Facilitating Long-term Outback Water Solutions (G-FLOWS Stage 3): Final Summary Report

Tim Munday, Mat Gilfedder, Adrian Costar, Teagan Blaikie, Kevin Cahill,
Tao Cui, Aaron Davis, Zijuan Deng, Brady Flinchum, Lei Gao,
Michael Gogoll, Georgina Gordon, Tania Ibrahimi,
Kent Inverarity, Jonathan Irvine, Sreekanth Janardhanan,
Zhenjiao Jiang, Mark Keppel, Carmen Krapf, Tessa Lane,
Andrew Love, James Macnae, Dirk Mallants,
Gregoire Mariethoz, Jorge Martinez, Dan Pagendam,
Luk Peeters, Trevor Pickett, Matthias Raiber, Xiuyan Ren,
Neville Robinson, Adam Siade, Nick Smolanko,
Camilla Soerensen, Liliana Stoian, Andrew Taylor,
Gerhard Visser, Ilka Wallis, Yueqing Xie

Goyder Institute for Water Research
Technical Report Series No. 20/08

www.goyderinstitute.org

Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, and the University of South Australia. The Institute enhances the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.

This project was also supported by CSIRO's Deep Earth Imaging Future Science Platform.

Enquires should be addressed to: Goyder Institute for Water Research
Level 4, Rundle Mall Plaza, 50 Rundle Mall,
Adelaide, SA 5000
tel: 08 8313 5020
e-mail: enquiries@goyderinstitute.org

Citation

Munday, T., Gilfedder, M.. Costar, A., Blaikie, T., Cahill, K., Cui, T., Davis, A., Deng, Z., Flinchum, B., Gao, L., Gogoll, M., Gordon, G., Ibrahimi, T., Inverarity, K., Irvine, J., Janardhanan, S., Jiang, Z., Keppel, M., Krapf, C., Lane, T., Love, A., Macnae, J., Mallants, D., Mariethoz, G., Martinez, J., Pagendam, D., Peeters, L., Pickett, T., Raiber, M., Ren, X., Robinson, N., Siade, A., Smolanko, N., Soerensen, C., Stoian, L., Taylor, A., Visser, G., Wallis, I., and Xie, Y. (2020) *Facilitating Long-term Outback Water Solutions (G-FLOWS Stage 3): Final Summary Report.* Goyder Institute for Water Research Technical Report Series No. 20/08.

Disclaimer

Contents

Figures

Tables

Executive Summary

Purpose of G-FLOWS Stage-3 project

Groundwater in remote arid areas of South Australia is often the only available water resource to support the livelihood of communities as well as to support opportunities for future water-dependent industries/enterprises. The third stage of the Goyder Institute's Facilitating Long-term Outback Water Solutions (G-FLOWS) research program followed on from the successful first two stages (Gilfedder & Munday 2013, Gilfedder et al. 2015) and aimed to help reduce significant risks faced when considering water resource development proposals for these areas, allowing for more informed decision-making and prioritisation for more targeted drilling to secure water supplies.

The G-FLOWS Stage-3 project has developed and applied an integrated approach to the measurement, analysis, and modelling of geophysical, geochemical and hydrogeological techniques, which aim to help more efficiently and effectively target groundwater resources in a remote part of arid Australia.

The project has focused on groundwater in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands, which is a remote arid area in northwest South Australia. It investigated the role that large buried palaeovalley systems can play as potential groundwater resources for community and enterprises. G-FLOWS Stage-3 involved a collaboration between CSIRO, Flinders University and the South Australian Department for Environment and Water.

This final summary report of the G-FLOWS Stage-3 project outlines the work undertaken to:

- Map palaeovalley locations with significantly improved accuracy across the APY Lands;
- use multiple lines of evidence to investigate palaeovalley evolution, aquifer character and palaeovalley architecture, groundwater chemistry, recharge and flow.

These combined efforts led to the refinement of a hydrogeological conceptual understanding of palaeovalley drainage in the APY Lands, as well as a more widely applicable probabilistic modelling approach to provide a framework for data-driven targeting for drilling locations.

Palaeovalley location

Palaeovalley location, geometry and size were more precisely mapped through the acquisition, processing and inversion of airborne electromagnetic (AEM) data from across the APY Lands. These data revealed areas of deep transported cover that filled ancient valley systems which developed in the area in the mid to late Mesozoic (~65 million years ago). This cover material is more electrically conductive than the underlying basement rocks and provides a good basis for using AEM data as a means for mapping its extent and thickness. There is also potential to map variations within the palaeovalleys, which is useful for helping locate compartmentalised aquifers. The AEM dataset also proved to be an ideal testbed for the development of machine learning approaches in palaeovalley mapping.

Palaeovalley architecture

Palaeovalley architecture was investigated using a range of techniques as part of a large ground-based and borehole data collection programme, involving drilling/coring and multiple on-ground and borehole geophysical techniques to help support and confirm the interpretation of the AEM data.

Palaeovalley architecture is an important aspect of understanding the water resources they contain. The drilling program in G-FLOWS Stage-3 provided an opportunity to obtain information on the infill materials and hydrogeologic properties down through a large palaeovalley. Drilling in the Lindsay East Palaeovalley (at Site DH1) has provided detailed information at this location.

Recharge and flow

Water chemistry, environmental tracer analyses, and groundwater modelling were undertaken to better understand the rate of groundwater recharge and the movement of water through the landscape. The review and reinterpretation of groundwater level, chemistry and environmental tracers from previous studies integrated with the geological modelling and findings from the interpretation of new and existing geophysical data has proved invaluable for confirming and refining knowledge of groundwater flow processes. The collation and reinterpretation of environmental tracer data with more stringent constraints, has helped to confirm and refine some previous characterisation of groundwater recharge and flow processes, and to refine groundwater recharge estimates for aquifers in key hydrogeological units. Groundwater recharge was estimated to be between 2–20 mm/year on the ranges and between 0.5 and 10 mm/year on the alluvial plains. Groundwater flow and age modelling were undertaken in order to test different plausible conceptual models of the groundwater regime within the palaeovalley to aid the understanding of the available groundwater resource. Groundwater ages in the upper part of the valley-fill sequences were ~900 years, but over 8500 years in the deeper parts of the palaeovalleys.

Hydrogeological conceptual understanding

The combined geophysics and groundwater hydrology work in G-FLOWS Stage-3 builds on the earlier work in the region by Munday (2013), Parsekian et al. (2014) and Gogoll (2016). This existing work was coupled with findings from the current study, to adapt and refine the conceptual understanding of palaeovalley drainage in the APY Lands.

Probabilistic modelling approach

A probabilistic modelling approach was developed as a framework for groundwater prospectivity mapping. The Groundwater Knowledge Integration System (GKIS) provides a stochastic framework for groundwater prospectivity mapping based on an explicit definition of sustainability requirements. It allows iterative updating of conceptualisation as new information becomes available. The level of confidence in the prospectivity estimate is expressed as a probability of success. The most attractive regions for groundwater production in the APY Lands are associated with palaeovalley systems. Outside the palaeovalley systems, prospectivity can also be high, provided drilling targets both the surficial and deeper aquifer.

Recommendations

G-FLOWS Stage-3 has clearly shown the benefits from the application of AEM surveys for providing understanding of the hydrogeology at a range of scales, both regional and finer. This includes spatial mapping of key hydrogeological units, as well as mapping the spatial extent and thickness of both alluvium/colluvium and palaeovalleys which are key targets for water resource exploration.

Localised drilling and ground-based geophysical investigations such as those conducted on the Lindsay East Palaeovalley have further characterised the hydrostratigraphy and nature of the groundwater present, the AEM survey provides increased confidence that these findings can be extrapolated to other areas of alluvium/colluvium and palaeovalleys, such as the Lindsay West Palaeovalley. The project has demonstrated the potential of different hydrogeophysical techniques to better understand the nature of the groundwater present in the Lindsay East Palaeovalley system.

The GKIS provides a systematic and transparent framework to integrate the available information into quantities relevant to water resource management. The prospectivity maps can easily be updated as new information becomes available and allows to extrapolate to data poor areas. It is recommended that the prospectivity maps continue to be updated as new information becomes available and the hydrogeological conceptualisation further evolves.

Acknowledgments

This study was carried out as part of the G-FLOWS Stage-3 Project. This project was funded jointly by the Goyder Institute for Water Research, and its partner organisations, including: Department for Environment and Water (DEW), Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Flinders University.

The South Australian Department of Energy and Mines (DEM) is also acknowledged for their support in the co-funding of the regional airborne electromagnetic (AEM) survey that formed the foundation for the work reported here and for supporting its acquisition through Geoscience Australia. We specifically acknowledge the work and support of Miles Davies, Steve Hill and Rian Dutch in helping make this happen. Mats Gulbrandsen from iGIS provided invaluable support in the application of the Smart Interpretation method employed on SkyTEM data in the eastern Musgrave Province. The AEM work would also not have been possible without the support of the Geological Survey of South Australia (GSSA) through the PACE Cu initiative.

We acknowledge the support of CSIRO's Deep Earth Imaging Future Science Platform in undertaking this research.

We acknowledge the traditional owners of the Aṉangu Pitjantjatjara Yankunytjatjara (APY) Lands, the Pitjantjatjara, Yankunytjatjara and Ngaanyatjarra people. We would also like to thank the APY General Manager and the entire APY Executive Board who were supportive of the G-FLOWS Stage-3 project.

We thank the Goyder Institute Research Advisory Committee (RAC) members: Kane Aldridge (Goyder Institute), Justin Brookes (The University of Adelaide), Jennie Fluin (DEW), Jim Cox (SARDI), Dirk Mallants (CSIRO), Neil Power (DEW), Darryl Day (ICE WaRM), Craig Simmons (Flinders University), Jacqueline Frizenschaf (SA Water), and Peter Teasdale (UniSA).

We are extremely grateful for the support of a wide range of people, organisations, companies, and departments who all provided assistance to help undertake and complete this project.

1 Introduction

Groundwater resources in remote arid areas of South Australia such as the Musgrave Province, are the only available water resources to support the livelihood of communities as well as economic development. However, the arid climate of the province combined with a geological setting dominated by crystalline basement at shallow depths presents a hydrogeological environment where both groundwater recharge and storage are low. For this reason, over the past two decades several important geological and hydrogeological studies varying from desktop analyses, drilling investigations, geophysical surveys and groundwater quality and resource assessments have taken place. These studies, while varying in nature, have all contributed to evaluating the opportunities and risks for future groundwater resource development in either isolated parts of the province or across extensive areas. However, given the remoteness, groundwater resources in large parts of the province remain poorly mapped and characterised, while demand for community water supplies is ongoing.

1.1 Purpose of the G-FLOWS Stage-3 project

The Department for Environment and Water’s Facilitating Long-term Outback Water Solutions (FLOWS) Initiative seeks to address an essential step on the critical path to delivering State Economic Priority 1: Unlocking the full potential of South Australia’s resources, energy and renewable assets.

Water is a critical resource in ensuring a healthy population and maintaining a vibrant agricultural sector but it is also an integral raw material for mineral exploration, mining and processing. The identification, characterisation and access to suitable water resources for exploration and processing is essential for the minerals and energy resources sector and sits at the heart of many of the relationships between the minerals industry and communities.

This G-FLOWS Stage-3 project has supported the South Australian Government’s FLOWS initiative to locate, define and quantify groundwater resources in key areas of the state including priority mineral prospective zones as identified in the South Australian Regional Mining and Infrastructure Plan 2014.

The G-FLOWS Stage-3 project has delivered new data and information regarding the location and extent of groundwater resources in the Musgrave Province. This will help to eliminate some significant risks faced when considering development proposals for the region, allowing for more informed decision-making and robust feasibility studies by potential developers and investors. In addition, it will reduce project assessment times, contributing substantially to economic outcomes in South Australia. This proposal was specifically designed to ensure the progress of economically viable mining developments are not impeded by a lack of information on suitable water supply sources in terms of quantity, quality and cost. The work program was driven by advances made though previous Goyder Institute research and integrates with the South Australian Government’s Plan for Accelerating Exploration (PACE) – Initiative. It also complements the ongoing research and collaborative efforts of the Geological Survey of South Australia (GSSA), particularly in the utilisation of regional geophysical surveys for exploration under deep cover, data integration and 3D and 4D geological modelling.

The airborne electromagnetic (AEM) geophysical interpretation techniques developed in the G-FLOWS Stage-1 project have already been applied by the Department for Environment and Water (DEW) to identify more secure groundwater supplies for a number of aboriginal communities in the Musgrave Province in the An̲angu Pitjantjatjara Yankunytjatjara (APY) Lands. The G-FLOWS Stage-3 project has provided additional information and interpretation that will be helpful in realising the potential for the provision of enhanced groundwater supplies to remote townships and communities outside of the resources sector.

This report provides a summary of the work undertaken with the G-FLOWS Stage-3 Project, including examples of key outputs (maps), and a list of the many publications where this work is published. Further detailed information can be found within the accompanying project reports.

1.2 Previous studies

Some of the earliest work was conducted by Fitzgerald et al. (2000) and focussed primarily on the quality of groundwater in aquifers where concerns about faecal contamination and poor-quality groundwater being supplied to Indigenous communities had been raised. Subsequent work by Dodds et al. (2001) focussed more on quantifying groundwater supplies to better evaluate the future suitability and sustainability of existing community groundwater supplies at nine communities. The findings by Dodds et al. (2001) highlighted the immediate need for establishing a regional water management plan across the province. The water plan was first initiated a year later in 2002 (APYWMP 2002) which also included the establishment of the Anangu Pitjantjatjara Yankunytjatjara Water Management Council (APYWMC).

Following work by Dodds et al. (2001), Australian Groundwater Technologies (AGT) was commissioned by the state water utility (SA Water) to undertake two groundwater supply sustainability assessments at key Indigenous communities initially in 2003 (AGT 2003) and then a broader assessment in 2008 (AGT 2008). Both assessments were desktop analyses combining groundwater level monitoring, metered groundwater use and climate data to assess the sustainability of individual community production bores. The key findings from AGT (2008) were that some of the community groundwater production bores that supported key northern communities (Amata and Pukatja) were under stress and alternative groundwater supplies needed to be sourced for use in the future.

The sustainability assessments by AGT led to further extensive desktop studies across the entire Musgrave Province, as well as geophysical surveys, drilling and multiple groundwater resource assessments at the regional scale to improve the understanding of groundwater resources across the entire province. The government of South Australia established its 'Water for Good' plan in 2009, which included the monitoring and management of non-prescribed groundwater resources to ensure their future sustainable use. Under this plan, Watt and Berens (2011) produced the most comprehensive (at that time) desktop evaluation of groundwater resources in the Musgrave Province. They concluded that the key knowledge gaps included estimates of groundwater storage, evaluations of potential groundwater yield rates, estimates of volumes of groundwater for abstraction and an understanding of the nature and volumes of groundwater recharge.

The evaluation by Watt and Berens (2011) led to the initiation of some key field studies by Leaney et al. (2013), Ley-Cooper and Munday (2013), Munday et al. (2013) and Kretschmer and Wohling (2014) that aimed to improve the understanding of important groundwater processes. The studies by Ley-Cooper and Munday (2013) and Munday et al. (2013) provided much improved hydrogeological mapping across the province by collating and reinterpreting existing airborne geophysics and using this to develop an improved hydrogeological map of the province. The studies by Leaney et al. (2013) and Kretschmer and Wohling (2014) involved targeted groundwater sampling for environmental tracers and chemistry which identified the presence of a regional-scale groundwater flow system, as well as mapping and quantifying groundwater recharge and flow. In addition, two honours studies were undertaken into the sustainability (Craven 2012), and the hydrogeochemistry (Custance 2012) of regolith-hosted aquifers in the region.

Since these regional scale studies, the search for alternative and sustainable community water supplies has continued with the new regional-scale hydrogeological mapping by Munday et al. (2013) underpinning further targeted local-scale work. Parsekian et al. (2014) successfully validated the improved hydrogeological mapping by Munday et al. (2013) to identify and better map a local-scale aquifer for one of the indigenous communities using near-surface geophysics. In 2015, Howles et al. (2017) successfully used the airborne geophysics from additional interpretations of the regional aeromagnetic data undertaken by Munday to undertake targeted drilling of the fractured and weathered bedrock aquifers, which resulted in 18 new production wells being drilled and installed at seven Indigenous communities. The most recent work which from a hydrogeology perspective will be summarised in this report has involved the acquisition of a new large-scale airborne electromagnetic (AEM) survey (Soerensen et al. 2018), as well as some targeted drilling in part of a key palaeovalley (Costar et al. 2019). The AEM survey summarised in Soerensen et al. (2018) now fills the large gaps between existing AEM surveys which when combined cover almost the entire Musgrave Province. In 2018, drilling of the eastern side of the Lindsay East Palaeovalley (Costar et al. 2019) was undertaken to characterise the depth, nature and hydrological connectivity of aquifers within palaeovalley fill.

1.3 Study area

The South Australian Musgrave Province forms part of a crystalline basement terrain that extends across the common borders of South Australian, Western Australian and Northern Territory. The topography and drainage of the Musgrave region is shown in Figure 1-1. The northern part of the region is occupied by the rugged hilly terrain of the Mann and the Musgrave ranges with Mt Woodroffe reaching an elevation of 1435 m AHD (Australian Height Datum). The Birksgate and the Everard ranges occur to the south. The topographical elevations decrease to around 350–400 m AHD towards the south and the southeast of the area where wide calcrete plains occur covered by aeolian deposits. The Great Victoria Desert to the south of the northern ranges is covered by sand plains and dune fields (Watt and Berens 2011).

