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High Resolution Seismic Reflection for Hydrogeology – Where is the Value?

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SUMMARY

With increasing demands on groundwater resources, concerns about the impacts of groundwater abstraction on groundwater dependent ecosystems and the new paradigm of large scale managed aquifer recharge, there comes a requirement for more robust definition for water resources. Seismic reflection surveying may offer this higher level of definition. Resolution at depth and the ability to map detailed structures cannot be matched with any other method. Seismic reflection is able to recover information that may contribute to revealing aquifer geometry and system fluxes. It also increases the value of existing borehole information. Take up of seismic reflection by the groundwater industry has been slow but is certainly gathering momentum with several high resolution basin scale surveys now providing clear examples of the value of seismic reflection. Seismic reflection surveying is expensive, so the key to success is strategic location of lines and selection of suitable acquisition parameters with sufficient resolution to answer key questions regarding the targeted hydrogeological system. We present several examples from the West Australian aquifer systems, compare the acquisition parameters selected and then clearly identify hydrogeological value of the outcome for each setting.

Key words: Seismic reflection, aquifer, hydrogeology, structures, model.

INTRODUCTION

There is an ever increasing demand for high quality water sources. In Western Australia, this is bought about by population growth and a water hungry resource sector. This increased pressure on groundwater resources requires development of increasingly detailed hydrogeological models. Seismic reflection surveying offers a high level of definition for complex hydrogeological systems. Around Western Australia, the seismic reflection method has been used for aquifer characterisation to great effect. This paper looks at value of seismic reflection for hydrogeology in a number of key Western Australian aquifers.

The increased demand on water resources has meant that more information is required at greater depth in aquifer systems. Many of the current popular geophysical techniques used for groundwater exploration have limited penetration and or low resolution, in particular, at depths of over 500m. For example, Airborne EM which is often considered an efficient technique (per square kilometre) for mapping groundwater conductivity distribution, lacks the ability to image depths greater than approximately 400m and also lacks resolution suitable for detailed aquifer classification. High resolution seismic on the other hand, has the ability to map structures up to several kilometres below the ground with a resolution of close to 10 X 10m squares (Urosevic et al., 2007). This advantage of the seismic reflection method for groundwater studies is starting to be realized and demand for seismic reflection surveying in aquifer definition is increasing.

In hydrogeological investigations, it is necessary to discriminate a number of essential properties of water bearing formations (aquifers) before confidence can be gained for long term supply, which preserves the integrity of the aquifer system for all present and future users. Seismic surveying can assist in the measurement and resolution of three essential aquifer characteristics, namely;

- Aquifer geometry and extent as defined by boundary conditions such as faults and other important structures.
- System fluxes which include recharge and discharge zones.
- Enhancement and extrapolation of sparse drill hole information.

METHODOLOGY

A detailed aquifer assessment requires a variety of hydrogeological information such as: (i) hydro-stratigraphy (ii) system boundaries, (iii) hydraulic property distributions and (iv), the connectivity between aquifers and aquitards. As detailed above seismic reflection can resolve system boundaries but cannot directly measure hydraulic parameters. However once aquifer properties can be connected to the character of the seismic images by drill hole correlations it may be possible to infer that property more generally with the seismic data in a particular setting.

Firstly, in order to obtain an interpretable image of hydrogeological system, it is crucial to have an understanding of the depth of the target aquifers. Once this is determined, acquisition parameters can be decided on in order to best enhance the areas of highest importance. Generally, the target aquifers are within the depth range of 0 to ~1000m. Hence there is a need for dense spatial sampling (receiver and shot separation) to illuminate near surface lithologies. In the examples provided below, 2D seismic data was acquired with between 200 and 400 active geophones spaced at 5m for each shot, with 10m shot spacing. These survey parameters are considered relatively cost effective for many hydrogeological applications.

An aquifer system's size is generally controlled by locating geological or topographic boundaries. Geological boundaries can take a range of different forms but are often associated with fault planes and the discontinuity of lithology. High resolution seismic reflection has proven value in determining the location of these boundaries. Horizontal and vertical boundaries are often determined by fault planes which can act as barriers impeding water flow or as zones stimulating water flow. The lithological conditions of a fault assist to determine its hydraulic nature. The following example from Allanooka illustrates how a large basinal fault to the east forms a constraint to the aquifer system.

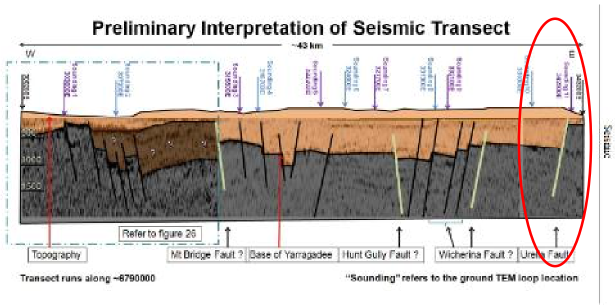

Figure 1: Seismic reflection transect with schematic interpretation overlay spanning across the Allanooka region of the Perth Basin. Notice the large scale structural fault illustrated by the red circle that acts as boundary extent for the basin (the image is taken from Gavin, 2010). Lisa's interpretation shows the boundaries and lateral geometry of the aquifer are directly related to faulting.

