Measurement of Hydraulic Conductivity, Porosity and Lithology by Neutron Activation Borehole Logging at High Spatial Resolution Increments

Waring C.L.*, Stepanyants Y.A., Hankin S.I., Airey P.L., Peterson M.A.

Australian Nuclear Science & Technology Organisation, PMB 1, Menai, NSW 2234, Australia, Tel: (02) 97179045, Fax (02) 97179286, E-mail: clw@ansto.gov.au

*Corresponding author.

Abstract

A new method of measuring the continuously variable hydraulic conductivity at 20 cm increments surrounding a borehole is described. The method requires injection of a tracer solution and measurement of the variable lateral distance the tracer has moved by prompt gamma neutron activation analysis (PGNAA) geophysical logging. Gamma spectra collected by PGNAA logging from 0.16 to 10 MeV are analysed to provide a relative abundance of elements H, Si, Al, Fe, Cl and possibly others if sufficiently abundant. The distance a NaCl or KCl tracer solution has migrated into the rock surrounding the borehole is calculated from the greater energy attenuation of a 1.95 MeV low energy Cl gamma emission compared to a 6.1 or 7.4 MeV high energy Cl emission. The differential gamma attenuation is verified by experiment.

A simple but sensitive method for measuring relative porosity surrounding a borehole is also presented by measuring the elemental abundances of common rock forming minerals and water, allocating elements to minerals and presenting a water/rock ratio. Relative porosity may be further simplified to H/(H+Si) particularly for sandstones typical from the Sydney Basin. Many boreholes of hydrological interest are drilled into sedimentary rocks and alluvium dominated by abundant quartz and clay, which can be quantified by relative Si and Al. Similarly, many sedimentary lithologies may be defined by variations in their mineralogy reflected in proportional changes in elemental abundance. Subtle variations in lithology not apparent by visual inspection such as degree of cementation or clay pore filling in sandstone may also be detected. Porosity and lithology estimation by PGNAA geophysical logging does not require a tracer solution to be injected and may be measured through borehole casing with screened or unscreened intervals.

Keywords: hydraulic conductivity, geophysics, neutron activation, porosity, borehole logging, PGNAA

1. Introduction

1.1. *Hydraulic conductivity measurement*

Current methods for calculation of hydraulic conductivity are based on the Darcy's law, which relates the rate of fluid flow to the applied hydraulic gradient. In practice these methods typically require measurement of changing pressure or head difference with time. A difficulty with this approach is the measurement only provides a single average hydraulic conductivity value over an isolated screened interval or over the entire borehole beneath the standing water level. Multiple zones cannot be isolated for measurement in a single borehole without considerable difficulty and expense. If multiple aquifers or significant lithological heterogeneity is anticipated, multiple boreholes are often drilled for individual assessment of target zones. Significant or even the dominant flow zones in a borehole may be missed if not targeted for measurement. Higher flow rates from fractures cannot be distinguished from distributed porous media flow when averaged across significant measurement intervals.

A nuclear geophysical logging technique, Prompt Gamma Neutron Activation Analysis (PGNAA) is used to trace the flow of an injected salt solution into fractures and into the porous and permeable sandstone surrounding the borehole. The variable distance the salt tracer moves into the porous rock under a known pressure increase (above standing water level), over a known time and tracer volume allows calculation of hydraulic conductivity at 20 cm increments along the length of the borehole. If there is significant flow of the tracer into fractures and beyond the PGNAA measurement range a relative tracer movement distance is provided by the PGNAA log, rather than hydraulic conductivity. Other relevant lithological and hydraulic parameters such as porosity may be derived from measured Si, H, Cl, ±Fe, ±Al elemental abundance provided by PGNAA borehole logging.