Climate for the study area is semi-arid to arid with a hot, dry desert climate, short cool to cold winters and low, unreliable rainfall (Watt and Berens 2011). The mean temperature ranges from 32°C to 36°C in the summer and drops to a mean of around 20°C in winter. Rainfall patterns are spatially variable, with average annual rainfall ranges from around 150–225 mm, although rainfall is unpredictable, and averages can be misleading. Rainfall occurrence and intensity is episodic. Average annual evaporation exceeds 3500 mm, resulting in the rapid evaporation of surface water runoff. Perennial surface water and connected drainage systems are absent.

The geology of the Musgrave Province is complex, and for the area of interest to the G-FLOWS study it has been summarised by Pawley and Krapf (2016). The Province comprises a region of crystalline basement consisting mainly of the amphibolite and granulite facies gneisses intruded by mafic – ultramafic dykes and granitoids, and swarms of dolerite dykes.

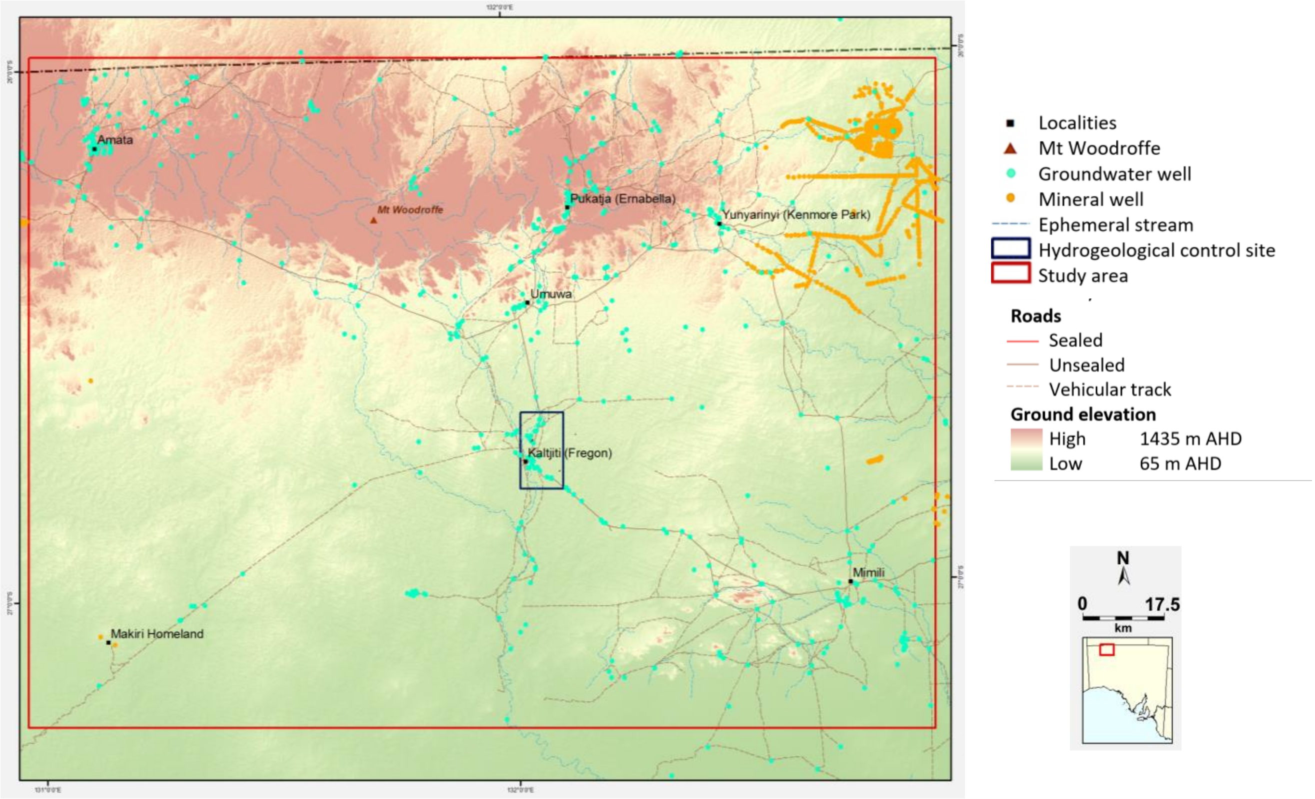


Figure 1-1. Regional study area located in the Anangu Pitjantjatjara Yankunytjatjara Lands. Blue rectangle depicts location of hydrogeological control site where drilling and sampling was conducted for the project.

2 Key project output

2.1 Preliminary field investigations

2.1.1 WELL SURVEY AND DATABASE

A groundwater well survey (bore audit) was conducted between 10 and 20 October 2017 to identify and confirm groundwater infrastructure (i.e. water wells) and the condition of such infrastructure to aid in establishing monitoring and field investigation requirements such as drilling and groundwater sampling.

The state's groundwater database identified 573 water wells (739 drill holes) as of 1 May 2017 spread across the G-FLOWS Stage-3 study area. Work on the database included a review of all geological and drillers logs as well as a review of well completion intervals. During the field survey it was not practical to visit every well and access requirements were required to be specific.

The bore audit was undertaken by navigating to the identified well location using a hand-held GPS, where the following well attributes were surveyed for 39 wells (Figure 2-1):

- Spatial coordinates (accuracy verification) using a differential global positioning system (DGPS);
- Ground elevation using differential global positioning system (DGPS);
- Well casing condition (material, diameter, headworks, surface seal);
- Cap identification;
- Standpipe condition and cementing;
- Reference point type and elevation (above ground level);
- Depth to water;
- Total well depth;
- Current status and purpose of use;
- Presence of logging devices;
- Access constraints; and
- Suitability for monitoring and sampling

Multiple digital photographs describing the location and condition of the well were also obtained.

Due to resourcing, budget and time constraints, sampling was not undertaken at this time as a routine component of this audit, however, a pump was used opportunistically for sampling basic salinity if a measurement was not recorded at all in the database.

The bore audit provided valuable information for planning of future field activities and input into numerical groundwater modelling tasks as part of the G-FLOWS Stage-3 project, including:

- Verification of well location and status for planning and design of drilling and sampling programs;
- Water level data for developing potentiometric surfaces, to aid initial groundwater modelling and the design of well drilling programs (i.e. design length and position of screen); and
- Identification of access issues/feasibility for future ground-based activities such as geophysical surveys and drilling operation.

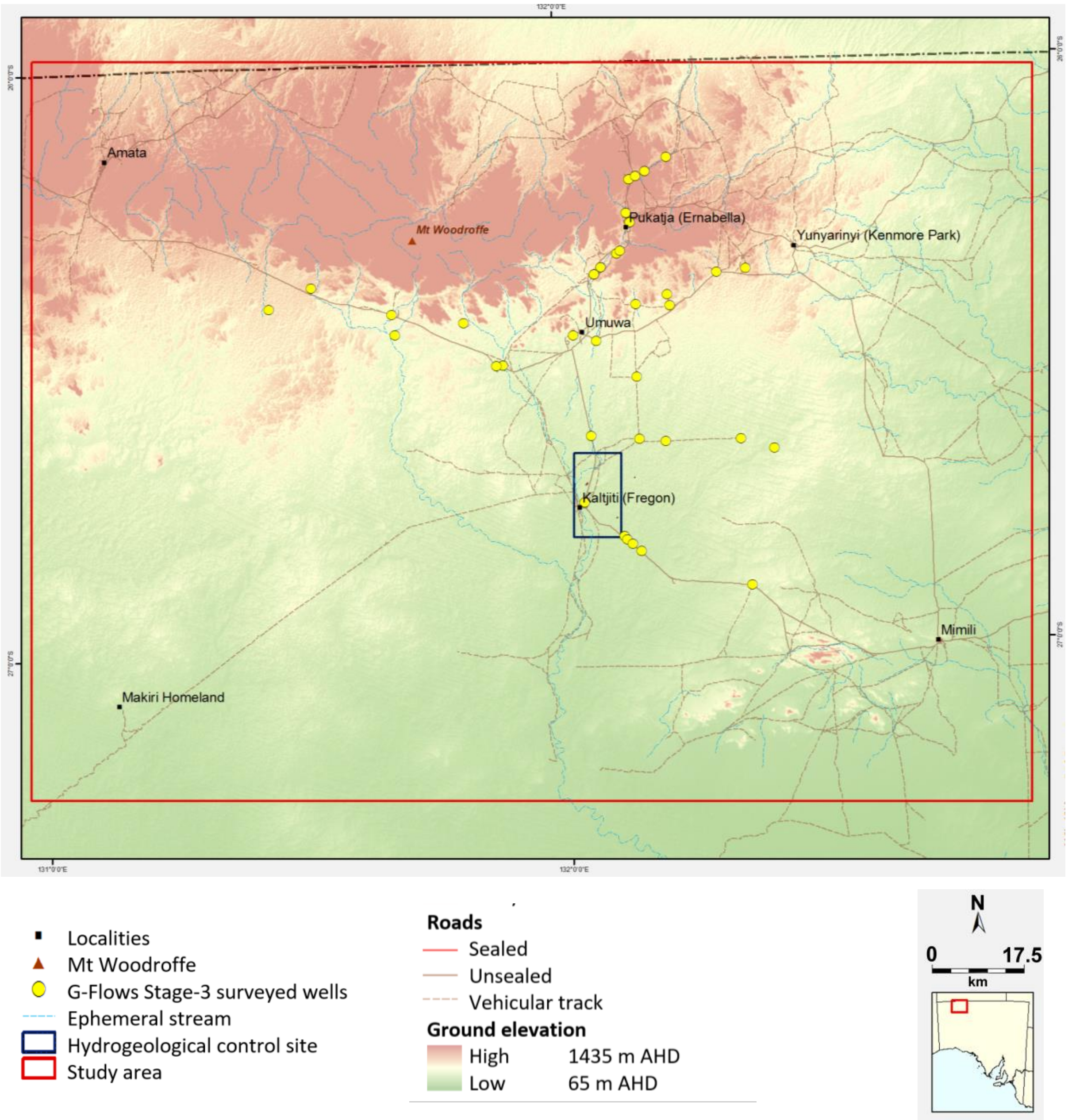


Figure 2-1. Well survey (bore audit) conducted in the initial stage of the G-FLOWS Stage-3 project.

2.2 Improved groundwater resource characterisation using airborne electromagnetic methods

The project provided interpreted AEM coverage across the APY Lands, revealing depth of cover and the location of deep palaeovalleys. The cover of the Musgrave Province, being more conductive than the underlying basement rocks provides a good basis for using AEM data as a means for mapping its extent and thickness. Fast, automated and objective methods that employ machine learning approaches have application for defining the basement morphology, and the regolith thickness. We have used the Smart Interpretation (SI) method that is a machine learning approach described by Gulbrandsen et al. (2017). The results provide an indication of trends in cover variability.

The conductivity structure of the Musgrave Province has been defined through the processing and inversion of two regional AEM data sets that were acquired by the South Australian Government through the Goyder Institute and the Geological Survey of South Australia as part of the G-FLOWS Stage-3 project and the PACE Cu initiative. Two time-domain AEM systems were employed in the regional surveys – the fixed wing TEMPEST High Moment and rotary wing SkyTEM^{312FAST}. Preliminary inversion results indicated that both systems effectively define the cover, which is relatively conductive, and map the location and geometry of buried palaeovalley systems in this area.

Conductivity-depth intervals or interval conductivities were generated from the inversion results of both the regional TEMPEST and the SkyTEM surveys, in 10 m intervals from surface to 200 m depth. Displaying inversion results as conductivity-depth images is a common way to visualise the spatial distribution of the conductivity within a survey area. In areas with large topographical variations it can be beneficial to display conductivities not only with depth but also as elevation intervals, accounting for variations caused by the topography. Example interval conductivities for the two regional surveys are shown overlaid on a first vertical derivative (1VD) of airborne magnetic data map (Figure 2-2). The intervals were gridded using kriging with a cell size of 400 m.

A more detailed map (overlain on hydrogeological framework for part of the Lindsay East Palaeovalley) provides more detailed information about the geometry at this site (Figure 2-3). The DH1 drilling site is located on this main palaeovalley along the road ~5 km Kaltjiti/Fregon.

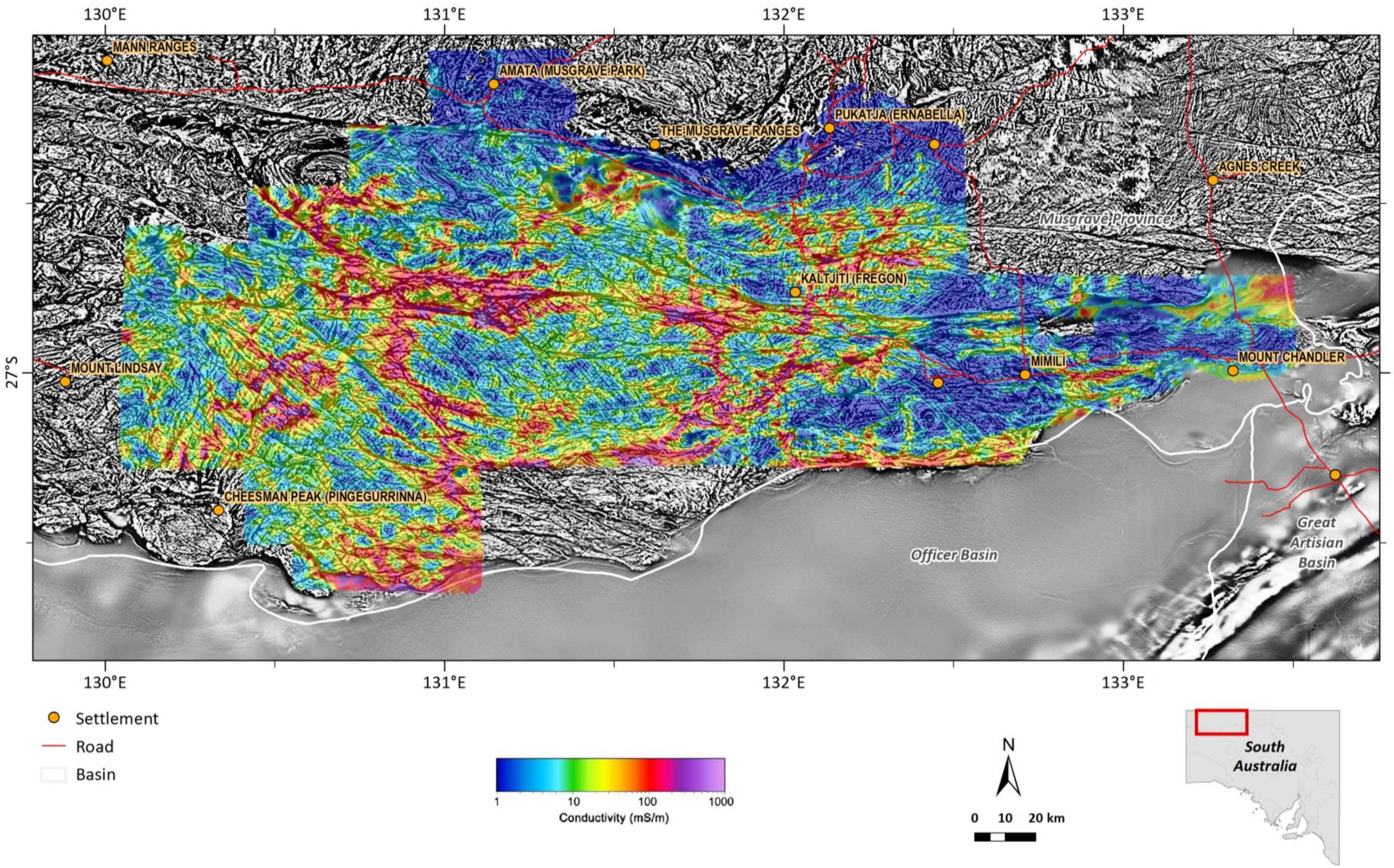


Figure 2-2. 50–60 m interval conductivity image for the combined SkyTEM^{312FAST} and TEMPEST high moment airborne electromagnetic surveys overlain on 1st vertical derivative magnetic greyscale image. The more conductive areas (reds) shown in the combined images are commonly associated with a conductive transported fill sitting within deep palaeovalleys that have incised along and across a predominantly east-west orientated set of fractures and faults (as indicated in the magnetics).