Also contributing to a detailed aquifer assessment is the analysis of system fluxes including recharge and discharge zones. Fluxes in an aquifer define the manner in which water flows throughout the system. If the seismic data is acquired over the full extent of the aquifer system it may greatly assist in the interpretation of a ground water recharge and discharge zones. For example an aquifer may be confined in the centre of a basin but sub-crops below at the margins. The recharge zone of an aquifer is any area where water is able to migrate either from rainfall or another aquifer.

Seismic attributes also play a very significant role in the value of seismic to hydrogeology. Attributes alter essential information found within a seismic trace such as time, amplitude, frequency, and attenuation (Brown, 2001). By applying attributes to seismic data, certain structural properties can be extracted. For example, the use of the instantaneous phase attribute will highlight texture at the expense of amplitude. The effectiveness of this attribute lies in its ability to resolve detailed bedding structure.

RESULTS

Canning Basin

In the canning basin, located approximately 200km east of Port Hedland, seismic reflection has been used to great effect in order to map the dimensions of the aquifer system and allow extrapolation of existing borehole information. The limited existing borehole information was enhanced by 50km of 2D high resolution seismic reflection that was acquired over the basin. The lithology intersected in single drill holes can be correlated over the full extent of the seismic survey. In the Canning Basin example, the aquifer has shown to be continuous across major basinal faulting and other bedrock constraints. In this case, the seismic survey was designed to tie into the existing borehole information then extend many kilometers out into the basin where no existing information was available. The results enabled an extension of the inferred aquifer; well beyond what was previously possible. Figure 2 below shows part of a seismic transect. Here, the major aquifer is clearly delineated. The seismic is also able to clearly discern large sedimentary packages within the major aquifer providing a higher level of understanding the important resource.

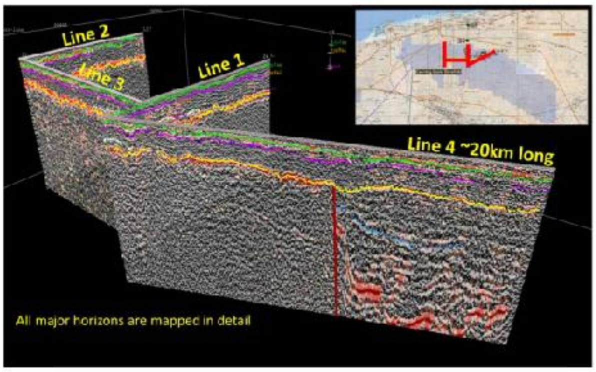

Figure 2:3D volume of all the 2D seismic transects over the Canning Basin. The aquifer can be traced across the large scale basinal fault located along line 4. This figure illustrates the value tracing aquifers in 2D transects over a large 3D area. Figure from FMG, 2012.

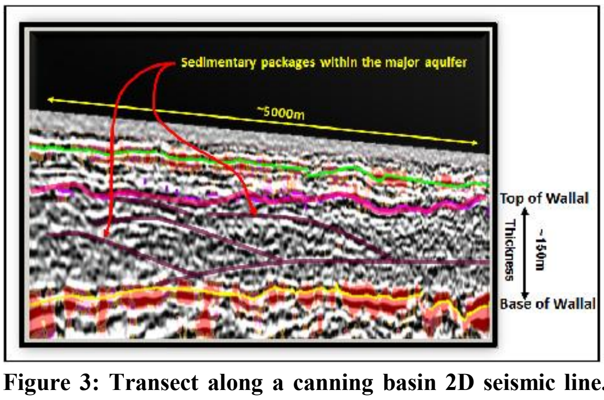

Figure 3: Transect along a canning basin 2D seismic line. Notice how well distinct packages of sedimentary rock are expressed within Wallal aquifer target. The seismic survey was specifically designed to have high resolution in the depth range 0 to 250m. Figure from FMG 2012.

Figures 2 and 3 above clearly demonstrate the value of seismic reflection for aquifer assessment. The 50 kms of seismic was acquired by HiSeis on behalf of FMG with the objective of extending the known occurrence and physical properties of the Wallal aquifer. The correlation between boreholes and seismic was excellent and provided confidence in the extension and continuity of this major aquifer unit in the Canning Basin.

