Neotectonic intra-plate fault zone mapping and hydrogeology in floodplain sediments: an inter-disciplinary approach

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SUMMARY

Over the past decade, a relatively rich record of neotectonics has been revealed in continental Australia, however very few investigations into the hydrogeological implications have been undertaken. While the most active intra-plate deformation zones are readily identified by seismicity monitoring and satellite and airborne terrain mapping, advances in airborne electromagnetic (AEM) technology and data optimization have made it possible to map numerous, more subtle 'blind' intra-plate fault systems concealed in near-surface floodplain landscapes. To date, fault geometries, displacements, and fault zone properties remain ambiguous due to the combination of AEM footprint resolution, the non-uniqueness of the conductivity models and derived hydrostratigraphy and fault geometry solutions produced by AEM equivalent inversion models, and the inherent uncertainty of stitched 1D AEM inversion models. The resultant uncertainty in fault zone characterisation inhibits investigations into the permeability heterogeneity and anisotropy introduced by these faults, making it difficult to resolve the significance of these structures for groundwater processes.

In this study, a novel, inter-disciplinary approach has been developed that helps characterise the hydrogeology of one such intra-plate fault zone in unconsolidated, near-surface floodplain sediments. The approach integrates the mapping of tectonic geomorphology, with mapping of sub-surface hydrostratigraphy and 'blind' intra-plate fault systems using AEM. Validation of fault zone geometry and displacement at local scales is provided by ground geophysics (e.g. seismic reflection, resistivity and surface nuclear magnetic resonance (SNMR)) and drilling. Fault zone hydrogeology, including permeability variability, has been assessed through the integration of geophysics with hydrochemistry, hydrodynamics, and studies of vegetation response to water availability (using Landsat time-series analysis). A combination of deterministic and stochastic approaches is then used to unravel complex fault zone conduit-barrier system behaviour that determines lateral and vertical groundwater flow, inter-aquifer leakage and recharge. This inter-disciplinary methodology has been used to parameterise numerical groundwater flow models and target potential groundwater resources.

Key words: Fault zone hydrogeology; airborne electromagnetics; seismic reflection; SNMR; groundwater modelling.

INTRODUCTION

Over the past two decades, the traditional 'regolith' view of an ancient, stable continent has been augmented by a deeper appreciation of the dynamic nature of the Australian plate (Sandiford, 2003, 2007; Braun et al., 2009), with a growing recognition of connection between plate-scale force balance, distribution of seismicity, and evolution of landscapes, geology and drainage systems (Reynolds et al., 2002; Sandiford et al., 2004; Hillis et al., 2008; Quigley et al., 2010). While the Australian continent is only weakly active seismically, neotectonic activity has resulted in significant in situ stress differentials (Coblentz et al., 1998; Sandiford et al., 2004).

These new insights have been made possible through quantitative studies of crustal deformation incorporating high-resolution geodetic measurements (Dawson, 2016); quantification of dynamic topographic effects (Sandiford, 2007; Czarnota et al., 2014); stress field, earthquake and seismicity analysis (Reynolds et al., 2002; Hillis et al., 2008; Braun et al., 2009); the use of geochronology, thermochronology and cosmogenic nuclide analysis to constrain the timing and rates of deformation, uplift, erosion and deposition (Gleadow, 2002; Pillans, 2008; Braun et al., 2009); local-scale studies of individual faults to constrain fault geometry and kinematics (Quigley et al., 2006; Clark et al., 2007, 2008, 2016; McPherson & Clark, 2016); and detailed geomechanical investigations that have revealed a depth-dependency of stress regime (Flottman et al., 2013; Brooke-Barnett et al., 2015; Rajabi et al., 2016). While much of the Australian continent may be ancient, recognition of active tectonic rejuvenation has important implications for energy, mineral and groundwater resources, and their development and management (Lawrie et al., 2016a).

At the land surface, a surprisingly widespread history of neotectonics has been mapped through seismicity monitoring (Sandiford, 2003), remote sensing (e.g. Landsat; Craig et al., 1984), and digital terrain mapping technologies (e.g. SRTM, LiDAR; Clark, 2010).

Digital terrain mapping coupled with longitudinal river profile analysis has enabled the quantification of dynamic topography effects (Czarnota et al., 2014), as well as the mapping of active fault systems and morphotectonic elements at a range of scales (Sandiford et al., 2003; Hill et al., 2003; Quigley et al., 2010). However, the sparse record of seismicity associated with surface ruptures, coupled with the high cost of investigations to validate fault geometries and kinematics, means that very few individual active faults have been studied in detail. In the subsurface, a number of geophysical techniques (e.g. high-resolution 3D seismic reflection and airborne electromagnetics (AEM)) have been used to identify discrete neotectonic faults, with often little if any morphotectonic expression noted (Lawrie et al., 2005, 2012). Furthermore, recent advances in AEM technology and AEM data optimization (Lawrie et al., 2015) have made it possible to map regionally extensive, intra-plate neotectonic fault systems with relatively small (<10m) vertical displacements concealed in near-surface floodplain environments (Lawrie et al., 2012, 2015). Together, these surface and sub-surface studies have revealed a unique neotectonic record of landscape, drainage and groundwater evolution, preserved in part due to relative aridity of the climate, subdued power of fluvial processes, low gradients in depositional landscapes, and in part due to the dynamics of our fast moving plate (Quigley et al., 2010; Lawrie et al., 2016a).

A key issue relating to intra-plate deformation is the extent to which individual faults are active, or have been recently active, and therefore have breached (or have the potential to breach) to the very shallow subsurface. While there is an extensive record of crustal deformation through the Tertiary, it is faults of Pliocene and younger ages that are considered to be 'active' in the current stress system (Sandiford et al., 2003). Individual faults in the shallow crust (in both erosional and depositional environments) commonly introduce permeability heterogeneity and anisotropy, with important implications for groundwater flow (Bense et al., 2013). However, with relatively recent recognition of the spatial extent and significant role that active tectonics plays in the evolution of Australia's landscapes, geology, drainage and palaeo-drainage, the hydrogeological implications have been largely under-estimated.