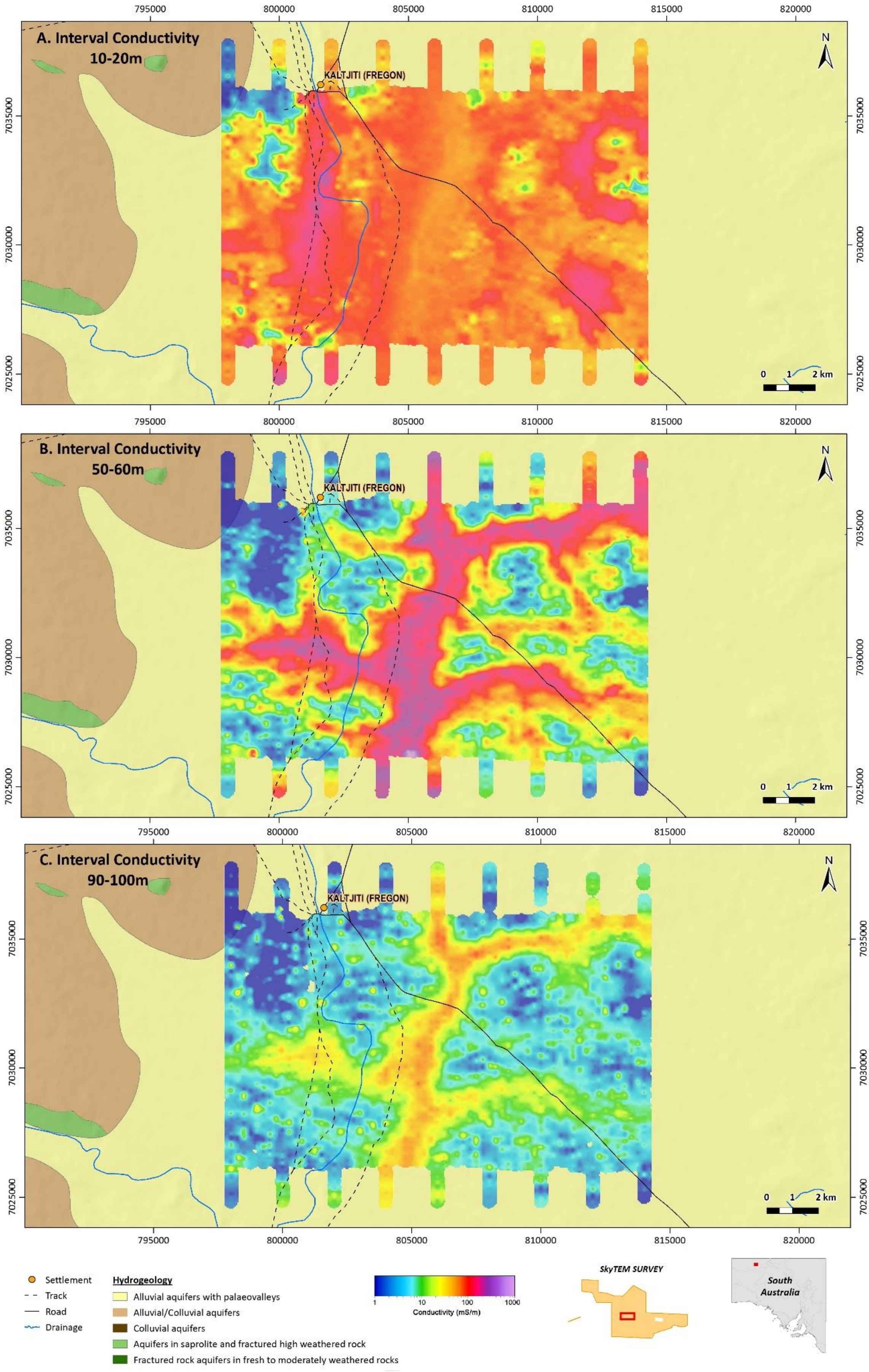


Figure 2-3. SkyTEM spatially constrained inversion interval conductivities for the infill area south of Kaltjiti/Fregon. Intervals are overlain on hydrogeological framework map.

Definition of the spatial complexity (at a regional scale) of the cover will enhance our understanding of the region's groundwater resource potential; important for communities, industry and the environment. The initial results also indicate a potential to map variations within the palaeovalley systems themselves, something that will be useful for assisting in locating compartmentalised aquifers, particularly in areas with limited drilling. Gaining an understanding of the cover thickness and spatial variability will also help reduce exploration risks in the area.

Project publications

Macnae J, Xiuyan R and Munday T (2020a) Stripping induced polarization effects from airborne electromagnetics to improve 3D conductivity inversion of a narrow palaeovalley. *Geophysics* 85(5): B133–B139.

Macnae J, Munday T and Soerensen C (2020b) Estimation and geologic interpretation of regolith chargeability and superparamagnetic susceptibility in airborne electromagnetic data. *Geophysics* 85(5): E153–E162.

Soerensen CC, Munday TJ, Ibrahimi T, Cahill K and Gilfedder M (2018a) *Musgrave Province, South Australia: Processing and inversion of airborne electromagnetic (AEM) data*. Technical Report Series No. 18/06, Goyder Institute for Water Research, Adelaide.

Soerensen C, Munday T, Krapf C, Love A, Costar A, Inverarity K, Gogoll M and Gilfedder M (2018b) Uncovering the Musgrave Province in South Australia using airborne EM: ASEG Extended Abstracts 2018, 1-5.

Soerensen C, Munday T, Raiber M, Gilfedder M, Krapf C, Costar A, Keppel M, Gogoll M, Love A, Gulbrandsen ML and Pallesen TM (2018c) Uncovering an ancient landscape and helping the exploration for groundwater and minerals – The Musgrave province, South Australia. Abstract presented at AGCC Conference, Adelaide Oct 2018.

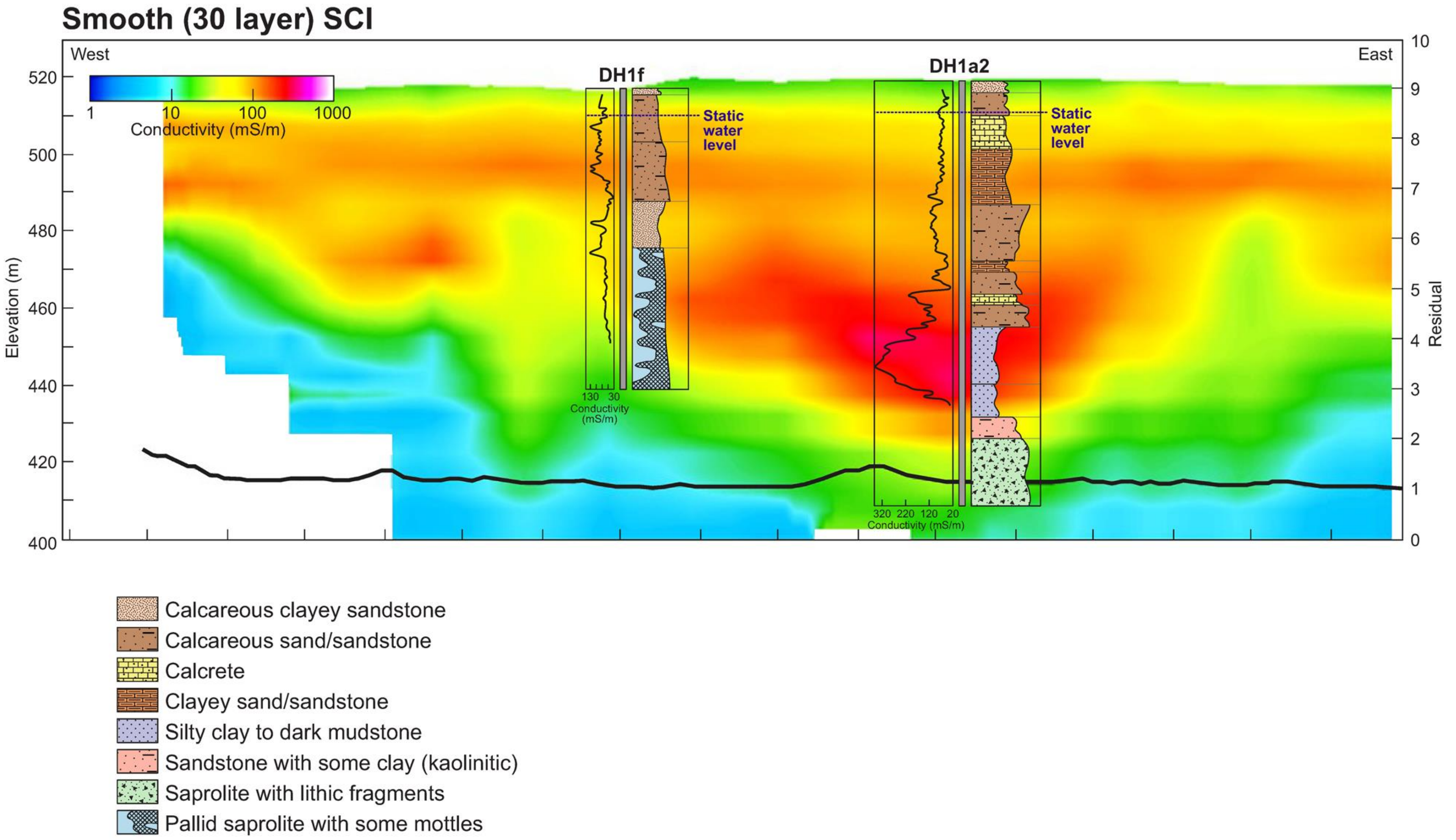
Sorensen C and Munday T (2018) The Musgrave Province – the untold story about Airborne IP. AEM 2018 / 7th International Workshop on Airborne Electromagnetics, June 17-20 2018 , Kolding Denmark, pp4.

2.3 Airborne electromagnetic inversion techniques for groundwater hydrology

The AEM inverted products were examined against available drill hole lithology data and borehole inductive conductivity data to assess their validity. The assessment of the inversion approach taken in this study involved the comparison between the smooth model one-dimensional (1D) constrained layered earth inversion and drilling data in several locations, including the Lindsay East Palaeovalley. Although a smooth regularisation was employed for the regional data sets, two other inversion methods were also examined. These included a few layered, and a multilayered, sharp regularisation.

The inversion was undertaken using AarhusInv (Auken et al. 2015). Commonly used inversion options include an Occam-style regularisation using smoothly varying 1D models with fixed vertical discretisation. These produce smooth models where layer boundaries are sometimes hard to recognise. Discrete or few layer models with a fixed number of layers, where the layer boundaries are allowed to change in the inversion, are also employed where the conductivity structure might be relatively simple and laterally extensive. The smooth layered models have shortcomings in terms of defining layer boundaries. With the few-layer model on the other hand it can be difficult to pick a number of layers that will be valid throughout a whole survey, and as a consequence artefacts can be introduced in areas of unexpectedly complex geology. The sharp inversion methodology outlined in Vignoli et al. (2017) is a focussed regularisation technique which allows for an accurate reconstruction of resistivity distributions while maintaining the capability to reproduce horizontal boundaries. The methodology promotes solutions that are compatible with the observed data and at the same time features a minimum number of spatial (vertical and lateral) model variations. In essence, the choice of an inversion approach should be determined by the target or targets we are trying to resolve. A useful strategy could be to start with a smooth model and then explore alternative approaches if additional detail is required.

The observed conductivity structure in the smooth model constrained inversion (Figure 2-4) and its correspondence with the conductivity structure in logs for both bores DH1a2 and DH1f, provides confidence that this inversion model adequately represents that required for this study and provides relevant insight into the groundwater quality and aquifer systems present in the study area. Interpretation of the smooth model inverted section, incorporating available drill hole lithology logs yields a section shown in Figure 2-5.



Smooth (30 layer) SCI

Figure 2-4. Conductivity-depth sections for the Lindsay East Palaeovalley transect for a smooth 30-layer inversion. Drill hole lithology (adapted from Keppel et al. (2019)) and inductive conductivity logs are overlain on the airborne electromagnetic (AEM) sections.

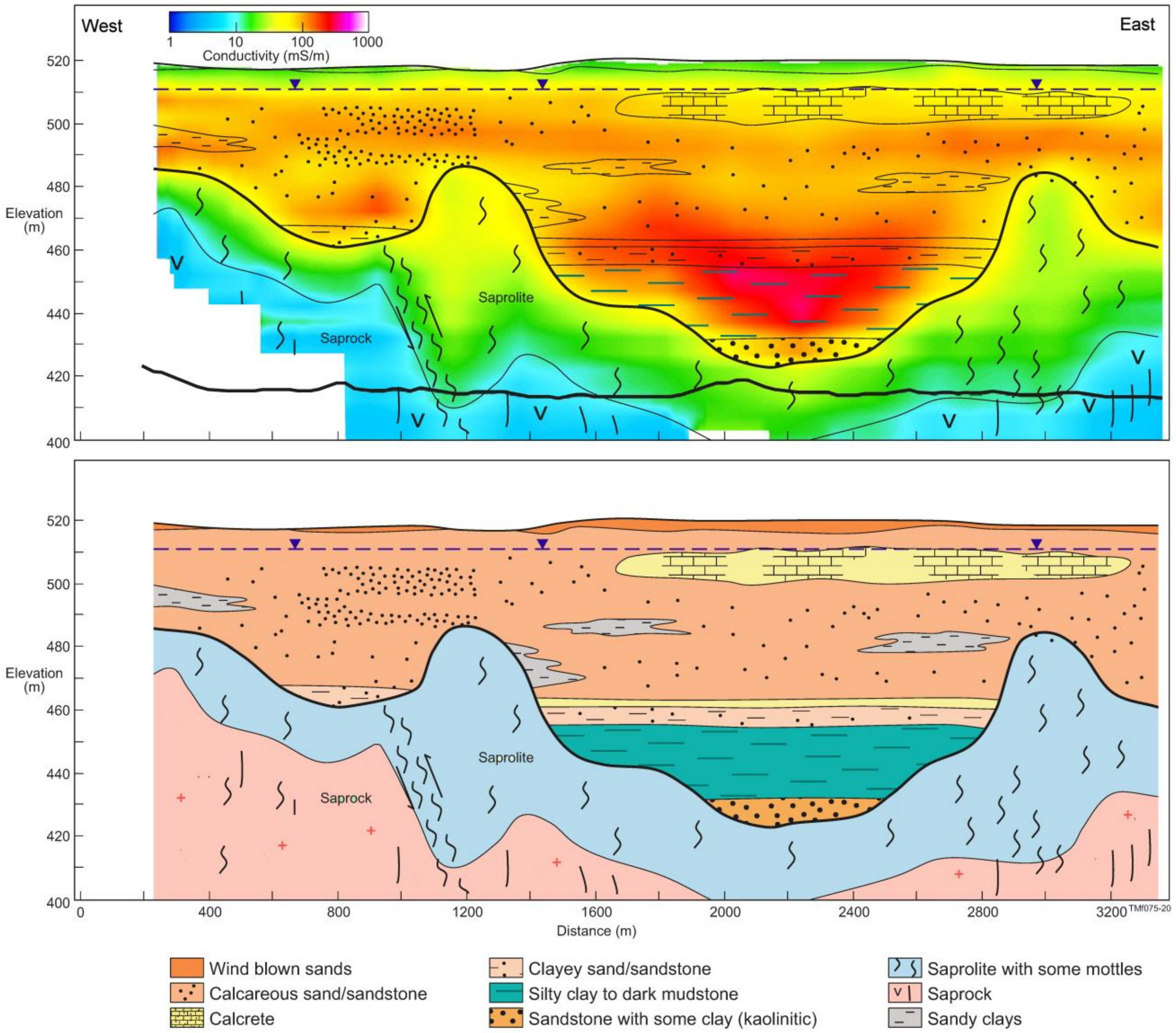


Figure 2-5. Interpreted geological section (lower panel) for the Lindsay East Palaeovalley transect. Top panel is the smooth model conductivity depth section with interpreted geology overlain.

Project publications

Munday T, Taylor A, Raiber M, Soerensen C, Peeters L, Krapf C, Cui T, Cahill K, Flinchum B, Smolanko N, Martinez J, Ibrahimi T and Gilfedder M (2020) Integrated regional hydrogeophysical conceptualisation of the Musgrave Province, South Australia. Technical Report Series No. 20/04, Goyder Institute for Water Research, Adelaide.

2.4 Three-dimensional geological model of the Musgrave Province

The 3D geological model of the Musgrave Province has been developed using AEM conductivity-depth slices from the inversion models presented in previous sections and shuttle radar topographic mission (SRTM) digital elevation data using SKUA-GOCAD® 3D geological modelling software (Figure 2-6). The conductivity-depth slices of the 10 m intervals were imported into the 3D geological modelling software framework, to assess the spatial patterns of subsurface conductivity at varying depth intervals below the ground surface. The regional AEM data allowed definition of the extent of the palaeovalley systems (Figure 2-7, Figure 2-8) and their spatial relationships to the geological basement (i.e. characterising the interface between the palaeovalley depositional system (representing alluvial aquifer systems) and the basement which is comprised of fractured rocks). In the current version of the 3D geological model developed for the Musgrave Province, two categories were differentiated - palaeovalley sediments versus undifferentiated basement (Figure 2-9).

From this, the interface between palaeovalleys and underlying bedrock was picked and a surface representing the base of the palaeovalley system was generated. This surface was then used to build a volumetric 3D geological model using SKUA's Structure & Stratigraphy (S&S) workflow. The resulting 3D geological model was compared with additional geological datasets such as geological structures to identify relationships between palaeovalley evolution and faults.

