ISSN 2047-0371

1.5.4. The emerging use of Magnetic Resonance Imaging (MRI) for 3D analysis of sediment structures and internal flow processes

Heather Haynes[1] & William M. Holmes[2]

[1] Water Academy, Heriot-Watt University, Edinburgh, UK (h.haynes@hw.ac.uk)

[2] Glasgow Experimental MRI Centre, Wellcome Surgical Institute, University of Glasgow, Glasgow, UK (william.holmes@glasgow.ac.uk)

Magnetic Resonance Imaging (MRI) can be used for 3D analysis of small-scale porous media structure and internal flow-related processes. It offers notable advantages over traditional sediment sampling (e.g. cores or surface-based scanning) as it is capable of high spatio-temporal resolution of the full 3D volume, including the sub-surface. Similarly, compared to X-Ray tomography, the extensive catalogue of MR pulse sequences typically provides: faster capture for imaging dynamic fluid processes; greater flexibility in resolving chemical species or tracers; and a safer radiation-free methodology. To demonstrate the relevance of this technique in geomorphological research, three exemplar applications are described: porous media structure of gravel bed rivers; measurements of fluid processes within aquifer pores and fractures; and, concentration mapping of contaminants through sand/gravel frameworks. Whilst, this emerging technique offers significant potential for visualizing many other 'black-box' processes important to the wider discipline, attention is afforded to discussion of the present constraints of the technique in field-based analysis.

KEYWORDS: Magnetic Resonance Imaging; sediment structure; porosity; permeability; 3D analysis

Introduction

Traditional geomorphological techniques for analysing small-scale sediment structure are typically constrained to 1D or 2D approaches, such as coring, photography etc. Even where more advanced techniques are available (e.g. laser displacement scanning), these tend to be restricted to imaging the surface of the sediment bed in a manner preclusive of true 3D analysis of volumetric space and the sub-surface particle characteristics and packing arrangements. Using Magnetic Resonance Imaging (MRI) overcomes these limitations, providing researchers with a technique with which to provide novel 3D spatio-temporal data on the internal structure of opaque porous media and the related fluid exchange and chemical reactions occurring within.

To date, MRI has been widely applied in the study of both porous media and mass transport phenomena in research disciplines such as biomedicine, separation science, food science, well logging, physical science, rheology, chemical engineering and petroleum engineering. This breadth of applications is well demonstrated in publications such as Huerlimann et al. (2008) and Fantazzini et al. (2011). Given that these studies have proven MRI's capability to non-invasively study sediment structure, advection and diffusion processes, molecular dynamics and chemical reactions, the technique is increasingly drawing attention from researchers involved in sedimentology and geomorphology. Recent examples include: monitoring porosities in geotechnical composites (Tyrologou et al. 2005); identifying sedimentary structures in seabed cores (Bortolotti et al. 2006); determining the permeability of rock fractures in aquifers (e.g. Nestle et al. 2003a); analysing the wetting of clays via diffusion (Vogt et al. 2002; Ohkubo & Yamaguchi 2007); visualising the mechanics of granular flows and fluidised beds (e.g. Kawaguchi 2010); and assessing river bed structure (Kleinhans et al. 2008, Haynes et al. 2009). Whilst application of MRI to sediment research is recognised to be a science in its infancy, maturation of this technique may offer geomorphologists crucial quantitative insight into many of today's black-box sediment systems. This technical note therefore focuses on the current strengths and weaknesses of MRI, using examples directly relevant to geomorphology to highlight its capability and future potential.

Magnetic Resonance Imaging

The theory of magnetic resonance

Certain nuclei (^{1}H, ^{13}C, ^{23}Na, ^{31}P etc.) possess spin angular momentum, and hence a nuclear magnetic moment, or "spin". Though many nuclei can give an MR signal, only hydrogen nuclei (^{1}H) found in water (in its liquid form) provide sufficient signal for the practical use of MRI for sediments. When ^{1}H rich samples are placed in a static magnetic field (Figure 1), B_0, they become polarized, resulting in a net magnetisation aligned (ie longitudinal) with the magnetic field. The net magnetisation exhibits precession about the static magnetic field at the Larmor Frequency, and will absorb and emit RF radiation at this resonant frequency.

By using an RF coil (Figure 1) tuned to resonate at the Larmor frequency, short pulses of RF radiation excite the nuclear spins, tipping the net magnetization into the plane transverse to B_0. The precession of this transverse magnetization then induces an alternating current in the RF coil, giving the MR signal. Further, using magnetic field gradient coils (Figure 1) to linearly vary the magnetic field across the sample causes precession to occur at slightly different frequencies at different locations across the sample; this labels the spatial position of the nuclei and is the basis of MRI.