Australia's surface and groundwater systems reflect geodynamic/tectonic influences at a range of scales (Lawrie, 2014; Lawrie et al., 2016b). At long wavelengths (>10^3 km), dynamic topographic effects induced by the northward motion of the Indo-Australian plate have contributed to tilting of the continent, while dynamic uplift has produced a relatively small topographic range and low hydraulic gradients. This has resulted in slow-moving regional groundwater flow systems. At intermediate (10^2-10^3 km) wavelengths, regional dynamic topography effects have played a significant role in the development of major drainage basins, valley and river morphology, and the character and distribution of aquifers and aquitards at the catchment scale. Intermediate-scale tectonics and regional tilting has important consequences for the development of regional- to intermediate-scale groundwater flow systems, impacting on their through-flow dynamics and capacity to flush accumulated salt. At short wavelengths (<10^2 km), active deformation is manifest by the development of discrete intra-plate fault systems that modifies local landscapes and often controls and modifies the surface water network, as represented by both modern and palaeo-drainage features (Hill et al., 2003; Clark et al., 2007, 2008; McPherson & Clark, 2016). This in turn can influence the configuration and evolution of fluvial depositional and erosional processes. At basin to local scales, mapped fault systems are often localised by reactivation of crustal-scale faults and/or are localised at zones of crustal heterogeneity (Lawrie et al., 2012; Flottman et al., 2016). In the Surat Basin, crustal-scale basement structures appear to exert a first order influence on the in-situ stress azimuths and neotectonic expressions of topography and drainage (Flottman et al., 2016).

Recent investigations have demonstrated that in several of Australia's low gradient floodplains, fault scarps and concealed 'blind' fault systems with even small vertical displacements may have large 'keystone' effects on surface water and groundwater systems (Lawrie et al., 2016b). A keystone element of a system is one which is disproportionately important to the workings of that system relative to its size, abundance and/or distribution. . This effect can involve step changes (abrupt transitions in space and time) for both the hydrological architecture (including the surface drainage network, river incision/erosion and alluvial sediment deposition) and hydrological processes, such as surface water-groundwater interaction (e.g. river leakage, groundwater baseflow), inter-aquifer connectivity and groundwater discharge features (e.g. mound springs). These changes influence the distribution, evolution and sustainability of surface drainage systems, groundwater resources and dependencies such as phreatophytic vegetation (Lawrie et al., 2012; Harrington et al., 2013). Examples of 'keystone' effects on surface drainage systems (and by inference, riverine ecosystems and associated groundwater dependent ecosystems) include episodic reactivation of fault scarps that defeated the Murray River and led to its avulsion (Bowler & Harford, 1961; McPherson et al., 2012), tectonic forcing and avulsion of the Darling and Talyawalka Rivers (Lawrie et al., 2012), and avulsion of the Campaspe River related to the Avonmore fault scarp (McPherson & Clark, 2016).

Recent investigations have also demonstrated the significance of active tectonics and stress and strain partitioning for groundwater processes and flow, and coal seam gas production, in shallow sedimentary basins (Flottman et al., 2013, 2016; Brooke-Barnett et al., 2015). Active tectonics influences the distribution of pore pressure and effective stress, leading to compartmentalisation of groundwater flow within these coal basins (Flottman et al., 2013; Brooke-Barnett et al., 2015). However, in Australia, outside areas of conventional and unconventional energy exploration and production there have been very few investigations into the permeability heterogeneity and anisotropy introduced by active intra-plate fault systems, particularly in depositional floodplain settings, and fewer studies into the implications of these structures for groundwater processes, particularly flow (Lawrie et al., 2012; Harrington et al., 2013). This paper documents a novel, inter-disciplinary approach to characterise neotectonic intra-plate fault zone hydrogeology in shallow, unconsolidated floodplain sediments. The paper reports largely on the results of Phase 4 of the Broken Hill Managed Aquifer Recharge (BHMAR) project and parallel Geoscience Australia strategic groundwater science activities in the Lower Darling Valley, in the western half of the Murray Basin, New South Wales (Figure 1).

METHOD AND RESULTS

Mapping neotectonic intra-plate fault zones and groundwater systems at regional scale

In Phases 1-3 of the BHMAR study, a number of potential morphotectonic features at surface including potential fault scarps, however, surface fault expressions are typically obscured by dune-mantling, erosion and/or burial by post-faulting sediment deposits, and the area has largely been seismically quiescent in historical times (Lawrie et al., 2012; Magee, 2016). The importance of these potential faults to groundwater processes and resources was not initially understood. Subsequently, significant 'blind' intra-plate fault systems were revealed using airborne electromagnetics (AEM) surveys (Lawrie et al., 2012, 2015). Critical to successful mapping of these intra-plate fault zones was development of a novel, trans-disciplinary approach that was used to map previously unidentified faulting of the unconsolidated sediments beneath the Darling Floodplain (Lawrie et al., 2012, 2013, 2015).