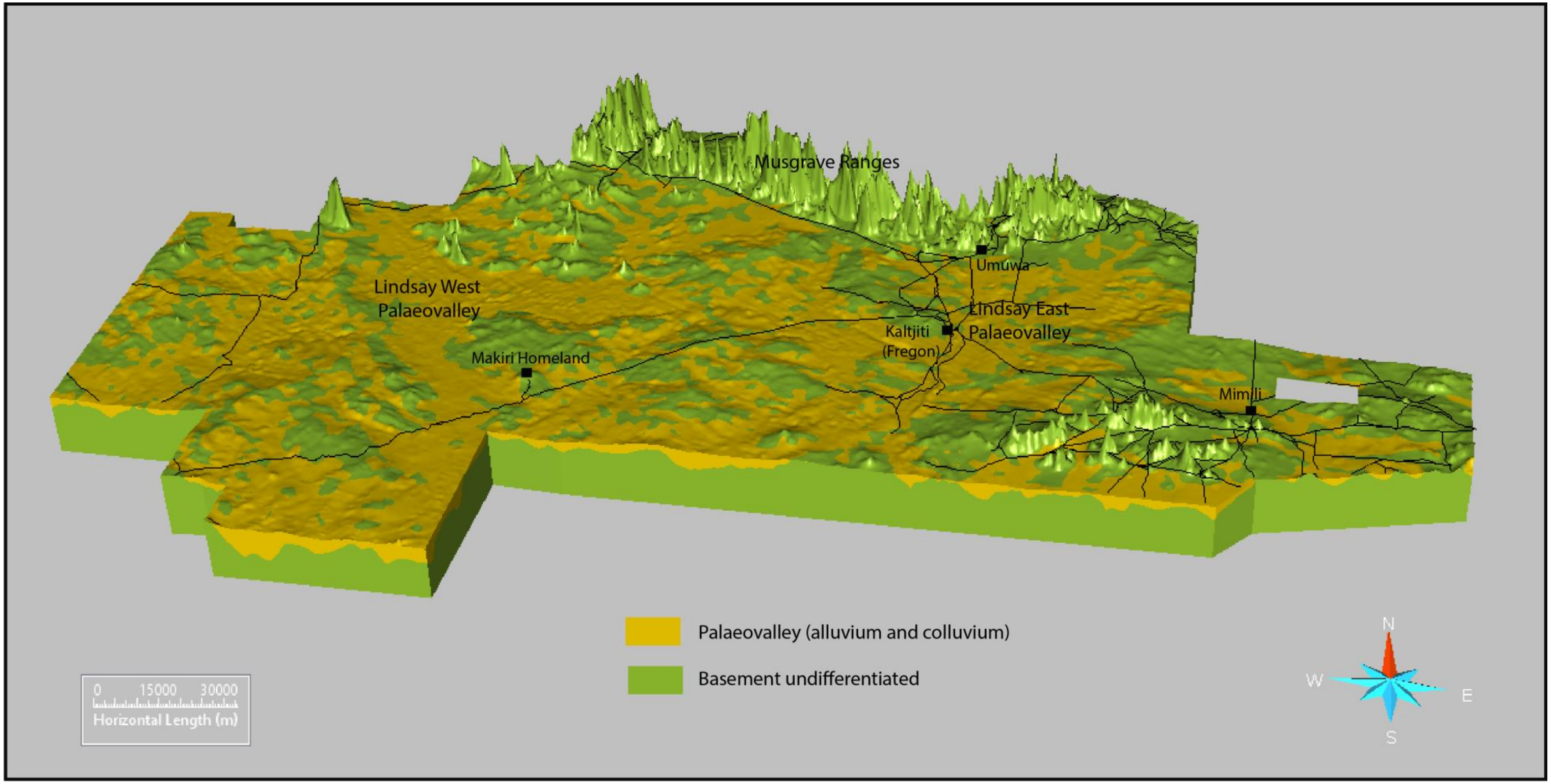
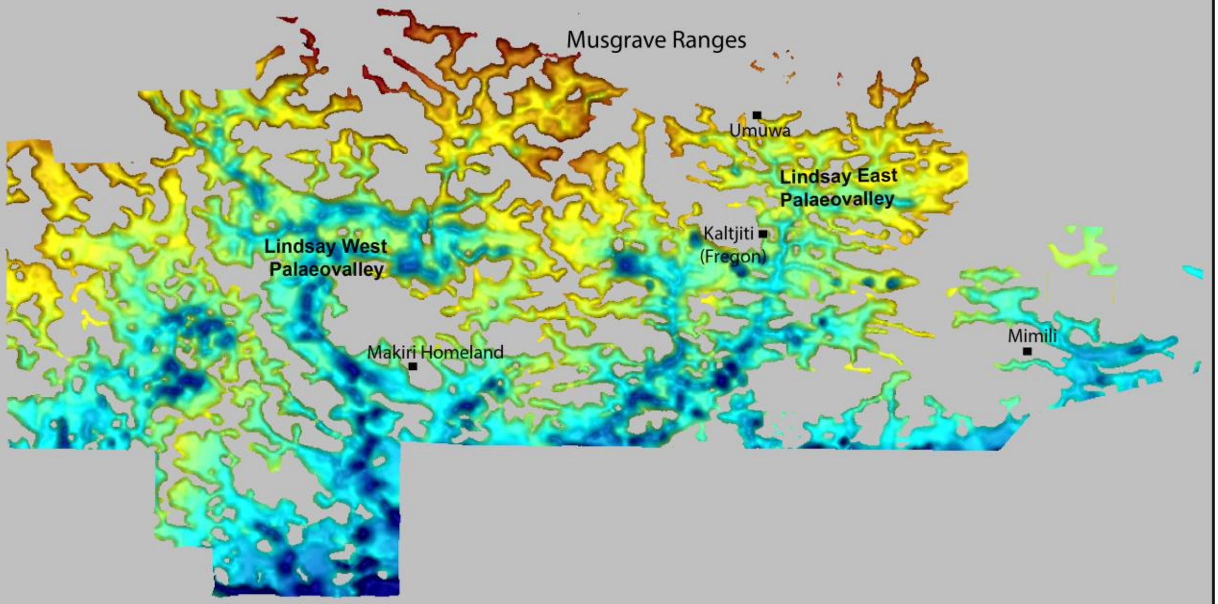
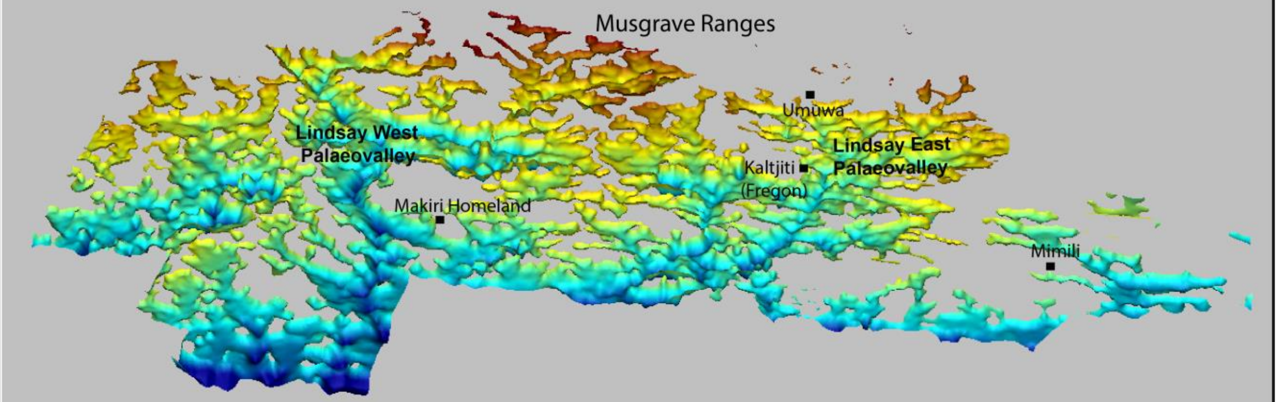


Figure 2-6. Three-dimensional geological model of the Lindsay West and Lindsay East palaeovalley systems with regional road network and communities.

a) 2D representation of extent and geometry of base of palaeovalley



b) 3D representation of extent and geometry of base of palaeovalley



c) 3D representation of extent and geometry of base of palaeovalley and basement outcrops (red colour)

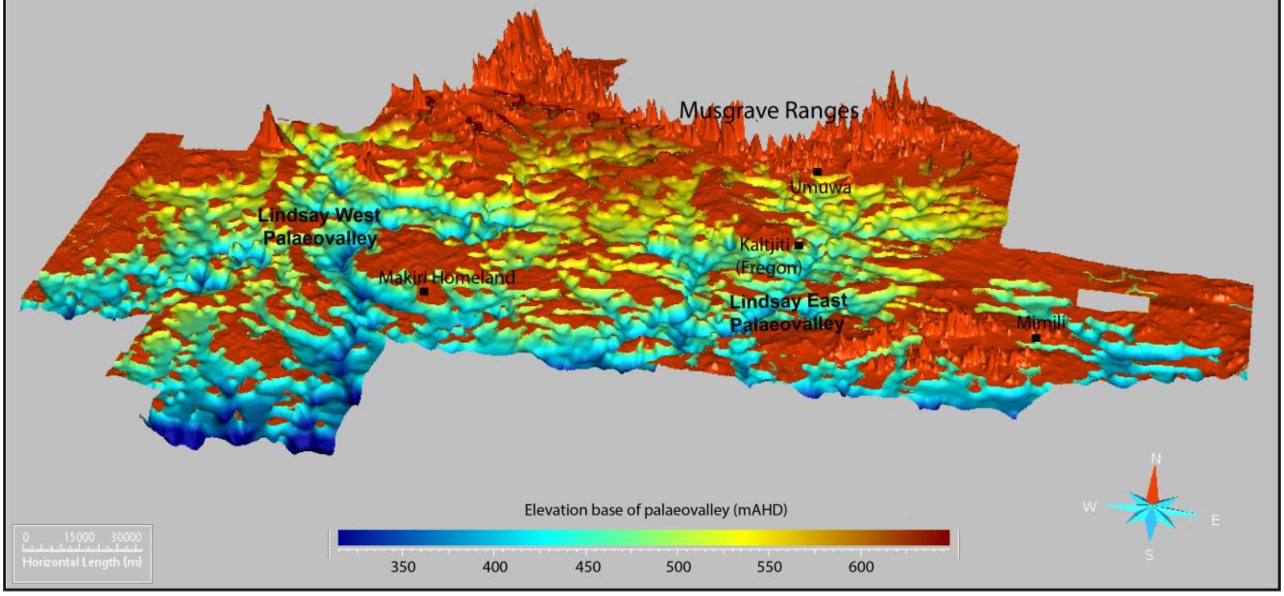


Figure 2-7. Three-dimensional (3D) representation of extent and geometry of base of palaeovalley in a) two-dimensional view b) 3D view and c) 3D view with outcropping basement.

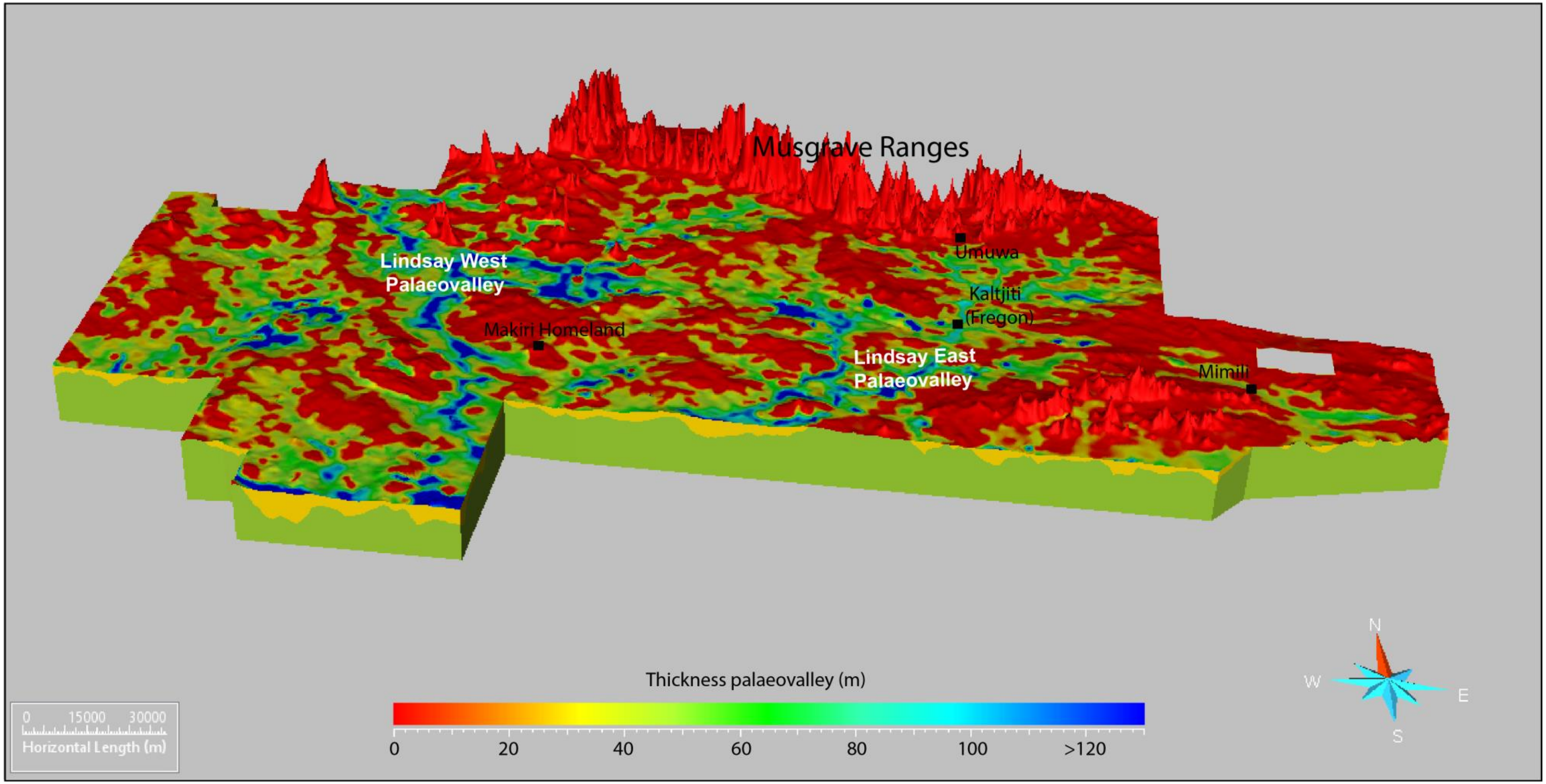


Figure 2-8 Thickness of palaeovalley systems.

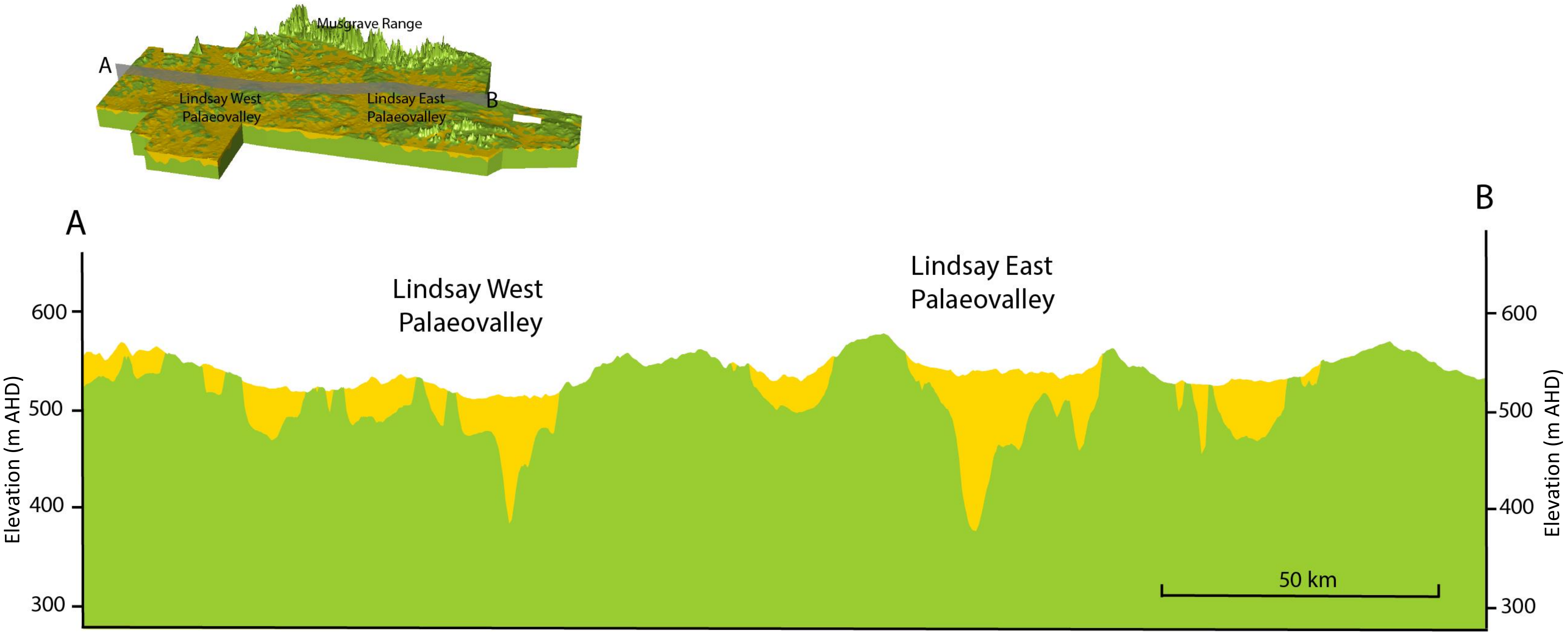


Figure 2-9. West-east geological cross-section through the Lindsay West and Lindsay East palaeovalley systems. The orientation of the cross-section is shown in the three-dimensional geological model above the section.

For the existing version of the 3D geological model, colluvial sediments at the foothills of the Musgrave Range, sandplain (aeolian) sediments and palaeovalley (alluvial) sediments were not differentiated. This was because there is insufficient spatial coverage of drill-hole data throughout the area to distinguish these units at the regional scale, with most existing bores located within the eastern part of the model domain north of Kaltjiti and only few bores drilled in the western part. However, based on the observation from the AEM data and if we assume that the thickness of the surficial sandplain deposits overlying the palaeovalley sediments is similar throughout the APY Lands, it is possible to use the information from DH1a and from the regional AEM to derive an additional model realisation where the upper approximately 30 m are considered as sandplain deposits.

Project publications

Munday T, Taylor A, Raiber M, Soerensen C, Peeters L, Krapf C, Cui T, Cahill K, Flinchum B, Smolanko N, Martinez J, Ibrahimi T and Gilfedder M (2020) Integrated regional hydrogeophysical conceptualisation of the Musgrave Province, South Australia. Technical Report Series No. 20/04, Goyder Institute for Water Research, Adelaide.

2.5 Ground-based geophysics

There were several extended fieldwork expeditions relating to this task over the life of the project. These included one focused on seismic testing along the main palaeovalley transect at DH1 (to the east of Kaltjiti/Fregon). Subsequent fieldwork undertook borehole nuclear magnetic resonance (NMR) measurements in seven of the newly installed wells, as well as ground-based time-domain electromagnetic (TEM) surveys.