One important type of image in MRI is relaxation weighting, where the net magnetization returns to equilibrium following an RF pulse. This is described by the loss of transverse magnetisation (T_2 transverse relaxation) and the return of longitudinal magnetisation (T_1 longitudinal relaxation). T_1 and T_2 relaxation can result from the close proximity of fluid molecules to the pore surface, thus the time of relaxation reflects the spatial scale of the pore space. At higher magnetic fields (>10MHz) T_2 relaxation is also affected by magnetic susceptibility broadening where fluid molecules diffuse through the internal magnetic field gradients (produced by magnetic susceptibility difference between the solid and fluid). These relaxation times can be shortened by paramagnetic contrast agents, thus enabling time-lapse imaging of fluid-related transport processes within porous media. An alternative MRI image for fluid transport analysis is a Pulse Field Gradient (PFG);this uses a pair of magnetic field gradients pulses to encode for molecular displacements, enabling the measurement of diffusion, dispersion and velocity imaging. For a more detailed explanation of the physics of these types of images and general theory of NMR, the reader is referred to Levitt (2002) or Callaghan (1993).

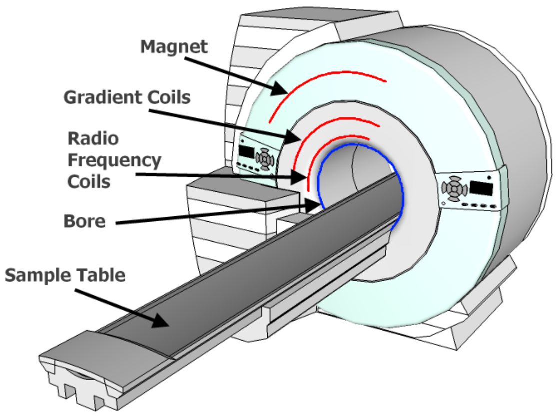


Figure 1: Schematic diagram of an MRI machine illustrating the concentric arrangement of coils (360º) and magnet.

Image Acquisition

The three gradient coils permit data acquisition in any orientation as 1D profiles, 2D slices or 3D volumes. The raw MRI dataset is a complex Cartesian grid with units of reciprocal space, which is termed k-space. For sediment-pore-fluid related research it is a volume which is of interest, hence the 3D k-space is inverse 3D Fourier transformed and the magnitude taken so as to produce a 3D image (MRI) which is spatially recognisable on an x, y, z co-ordinate grid of voxels (i.e. 3D pixels). Whilst areas of the image where nuclei are mobile (e.g. fluids) return a signal and are observed as bright regions on a grey-scale spectrum, regions of solid fail to return a signal and appear black. Figure 2 illustrates this process, culminating in 3D data of the internal structure of the sample volume which can be quantitatively analysed using standard image processing software packages.

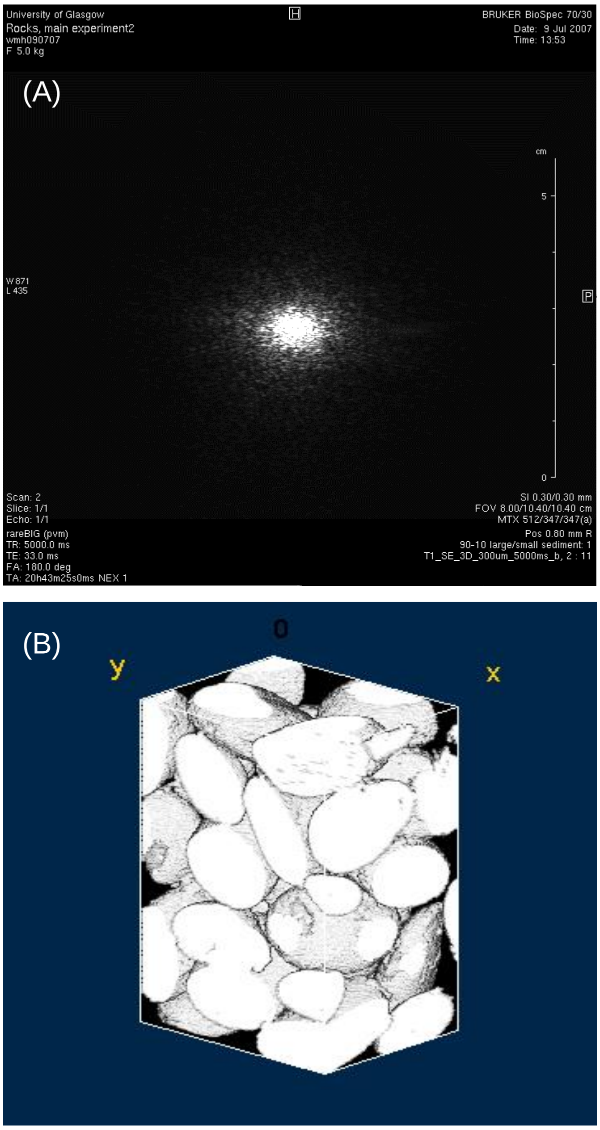


Figure 2: Example of image reconstruction, including (A) k-space signal, where the white signal indicates the presence of ^{1}H nuclei; (B) Fourier-transformed signal into spatial 3D volume of sediment immersed in water, as generated using ImageJ software.

Examples of use

To date, MRI has been used for a number of sedimentological analyses in a wide range of disciplines (see review papers of e.g. Mantle & Sederman 2003; Werth et al. 2010). Despite this, it is still considered an 'embryonic' technique for geomorphological investigation and three relevant exemplar topics are briefly explored below.