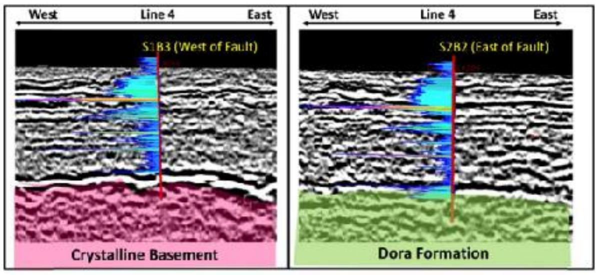

Figure 4: seismic reflection transect of Line 4 with gamma log mapped over the seismic. "The seismic appears to have mapped significant units including a basal sand unit within the Wallal Sandstone immediately above crystalline basement (~195 to ~240m). The yellow and green spikes in the gamma log are high gamma and relate to clay/claystone horizons" (FMG, 2012). This gamma log information can be extrapolated across the length of the seismic.

Perth Basin (below the Gnangara Mound)

The Gnangara Mound is Perth's largest water source spanning 2200 square kilometres. This complex aquifer system has undergone extensive high resolution seismic surveying by both Water Corporation and Department of Water Western Australia (Harris et al. 2011) The objectives of these surveys have been to resolve the aquifer extent, the boundaries between major underlying aquifers, and the large scale rift style faulting.

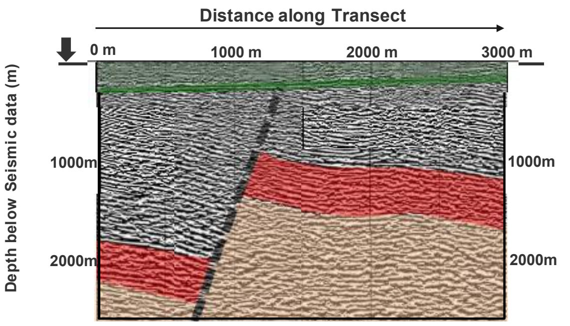

Figure 4: Seismic transect targeting a large north south fault in the northern Gnangara mound, Perth Basin, WA. Carefully targeted seismic provides a clear hydrogeological framework for a fault and upper angular unconformity surface. The stacked seismic data is presented as a cosine of phase attribute.

The value of seismic reflection in these types of sedimentary basins lies in the fact that it can map both basin scale and local sedimentary structure in detail. Figure 4 illustrates a large scale fault running through the Yarragadee Formation and being terminated at an angular unconformity with the Leederville formation above. The seismic reflection survey was specifically targeted to reveal the hydrostratigraphy at the fault. The seismic has clearly resolved the geometry of the aquifer and allowed the drilling of specifically targeted bores to test the flow hydraulics across (or proximal) to the fault.

Perth Basin (Allanooka)

Approximately 40 km of seismic reflection data has been acquired by Department of Water to in the Northern Perth Basin 50km southeast of Geraldton (Harris et al. 2011). Large scale faulting together with geometrical variations in aquifer extent, were extractable from this seismic data. In general however the subsidiary faulting in the Allanooka area is not strongly expressed in the Yarragadee Formation, where the sediments are relatively uniform. As expected, faulting is strongly expressed across the interface with shale dominated sediments within and below the Yarragadee Formation (Martin et. al., 2011).

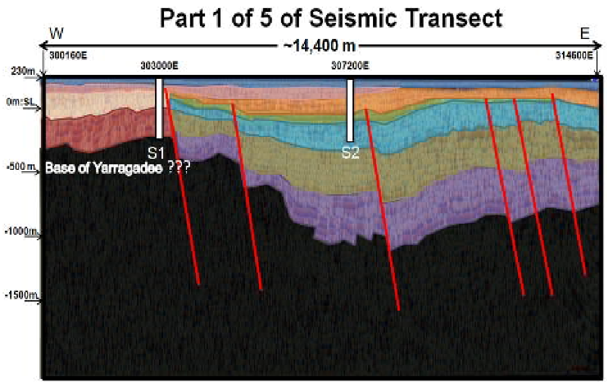

Figure 5: Example of interpretation of Department of Water WA seismic data, including major shallow units and faulting in the Allanooka Area of the Northern Perth Basin as complete by Lisa Gavin in 2010 (the image is taken from Gavin, 2010). The key point from Lisa's work was that the shallow formations and extent of faulting was well resolved in the seismic data which facilitated a greatly improved understanding of the hydrogeology. Note that this data was combined with TEM data to aid interpretation of solute concentration distribution (see Martin et. al. 2011).

CONCLUSIONS

We have demonstrated that the value of seismic reflection for detailed aquifer assessment is in its ability to map structure, boundaries, fluxes and extrapolate 1D borehole data. The ability of seismic to map such features has been illustrated throughout a number of examples in Western Australia's aquifer systems. We have discussed how it is necessary to increase the sampling density of the acquisition parameters in order to produce high resolution images of the near surface, which is critical in hydrogeological investigations. Furthermore, the use of seismic attributes was demonstrated in order to enhance interpretation of basinal structures. If the seismic lines can be planned to intersect existing boreholes, the borehole information can be extrapolated to and beyond the extent of the seismic survey. The application of seismic for exploration of sedimentary basins is a common practice, but the value of seismic for hydrogeology exists in its ability to resolve local and basin scale aquifer characteristics.

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