Sandstone aquifers within the Sydney Basin have been identified as a significant source of emergency groundwater supply for Sydney that may be affected by longwall mine subsidence. Considerable variation in flow rates during pump testing is observed for closely spaced boreholes (PB 2006). The variability may be due to the intersection of fractures or interpreted as significant variations in sandstone composition and inter-granular fabric. Distinction between these interpretations and definition of preferential flow paths is possible with the high spatial resolution offered by the PGNAA logging technique. Hydraulic conductivity, porosity and lithological measurements from PGNAA logging of boreholes in the Hawkesbury Sandstone are compared to pump test and laboratory measurements. Passive environmental tracer techniques are widely used to assess surface – groundwater interactions (eg. Michel & Turk 1996), and within the Sydney Basin (Waring et al. 2007a), whilst the PGNAA hydraulic conductivity measurement technique requires a tracer to be actively injected.

2. Technique and equipment

2.1. Neutron activation analysis

Neutron activation analysis is a family of extremely useful quantitative elemental analysis techniques that have not been widely applied to field applications because of previous hardware limitations, availability and cost. Precise laboratory neutron activation measurements have utilised either a nuclear reactor for delayed Neutron Activation Analysis (NAA) or a pulsed neutron generator (Nargolwalla & Przybylowicz 1973) for prompt gamma neutron activation analysis (PGNAA), combined with DNAA and inelastic neutron scattering (INS) techniques.

Field techniques cannot use high neutron flux reactor neutron sources and must rely on either low neutron flux isotope neutron sources (^{252}Cf & AmBe) to limit radiation exposure risk to the operator or old design Penning diode neutron generators. The latter are miniature high-voltage accelerator D-T nuclear fusion devices which have a limited lifetime before wearing out and requiring expensive tube replacement. Large oil and gas industry service companies have built geophysical borehole logging tools incorporating neutron generators but have not sold the equipment. Commercially available neutron activation analysis field equipment is currently limited to some large industrial conveyor belt online analysis applications using accelerator neutron generators (eg Sodern) or the use of low-flux isotope neutron sources in borehole logging equipment (eg CSIRO Exploration & Mining). New design accelerator neutron sources with pulsed operation, high-flux and a long lifetime are now available and are likely to be incorporated into the next generation of neutron activation field equipment.

The other essential component to neutron activation analysis field equipment is the gamma scintillation detector. Laboratory NAA has long used cryogenically cooled High Purity

Germanium (HPGe) detectors for very high gamma spectral resolution and long static count times. Field applications of NAA have been restricted to coarse spectral resolution provided by NaI or BGO (Bismuth Germinate) detectors, which do not require cooling. New $LaBr_3Ce$ scintillation detectors are now available with 3 times the spectral resolution of BGO and do not require cryogenic cooling.

The combination of new design high-flux neutron generators that can be switched off for safe handling and new scintillation detectors promises greater sensitivity and precision for in-situ Neutron Activation elemental analysis.

2.2. PGNAA geophysical logging

CSIRO Exploration and Mining build and supply PGNAA borehole logging tools, which use an isotope neutron source and a BGO gamma detector. An upgraded modification to this configuration substituting the BGO detector with a $LaBr_3Ce$ detector is currently being used by ANSTO. The SIROLOG logging tool has 480 channels (gamma energies), is 72mm diameter, 1.8m long and uses an AUSLOG single conductor winch for logging borehole depths up to ~500m. The SIROLOG equipment may also be operated without the neutron source to give the natural gamma radiation variation up the borehole due to K, U, & Th in the surrounding rock.

To measure subtle lithological or porosity variations for hydrogeology applications is a simple standard logging procedure, withdrawing the logging tool up the borehole at <2 m per minute. Gamma spectra are acquired and integrated over 20 cm increments up the borehole. These stacked gamma spectra may be viewed graphically during logging. Gamma spectral analysis software identifies peaks from a spectral library, measures peak area and quantifies the elemental abundance by comparison with known standards. Major elements found in the sandstones of the Sydney Basin (H, Si, Fe, Cl, ±Al) are able to be measured with the standard SIROLOG configuration. The new $LaBr_3Ce$ detector is likely to improve sensitivity and allow measurement of some minor to trace elements (Na, K, Ca, Mg, S, Ti, ..) if sufficiently abundant.