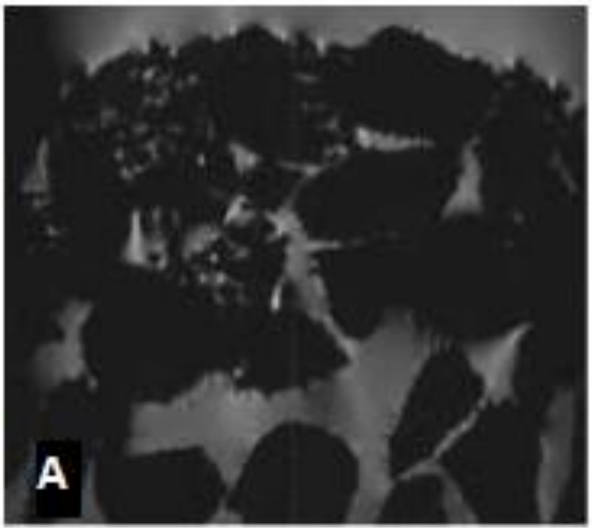
Porous media structure

Grain packing arrangements and pore size distributions are well studied using dynamic MRI (e.g. Baldwin et al. 1996; Baumann et al. 2000; Sederman & Gladden 2001; Sederman et al. 2004), including recent examples specific to geomorphology (e.g. Bortolotti et al. 2006; Kleinhans et al. 2008; Haynes et al. 2009; Haynes et al. 2012). River bed structure analysis is one such research arena where high strength MRI (3T–7T) has been used to yield 3D volumetric images (resolution 300-500µm) of water-worked sediment patches or artificially-generated packed columns comprising sediments of 0.5-22.5mm diameter (Kleinhans et al. 2008; Haynes et al. 2009; Haynes et al. 2012). Image thresholding procedures, based on the signal intensity of each voxel, were applied in order to separate the grey-scale image into local regions of solid and fluid. Subsequent analysis included: (i) accurate measurement of grain axial dimensions, made possible if isotropic voxels are acquired such that the data set can subsequently be re-sliced in any orientation; (ii) porosity and void ratio measurements, taken as bulk averages of each horizontal slice of the volume space; (iii) description of fine sediment infiltration spatial patterns of sealing and siltation processes (Figures 3a and 3b); and (iv) porosity-based descriptors appropriate to resolving the surface-subsurface transition of river beds. These papers indicate that accuracy in measurements is dependent on the size of particles relative to that of the image resolution; typically <1% error can be achieved. Such outputs clearly highlight the particular benefit of visualising the sub-surface structure and illustrate the potential of MRI in fluvial sediment research, ranging from active layer processes and armour layer development to changes to hyporheic exchange processes.

Fluid processes

Single and multi-phase flows have been analysed over a range of scales using MRI, including research into rock fractures, sediments and simplified bead packs (e.g. Baumann et al. 2000; Sederman & Gladden

2001; Hermann et al. 2002; Mantle & Sederman 2003). Aquifer-related research undertaken by Li et al. (2009) mapped water flow velocities in cm-diameter cores of sand packs (0.2-0.8mm grain diameter) and natural carbonate limestone cores extracted from the field. Data clearly demonstrated preferential flow routes local to high permeability channels in the samples, with calibrated velocity data indicating 0.9mm/s in sand and 0.2mm/s in rock fractures. Similar research has been undertaken in coarser porous media (particle diameter ~5mm) where direct imaging of flow velocities up to 150mm/s have been measured in artificial bead pack arrangements (e.g. Sankey et al. 2009; Sains et al. 2005) placed within bespoke MR-compatible flow columns (details can be found in the respective papers). Here, 2D and 3D visualisation images of flow fields are presented over a range of scales from full samples (cm) to individual conduits (µm), clearly demonstrating complex flow structures such as high speed channels, stagnant zones, vortices at conduit confluences and back-flow. Such examples of MR sequences are continually being advanced to reduce image acquisition times towards real-time acquisition of 3D Cartesian component velocity (e.g. Bock et al. 1995; Sederman et al. 2004; Li et al. 2009) and shear stress images (e.g. Sederman & Gladden 2001; Swider et al. 2007). Yet, data on the porous structure can also be used to *indirectly* simulate the internal permeability (Figure 4) or flow field (e.g. Mantle et al. 2001) using numerical models superimposed onto MRI datasets.



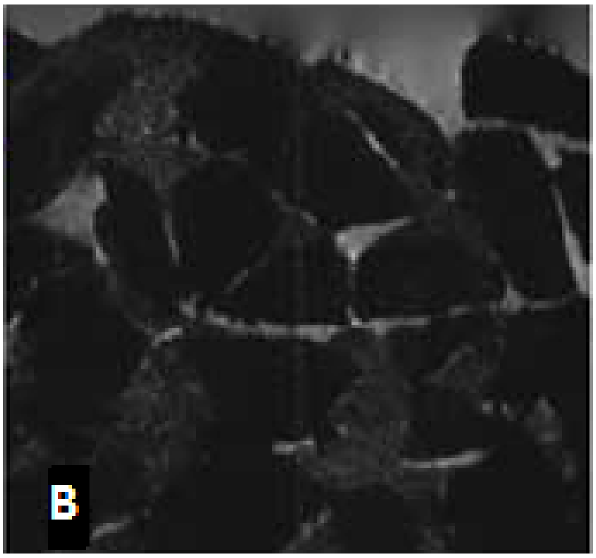


Figure 3a: Grey-scale (un-thresholded) MRI data slices (2D) of fine infiltration into a gravel framework following water-working. Image (A) shows sealing, where coarse sand deposits confined to the upper layers of the bed. Image (B) shows siltation by fine sand throughout the sample depth with isolated and interconnected voids present on the underside of gravel particles. Image adapted from Haynes et al. (2009).