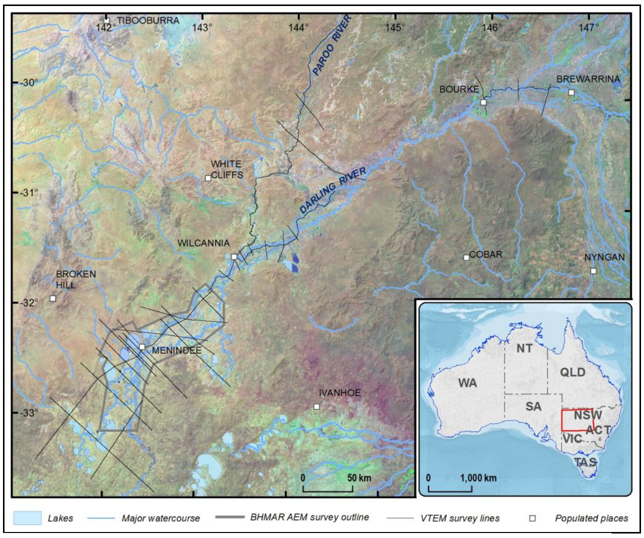

Figure 1 (above). Map showing the location of the BHMAR Project area (grey outline around Menindee) and the VTEM^{plus} and selected SkyTEM ^{312} transects in the Darling River Valley.

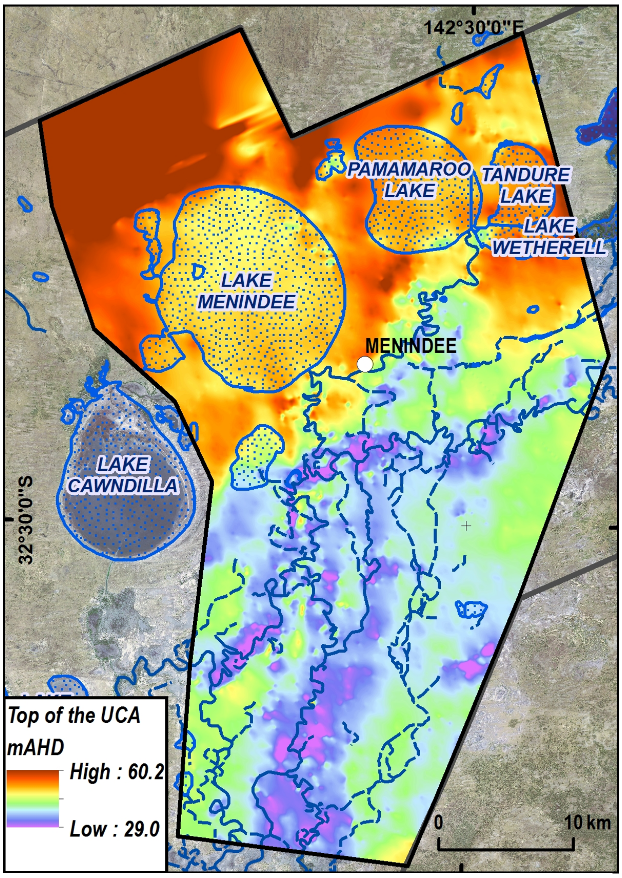

Figure 2 (right hand side). Map of the top of the Blanchetown Clay (AHD). The purple colours indicate the greatest depths, and the brown colours indicate the shallowest depths. There is a 70m elevation difference across the whole study area. The purple colours define deformation corridors related to the Menindee (N-S) and Talyawalka (ENE-WSW) fault systems.

In the BHMAR study, optimization of AEM data included consideration of AEM system suitability, calibration, validation and inversion methods (Lawrie et al., 2012a, Christensen & Lawrie, 2012, 2014). At a regional scale, the resultant improved 3D conductivity model revealed that post-Pleistocene deformation has resulted in regional deformation of an extensive lacustrine clay marker horizon (Blanchetown Clay), deposited in the fault-dammed mega-lake Bungunnia (Stephenson, 1986; McLaren et al., 2009, 2012). The top surface for the Blanchetown Clay interpreted from the AEM and drill holes shows up to 70 m elevation difference in this once relatively 'flat' surface, suggesting that it has been affected by significant warping and faulting, as well as regional tilting due to basin subsidence or margin uplift. Several of the sharp offsets in the conductivity layers are coincident with lineaments observed in LiDAR data, with the main faults coincident with underlying basement faults mapped from airborne magnetics, seismic reflection and gravity data (Lawrie et al., 2012, 2015).

Integration of surface and sub-surface mapping reveals that intra-plate deformation is largely focussed in two main corridors (Figure 2): the NNE-SSW- trending Menindee fault system (8-10km wide, >80km in strike length) and E-W-trending Talyawalka fault system (2-3km wide, and with a surface rupture expression of >180km). Within these first order structures are a system of half-grabens, grabens, horst blocks, and anastomosing fault networks consistent with interpretation as 'step-overs' and 'horsetails' within complex intra-plate fault systems. Vertical displacements across individual faults are typically <10m, but up to 25m, with stratigraphic offsets confirmed through drilling and ground geophysics including seismic reflection (Symington et al., 2016). While the present stress field is compressional with the maximum horizontal stress (SHmax) most likely oriented ENE-WSW (Hillis et al., 2008), some of the fault architecture may be inherited from pre- to syn- early Pliocene strike slip deformation (Roy and Whitehouse, 2003), and/or be influenced by oblique reactivation of favourably oriented basement structures (Lawrie et al., 2012).

In the initial BHMAR study, the AEM survey utilised the SkyTEM (2009) system (Lawrie et al., 2012) to map hydrostratigraphy and tectonic elements to depths of ~100m (Lawrie et al., 2012, 2015). Subsequently, AEM technology trials and regional groundwater investigation surveys involving the SkyTEM 312, SkyTEM 312^{FAST} and VTEM^{plus} systems (Lawrie et al., 2015) extended the mapping of these intra-plate fault systems to greater depths in the BHMAR study area, confirming fault offsets of the underlying interface between the Murray and Darling Geological Basins. The latter surveys also confirmed the presence of similar intra-plate fault systems outside the area of palaeo-lake Bungunnia. Recently deployed temporary seismometers have confirmed active seismicity associated with faulting in the Anabranch area in the southern half of the Lower Darling area (Sandiford, written communication, 2015). Overall, the pattern of neotectonic regional deformation reveals an asymmetric distribution in the Murray Basin, with increasing prevalence of these intra-plate deformation zones to the west.