2.5.1 LINDSAY EAST PALAEOVALLEY - SEISMIC SURVEY AT DH-1

Seismic reflection and refraction surveys were undertaken in the APY Lands in August 2018. A primary goal of the survey was to provide a detailed image of the main stem of a palaeovalley system that has been identified by AEM surveys (the DH1 site on the Lindsay East Palaeovalley, on the road ~5 km east of the community of Kaltjiti/Fregon). Over the course of five days the four-person team was able to collect a 1974 m of profile running perpendicular to the main trunk of the palaeovalley. An objective of the study was to obtain another independent measurement of the location of bedrock to help validate the AEM interpretation and elucidate details about the fill within the palaeovalley. The seismic data set is supported by several boreholes that had been drilled along the seismic profile earlier in the month. The seismic refraction results show significant variation in the near surface (top 10 m) velocity structure and a deep (~100 m) refractor that is believed to be the top of unweathered bedrock. The seismic reflection results show significant variability, both lateral and vertical, in the top of bedrock reflector and reveal prominent and clear reflections down to depths greater than 400 m.

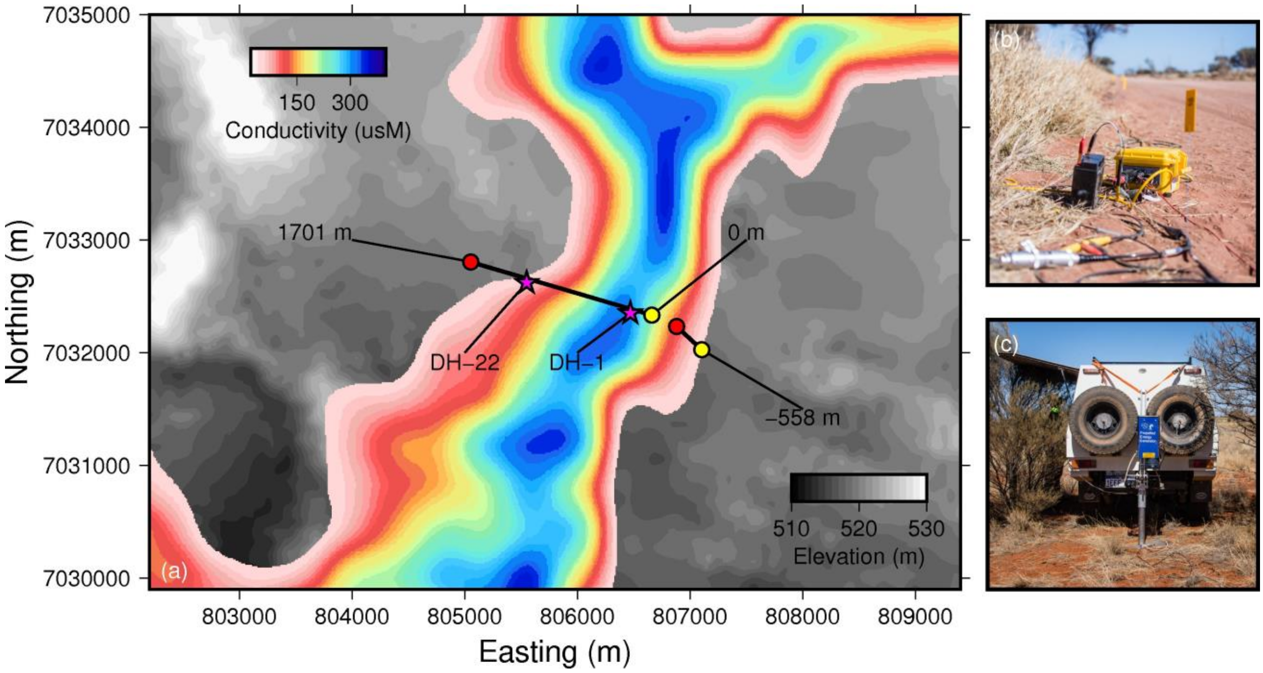


Figure 2-10. Location of the seismic surveys. (a) Underlying 10 m elevation data from Shuttle Radar Topography Mission. Overlaid on top of the elevation map is a conductivity depth section from 60–70 m below the surface. Electrical conductivity values greater than 55 µs/m are marked out to highlight the palaeovalley location. The airborne data were inverted using 400x400 m pixels, but a minimum curvature interpolation was applied for visualisation. The seismic profile running perpendicular to the channel was collected from southeast to northwest because we were required to shoot along the road. The yellow circles represent starts of profiles where the reference location is near the centre of the palaeovalley and is marked accordingly. (b) Image of a geometrics Geode and cable along the side of the road. (c) Image of the vehicle-mounted PEG and steel plate used as the source. Here it is shown mounted onto the CSIRO vehicle and the 40 kg weight drop is fully extended.

Using the map of the palaeovalley obtained from the AEM survey we can compare it to the seismic reflection and refraction results (Figure 2-11). There are some very notable differences. The airborne EM defined valley has been defined from a widely spaced survey (250 m line spacing) which indicates the valley to be both broad and rolling. The base of the conductive response in the AEM matches the transition from transported sediments to saprolite as defined by drilling (Figure 2-12). There are a few locations, particularly in the centre of the valley where the seismic defined boundary and the airborne boundary match quite well (Figure 2-11). In contrast near the valley's edges, on both sides of the reflection survey, the match between the airborne and seismic deviates. This vertical deviation can be over 70 m in places. This difference appears real and is attributed to a change in the physical properties of the materials present which is picked up by one measurement technique but not the other. Therefore the deviation is likely not the result of ambiguities associated with the airborne inversion. It is unlikely that airborne data could be matched with an alternative boundary location that is 70 m below the current predicted locations of the base of the palaeovalley system.

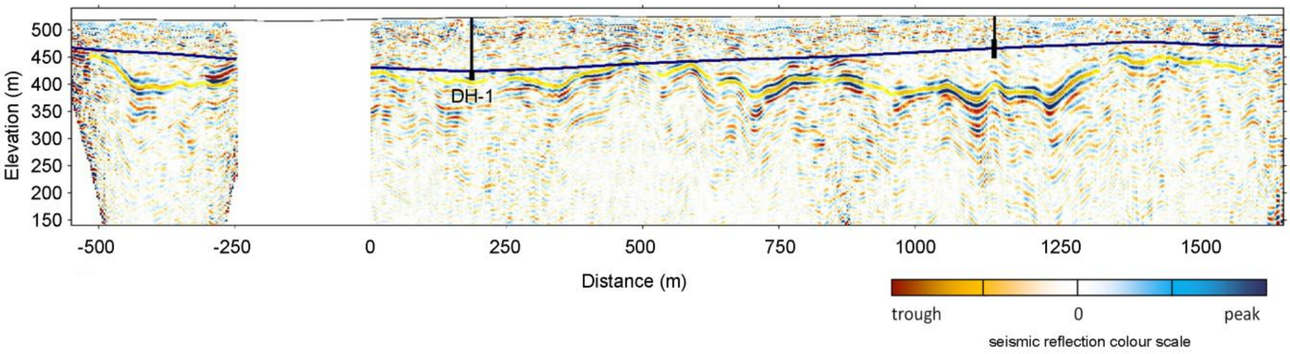


Figure 2-11. Results from the seismic reflection survey. Data were processed following a basic flow: 1) band-pass filtered, 2) trace normalised, 3) common midpoint (CMP) sorted, 4) muted surface waves, 5) normal moveout applied (one velocity per gather), 6) stacked, and 7) a time to depth conversion was applied using a single velocity. The main reflector (clearly visible in the raw CMP gathers) is highlighted in yellow. The boreholes are shown as black vertical lines. Where the black line gets thicker is where drillers intersected saprolite (*in situ* rock). The blue line is the extracted depth to bedrock value (from airborne electromagnetics) —note the large difference between 1000 and 1250 and -500 and -250 m along the profile.

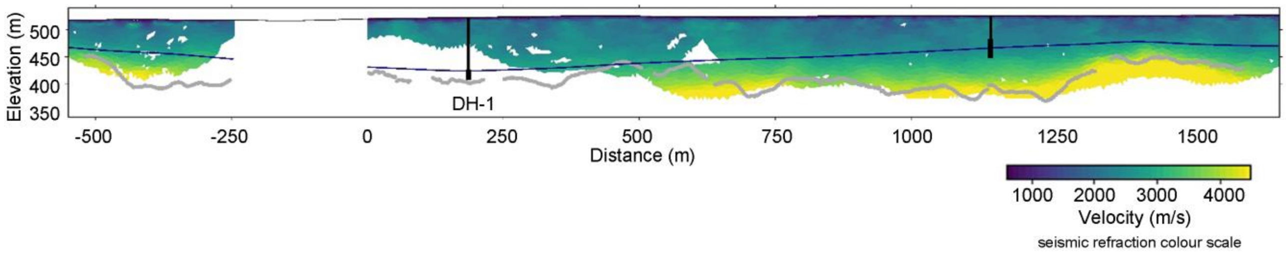


Figure 2-12. Results for the seismic refraction survey. The velocity model was inverted using travel-time tomography and is comprised of ~20,000 picks. Regions that are white have no ray paths passing through them. The main reflection results (from Figure 2-11) are plotted on the image as a grey line, the blue line is from the airborne electromagnetic data, and the boreholes are shown as in Figure 2-10 (Panel a). The match between the strong reflector and strong velocity change means that the depth conversion is done well.

It appears from the stratigraphic bore data that the AEM data does an excellent job at defining the bottom of transported regolith and the seismic data will define the top of unweathered bedrock. From a hydrologic standpoint, most of the water is in the transported cover so AEM is an excellent tool to site new water wells. Most of the water found at DH-1 came from just above the large conductor that was identified as a clay layer in the AEM. On the other hand, if the aim is to precisely locate the top of bedrock itself (not saprolite), then the seismic refraction method is likely to be better.

Project publications

Davis A, Flinchum B, Munday T, Cahill K, Peeters L, Martinez J, Blaikie T, Gilfedder M and Ibrahimi T (2020) Characterisation of a palaeovalley system in Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia using ground-based hydrogeophysical methods. Technical Report Series No. 20/05, Goyder Institute for Water Research, Adelaide.

2.5.2 BOREHOLE NMR

Borehole Nuclear Magnetic Resonance (NMR) methods have seen extensive use in the oil and gas industry with the first NMR logging tools developed for oil exploration in the 1960s (Brown and Gamson 1960). The relatively recent development of small-diameter, and highly portable NMR tools (see Walsh et al. (2013) and Trofimczyk et al. (2018)) now permits the non-invasive use of this technology within existing PVC/fibreglass-cased bores or open holes that commonly support hydrogeological investigations. Borehole NMR logging offers a method to directly measure water content (free and bound), porosity, pore-size distribution, and estimates of hydraulic conductivity (see, for example, Coates et al. (1999), Dunn et al. (2002), Stapf and Han (2006), and Walsh et al. (2013)). This method is regarded as having significant potential in hydrogeological investigations.

Borehole NMR logging was undertaken for seven of the newly installed wells in the APY Lands in late September 2019. Example is provided here for the upper 80 m of the main DH-1 well in the Lindsay East Palaeovalley (Figure 2-13).

All the bores logged in around DH1a (e.g. Figure 2-13) indicated that estimated porosities from the borehole NMR are highly variable, both vertically and laterally. Estimates of bound (capillary) and free or mobile water vary significantly, averaging from 15–20% in the upper ~40 m. Trends in the mobile and capillary water content also suggests fining or coarsening upward sequences which are not always reflected in the lithology logs. In part that may reflect limitations in the drilling procedure employed which involved air rotary and mud rotary methods with drill cuttings used to define the lithology. With both approaches, there is potential to misinterpret the relative abundance of finer-grained materials.

The highest relative water content here is deeper than 70 m, although this is mainly bound up in the saline claystone (green in Figure 2-13). The highest mobile water content (pale blue in Figure 2-13) is at a much shallower depth (~15-30 m) in the unconsolidated sand layers.

Project publications

Davis A, Flinchum B, Munday T, Cahill K, Peeters L, Martinez J, Blaikie T, Gilfedder M and Ibrahimi T (2020) Characterisation of a palaeovalley system in Aṉangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia using ground-based hydrogeophysical methods. Technical Report Series No. 20/05, Goyder Institute for Water Research, Adelaide.

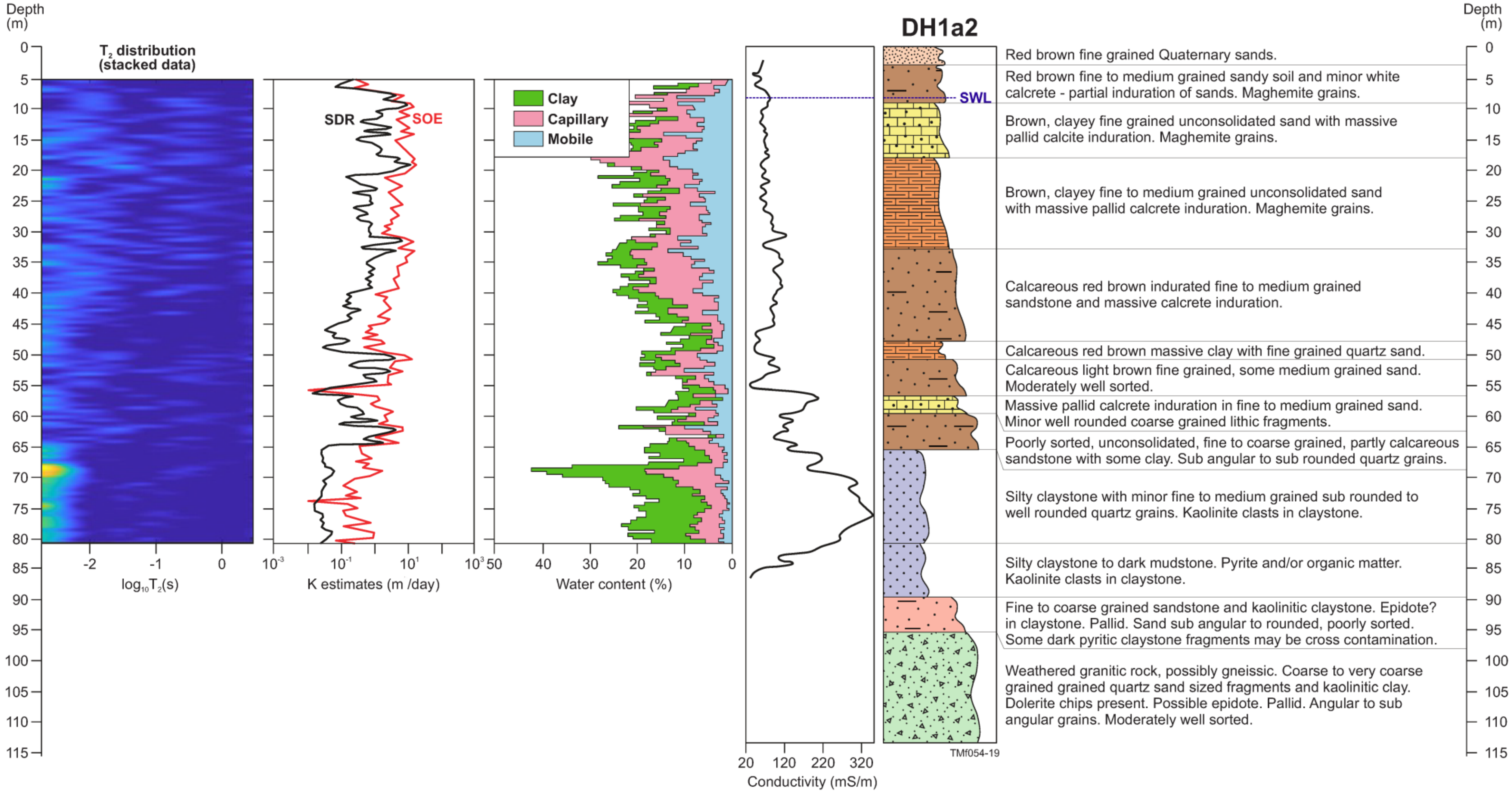


Figure 2-13 Borehole nuclear magnetic resonance results for DH1a2 (east of Kaltjiti/Fregon), compared to drilling lithology.

2.5.3 TIME-DOMAIN ELECTROMAGNETICS

Ground time-domain electromagnetics (TEM) methods have a long-standing application in near surface geophysical investigations of groundwater resources. An ungrounded loop of electrical wire is placed on the ground and a time-varying current is transmitted through it using a specialised transmitter. A magnetic field is induced (referred to as the primary magnetic field) in the ground while current is being transmitted. When the current is turned off abruptly, the magnetic field is then left without its source and responds by inducing an image of the source loop in the subsurface. Initially this is equal to the primary magnetic field but is rapidly weakened by the electrical resistivity of the ground and it dissipates or decays. The induced current moves in circular horizontal paths and generates another magnetic field (the secondary field).

The workflow employed in this pilot study is summarised in Figure 2-14 and involves the targeted acquisition, processing and inversion of ground-based time-domain electromagnetic data, followed by their processing, inversion and subsequent interpretation against available hydrogeological information. In this study the interpretation also involved their forward modelling to provide some guidance as to how an airborne time-domain EM system would perform in this environment.