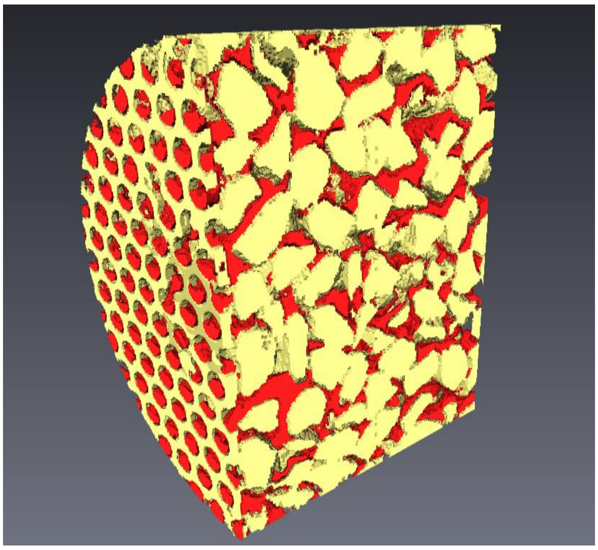


Figure 3b: Post-processed MRI data (3D volume) indicating kaolin deposition (red) within a 10mm gravel framework (yellow). Remaining pore spaces are shaded grey. This follows 10 days of clogging at 50ml/min and average sedimentation rates of 0.54g/hour. Pipe diameter was ~100mm with flow entering via a perforated plate (left of image). Images generated using Avizo software, courtesy of J. Minto, University of Glasgow.

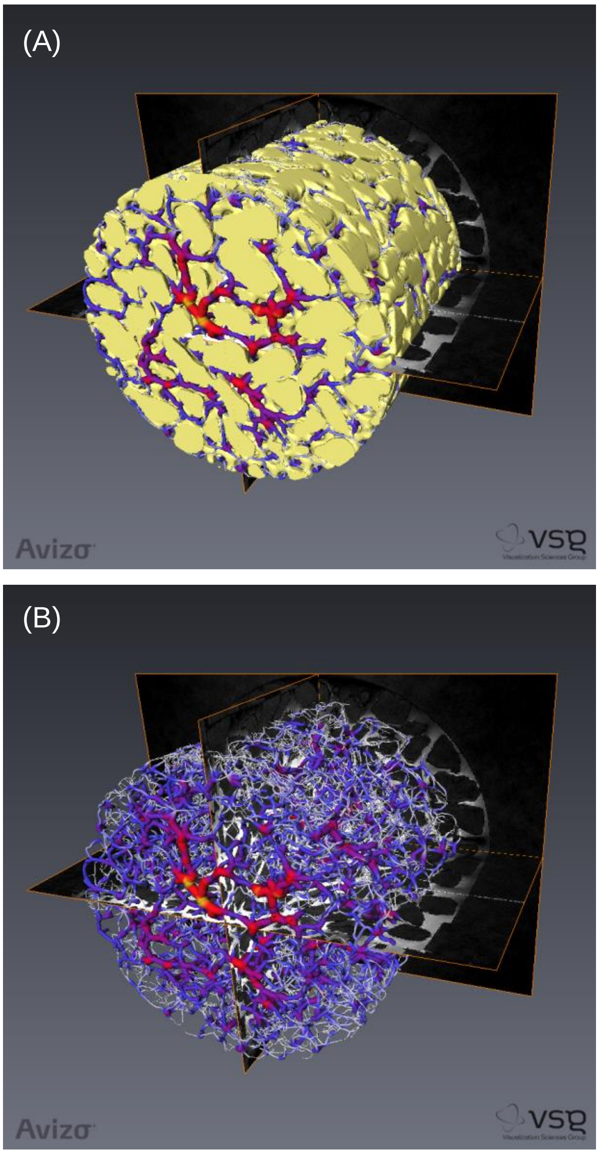


Figure 4: Permeability within a porous gravel media (field of view 86mm core diameter x 62mm length). Image (A) shows the 3D reconstruction of the MRI data with simulated permeability superimposed. Regions of sediment are shown in yellow. Image (B) shows permeability; blue represents low permeability and red indicates high permeability. Images generated using Avizo software, courtesy of J. Minto, University of Glasgow.