The mapped faults are an important element in the hydrogeological conceptual model. The Darling River is a losing system within the study area (CSIRO, 2008). Hydrochemical data show that the Calivil Formation semi-confined aquifer (at depths >30m) is recharged primarily during high flow events along the Darling River. The groundwater hydrograph response to a flood event in 2010 demonstrated that recharge of the Calivil Fm aquifer occurred prior to overbank flooding, with some boreholes recording responses within a few days of high flows being recorded in the river. Studies of overlying aquitards, including permeability measurements and modelling of aquitard advection and diffusion rates, indicate that bypass flow is essential to explain the timing of the groundwater responses. With very few 'holes' in the aquitard mapped, leakage through fault juxtaposition of the upper unconfined aquifer (connected to the river) with the underlying Calivil Fm aquifer is considered a key recharge mechanism.

This new inter-disciplinary mapping approach that integrates surface and sub-surface mapping has enabled improved recognition and interpretation of Lower Darling and western Murray Basin landscape features such as older pre-dunefield river courses; regional scale (~10 km) uplifted blocks; disruptions such as river diversions, crossing lake shorelines, uplifted former lake floors or boinkas, fault-control on localisation of individual lakes; abandoned dune plinths; compression ridges, and relict landscape vegetation and/or mineral assemblage associations. Additionally, at a regional scale, the recognition of underlying crustal deformation elements has allowed interpretation of landscape features that have defied explanation since geomorphic mapping in the 1970s and regolith mapping over the past decade. These features include: the origin of the en-echelon overflow Willandra Lakes; the origin and valley-margin location of the flood-out Menindee Lakes; the overflow pattern and defeat of the Teryawenya Lakes; the highly variable location and morphology of the flood-out Anabranch Lakes; the repeated course switching of the lower Darling river and the multiple intersection of scroll-plain tracts just south of Menindee (Magee, 2016).

Neotectonic fault zone hydrogeology at bore field scales

In Australia, regional groundwater numerical models and workflows have generally been established for data-poor areas, typified by extrapolation of sparse geological and hydrogeological data between few boreholes. This creates inherent uncertainties introduced by significant gaps in our knowledge of the 3D hydrogeological framework and groundwater processes, while approaches to model calibration reflect that data sparsity and uncertainty. A tension always exists between the desire to build simple models that run in short timeframes, yet do not accurately reflect geological and hydrogeological heterogeneity, and complex models that more accurately reflect geological heterogeneity, yet are computationally intensive, take much longer to run, and may be less robust. Selecting the appropriate complexity of a numerical groundwater model is itself not a simple decision (Doherty, 2011; Doherty & Simmons, 2013). The complexity of groundwater models is only increased through the incorporation of fault zone hydrogeology, and careful weighing of the value in building more complex models is required. For example, in shallow sedimentary basins, intra-plate faults might not produce basin-scale impacts on groundwater flow, however local to intermediate scale impacts (e.g. through inter-aquifer leakage) may be significant enough to warrant the construction of more complex models that incorporate an understanding of fault zone permeability heterogeneity and anisotropy, and influence on groundwater flow (Schoning et al., 2016).

In Australia, the paucity of groundwater data and systems understanding contrasts with the depth of understanding of minerals and petroleum systems, and reflects the disparity in investment in geoscience data acquisition and analysis between these sectors. However, over the past decade, advances in new satellite and airborne sensor technologies provide an opportunity for rapid multi-scale mapping, measurement and monitoring of the physical state of the crust, including resolution of key elements of surface and sub-surface hydrological systems (Lawrie et al., 2016a). These advances have been mirrored by the development in advanced computational research infrastructure which is now giving the groundwater research community access to high-resolution (spatial and temporal) biophysical datasets (e.g. climate, ecology, geoscience and geospatial) relevant to broader hydrological systems understanding. This infrastructure facilitates integration of multiple datasets and rapid and improved signal processing, inversion, and sophisticated analysis, and semi-automated mapping through machine learning. These datasets provide a catalyst for collaboration, with inter-disciplinary approaches enabling new discovery science in a 'big data' environment, and enabling the qualitative and quantitative mapping, analysis and modelling of landscape and hydrological system processes.

Data-rich environments create new challenges for regional groundwater flow modelling. For example, there has been an enormous investment in collecting a wide range of geological, geophysical, geomechanical and hydrogeological data to understand and predict groundwater flow and gas production for coal seam gas projects in Eastern Australia's shallow coal basins (Flottman et al., 2013). Yet, despite significant advances in conceptual understanding, and advances through adapting groundwater modelling code (e.g. unstructured MODFLOW-USG grids) to incorporate permeability heterogeneity and anisotropy, challenges remain in producing calibrated groundwater models for these hydrogeologically and structurally complex environments (Schoning et al., 2016). Outside areas of resource industry activity, investment in understanding Australia's groundwater systems is much lower, and uncertainties due to data paucity are commensurately higher. In the BHMAR study area, which is an atypically data-rich area, definition of the 3D architecture exists at a fine-scale (e.g. from ~200m line-spaced AEM data), and there is an evolved groundwater conceptual model that constrains groundwater processes, surface-groundwater interactions and groundwater flow modelling (Brodie et al., 2015). Despite this, one groundwater modeller's view is that this "dense geological and hydrogeological data actually serves to increase groundwater model uncertainties"! This arises, because even in this area, there remains ambiguity in resolving critical elements of the hydrological system at local scales in complex near-surface environments. In some respects, through this greater data density, we are only just now recognising just how complex these environments actually are, and also how over-simplified were our previous conceptualisations. This is particularly true in respect to determining fault zone hydrogeology and its role in inter-aquifer leakage and recharge processes. The investment that would be required in geoscientific investigations to map and characterise all segments of complex regional fault systems in these landscapes is prohibitive.