Conductivity-depth models from the TEM soundings are comparable with those generated from the AEM data, and an interpretation of the observed conductivity structure is similar to that obtained from the AEM data transect (Figure 2-15). The saturated zone appears to be coincident with a marked increase in ground conductivity which may relate to the concentration of salts through evapotranspiration at the interface between the saturated and vadose zones. A more resistive unit, possibly related to lower salinity groundwater, is encountered at about 30 m below the ground surface. The deeper parts of the palaeovalley are more conductive, and this is partially coincident with the presence of muds and clays associated with fluvial-lacustrine and marginal marine sediments as reported in Krapf et al. (2019). Perhaps the biggest difference between the ground and airborne EM data sets is observed in the eastern part of the transect where the ground TEM data suggests the presence of a more resistive unit (saprock/bedrock) nearer surface. This is reflected in the revised interpreted geological section (determined from a combination of drilling and the ground EM data) shown in Figure 2-15.

Further work on ground TEM methods is planned, including the acquisition of data from different TEM systems, and interpretation of the derived data using alternative inversion approaches.

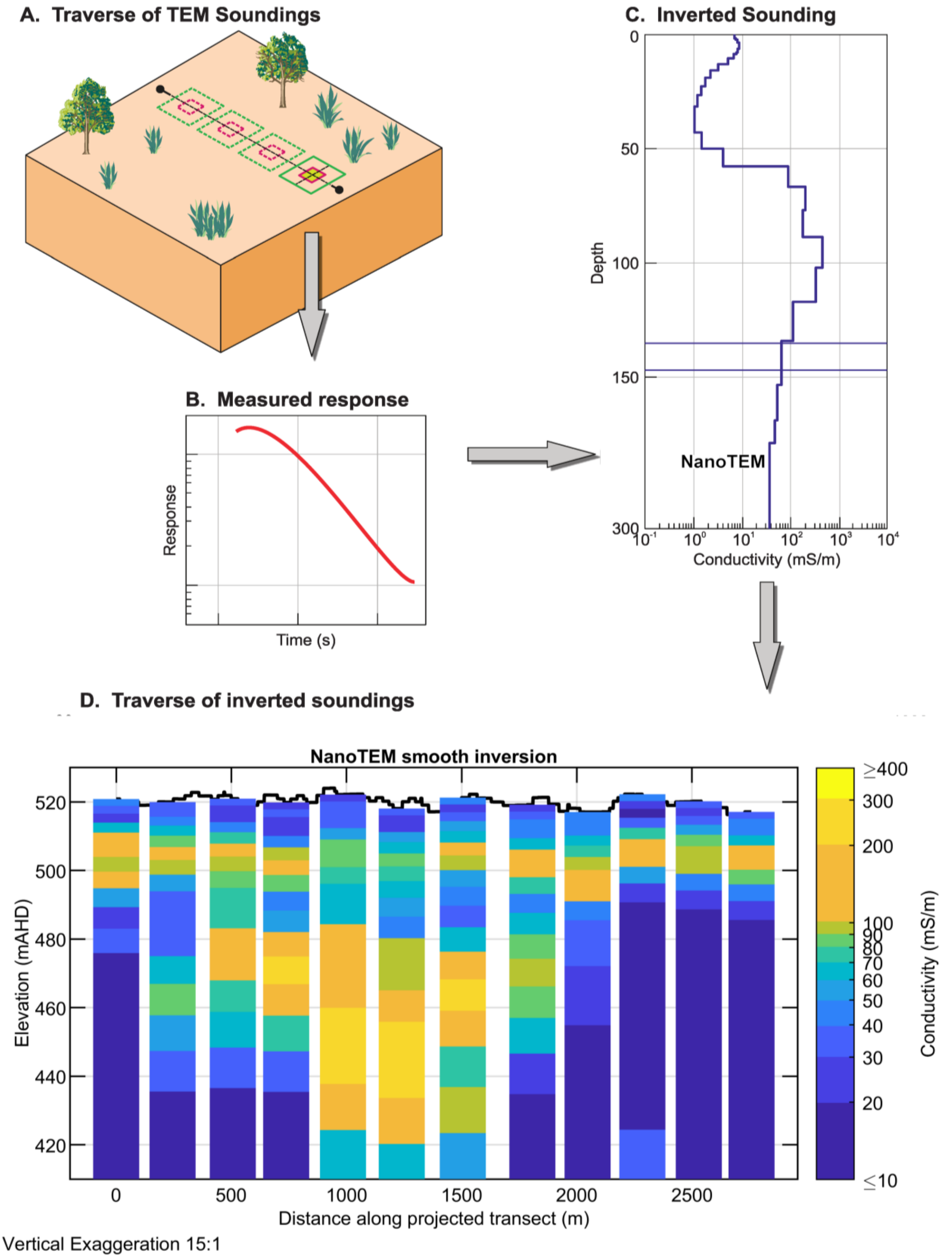


Figure 2-14. Schematic representation of the time-domain electromagnetic acquisition (A), measurement (B), inversion (C) workflow, with section/traverse of pseudocoloured soundings to aid interpretation (D).

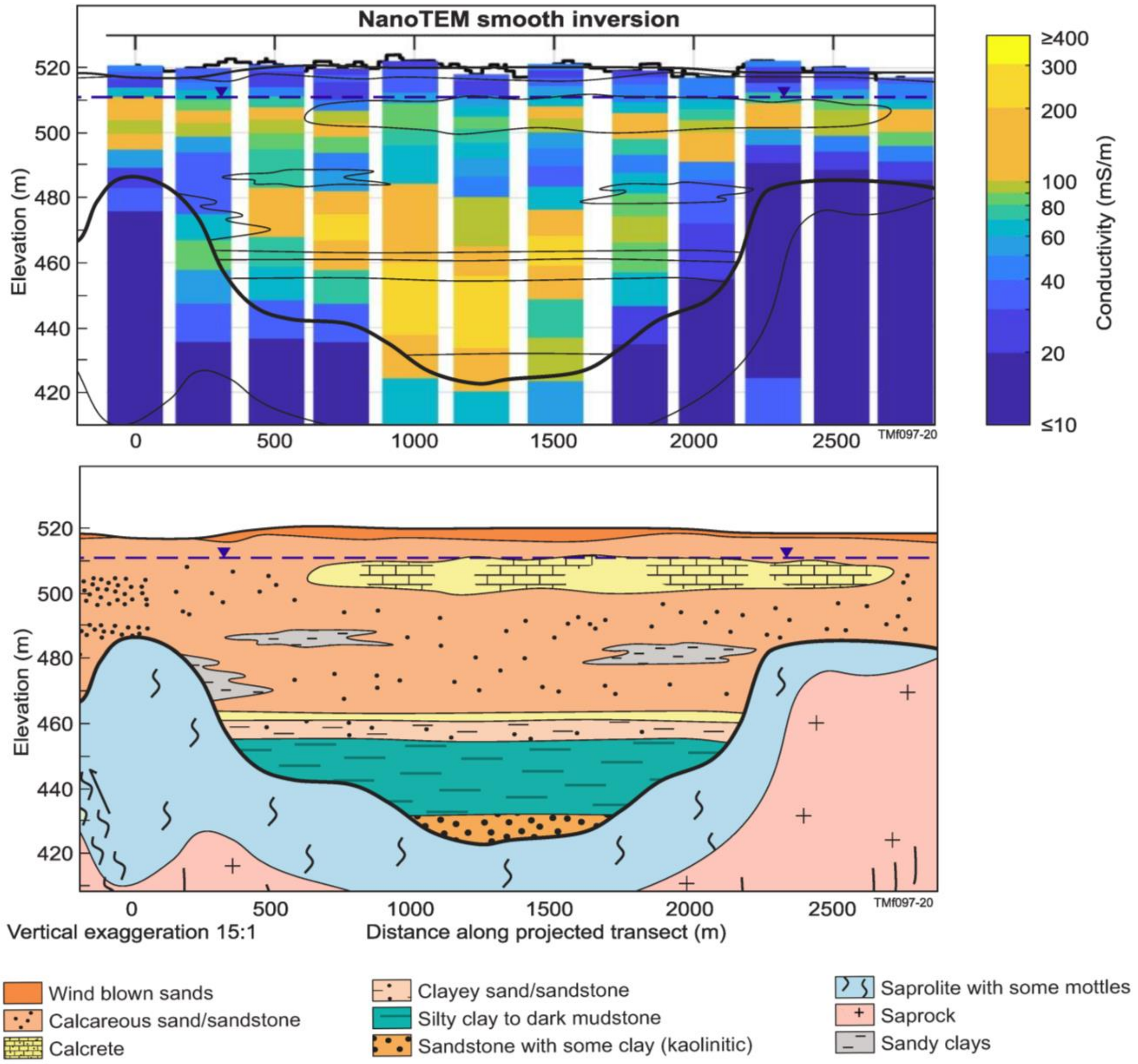


Figure 2-15. Smooth-model conductivity depth section from the inverted NanoTEM soundings (top panel) and the interpreted geology for the transect (lower panel). The geological section was determined from the combined interpretation of the drill hole and the conductivity section data. Geological linework is superimposed on the conductivity-depth soundings for added clarity.

2.6 Palaeovalley architecture

Palaeovalley architecture is an important aspect of understanding the water resources they contain. The drilling program in G-FLOWS Stage-3 provided an opportunity to obtain information on the materials and hydrogeologic properties down through a large palaeovalley. Drilling in the Lindsay East Palaeovalley (at Site DH1) has provided detailed information at this location. Along the length of the palaeovalley some changes would be expected, but the fill materials are likely to be consistent.

Results from the borehole NMR were imaged against an AEM conductivity-depth section which traversed the Lindsay East Palaeovalley. The borehole lithology information (Keppel et al. 2019) provides spatial context for the hydraulic information to help support the AEM interpretation. The modelled water contents from the borehole NMR shown some correspondence with the conductivity structure in the AEM data. For example, the clayey fine to medium grained unconsolidated sand unit between 17 and 33m (below the ground surface) identified in DH1a2 has a lower free water content (and lower porosity) than units above and below (Figure 2-16 and Figure 2-13). It coincides with a zone of elevated conductivity in the AEM data. Whether this relates to a slight increase in the solute content of the contained water is unknown but likely. At depth, the lacustrine-estuarine-marginal marine facies described by Krapf et al. (2019) have high porosities, less mobile water, but the borehole NMR data also indicate lower permeabilities (Figure 2-13 and Figure 2-16). The AEM data show this zone to be relatively conductive.

The well lithology information (Keppel et al. 2019) provides information to help support the AEM interpretation. There are large clay units at depth in the palaeovalley. These have higher electrical conductivity but contain less mobile water. Borehole NMR has provided relative estimates of how available-water varies with depth in the palaeovalley (capillary and mobile, compared to clay water components in Figure 2-16).

The shallower parts of the palaeovalley at DH1 are more prospective for water, with lower groundwater salinity (see Figure 2-4), and a static water level around 8 m below the land surface. Shallow wells (20-40 m) may provide the best target in this area, as opposed to going very deep (80-100 m).

2.6.1 GEOLOGICAL MODEL OF THE PALAEOVALLEY

The evolution of the palaeovalley system in the APY Lands, particularly the Lindsay East Palaeovalley located at hydrogeological control site DH1, is well documented by Krapf et al. (2019). Krapf et al. (2019) produced the following figures (Figure 2-17 a-e) that used knowledge and information derived from the core at drill hole DH1a.

Drilling the full thickness of the Lindsay East Palaeovalley provided for the first time evidence that the palaeovalley was incised up to 40 m into the underling weathered crystalline bedrock (Figure 2-17a). A combination of data captured by DH1a and the AEM dataset, enabled extension of the findings beyond the control site, which suggests that this incision depth may also apply to other palaeovalleys in the wider Musgrave Province region.

Infilling of the palaeovalley began with the deposition of a sandy fluvial succession (Figure 2-17a and (Figure 2-17b). The identification of two marginal marine to estuarine intervals within the mud unit of drill core DH1a based on palynological constraints (Krapf et al. 2019) suggests that the Lindsay East Palaeovalley periodically experienced marine influences with the sea transgressing far inland beyond the coastal margin and wetlands areas of the Eucla Basin (Figure 2-17b). The combined effects of a warm and humid climate and a rising sea level accompanied by subsidence and orogenic movements during the Late Miocene (Hou et al. 2008) can explain the presence of marginal marine deposits in the Lindsay East Palaeovalley at the foothills of the Musgrave Ranges more than 300 km NNE of the palaeocoastline.

The modern day landscape is characterised by extensive sandplains and dunefields with minor creeks. Pedogenic calcretes and chalcedonic silcretes, which have widely formed within the sandplain deposits, are frequently cropping out as resistant mounds in low-lying areas (Figure 2-17e).

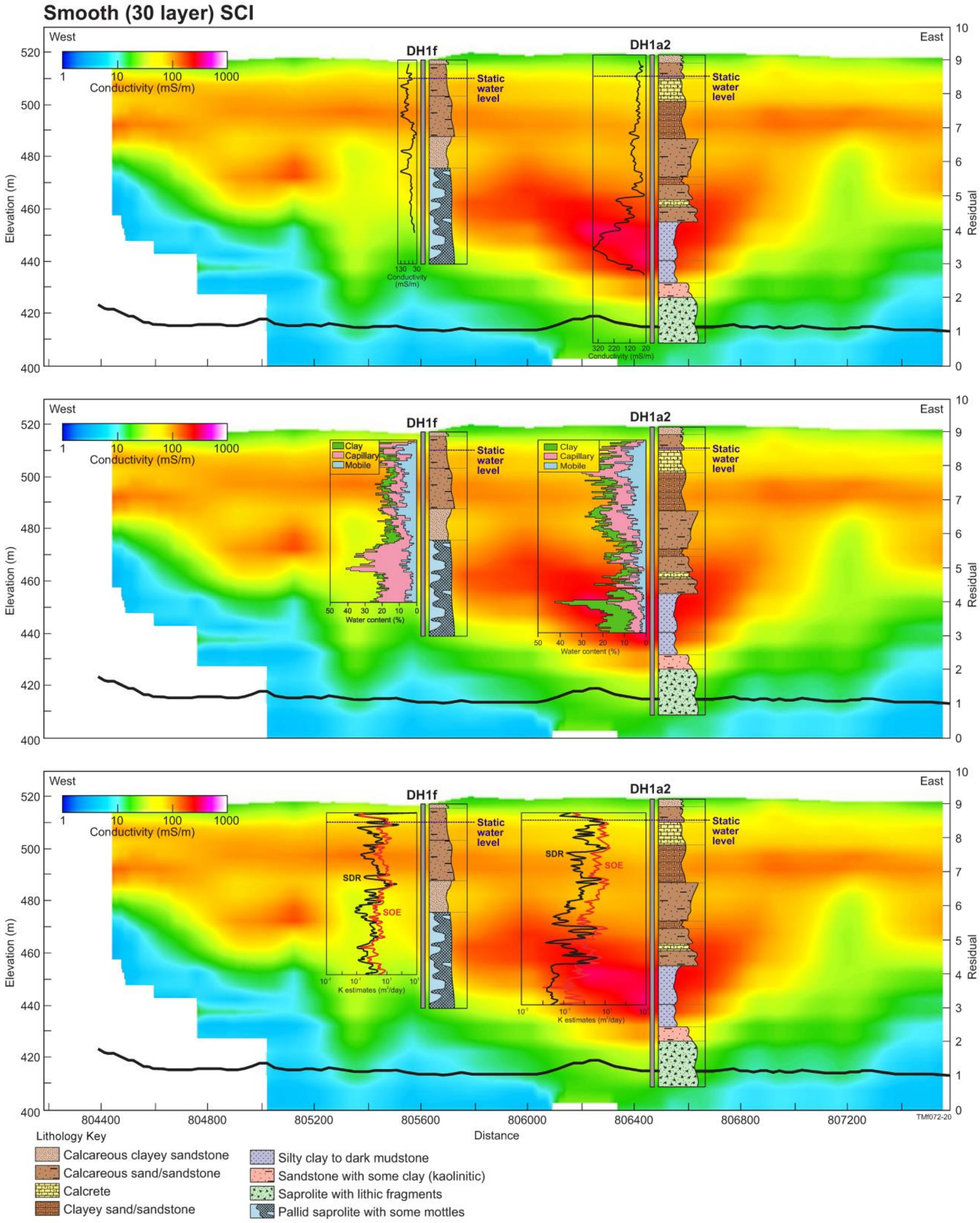
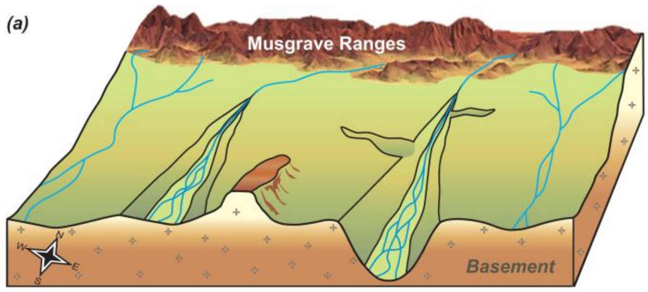
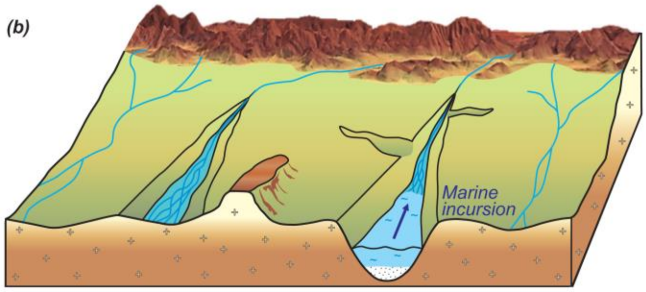


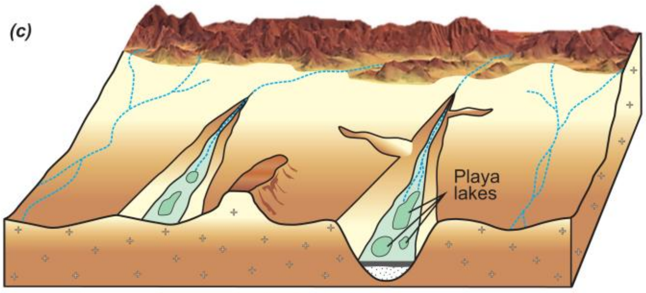
Figure 2-16. The conductivity-depth sections for the Lindsay East Palaeovalley transect for a smooth 30-layer inversion. Drill hole lithology (adapted from Keppel et al. (2019)) and inductive conductivity logs are overlain on the airborne electromagnetic section in the top panel. Water contents from the borehole nuclear magnetic resonance (BNMR) are overlain on the section in the middle panel and modelled hydraulic conductivity estimates (Schlumberger Doll Research (SDR) and sum of echoes (SOE)) are overlain on the section in the lower panel. Adjustments to the predicted lithology textures (whether fining or coarsening upwards) have been made based on the BNMR logs.