Contaminant & nutrient tracing

Due to its importance in hyporheic habitat, aquifer processes and environmental remediation, it is important to highlight that MRI studies have demonstrated the feasibility of using T_1 and T_2 relaxation times to analyse the mobilisation, transport and adsorption of paramagnetic ions (e.g. Gd^{3+}, Fe^{3+}, Cr^{3+}, Cu^{2+}) within the porewaters of saturated sediment matrices. Here, MRI is possible at micromolar concentrations of heavy metal solution (e.g. Nestle et al. 2003a and b; Ramanan et al. 2012). The most recent example of this is analysis of the transport behaviour of different iron-oxide based nanoparticles (NP) within saturated heterogeneous gravels (3.5mm grain size). Using 7T field strength, Ramanan et al. (2012) used T_2-weighted images to track the local concentration of NP and its transport through a closed-conduit flow column with a time-lapse interval of 5 minutes between captured images (Figure 5). This provided quantitative spatio-temporal data of NP transport inhibition caused adsorption of NPs onto gravel surfaces of opposite charge; this data was also employed in estimating and validating the coefficients of dispersion and retardation within a numerical convection-dispersion model. This indicates excellent potential for using MRI for wider contaminant tracing, leaching analysis, doping for sub-surface flow process studies, and flow model parameterization and validation.

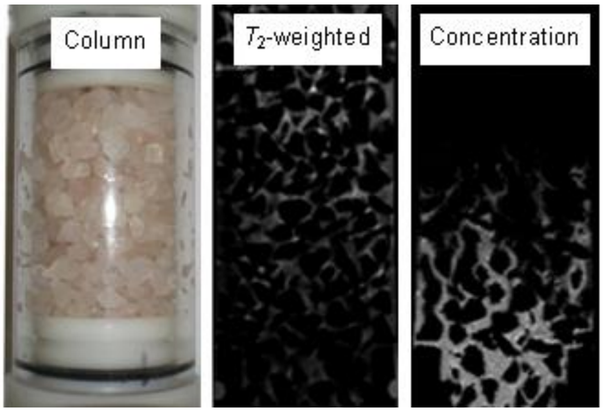


Figure 5: Packed column (100mm high x 45mm diameter) of 3.5mm diameter rose quartz grains, through which a solution of nanoparticles is flowed. A time series of T_2-weighted images (taken at 5 minute intervals) was acquired and converted to grey-scale concentration maps (after Ramanan et al. 2012).

Wider potential for geomorphology

It is recognised that the examples included above are far from an exhaustive list of possible MRI applications relevant to geomorphology. Other measurements of sediment structure of either a surface or, of particular merit, the sub-surface volume include: pivoting angle; grain orientation; pore throat radii; and, strata depths (e.g. Haynes et al. 2012). Similarly, time-resolved imaging shows potential for analysing flow related processes using bespoke image sequencing or paramagnetic contrast agents, *inter alia*: surface-subsurface flow interactions; biological colonisation and growth in pores; monitoring faunal movements in the benthic / hyporheic zone. Such fluid-based research is dependent on the development on appropriate MR-compatible flow chambers (e.g. Ramanan et al., 2012) constructed out of non-magnetic materials. Previous studies have employed closed conduits of vertical (e.g. Figure 5) or horizontal orientation fully-packed with material and subjected to pressurized flow. However, collaborative research funded by the Carnegie Trust for the Universities of Scotland is underway (in 2013) to investigate the viability of constructing bespoke MR-compatible open-channel flumes for flow-sediment research (Figure 6). The intention is to provide in-situ, dynamic and fully-coupled 3D flow-sediment data for the detailed description of bed evolution (surface and sub-surface) under a range of forcings.

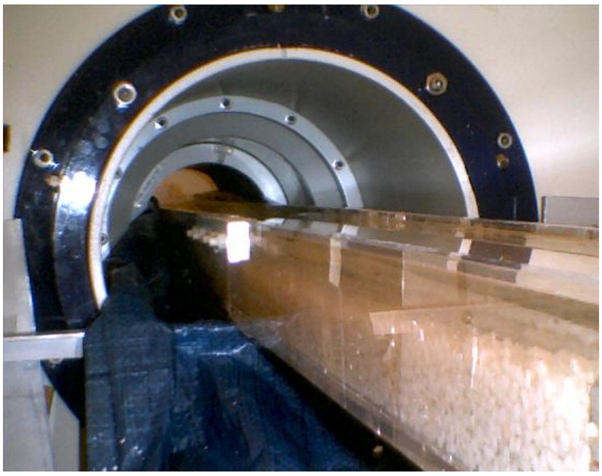


Figure 6: Trials of a bespoke MR-compatible open-channel flume (100mm rectangular cross-section) within the bore of the 7T MRI system at Glasgow's Experimental MRI Centre. All flume components and fixings within the MRI room are Perspex, made water-tight via rubber seals. The flow-recirculation pump is housed in a separate ante-room (due to metal components) with plastic pipes and connectors running through the wall between the pump and MRI rooms. The flume set-up shown includes a 60mm deep bed of 4mm dolomite sediments and a recirculating flow of water. At the time of press, this research is ongoing as a collaborative project between the Universities of Heriot-Watt, Glasgow, Dundee, Aberdeen & Strathclyde and funded by The Carnegie Trust for The Universities of Scotland (2013).