2.3. Tracer injection and parameter monitoring

The principle requirement for the tracer injection is to be able to reduce the measured tracer gamma counts firstly to a radial distance from the borehole and then to a hydraulic conductivity within the detection limits of the borehole logging equipment (Waring et al., 2007). Prior to tracer injection pressure, flow and electrical conductivity sensors are placed in the borehole. The tracer flow is monitored and controlled by borehole and surface pumps. A simplified practical tracer injection procedure described has a repeatable sequence.

The first stage involves mixing a uniform concentration of the tracer solution in the bore as well as in the surface tank whilst maintaining the constant equilibrium SWL. Compensation for density change is required.

The second stage injection step applies a pressure head to the solution in the bore by draining tracer from the surface tank to effect the injection. After the tracer has been injected into the rock surrounding the bore the bore is logged by the PGNA logging equipment. Multiple steps of tracer injection followed by PGNA logging are possible to observe incremental change of tracer movement. The tracer may also be removed from the bore and replaced by fresh water at constant SWL (with density compensation), in effect the mix stage in reverse. Further addition of fresh water will push the tracer further into the rock allowing measurement biased to tracer signal further from the detector.

Tracer injection by this method will produce a radial distribution of the tracer at constant concentration away from the borehole, which is described as the; 1) Smooth uniform injection case. Other methods of injection; 2) where the tracer is progressively diluted throughout the injection Fast injection case and 3) where the tracer diffuses into the rock Diffusive intrusion, are also developed.

An important advantage of the technique is the independence of the radial distance calculation from variations in tracer concentration due to variations in porosity of the host rock. Tracer concentration variations do not matter so long as the concentration and distance remains within the detection limits of the equipment. The radial distance travelled by the tracer is derived by measuring the ratio of 2 tracer gamma peaks, one at low energy and one at high energy. Low energy gamma radiation will be attenuated by the intervening rock more than high energy gamma radiation. Tracer concentration variations will affect both peaks similarly but not affect the peak area ratio.

3. Method

3.1. Hydraulic conductivity calculation method description

The method of calculating hydraulic conductivity is dependent upon measuring the variable distance a tracer moves into permeable rock surrounding a borehole under a known hydraulic gradient over a known time interval. The hydraulic gradient in this case is the head difference from the standing water level and the duration of the tracer injection. Calculation of the average hydraulic conductivity over the injection interval is a derivation from Darcy's Law.

$$\mathbf{V}_{sp} = -K\nabla\Psi, \qquad \text{(Eq. 1)}$$

where $\mathbf{V}sp$ is the seepage velocity in m/s, K is the hydraulic conductivity in m/s, $\Psi = \psi + p/(\rho g)$ is the total pressure head in metres with ψ being the liquid head, p – atmospheric pressure, ρ – liquid density, g – acceleration due to gravity, and ∇ stands for the gradient operator. In cylindrically-symmetrical 1D case Darcy law simplifies and reads as

$$V_{sp} = -K\frac{d\Psi}{dr}, \qquad \text{(Eq. 2)}$$

where Vsp is the radial component of the seepage velocity, and r is the radial coordinate. This formula can be inverted to obtain K via seepage velocity and pressure-head gradient:

$$K = -\frac{V_{sp}}{d\Psi/dr}. \qquad \text{(Eq. 3)}$$

Thus, to calculate the hydraulic conductivity one needs to know a local value of the seepage velocity $Vsp(r)$ and pressure-head gradient $d\Psi/dr$ as a function of r. However, the detail knowledge of both these values is practically unavailable, therefore Eq. (3) can be used in its approximate finite-difference form to obtain at least an estimation of the hydraulic conductivity:

$$K \approx -V_{sp}\times\frac{\Delta r}{\Delta\Psi} \approx -\frac{\Delta r}{\Delta t}\times\frac{\Delta r}{\Delta\Psi} = -\frac{(\Delta r)^2}{\Delta\Psi\Delta t}. \qquad \text{(Eq. 4)}$$

In this equation the pressure-head gradient was replaced with its finite-difference approximation $d\Psi/dr \approx \Delta\Psi/\Delta r$, and the seepage velocity was replaced by the finite-difference approximation $Vsp(r) \approx \Delta r/\Delta t$, for the liquid to travel Δr within the porous medium. If the drop of the pressure-head $\Delta\Psi$ over distance Δr is known and time interval over which this drop occurs is also known, one can estimate the hydraulic conductivity on the basis of Eq. (4), provided Δr can be measured. In practice the distance a NaCl or KCl tracer solution has migrated into the rock surrounding the borehole is calculated from the greater energy attenuation of a 1.95 MeV low energy Cl gamma emission compared to a 6.1 or 7.4 MeV high energy Cl emission.