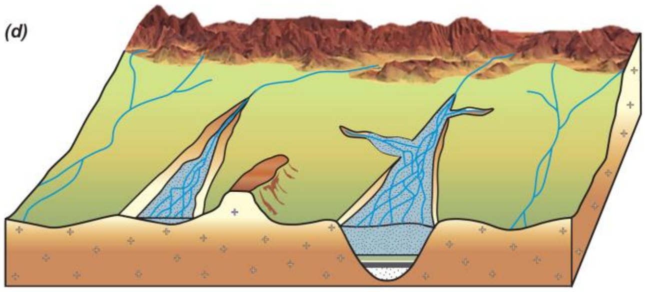
Formation of incised valleys *(Late Mesozoic to Early Palaeogene)*.
First fluvial deposition *(Eocene)*.



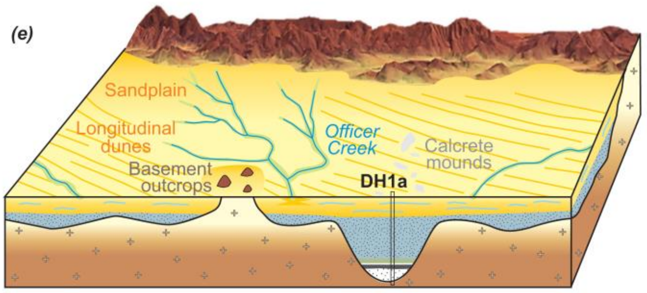
Freshwater and marine environmental reversals *(Late Miocene to Early Pliocene)*.
Marine incursion into incised palaeovalley estuarine environment.



Evaporation event between freshwater and marine environmental reversals
(Late Miocene to Early Pliocene).



Second fluvial deposition final infill of palaeovalley *(Early to Late Pliocene)*.



Modern day landsurface and landforms.

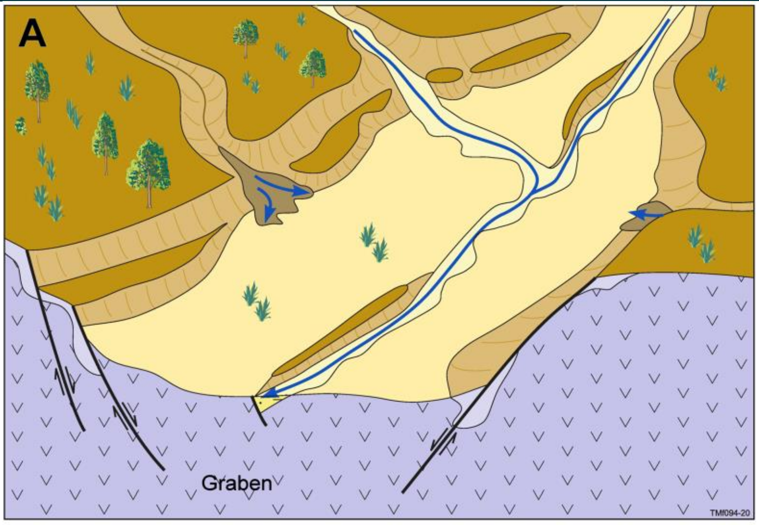
205197-010

Figure 2-17. Geological evolution model of the Lindsay East Palaeovalley (from Krapf et al. 2019).

As part of the conceptualisation of palaeovalley formation in the APY Lands, Figure 2-18 indicates a conceptualisation of the development and subsequent valley filling of palaeovalleys.

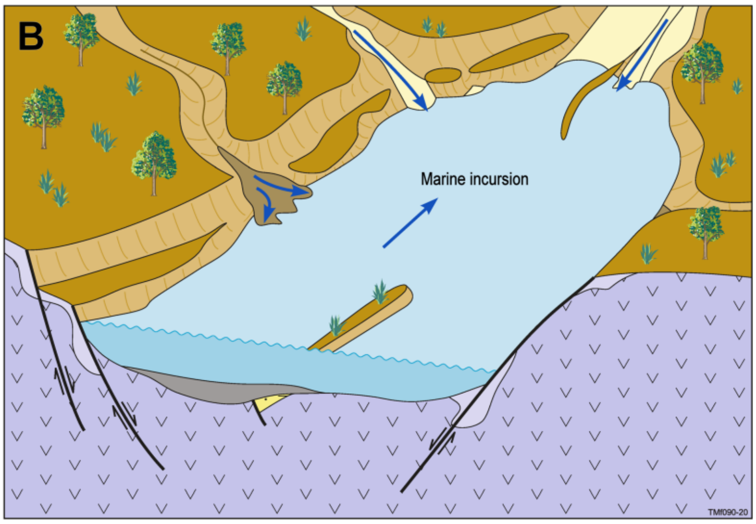
A: Onset of deep weathering

(Late Mesozoic to Early Palaeogene – ~65Ma), with fluvial erosion and sedimentation of faulted crystalline Mesoproterozoic basement rocks. Erosion and sedimentation developed preferentially along structural discontinuities with fluvial deposition occurring through the Palaeocene and Eocene (~6—30Ma).



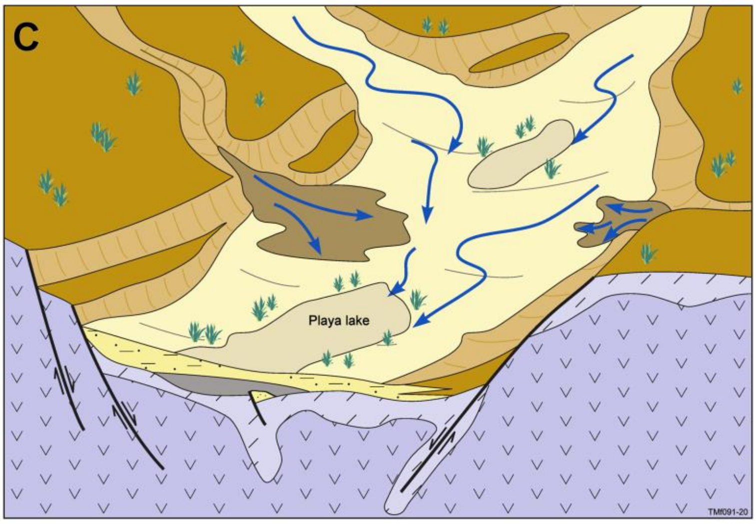
B. Freshwater and marine environmental reversals

(Palaeogene - Neogene), with intermittent marine incursion and sediment deposition into incised palaeovalley estuarine environment through the Miocene to mid-Eocene (~40 - 13Ma). The marine influence receded with brackish to freshwater lake systems occupying the valley floors. Deposition of organic rich fine grained sediments occurred in parts.



C. Drying out and evaporation starts to dominate

(mid Neogene) with the development of playa lakes accompanied by intermittent fluvial sedimentation through the Late Miocene to Early Pliocene (~10 – 3Ma).



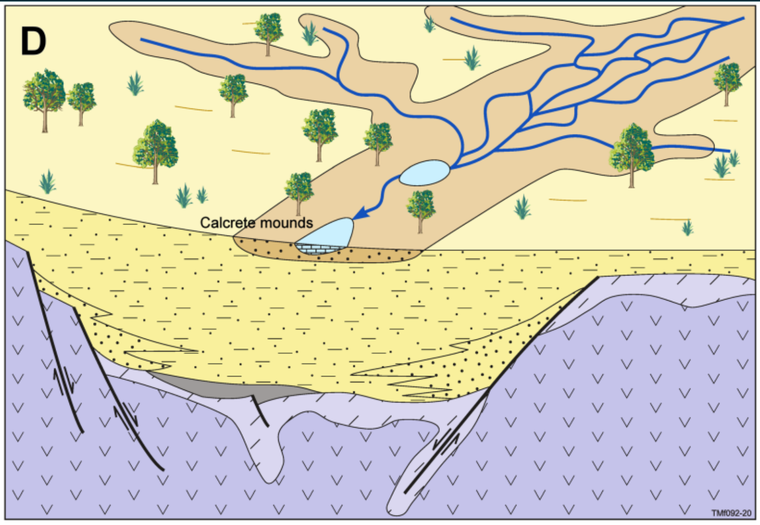
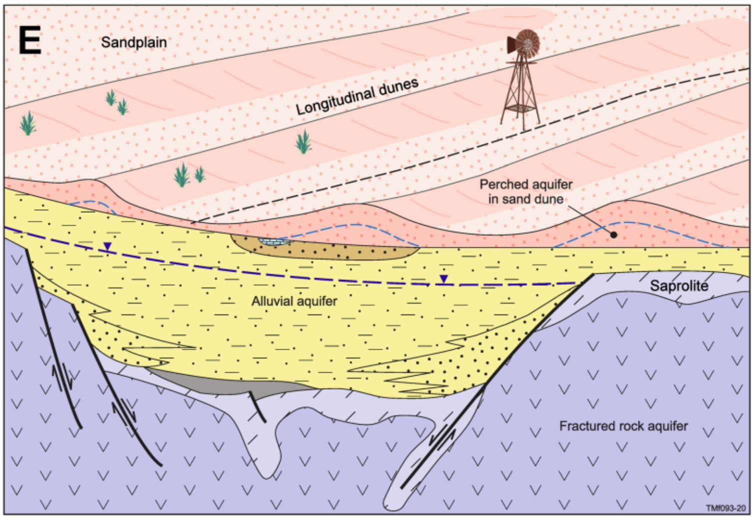
D. Wetter conditions through the early Neogene resulted in increased erosion of the ranges to the north, and an acceleration of sequential fluvial sedimentation infilling the palaeovalley systems. (Early to Late Pliocene - ~ 2.5 – 5Ma).	
E. Sedimentation continued after the palaeovalley systems were infilled through the early Neogene into the Quaternary, with sheetwash, fluvial and colluvial sediments being deposited across the landscape with increased aridity. Aeolian processes started to dominate in the Holocene with the development of extensive sand plains and sand sheets. Local induration occurred forming calcrete in subdued, shallow and laterally extensive valley floors. (Pliocene – Holocene ~4Ma to present).	

Figure 2-18. Conceptualised landscape development processes leading to current palaeovalleys.

2.6.2 REINTERPRETED PALAEOVALLEY MAP FOR THE ANANGU PITJANTJATJARA YANKUNYTJATJARA LANDS

More complete AEM coverage (Soerensen et al. 2018) has allowed the refinement of the existing WASANT Palaeovalley Map (Bell et al. 2012) for the APY Lands area. This has been published as “Palaeovalley map of the Anangu Pitjantjatjara Yankunytjatjara Lands” (Krapf et al. 2020) as part of the G-FLOWS Stage-3 Project (Figure 2-19). The new map shows the major refinement in palaeovalley detail which was made possible through the detailed AEM coverage.

Project publications

Davis A, Flinchum B, Munday T, Cahill K, Peeters L, Martinez J, Blaikie T, Gilfedder M and Ibrahimi T (2020) Characterisation of a palaeovalley system in Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia using ground-based hydrogeophysical methods. Technical Report Series No. 20/05, Goyder Institute for Water Research, Adelaide.

Jiang Z, Mallants D, Peeters L, Gao L, Soerensen C, Mariethoz G (2019) High-resolution paleovalley classification from airborne electromagnetic imaging and deep neural network training using digital elevation model data. *Hydrology and Earth System Sciences* **23**: 2561–2580.

Krapf C, Costar A, Keppel M, Inverarity K, Love A, Stoian L, Gordon G, Soerensen C and Munday T (2019) Backing up the AEM – unravelling a palaeovalley fill for groundwater exploration in the APY Lands, *ASEG Extended Abstracts 2019*: 1–6.

Krapf C, Costar A, Stoian L, Keppel M, Gordon G, Inverarity K, Love A and Munday T (2019) A sniff of the ocean in the Miocene at the foothills of the Musgrave Ranges – unravelling the evolution of the Lindsay East Palaeovalley. *MESA Journal* 90(2), 4–22.

Krapf CBE, Costar A, Munday T, Irvine JA and Ibrahimi T (2020) Palaeovalley map of the Anangu Pitjantjatjara Yankunytjatjara Lands (1st Edition), 1:500 000 scale. Department for Energy and Mining.

Macnae J, Xiuyan R and Munday T (2020a) Stripping induced polarization effects from airborne electromagnetics to improve 3D conductivity inversion of a narrow palaeovalley. *Geophysics* 85(5): B133–B139.

Munday T, Sørensen C and Gulbrandsen ML (2018) Peeling back the cover on an ancient landscape – AEM in the Musgrave Province, South Australia. AEM 2018 7th International Workshop on Airborne Electromagnetics, June 17-20 Kolding Denmark. pp4.

Munday T, Taylor A, Raiber M, Soerensen C, Peeters L, Krapf C, Cui T, Cahill K, Flinchum B, Smolanko N, Martinez J, Ibrahimi T and Gilfedder M (2020) Integrated regional hydrogeophysical conceptualisation of the Musgrave Province, South Australia. Technical Report Series No. 20/04, Goyder Institute for Water Research, Adelaide.

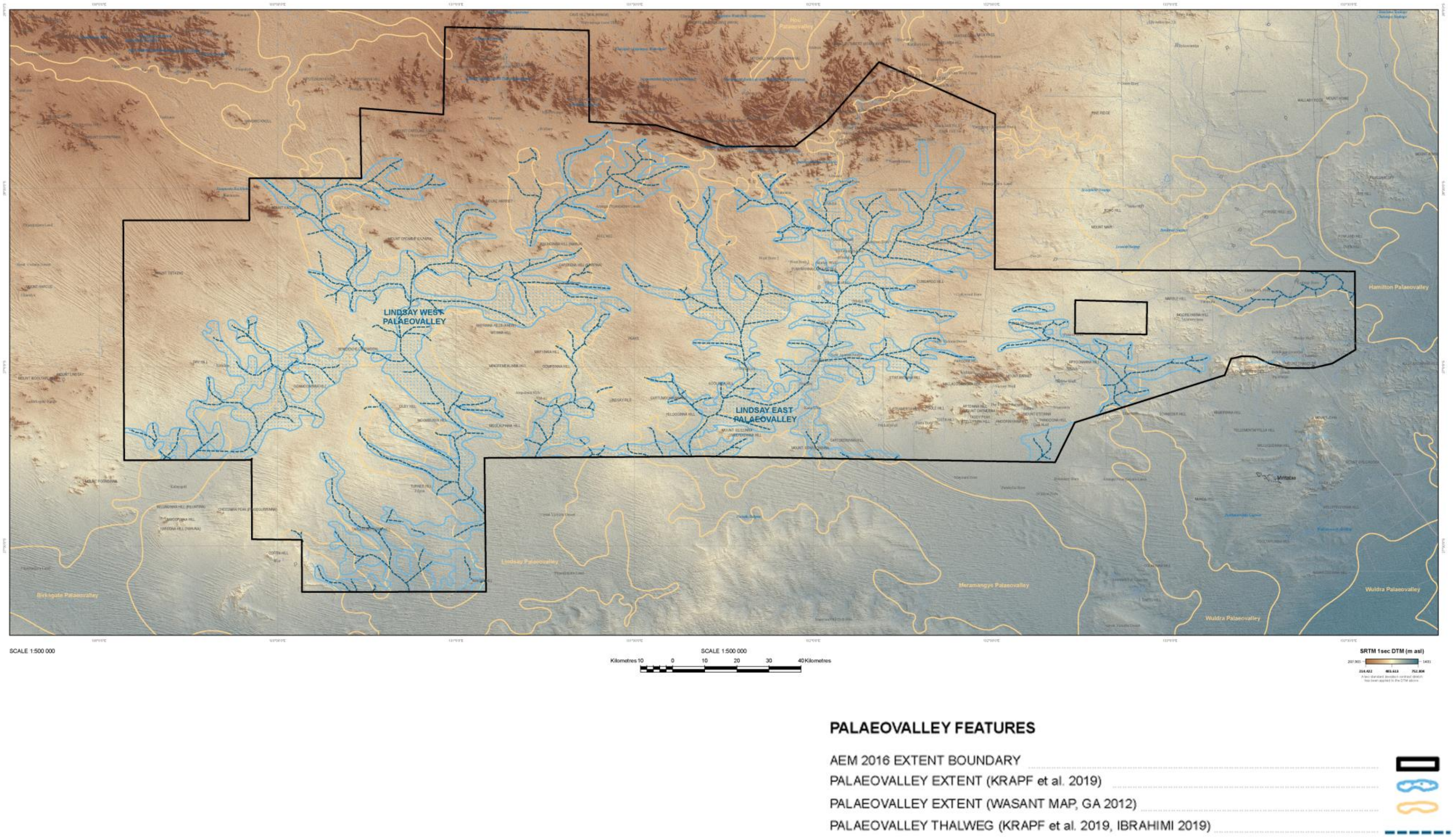


Figure 2-19. Map of palaeovalley reinterpretation (extent + thalweg/deepest part) across the Anangu Pitjantjatjara Yankunytjatjara Lands study area (Amata-Mimili). (Reproduced from Krapf et al. 2020).