Previous studies of fault zone structure and permeability within inter-layered unconsolidated sand-clay sequences within unconsolidated sedimentary sequences point to likely complexity in fault zone hydrogeology. Reductions in porosity, permeability and groundwater flow within fault zones can be caused by inter-layer mixing, cataclastic deformation, clay smearing and diagenesis (Bense et al., 2013). Equally, fault zone permeability can be enhanced by particulate flow of sands (Lewis et al., 2002), or the formation of dilation bands in unconsolidated material. Anisotropy can be altered where along-fault flow is enhanced and across-fault flow is impeded, leading to complex conduit-barrier systems (Bense et al., 2013). In this study, ambiguity in fault geometries and fault zone characterisation occur when relying largely on broad-acre mapping technologies such as AEM, to map fault systems over large areas. Difficulties occur due to scale and system footprint issues, the range of hydrostratigraphic and fault geometry solutions produced by equivalent inversion models, and inherent uncertainty introduced using standard stitched 1D inversion models. The resultant uncertainty in fault zone characterisation inhibits investigations into the permeability heterogeneity and anisotropy introduced by these faults, making it difficult to resolve the significance of these structures for groundwater processes.

In this study, a novel, inter-disciplinary approach has been developed to characterise neotectonic intra-plate fault zone hydrogeology in unconsolidated, near-surface, floodplain sediments. The approach builds on earlier success in using a trans-disciplinary approach to map intra-plate fault systems and derive a hydrogeological conceptual model consistent with all relevant hydrogeological, hydrochemical, hydrodynamic and hydrogeophysical data (Lawrie et al., 2012, 2015). Fault zone hydrogeology, including permeability and anisotropy, has been assessed through the integration of geophysics with hydrochemistry, hydrodynamics, and studies of vegetation response to water availability (using Landsat time-series analysis). Stress field analysis is also considered. In the study area there is no outcrop or drill core of the faults, and the majority of the 'blind' faults are covered by 5-20m of sediment. To map the faults, hydrostratigraphy was systematically mapped in cross-sections using the AEM conductivity profile data validated by drilling and borehole geophysics. Mapped layers include the upper confining (Blanchetown Clay), near-surface clay drape, and the top of the Renmark Group (which underlies the Calivil Fm aquifer) and interface with underlying Darling Geological Basin basement (Figure 3). This enabled discontinuities in the layers to be identified, and anastomosing fault networks (and adjacent fault blocks) to be then mapped in 3D. It was not possible to discern from 1D stitched AEM inversions whether there are discrete fault offsets with unconsolidated sands mixed in the fault zone; or if clay layers are dragged into the fault zones; or if there is diagenesis within discrete fault damage zones. Analysis is made more complex when the orientations of faults relative to flight line orientations are taken into consideration.

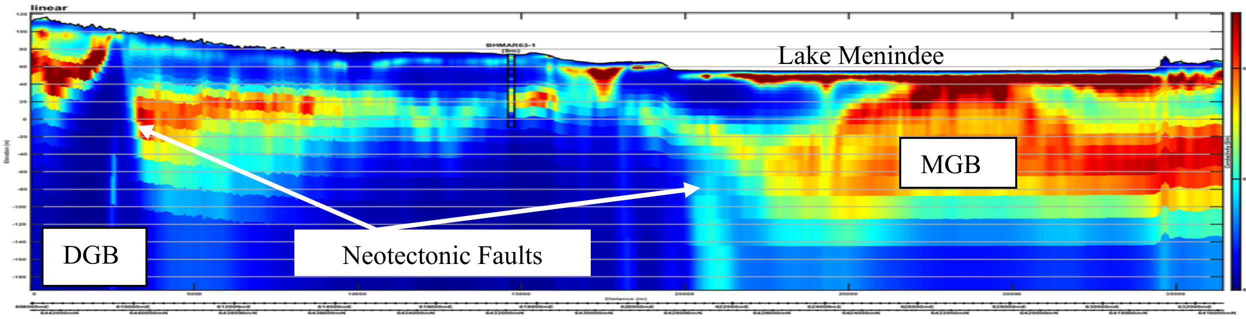

Figure 3. A conductivity section (GALEIALLATONCE inversion of VTEM 2014 data) showing the interface between Darling Geological Basin (DGB) basement and overlying Murray Geological Basin (MGB) sediments. The VTEM (and SkyTEM 312 system) map to depths of ~150-200m compared to SkyTEM 2009 (80-110m). In this image, MGB sediments are deposited in sub-parallel fault-controlled half-grabens. There are small fault scarps at surface coincident with these faults.

To resolve these issues, the faults were categorised in terms of (a) fault strike length-vertical offset relationships; (b) fault orientation; (c) possible and probable clay smearing based on the observed conductivity responses (i.e. possible Blanchetown Clay presence) within the fault zones; and (d) ancillary data. The latter includes all relevant geophysical and broader biophysical data. For example, where there are no holes observed in the upper confining (Blanchetown Clay) aquitard, hydrodynamic and hydrochemical data require the mapped faults to be lateral groundwater flow pathways enabling inter-aquifer leakage across faults that juxtapose the upper (Coonambidgal Formation) and lower Pliocene aquifers (Calivil Formation and Loxton-Parilla Sands; Figure 3; Lawrie et al., 2012). Vertical flow along some faults has been confirmed through the use of He^3:He^4 ratio analysis of shallow groundwaters, which points to a contribution of deep crustal fluids into the shallow aquifers through several kilometres of sedimentary sequence. In other instances, some fault zones were interpreted as potential barriers to lateral groundwater flow, notably where abrupt linear changes in electrical conductivity (reflecting marked differences in groundwater salinity) are observed in conductivity depth slices within the Pliocene aquifers (Figure 4). In two locations, these potential fault 'barrier zones' were drilled, and found to be heavily indurated, with drilling abandoned.