3.2. Tracer distance model relationship

The key parameter for the variable hydraulic conductivity calculation is the measurement of the variable distance the tracer has moved from the borehole. A simple mathematical basis for relating measured injected tracer gamma-radiation counts in a borehole to the distance the tracer has moved is developed. Gamma-radiation comes from the distributed radiotracer source in the form of either a radioactive solution or a solution containing a high gamma yield activatable element such as Cl. A theory is developed in general for 2D and 3D cases and in detail for the 1D case. Different types of distribution functions are considered for the last case and the results compared.

The first section contains a theoretical background for calculating gamma-radiation counts in a borehole. It is supposed that the gamma-radiation comes from the distributed source (radiotracer). The theory is developed in general for 2D and 3D cases (Waring et al.. 2007) and in a detail for the 1D case here.

Laboratory experiments of gamma-radiation attenuation from different radioactive sources (Co-60, Cs-137) were conducted to verify the theory developed. The measurements were conducted in air, water and river sand (both dry and water saturated). The decay rate of gamma-radiation has been measured as a function of distance for all types of media mentioned above. The experimental data can be interpreted within 1D theory with the appropriate model of distribution function.

3.3. Theoretical basis for injected tracer distribution

1D case

Considering first a 1D model when the radioactive tracer is distributed along the axis x (Fig. 1).

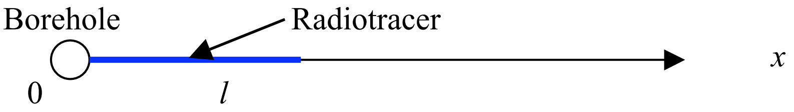

Figure 1 A schematic diagram showing a 1D case of radial tracer distribution around a borehole

Assume that the radioactive tracer is distributed non-uniformly with a density of distribution characterised by the function $F(x) = I_0(x)e^{-t\ln 2/\tau}$, where τ is the half-life time of radioactive material.

The intensity of received gamma-radiation by a detector placed into the borehole from a tracer at distance x is $F(x)dx = I_0(x)e^{-t\ln 2/\tau}e^{-\mu x}dx$, where μ is the attenuation factor which depends on the excitation energy. Hence, the total intensity of the received gamma-radiation at a borehole from the whole interval $[0, l]$ is:

$$I_{tot}(l) = \mathrm{e}^{-t\ln 2/\tau}\int_0^l I_0(x)\mathrm{e}^{-\mu x}dx\,. \qquad \text{(Eq. 5)}$$

This value depends both on the spatial interval *l* across which the radioactive tracer is distributed and on the distribution function $I_0(x)$. We consider three particular cases, which model different regimes of radiotracer injection.