Strengths and Weaknesses

Strengths of MRI

The examples above indicate that MRI is of particular benefit to geomorphologists where small-scale samples (such as representative cores of centimetre scale) require analysis for: (i) 3D sediment arrangement; (ii) sub-surface sediment structure/stratigraphy; (iii) or sub-surface flow. At present, MRI is complementary with core-based sampling approaches to field investigations in geomorphology; the structural integrity of the core is maintained during grain-scale analysis via MRI, thus minimising uncertainty of sample structure and permitting multiple or repeat tests (e.g. stratigraphic followed by permeability analysis) post-imaging.

Some preliminary research has been undertaken specifically comparing MRI to other commonly employed techniques for sediment investigation. Haynes et al. (2012) contrasts MRI to high-resolution laser displacement scanning over small-scale patches (cm-scale); this specifically focuses on the benefit of MRI data of sub-surface bed structure for porosity analysis and accurate modelling of surface topography.

Similarly, it is prudent to compare MRI with 3D X-ray tomography (see Section 1.5.4 of Geomorphological Techniques) previously applied to porous media research. Here, the use of synchrotrons provides the highest energy X-rays capable of tuning photon energy to specific material types in the sample; hence Synchrotron X-ray Microtomography (SMT) is most comparable to MRI in terms of imaging capability, flexibility and resolution (µm-scale). Detailed information, including the science underpinning the SMT technique and its advantages, can be found in Werth et al. (2010); this indicates that that the relative advantages of MRI include: (i) flexibility in 1D, 2D or 3D acquisition and the scale/resolution of data; (ii) faster imaging sequences appropriate to fluid flow data capture at frequencies up to millisecond temporal resolution; (iii) greater capability to resolve different chemical species; and, (iv) improved image contrast.

Difficulties with MRI

When MRI is considered, the following user-based set-up decisions are important. Implicitly, these can pose limitations to MRI use; this section highlights to what extent these can be minimised and, in doing so, what compromises will be made to other set-up parameters and variables:

Magnet strength and bore diameter affects the image resolution. The stronger the static magnetic field, the larger the NMR signal and the greater the potential for finer imaging resolution; however, the cost of superconducting magnets increases steeply with both field strength and bore diameter. The restriction of bore diameter may compromise sample size in terms of Representative Elementary Volume (REV). For example, whilst a 1.5T MRI machine offers bore diameter ~600mm it offers only mm-scale image resolution; conversely, a 7T MRI machine has a bore size only ~150mm (Figure 6) but image resolution of ~100µm. MRI is, therefore, compatible with field-based surface rock/sediment coring techniques which extract cm-scale samples (e.g. drilling, vacuum, freezing). Yet, future research is needed to develop methods appropriate to cutting larger samples into smaller sub-samples, compatible with the narrower MR bores of the higher strength magnets offering improved image resolution. These methods must account for possible disturbance at the cutting face in order to provide larger REVs and the potential for sub-sample images to be 'stitched' back together during post-processing. Similarly, recent technological advances towards human MRI "open bore" magnets may remove the bore-size constraint entirely, proving highly beneficial to future sedimentary research where larger samples require imaging. That said, it should be highlighted that this system is not yet designed to be portable nor intended to operate over very large spatial areas (such as that offered by surface-based Terrestrial Laser Scanning).

Image acquisition time is a function of the sample volume, required image resolution and relaxation time of the magnetic nuclei. For example, Haynes et al. (2009) state that doubling the spatial resolution of the image matrix increases the number of voxels (3D pixels) by 2^3 and increases the scan time by a factor of 4. Thus, to achieve the same signal-to-noise ratio would require scan durations 32 times that of the original. High resolution scanning can prove expensive in terms of facility hire time, with even small cores (Ø100mm x 100mm) taking nearly a day to scan in their entirety at ~100µm resolution. In addition, the sediment framework needs to be immobile during this period, which precludes dynamic trials such as pore-clogging during the scan. Kleinhans et al. (2008) therefore illustrated how the signal intensity within each voxel may be used to increase the resolution of analysis, without increasing image acquisition times; detailed analysis of uncertainty is provided in their paper

Sediment geochemistry will dictate the magnetic susceptibility of the sample. Where materials contain a range of transition metal species, particularly iron, the relaxation times of the saturating fluid can be significantly affected by surface relaxation. In addition, at higher magnetic fields T_2 relaxation becomes dominated by magnetic susceptibility broadening, which can increase with the square of the magnetic field; this becomes more prominent the smaller the pore size and can make MRI extremely difficult (e.g. Haynes et al., 2009). As relaxation times depend greatly on sediment geochemistry in relation to field strength and pore size distribution, the reader is referred to Kleinberg et al. (1993, 1994) and Packer (1996) for detailed insight. Such relaxation effects are the reason 'clean' sediments (e.g. dolomite, limestone, sandstone and quartz) have been used in recent high resolution scanning (µm-scale); yet, it is important to note that mm-scale MRI is viable for 'dirty' sediments as demonstrated widely by the oil-industry during the last two decades (Packer, 1996).

Access to facilities specific to non-medical MRI research is a notable challenge to the widespread use of this technique in geomorphology. Facility access is largely constrained to academic engineering and science schools, yet collaborative ventures here are broadly welcomed. This is important, as the complexity of applying this technique to non-medical research requires expert knowledge. Typical costs are therefore in the region of £250-500 per scan.