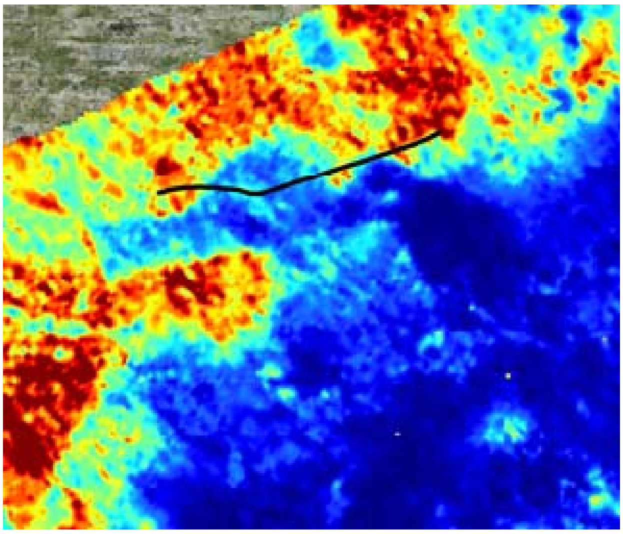

Figure 4. Conductivity depth slice showing abrupt linear changes in conductivity interpreted as faults. The location of a high-resolution seismic reflection line is shown in black (see Symington et al., 2016).

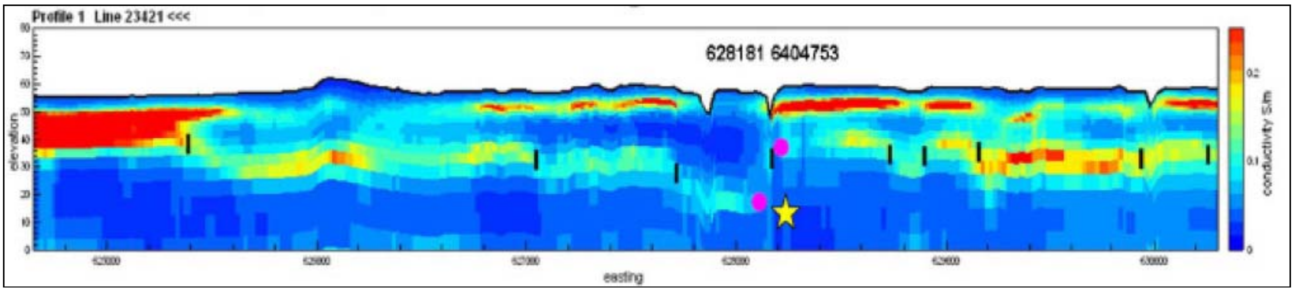

Figure 5. A conductivity section (WANDA inversion of SkyTEM 2009 data) showing the location of a fault offsetting the conductive Blanchetown Clay aquitard (between the pink dots). Inter-aquifer leakage is facilitated between the river, overlying aquifer and the Calivil Formation aquifer (yellow star) at this location.

To provide further confidence in fault zone hydrogeology at the bore field scale, ground geophysics has been used to provide enhanced imaging of hydrostratigraphy and fault geometries within the fault zones in type locations. Due to logistic and cost constraints, a limited program of seismic reflection profiling has been undertaken to discern structural styles and fault geometries (Symington et al., 2016). Further seismic reflection transects, ground resistivity, and SNMR techniques are also planned to provide higher-resolution imaging of aquifer and aquitard distribution and transmissivity contrasts across type fault segments. Trials of 2D inversion software is also planned for these transects, while baseline InSAR data are being collected for long-term mapping and monitoring of natural groundwater responses to flooding and drought, and to monitor groundwater extraction. The InSAR data also have the potential to reveal fault zone hydrogeology (Chaussard et al., 2014).

In summary, a combination of deterministic and stochastic approaches has been used to unravel complex fault zone conduit-barrier system behaviour that determines lateral and vertical groundwater flow, inter-aquifer leakage and recharge. Fault zone hydrogeology developed using this methodology has been incorporated in numerical groundwater flow models for proposed bore fields in the study area. The inter-disciplinary approach developed in this project has confirmed the important role that neotectonic faults play in inter-aquifer leakage and the rapid recharge of Pliocene aquifers during high-flow events in the Darling River within the study area. The methodology described above has also been applied to groundwater exploration elsewhere in the Darling River Valley (Lawrie et al., 2015). A common factor in the design of this survey was consideration of neotectonics, and the potential for active faulting to reactivate basement structures, breach near-surface aquitards and enable recharge from the river to Pliocene aquifers.

CONCLUSIONS

Over the past two decades, a paradigm shift has occurred in our understanding of active deformation within the Australian plate. There is a growing recognition that the intra-plate stress field, and associated pattern of recent deformation, reflects fundamental plate scale dynamic processes, with influences at a range of scales, and with important implications for energy, mineral and groundwater systems and resources. Due to the low gradients of many Australian floodplains, and inter-layering of thin sand and clay layers in the near-surface, faults with small offsets may have large 'keystone' effects on surface water and groundwater systems.

New inter-disciplinary methods that use a range of high-resolution sensor technologies aided by data optimization techniques enable Australia's rich record of neotectonics in the near-surface to be mapped. However, characterisation of fault zone hydrogeology in depositional landscapes (and shallow sedimentary basins) remains challenging. The inter-disciplinary approach developed in this study integrates deterministic and stochastic approaches to unravel complex conduit-barrier system behaviour and parameterise numerical groundwater flow models. The hydrogeological conceptual model has also been adapted to successfully target potential groundwater resources elsewhere in the Murray Basin and northern Australia. The fault mapping and characterisation methods developed in this study have utility for mineral and energy resource exploration and seismic and environmental hazard assessments.