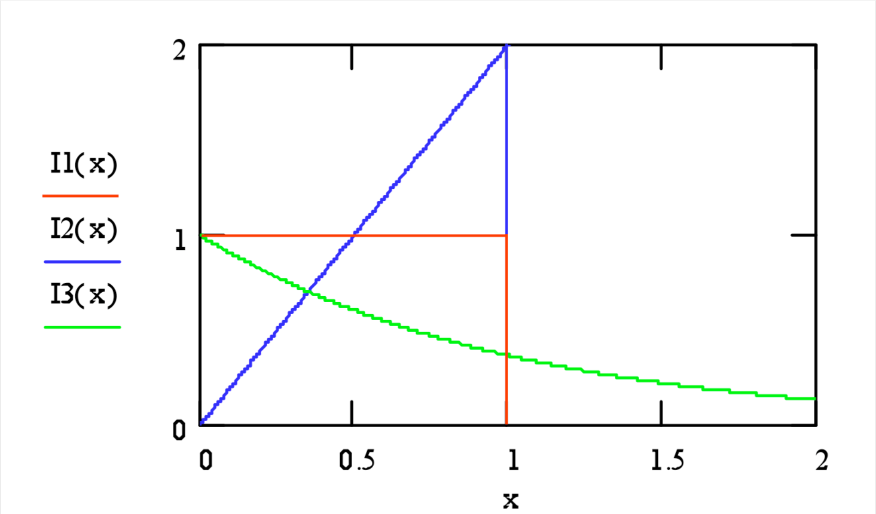

Figure 2 Tracer concentration versus distance from borehole. Three different types of tracer injection distribution functions; smooth uniform injection (red), fast injection (blue), diffusive intrusion (green). I = concentration, x = dimensionless distance from borehole

1) <u>"Smooth uniform injection case".</u> In this case the radioactive material supposed to be uniformly distributed on the interval $0 < x < l$ with the density $I_0 = M/l = \text{const}$, where *M* is the total "mass" of radioactive material. Formula (1) gives

$$I_{tot}(l) = \frac{M}{\mu l}\left(1 - \mathrm{e}^{-\mu l}\right)\mathrm{e}^{-t\ln 2/\tau} \qquad \text{(Eq. 6)}$$

This dependence is illustrated in Fig. 2 (red curve) in normalised variables:

$$Y1(z) = \frac{1}{z}\left(1 - \mathrm{e}^{-z}\right), \qquad \text{(Eq. 7)}$$

where $Y1 \equiv \frac{I_{tot}}{M}\mathrm{e}^{t\ln 2/\tau}, \quad z \equiv \mu l\,.$

2) <u>"Fast injection case".</u> It is supposed that the radioactive material is distributed linearly with the density of distribution $I_0(x) = 2Mx/l^2$ at $0 < x < l$. Formula (1) gives

$$I_{tot}(l) = \frac{2M}{\mu^2 l^2}\left[1 - (1 + \mu l)\mathrm{e}^{-\mu l}\right]\mathrm{e}^{-t\ln 2/\tau}. \qquad \text{(Eq. 8)}$$

This dependence is illustrated in Fig. 2 (the blue curve) in the same normalised variables:

$$Y2(z) = \frac{2}{z^2}\left[1 - (1 + z)\,\mathrm{e}^{-z}\right]. \qquad \text{(Eq. 9)}$$

3) <u>"Diffusive intrusion".</u> Radiotracer is assumed to be distributed exponentially: $I_0(x) = (M/l)e^{-x/l}$. Formula (1) gives

$$I_{tot}(l) = \frac{M}{1+\mu l} e^{-t \ln 2/\tau} . \qquad \text{(Eq. 10)}$$

In the normalised variables it can be represented as (see the green curve in Fig. 2):

$$Y3(z) = \frac{1}{1+z} . \qquad \text{(Eq. 11)}$$

The results obtained show that for all three types of distribution function, the dependence of gamma-radiation counts on distance is qualitatively the same. The larger the distance the radiotracer is distributed the smaller the signal received by the detector placed in the borehole. The decay rate of the received signal decreases faster (slower) if a maximum of distribution function is shifted in the space to the remote (nearby) part of a domain of distribution.

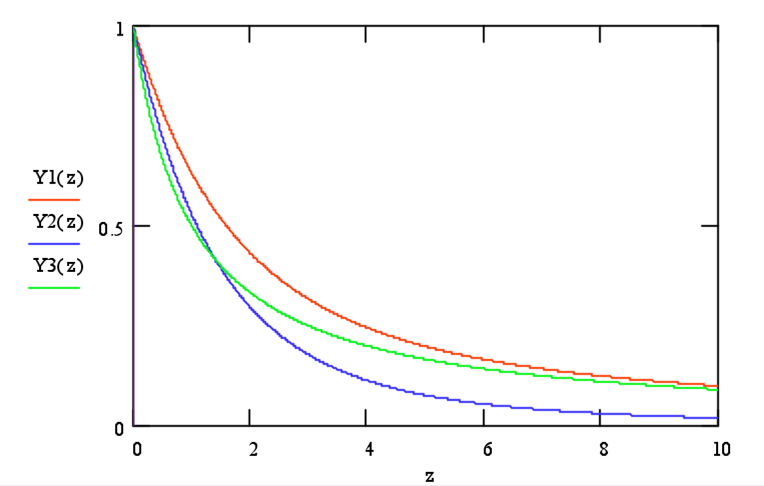

Figure 4 Tracer gamma counts versus distance from borehole. Three different types of tracer injection distribution functions; smooth uniform injection (red), fast injection (blue), diffusive intrusion (green). Y = gamma counts, z = dimensionless distance from borehole

