://dx.doi.org/10.1016/S0926-9851(02)00127-1

Vouillamoz, J.M., Sokheng, S., Bruyere, O., Caron, D., Arnout, L. (2012) Towards a better estimate of storage properties of aquifer with magnetic resonance sounding, *Journal of Hydrology*, 458–459, p51–58, http://dx.doi.org/10.1016/j.jhydrol.2012.06.044

Impact/value of the project (M*ax 500 words*):

The project demonstrated the feasibility of using Magnetic Resonance Sounding as a non-intrusive survey method for determining key aquifer parameters in Irish fractured bedrock aquifers and the integration of MRS data into groundwater flow models in support of catchment scale water resource management. In doing so, the project advanced the generic scientific understanding regarding the hydrogeological application of MRS in fractured bedrock aquifers and supported further method development. Within the Irish context, the project provided new insights into storage properties of Irish fractured bedrock aquifers across weathered and unweathered bedrock profiles and their relationship to the previously investigated structural framework of these complex aquifer systems.

The project also supported knowledge transfer and training to junior researchers from the partner institutions as well as fellow researchers and practitioners on the application of MRS in hydrogeology and thus provided the wider community of stakeholders involved in water resource management across the Island of Ireland with a promising research and management tool, not commonly applied across the Island of Ireland to date. Further dissemination routes via journal publications and conference presentations highlight the project findings to the wider research community.

Appendix 1 – Publications & Presentations:

Lawson, FMA, Vouillamoz, JM, Legchenko , A, (2016) Is magnetic resonance sounding efficient to characterise hydrogeological properties of bed rock aquifers ?, Geological Society of London Conference 'Groundwater in Fractured Bedrock Environments', Belfast, 10 June 2016

Legchenko, A., Ofterdinger, U., Comte, J.-C., Walsh, J. (2016) MRS (Magnetic Resonance Spectroscopy) study of a fractured hard rock aquifer in County Donegal, Ireland, IAH-TDM, 4 October 2016, Dublin

Legchenko, A., Comte, J.-C., Ofterdinger, U., Walsh, J. (2016) MRS Study of a Fractured Hard Rock Aquifer in County Donegal, Ireland, 2016, GSI Geoscience 2016 Conference, 2 November 2016, Dublin

Legchenko, A., Comte, J.-C., Ofterdinger, U., Walsh, J., Vouillamoz, J.-M., Lawson, F. (2017) Characterisation of hard rock aquifers by integrating MRS and ERT data – a case study from Co. Donegal, Ireland, *Near Surface Geophysics*, under review

Legchenko, A., Comte, J.-C., Ofterdinger, U., Vouillamoz, J.-M., Lawson,F., Walsh, J. (2017) MRS inversion for water volume, *Journal of Applied Geophysics*, under review

Legchenko, A., Comte, J.-C., Ofterdinger, U., Walsh, J., Vouillamoz, J.-M., Lawson, F. (2017) Combining MRS and ERT surveys to characterise hard rock aquifer properties, EGU General Assembly 2017, 23–28 April 2017, Vienna (Austria), under review

Comte, J.-C., Legchenko, A., Ofterdinger, U., Walsh, J. (2017) Integrating MRS and ERT data into groundwater flow models for hard rock aquifers, *Hydrological Processes*, in prep.