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REFERENCES

Bense, V.F., Gleeson, T., Loveless, S.E., Bour, O. & Scibek, J., 2013. Fault zone hydrogeology. Earth Sci. Rev. 127, 171-192.

Bowler, J. M. & Harford, L. B., 1966. Quaternary tectonics and the evolution of the riverine plain near Echuca, Victoria, Journal of the Geological Society of Australia, 13:2, 339-354.

Braun, J., Burbidge, D.R., Gesto, F.N., Sandiford, M., Gleadow, A.J.W., Kohn, B.P. & Cummins, P.R., 2009. Constraints on the current rate of defomration and surface uplift of the Australian continent from a new seismic database and low-T thermochronological data. Aust. J. Earth Sci., 56, 99-110.

Brodie RS, Lawrie K, Tan KP, Magee J & Halas L, 2015. Insights from the evolution of a conceptual model for recharge to the Lower Darling River floodplain aquifers, Murray-Darling Basin, Australia. AQUA 2015, IAH Congress, Rome, Italy.

Brooke-Barnett, R., Flottman, T., S. Paul, P. K., Busetti, S., Hennings, P., Reid, R. & Rosenbaum, G., 2015. Influence of basement structures on in situ stresses over the Surat Basin, southeast Queensland. J. Geophys. Res. Solid Earth, 120.

Chaussard, E., Burgmann, R., Shirzaei, Fielding, E.J. & Baker, B., 2014. Predictability of hydraulic head changes and characterization of aquifer-system and fault properties from InSAR-derived ground deformation, J. Geophys. Res. Solid Earth, 119, 6572–6590.

Christensen, N.B. and Lawrie, K.C. 2012. Resolution analyses for selecting an appropriate airborne electromagnetic (AEM) system. Exploration Geophysics, 2012, 43, 213–227.

Clark, D., 2010. Identification of Quaternary scarps in southwest and central west Western Australia using DEM-based hill shading: application to seismic hazard assessment and neotectonics. International Journal of Remote Sensing 31, 6297–6325.

Clark, D., Van Dissen, R., Cupper, M., Collins, C.D.N., Prendergast, A., 2007. Temporal clustering of surface ruptures on stable continental region faults: a case study from the Cadell Fault scarp, south eastern Australia. Proceedings of the Australian Earthquake Engineering Society Conference, 23–25 November 2007, Wollongong.

Clark, D., Dentith, M., Wyrwoll, K.-H., Yanchou, L., Dent, V., Featherstone, C., 2008. The Hyden fault scarp, Western Australia: paleoseismic evidence for repeated Quaternary displacement in an intracratonic setting. Aust. J. Earth Sciences 55, 379–395.

Clark, Dan; McPherson, Andrew; Nakamura, Aki; Pillans, Brad; Macphail, Mike, 2016. Late Neogene to Quaternary Tectonic Evolution of the Lake George Basin, Southeast Highlands, Australia. *In* Lawrie, K (Ed.). Proceedings of 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment'. (Abs.) p.20.

Coblentz, D., Zhou, S., Hillis, R., Richardson, R., Sandiford, M., 1988, Topography, plate-boundary forces and the Indo-Australian intraplate stress field, J. Geophysical Research, 103, 919-931.

Craig, J., Downey, J.W., Gibbs, A.D., Russell, J.R., 1984. The application of Landsat imagery in structural interpretation of the Canning Basin, WA. In: Purcell, P.G. (Ed.), Proc. of the Petroleum Exploration Soc. of Australia Symposium, Perth, p. 57–72.

CSIRO. 2008. Water availability in the Barwon-Darling. CSIRO Murray-Darling Basin Sustainable Yield Project. CSIRO Australia.

Czarnota,K., Roberts, G. G., White, N. J. and Fishwick, S. 2014. Spatial and temporal patterns of Australian dynamic topography fromRiver Profile Modeling. J. Geophys. Res. Solid Earth, 119.

Dawson, J., Moore, M., Guorong, H., & Minghai, J., 2016. Geodetic constraints on crustal deformation of the Australian plate. *In* Lawrie, K (Ed.). Proceedings of 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment'. (Abs.) p. 11.

Doherty, J., 2011. Modeling: Picture Perfect or Abstract Art? Ground Water 49(4): 455.

Doherty, J. and Simmons, C.T., 2013. Groundwater modelling in decision support: reflections on a unified conceptual framework, Hydrogeology Journal 21: 1531-1537.

Flottman, T., S. Brooke-Barnett, R. Trubshaw, S. K. Naidu, E., Kirk-Burnnand, P. K., Busetti, Paul, S., and Hennings, P., 2013, Influence of in-situ stresses on fracture stimulations in the Surat Basin, southeast Queensland, paper SPE 167064 presented at the Unconventional Resources Conference and Exhibition-Asia Pacific, 14 pp., Soc. of Petrol. Engineers, Brisbane, Australia.

Gleadow A. J. W., Kohn B. P., Brown R. W., O'sullivan P. B. & Raza A. 2002. Fission track thermotectonic imaging of the Australian continent. Tectonophysics 349, 5–21.

Harrington, G.A., Gardner, W.P. and Munday, T.J. (2013). Tracking groundwater discharge to a large river using tracers and geophysics. Ground Water, 52(6): 837-852.

Hill, S. M., Eggleton, R. A., and Taylor, G. 2003. Neotectonic disruption of silicified palaeovalley systems in an intraplate, cratonic landscape: Regolith and landscape evolution of the Mulculca range-front, Broken Hill Domain, New South Wales, Australian Journal of Earth Sciences 50(5), 691-707.

Hillis R. R., Sandiford M., Reynolds S. D., Quigley M.C., 2008. Present-day stresses, seismicity and Neogene-to-recent tectonics of Australia's 'passive' margins: intraplate deformation controlled by plate boundary forces. *In* Jonhson H, et al., (eds.), The Nature and Origin of Compression in Passive Margins. Spec. Pub. 306. Geol. Soc. London; 71–89.