In reality, when a tracer solution is injected into a borehole flow is assumed to be horizontal, with uniform radial distribution around the borehole. This is the 2D injection case, which differs from the 1D injection case presented above only in its greater geometrical / mathematical complexity. The 2D tracer injection case (Waring et al.. 2007) is beyond the scope of this paper.

4. Results

4.1. Field results MW6

Several shallow open boreholes were drilled into the Hawkesbury Sandstone on site at Lucas Heights for geophysical testing, adjacent to 28 cased monitoring wells. One of these open boreholes MW6 is 24m deep with a standing water level at 2m below the surface. Average hydraulic conductivity has been measured by conventional pump test in the adjacent shallow (0.5 – 9.5m interval, K = $7.8 * 10^{-8}$ m/sec) and deep (18.5 – 24.5m interval, K = $3.7 * 10^{-10}$ m/sec) monitoring wells after installation (PPK Environment & Infrastructure 2000).

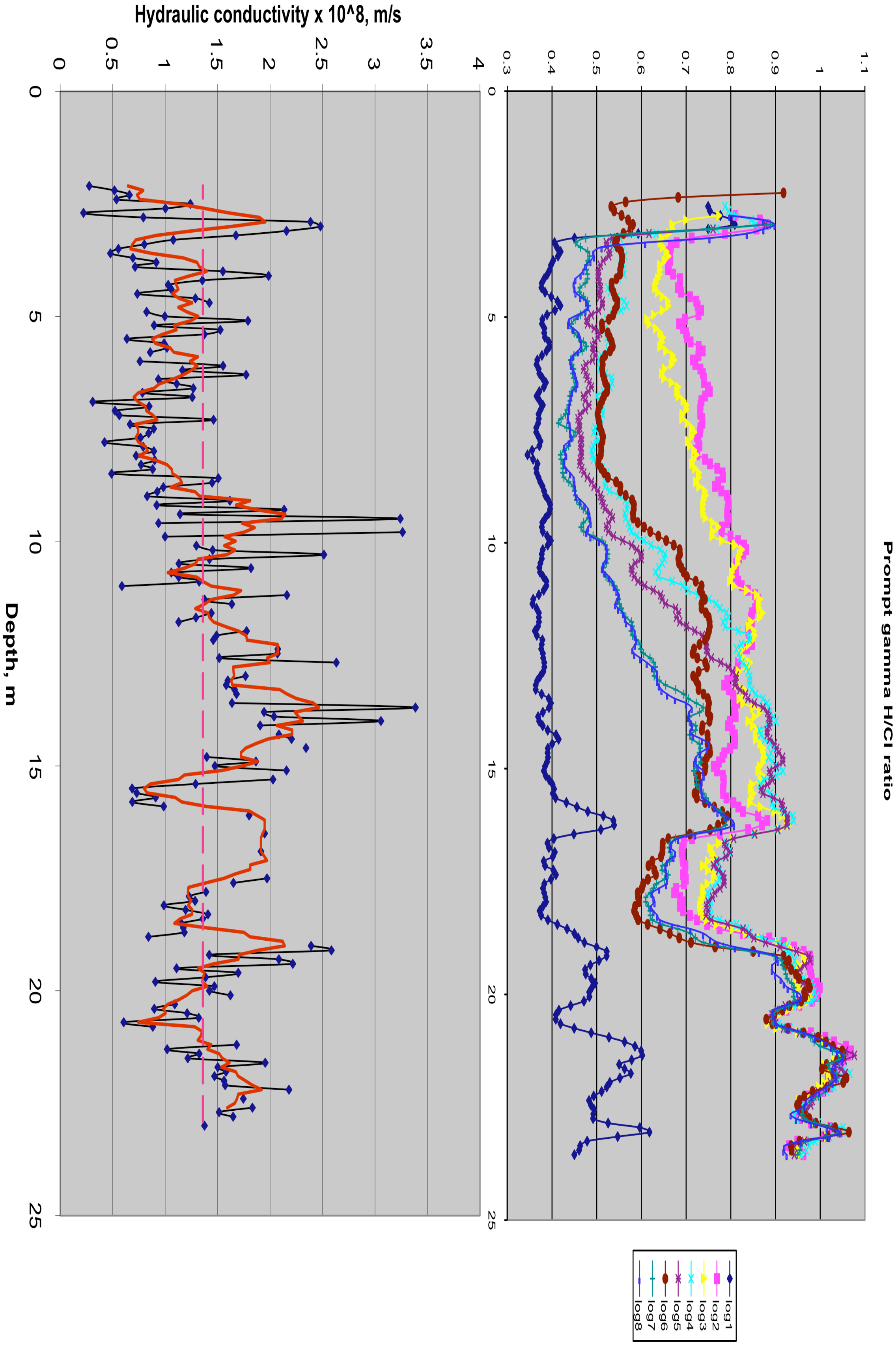

Figure 5 a) Hydraulic conductivity in MW6 borehole with 5 point running mean (red) & hole average (pink) b) Cl/H gamma count ratio for 7 sequential tracer injections. Note dark blue trace is the original Cl/H prior to NaCl tracer injection. The first NaCl injection traces (pink & yellow) are separated from later injections at the top of the borehole but are coincident at the bottom.

The 20 cm incremental hydraulic conductivity has been calculated for MW6 by the method described above with a 5 point (1 m) smoothing function also applied (Fig. 5a). MW6 bore-log does not distinguish any visible changes to the Hawkesbury Sandstone, yet significant subtle variations in hydraulic conductivity are apparent.

Figure 5b shows the presence of the NaCl tracer in a series of sequential tracer injections. These data are presented as Cl/H gamma count ratio. The gamma counts measured for Cl and H, each from a single peak are proportional to the respective Cl and H concentration. The H concentration will vary with porosity surrounding the borehole and will not vary between successive NaCl tracer injections. Effectively the successive traces show the cumulative amount of tracer surrounding