Challenges of application to field samples

The examples and discussion provided above clearly demonstrate that MRI is an emerging technique of merit to geomorphology-related sedimentary science, in particular for grain-scale analysis of sub-surface structure and dynamic imaging of related flow-transport processes.

At present, MRI is restricted to a laboratory-based technique which is dependent upon, and appropriate to, small-scale core-based samples being extracted from the field and transported to the MRI. Whilst magnetically 'clean' materials may be scanned using any magnet strength, the use of low strength magnets (e.g. 1.5T or 3T) permits 3D imaging of natural sediment even where magnetic properties are present. The sensitivity of image quality and image resolution to the material type should be implicit to the choice of MR facility and associated set-up. A key challenge of the future is, therefore, to explore development of a toolbox of techniques specific to field sample analysis via MRI, including: methods of sample extraction/preservation as commensurate with solid-phase transport and fluid-state imaging; Representative Elementary Volumes in relation to the size of the bore size of the MRI facility; optimisation of magnet strength to both image resolution and sample geochemistry etc.

Whilst portable Nuclear MR (NMR) devices are mentioned in the literature (e.g. Blümich et al. 1995; Blümich 2007; Stork & Nestle 2007), modifications for MRI do not yet have evidence of field-based deployment for geomorphological research. Similarly, new open-bore MRI systems offering the potential to analyse larger samples (metre scale) have not been trialled on sediment/rock samples. Whilst combined portable and open-bore capability would be both idealistic and futuristic for field-based geomorphological purposes, this appears unlikely for a technology primarily motivated by medical application and funding. Thus, as the greatest benefits to field-based investigations are offered by portable systems, focus should be placed on how best develop future portable MRI systems in a manner appropriate to our end-user requirements. This requires geomorphologists to both, ascertain the benefits and limits of existing MRI for sediment analysis and, engage in new collaborations with the MR scientists and manufacturers to refine imaging sequences and magnet designs. As MRI use for geomorphological application is at such an early stage, the opportunities for new scientific insight and methodological development provide an exciting research arena of the future.

Conclusions

MRI offers a flexible non-intrusive technique with which to visualize and quantitatively analyse 3D internal structure and processes within an opaque porous media, including the sub-surface. Whilst this is recognised as an 'emerging' methodology for geomorphological research, the handful of existing studies clearly indicate the significant benefits of MRI for high resolution spatio-temporal measurement of sediment packing arrangement, porosity, permeability, fluid flow and contaminant tracing. As this approach appears well suited to a wide range of porous media environments, there exists significant scope to develop MRI sequences to unlock the 'black-box processes' of many geomorphological research disciplines.

Acknowledgements

This research was funded by a research grant awarded from The Carnegie Trust for The Universities of Scotland into the use of MRI for analysing flow-sediment-biology processes in river systems. Data collection for the images used was provided by James Minto & Dr. Elisa Vignaga during PhD research at The University of Glasgow (2006 and 2012) as undertaken with supervision by the paper authors; here, co-supervision by Dr. Vernon Phoenix proved invaluable. The authors also sincerely thank the technical staff of GEMRIC, the School of Engineering at the University of Glasgow, and the School of the Built Environment at Heriot-Watt University for their assistance in this research.

References

Baumann T, Petsch R, Niessner R. 2000. Direct 3-D measurement of the flow velocity in porous media using magnetic resonance tomography. *Environmental Science & Technology* **34** : 4242-4248

Baldwin CA, Sederman AJ, Mantle MD, Alexander P, Gladden LF. 1996. Determination and characterization of the structure of a pore space from 3D volume images. *Journal of Colloidal and Interface Science* **181** : 79-92.

Blümich B, Blümler P, Eidmann G, Guthausen A, Haken R, Schmitz U, Saito K, Zimmer G. 1998. The NMR MOUSE: Construction, Excitation, and Applications. *Magnetic Resonance Imaging* **16** : 479–84

Blümich B. 2007. Mobile NMR: concepts and applications. http://www.nmr-mouse.de/index.php

Bock M, Schad LR, Müller E, Lorenz WJ. 1995. Pulsewave velocity measurement using a new real-time method. *Magnetic Resonance Imaging* **13** : 21-29

Bortolotti V, Gombia M, Cernich F, Michelozzi E, Fantazzini P. 2006. A study to apply nuclear magnetic resonance porosity measurements to seabed sediments. *Marine Geology* **230** : 21–27

Callaghan PT. 1993. Principles of Nuclear Magnetic Resonance Microscopy. Oxford University Press : Oxford

Fantazzini P, Bortolotti V, Kärger J, Galvosas P. (Eds.) 2011. Proceedings of the Tenth International Bologna Conference on Magnetic Resonance in Porous Media, 12 – 17 September 2010, Leipzig Germany, *Conference Proceedings Series American Institute of Physics* **1330**

Haynes H, Vignaga E, Holmes WM. 2009. Using magnetic resonance imaging for experimental analysis of fine-sediment infiltration into gravel beds. *Sedimentology* **56** : 1961-1975