Lawrie, K.C., Fitzpatrick, A., Clarke, J., Pain, C., Heczeg, A., Wilkinson, K., and Lane, R., 2005. Successful application of airborne geophysics for salinity mapping and assessment in a cotton irrigation district, Lower Balonne, S.W. Queensland, Australia, International Salinity Forum 2005. (Ext. Abs.).

Lawrie, K.C., Brodie R.S., Tan, K.P., Gibson, D., Magee, J., Clarke, J.D.A., Halas, L., Gow, L, Somerville, P., Apps, H.E., Christensen, N.B., Brodie, R.C., Abraham, J., Smith, M, Page, D., Dillon, P., Vanderzalm, J., Miotlinski, K., Hostetler, S., Davis, A., Ley-Cooper, A.Y., Schoning, G., Barry, K. and Levett, K., 2012. BHMAR Project: Data Acquisition, processing, analysis and interpretation methods. Geoscience Australia Record 2012/11. 520p. Geocat 73819.

Lawrie, K.C., Christensen, N.B., Brodie, R.S., Abraham, J., Halas, L., Tan, K.P., Brodie, R.C. and Magee, J., 2015. Optimizing AEM inversions for hydrogeological investigations using a trans-disciplinary approach. In Proceedings of ASEG-PESA 2015. (4p.).

Lawrie, K., Sandiford, M. & Johnson, J., 2016a. Neotectonics on the Australian Plate: new science for energy, mineral and groundwater systems, and hazard assessments. *In* Lawrie, K (ed.). 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment'. (Abs). p.8

Lawrie, K., Brodie, R.S., Gibson, D., Halas, L. & Magee, J., 2016b. Inter-disciplinary approaches to mapping neotectonic intra-plate fault systems & their hydrological effects in Australia's floodplain landscapes. *In* Lawrie, K (ed.). 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment'. (Abs). p.31.

Leonard, M., Clark, D., 2011. Constraining large earthquake recurrence in stable continental region crust using historic and palaeo-records. Earth and Planetary Science Letters 309, 207–212.

Lewis, G., Knipe, R.J., Li, A., 2002. Fault seal analysis in unconsolidated sediments: a field study from Kentucky. In: Koestler, A.G., Hunsdale, R. (Eds.), Hydrocarbon Seal Quantification. Vol. 11 of NPF, Special publication. Elsevier B. V., Amsterdam, pp. 243–253.

McLaren, S., Wallace, M.W., Pillans, B.J., Gallagher, S.J., Miranda, J.A. and Warne, M.T., 2009. Revised stratigraphy of the Blanchetown Clay, Murray Basin: age constraints on the evolution of paleo Lake Bungunnia, Aust. J. Earth Sci. 56(2):259-270.

McLaren, S., Wallace, M.W. and Reynolds, T., 2012. The Late Pleistocene evolution of palaeo megalake Bungunnia, southeastern Australia: A sedimentary record of fluctuating lake dynamics, climate change and the formation of the modern Murray River. Palaeogeography, Palaeoclimatology, Palaeoecology 317-318: 114-127.

McPherson, Andrew and Clark, Dan, 2016. The Avonmore Scarp: Implications for Seismic Hazard, Mineral Exploration and Groundwater Resources in the Campaspe River Valley, Victoria. *In* Lawrie, K (Ed.). Proceedings of 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment'. (Abs.) p.21.

Pillans, B., 2008. Regolith Dating Methods: A Guide to Numerical Dating Techniques in Australia. CRC LEME, Perth, 43 pp.

Quigley M., Cupper M. & Sandiford M., 2006. Quaternary faults of southern Australia: palaeoseismicity, slip rates and origin. Australian Journal of Earth Sciences 53, 285–301.

Quigley, M.C., Clark, D. & Sandiford, M., 2010. Tectonic Geomorphology of Australia. *In* Bishop, P. & Pillans, B. (eds) Australian Landscapes. Geological Society, London, Special Publications, 346, 243–265.

Rajabi, M., Tingay, M. & Heidbach, O., 2016. The Present-Day Tectonic Stress Pattern of Australia: The New Release of the Australian Stress Map Project. *In* Lawrie, K (Ed.). Proceedings of 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment' (Abs.). p.25.

Reynolds S. D., Coblentz D. D. & Hillis R. R. 2002. Tectonic forces controlling the regional intraplate stress field in continental Australia: results from new finite element modeling. Journal of Geophysical Research 107: 10.1029/2001JB000-408.

Roy, P.S and Whitehouse, J., 2003. Changing Pliocene Sea Levels and the Formation of Heavy Minerals Beach Placers in the Murray Basin, Southeastern Australia. Economic Geology, 98:975-983.

Sandiford M. 2003. Neotectonics of southeastern Australia: linking the Quaternary faulting record with seismicity and in situ stress. In: Hillis R. R. and Muller R. D. (eds). Evolution and Dynamics of the Australian Plate, pp. 107–119. Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper 372.

Sandiford M., Wallace M. & Coblentz D. 2004. Origin of the in situ stress field in southeastern Australia. Basin Res. 16, 325–338.

Sandiford M. 2007. The tilting continent: a new constraint on the dynamic topographic field from Australia. E.P.S.L., 261: 152–163.

Stephenson, A.E., 1986. Lake Bungunnia – A Plio-Pleistocene megalake in southern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 57:137-156.

Symington, N., Tan, K.P., Ziramov, S. Urosevic M. & Lawrie, K., 2016. Using Shallow Active Seismic Reflection Data to Validate Neotectonic Faulting Observed in AEM Datasets within Unconsolidated Alluvial Sediments of the Lower Darling Valley, N.S.W. *In* Lawrie, K (Ed.). Proceedings of 'Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment'. (Abs.) p. 42.