the borehole normalised for the porosity. The results show an unexpected diminution of Cl at the top of the borehole with successive PGNAA logs over 2 days and a small 20 L additional injection of fresh water. There appears to be less tracer in the top zone of MW6 due to the tracer moving beyond the zone of detection or due to advective circulation through the adjacent sandstone. A simple volumetric calculation of the cumulative amount of tracer solution injected (50 L 5% NaCl + 20 L fresh water) with a uniform cylindrical distribution through sandstone with 8% porosity (~1,500 L) does not exceed the 50cm detection distance. The alternate mechanism, advective circulation is caused by a density contrast between the saline tracer in the borehole and fresh water in the sandstone. The denser salt water in the borehole has an effective head to continue to flow into the sandstone at the bottom of the borehole, assuming a constant SWL. If the denser salt tracer continues to flow out into the sandstone at the base the SWL in the borehole will fall relative to the surrounding sandstone, causing an inflow to the borehole at the top. This advective circulation model also shows that the sandstone surrounding the borehole is hydraulically connected over the 24m vertical length of the borehole.

5. Conclusion

5.1. Porosity and hydraulic conductivity

PGNAA borehole logging is capable of detecting subtle variations in relative porosity in otherwise homogeneous sandstones without tracer injection. A new method for measuring high spatial resolution increments of hydraulic conductivity in a borehole is described and demonstrated in practice.

5.2. Vertical hydraulic connection

Sequential tracer injection and PGNAA logging can identify induced advective circulation cells in sandstone adjacent to a borehole. This method could identify aquitards to vertical flow in thick sandstone sequences with variably low hydraulic conductivity. In the Sydney Basin establishing vertical hydraulic connection by either porous media flow or by fractures could be very useful in assessing the impact of longwall mining on the groundwater hydrology.

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