Haynes H., Ockelford A-M, Vignaga E, Holmes WM. 2012. A new approach to define surface/sub-surface transition in gravel beds. *Acta Geophysica* **60** : 1589-1606

Hermann K-H, Pohlmeier A, Gembris D, Vereecken H. 2002. Three-dimensional imaging of pore water diffusion and motion in porous media by nuclear magnetic resonance imaging. *Journal of Hydrology* **267** : 244-257

Huerlimann M, Song Y-Q, Fantazzini P, Bortolotti V. (Eds.) 2008. Proceedings of the Ninth International Bologna Conference on Magnetic Resonance in Porous Media, 13-17 July 2008, Cambridge, USA, *Conference Proceedings Series American Institute of Physics* **1081**

Kawaguchi T. 2010. MRI measurement of granular flows and fluid-particle flows. *Advanced Powder Technology* **21**: 235-241

Kleinberg RL, Farooqui SA, Horsfield MA. 1993. T(1)/T(2) ratio and frequency-dependence of NMR relaxation in porous sedimentary rocks. *Journal of Colloid and Interface Science* **158** : 195-198

Kleinberg RL, Kenyon WE, Mitra PP. 1994. Mechanism of NMR relaxation of fluids in rock. *Journal of Magnetic Resonance* **108** : 206-214

Kleinhans MG, Jeukens CRLPN, Bakker CJG, Frings R. 2008. Magnetic resonance imaging of coarse sediment. *Sedimentary Geology* **208** : 69-78

Levitt MH. 2002. Spin Dynamics. John Wiley & Sons : England

Li L, Chen Q, Marble AE, Romero-Zerón L, Newling B. 2009. Flow imaging of fluids in porous media by magnetization prepared centric-scan SPRITE. *Journal of Magnetic Resonance* **197** : 1-8

Mantle MD, Sederman, AJ. 2003. Dynamic MRI in chemical process and reaction engineering. *Progress in Nuclear Magnetic Resonance Spectroscopy* **43** : 3-60

Mantle MD, Sederman AJ, Gladden LF. 2001. Single- and two-phase flow in fixed-bed reactors: MRI flow visualisation and lattice-Boltzmann simulations. *Chemical Engineering Science* **56** : 523-529.

Nestle N, Baumann T, Wunderlich A, Niessner R. 2003a. MRI observation of heavy metal transport in aquifer matrices down to sub-mg quantities. *Magnetic Resonance Imaging* **21** : 345-349

Nestle N, Wunderlich A, Niessner R, Baumann T. 2003b. Spatial and temporal observations of adsorption and remobilization of heavy metal ions in a sandy aquifer matrix using magnetic resonance imaging.

Environmental Science & Technology **37** : 3972-3977

Ohkubo T, Yamaguchi M. 2007. Time-dependent diffusion of water in clay gel-saturated porous media. *Magnetic Resonance Imaging* **25** : 577-8

Packer KJ. 1996. Oil Reservoir Rocks Examined by MRI. In: Encyclopedia of Magnetic Resonance. John Wiley & Sons. London : 3365-3376

Ramanan B, Holmes WM, Sloan WT, Phoenix VR. 2012. Investigation of nanoparticle transport inside coarse-grained geological media using magnetic resonance imaging. *Environmental Science Technology* **46** : 360-366.

Sains MC, El-Bachir SM, Sederman AJ, Gladden L. (2005) Rapid imaging of fluid flow patterns in a narrow packed bed using MRI. *Magnetic Resonance Imaging* **23** : 391-393

Sankey MH, Holland DJ, Sederman AJ, Gladden LF. 2009. Magnetic resonance velocity imaging of liquid and gas two-phase flow in packed beds. *Journal of Magnetic Resonance* **196** : 142-148

Sederman AJ, Gladden LF. 2001. Magnetic resonance visualisation of single- and two-phase flow in porous media. *Magnetic Resonance Imaging* **19** : 339-343

Sederman AJ, Mantle MD, Buckley C, Gladden LF. 2004. MRI technique for velocity measurement of velocity vectors, acceleration and autocorrelation functions in turbulent flow. *Journal of Magnetic Resonance* **166** : 182-189

Stork H, Nestle N. 2007. A low-cost, large volume, easy-access design for a portable NMR magnet. *Magnetic Resonance Imaging* **25** : 544-591

Swider P, Conroy M, Pedrono A, Ambard D, Mantell S, Søballe, K, Bechtold JE. 2007. Use of high-resolution MRI for investigation of fluid flow and global permeability in a material with interconnected porosity. *Journal of Biomechanics* **40** : 2112-2118

Tyrologou P, William A, Dudeney L, Gattoni CA. 2005. Evolution of porosity in geotechnical composites. *Magnetic Resonance Imaging* **23** : 765-768

Vogt, C, Galvosas P, Klitzsch N, Stallmach F. 2002. Self-diffusion studies of pore fluids in unconsolidated sediments by PFG NMR. *Journal of Applied Geophysics* **50** : 455-467

Werth CJ, Zhang, C, Brusseau ML, Oostrom, M, Baumann T. 2010. A review of non-invasive imaging methods and applications in contaminant hydrogeology research. *Journal of Contaminant Hydrology* **113** : 1-24