2.7 Drilling program

A drilling program conducted in 2018 (Keppel et al. 2019) established a hydrogeological control test site within the spatial extent of the Lindsay East Palaeovalley (site DH1). Seven groundwater wells were constructed at this site to assist in the development of geophysical and hydrogeological conceptualisation of the palaeovalley groundwater flow system.

Site DH1 is located on the Fregon-Mimili road approximately 6 km southeast of Kaltjiti. This location was selected for drilling investigations due to its proximity to the mapped extent of the Lindsay East Palaeovalley (Figure 2-20). This extent was identified from AEM survey data and is located adjacent to a main road, which aided site access and clearance. Investigation drilling and well construction at site DH1 was designed to enable palaeovalley aquifer testing. In addition to the seven wells and one cored hole that were initially planned, an additional well was installed to replace well 1a, which encountered construction issues after coring.

Two primary objectives of the drilling program included:

1) Confirm the stratigraphy and depth of the Lindsay East Palaeovalley and to help validate the AEM geophysical data and geophysical model presented in Soerensen et al. (2018), including the identification of water bearing zones within the palaeovalley; and

2) Develop further understanding of the groundwater characteristics in the shallow groundwater system.

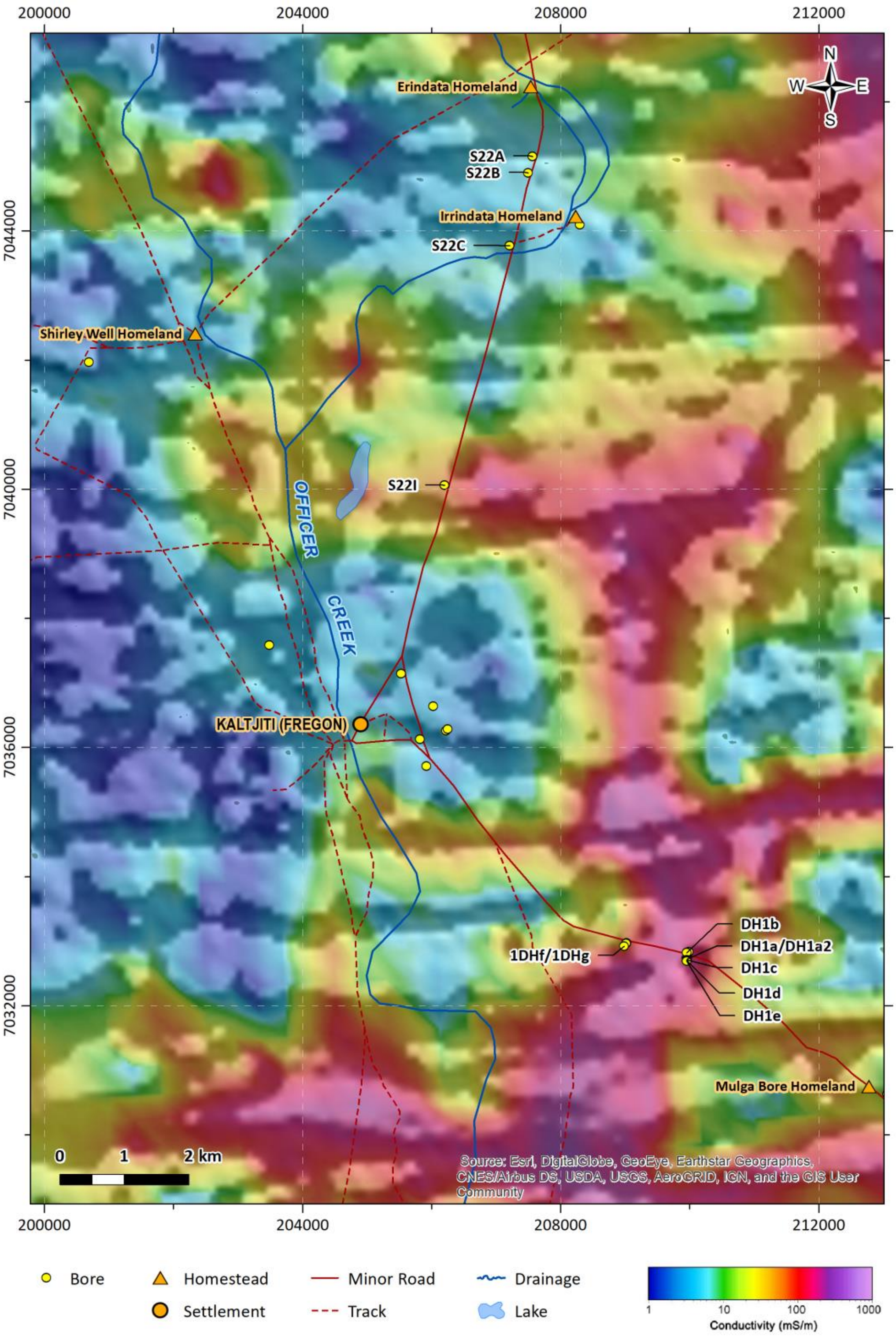
On-site drilling works was conducted between 10 July and 5 September 2018 in the APY Lands (Musgrave Province). In total, 11 groundwater wells (including one replacement well) were constructed including two drill hole cores at two hydrogeological control sites namely DH1 and S22.

DH1 was centred on the main Lindsay East Palaeovalley, located approximately five kilometres east of Kaltjiti (Fregon). This site was targeted using the 2016 AEM survey data (Soerensen et al., 2018) that located the nominal location of the main palaeovalley in the area. In choosing this site, consideration was given to the proximity of other historical wells and road access.

A further four observation wells were completed at S22, with one cored sample collected (S22i). This site is located approximately nine kilometres north of Kaltjiti (Fregon) and was designed to examine the shallow water-table (or phreatic groundwater surface) and dependence on topographic features. At this location a core was collected since S22i was located adjacent to a smaller “tributary” of the main palaeovalley system.

Drilling methodologies included a combination of air and mud rotary with mud used for deeper palaeovalley wells (including S22i) where deeper unconsolidated formations needed to be held back to enable downhole geophysical surveys in the open hole and well construction. Air was used for shallower (<35 m) wells targeting the water-table.

Drilling near the centre of the Lindsay East Palaeovalley (DH1) identified at least three groundwater bearing sequences (or aquifers); the shallow phreatic water-table of calcareous mixed sand plain deposits, an interlayered coarse-grained sandstone and clay horizon and a very fine to coarse grained residual sand; a saprolite/fractured rock aquifer underlays these palaeovalley sedimentary rocks (Figure 2-21). While data is preliminary and based on air development (which can be subjective), the coarse-grained sandstones (which overlays a lacustrine claystone and mudstone) shows promise as a productive aquifer, with development yields varying between 5 and 20 L/s and salinities <1000 mg/L total dissolved solids (TDS).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2-20. Airborne electromagnetic depth slice 50-60 m below natural surface (pseudocolour) draped over first vertical derivative image of the total magnetic intensity data (intensity). The presence of east-west structures in the magnetics and their influence on the location of palaeovalleys is shown.

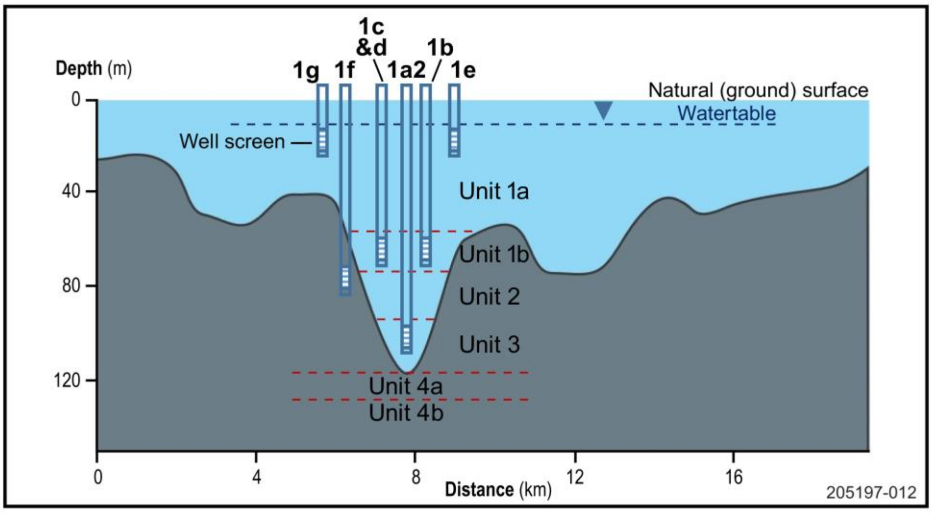


Figure 2-21. Basic schematic across hydrogeological control site DH1 showing well locations and indicative screen depths (from Costar et al. 2019).

The DH1 site configuration incorporated the following aspects:

1) The main site was located south of the Fregon-Mimili road and centred on the Lindsay East Palaeovalley. One cored hole (DH1a) and four wells (DH1a2, c, d and e) were completed. DH1a was plugged (no screen) and replaced by DH1a2.

2) A second site was located north of the Fregon-Mimili road, approximately 100 m north of the main site. One well (DH1b) was completed.

3) A third site was located approximately one kilometre north of the main site, adjacent to the Fregon-Mimili road. Two wells (DH1f and g) were completed.

Drill holes at DH1 were situated in order to target geological features and water bearing zones hosted within the palaeovalley sediments as inferred from the AEM. Wells were constructed to allow aquifer testing of any water bearing zones encountered.

Investigation drilling was also undertaken at an additional site (S22) over four locations (i.e. S22a-d) situated 7-10 km to the north of site DH1. Investigations at site S22 were intended to aid the understanding of the phreatic (shallow) groundwater system. However, as discussed later in this report, no aquifer testing was conducted at site S22 but may be undertaken beyond G-FLOWS Stage-3.

2.7.1 CORING THE PALAEOVALLEY

The drilling program provided the opportunity to acquire a diamond drill core taken from the thickest part of the sedimentary infill of the Lindsay East Palaeovalley and, ideally, also including the top of the underlying basement. Notably this core is one of a limited few drilled in sedimentary cover in the APY Lands and certainly the only core taken through the centre of a palaeovalley system. As discussed at length in Keppel et al. (2019), Costar et al. (2019) and Krapf et al. (2019), drill hole DH1a was designed for this purpose and thereby tested the AEM data and geophysical model of Munday et al. (2020).

Drill cores were successfully retrieved from drill hole DH1a to a depth of 93.4 m below natural ground surface (m BNS). This drill hole intersected three main sandy successions with the lower two separated by a thick interval of mud. No core material could be recovered from below 93.4 m BNS depth due to continued core loss. Successive rotary mud drilling produced cuttings up to a depth of 117 m BNS with the palaeovalley fill – basement contact intersected at ~108 m BNS.

The contact between weathered basement and the overlying, also intensively weathered, palaeovalley fill sediments was not very distinctive in the drill cuttings, which is also reflected in the diffuse boundary seen in the AEM model (Munday et al. 2020). However, thorough inspection of the cuttings identified a noticeable change of quartz grain morphology with depth. Above ~108 m, quartz grains are mainly subangular to subrounded indicating that the grains have experienced mechanical abrasion during sedimentary transport. Below ~108 m BNS, quartz grains display more angular to subangular morphologies and are interpreted to be *in situ* within the weathered basement (Krapf et al. 2019), likely granites of the Pitjantjatjara Supersuite (Pawley and Krapf 2016).

By design, the target at S22 was the phreatic water-table aquifer and as such development yields were generally low (<1 L/sec) and salinity was generally between 1000 and 1500 mg/L TDS); although it should be noted that S22i (located near a palaeovalley tributary feature) appears to have slightly higher yields.

Palaeovalley systems can be identified using AEM surveys by identifying conductivity variations at depth over large areas however, verification to date of AEM data, in terms of viable a groundwater resources, has been limited. The recently acquired 2016 AEM data (Soerensen et al. 2018) proved useful with respect to identifying the location of the main Lindsay East Palaeovalley for drilling targets. According to the preliminary results of the G-FLOWS Stage 3 Drilling Program, these palaeovalley sediments appear to be viable groundwater resources for remote and arid regions such as the APY Lands where water is a limiting factor to community wellbeing and economic growth of the area. This drilling data will help to further ground-truth the AEM data and enable it to be up-scaled to the wider APY region where an AEM footprint exists.

The successful completion of this drilling program has not only enabled further AEM verification but also established important groundwater data points and helped further characterise the palaeovalley and shallow groundwater systems. This was achieved through hydraulic testing and hydrochemical sampling of the groundwater resource, which is a vital resource for the region.

Table 1: Summary of groundwater parameters for the palaeovalley sediments.

UNIT	AQUIFER CHARACTERISTICS	DEPTH (m)	SALINITY (mg/L)	YIELD (L/s)	HYDRAULIC CONDUCTIVITY (m/DAY)	DEPTH TO WATERTABLE (m)	LITHOLOGICAL DESCRIPTION
1	Unconfined	8–55	1000–1500	<1	NA	7.7	Sandplain system
1b	Unconfined	55–65	870	10–18	50	7.6	Main water-bearing zone within the palaeovalley sediments (i.e. target-water-bearing palaeovalley zone)
2	Confining bed	65–85	NA	NA	NA	NA	Silty clay (mud)
3	Confined	85–108	1200	<2	NA	8	Basal palaeovalley sediments
4a	Weathered basement	108–117+	1000	<1	NA	8	Weathered rock (saprolite)
4b	Fresh basement	>117	NA	NA	NA	Na	Fresh rock with possible fractures

NA – not available

Project publications

Costar A, Love A, Krapf C, Keppel M, Munday T, Inverarity K, Wallis I and Soerensen C (2019) Hidden water in remote areas – using innovative exploration to uncover the past in the Anangu Pitjantjatjara Yankunytjatjara Lands. *Mesa Journal,* 90(2), 23–35.

Keppel M, Costar A, Love A and Krapf C (2019) G-FLOWS Stage 3 APY Lands Drilling Program, north-western South Australia. Technical Report Series 19/39, Goyder Institute for Water Research, Adelaide.

Krapf C, Costar A, Stoian L, Keppel M, Gordon G, Inverarity K, Love A and Munday T (2019) A sniff of the ocean in the Miocene at the foothills of the Musgrave Ranges – unravelling the evolution of the Lindsay East Palaeovalley. *MESA Journal* 90(2), 4–22.

Love A, Costar A, Krapf C, Xie Y, Wallis I, Lane T, Keppel M, Inverarity K, Deng Z, Munday T and Robinson N (2020) G-FLOWS Stage 3: Hydrogeological conceptual understanding of the APY Lands groundwater system including the Lindsay East Palaeovalley. Goyder Institute for Water Research Technical Report Series No. 20/06, Goyder Institute for Water Research, Adelaide.

2.8 Groundwater recharge and flow

The review and reinterpretation of groundwater level, chemistry and environmental tracers from previous studies integrated with the geological modelling and findings from the interpretation of new and existing geophysical data has proved invaluable for confirming and refining knowledge of groundwater flow processes. The collation and reinterpretation of environmental tracer data with more stringent constraints (i.e. accounting for sampling depths and aquifer geometry) compared with previous work (Dodds et al. 2001, Craven 2012, Custance 2012, Leaney et al. 2013, and Kretschmer and Wohling 2014) has helped to confirm and refine some previous characterisation of groundwater recharge and flow processes, and also to refine groundwater recharge estimates for aquifers in key hydrogeological units.

The collation and re-interpretation of chemistry data (with a charge balance error (CBE) of <20%) has confirmed spatial trends in groundwater chemistry associated with recharge, throughflow and discharge. Groundwater from bedrock aquifers and alluvial/colluvial aquifers in the north of the province in and around the ranges where recharge predominantly occurs is of a calcium-magnesium-bicarbonate composition and low salinity. Whereas, groundwater from alluvial/colluvial and bedrock aquifers further south of the ranges in the Great Victoria Desert progressively develops a sodium-chloride composition and salinity gradually becomes brackish. Groundwater from fractured and highly weathered bedrock aquifers around Indulkana Range and Mount Chandler in the south-east of the province on the geological boundary with the Great Artesian Basin is both highly variable in composition and salinity reflecting the complex hydrogeology. The ionic composition and salinity changes from calcium-magnesium-bicarbonate to sodium-chloride and fresh to saline over relatively short distance (a few km). Some groundwater samples in recharge and throughflow areas are enriched in calcium and bicarbonate due to long-term mineral weathering of patchy pedogenic calcrete horizons as a result of subtle groundwater flow. Sodium-chloride type waters in discharge areas away from outcropping basement and have developed due to evapoconcentration of salts in the vadose zone that are leached to the watertable during highly episodic recharge events. This is also evidenced by the slightly elevated electrical conductivities observed in the AEM and ground TEM data at or near the present day water levels in sediments overlying the palaeovalley systems.

Groundwater chloride data was used in the chloride mass balance (CMB) method to refine previous estimates of groundwater recharge by Craven (2012), Custance (2012), Leaney et al. (2013) and Kretschmer and Wohling (2014). Compared with previous estimates of recharge using CMB, in this study any groundwater chloride sampled from a depth greater than 10 m below the water table was excluded from the estimates. This was to adhere more stringently to the assumptions of the CMB method by excluding any chloride at depth that may have accumulated due to lateral groundwater flow upgradient of the sampling point. Overall, the mean annual recharge rate using CMB is very low for all aquifers (<2 mm/yr) which is not surprising given the arid nature of the Musgrave Province. Higher recharge rates (up to 7 mm/yr) were estimated for bores in outcropping bedrock aquifers where vertical recharge occurs directly to saprolite, fractures, joints and faults. Overall and despite more stringent conceptual assumptions using CMB, the recharge rates estimated are similar to those reported by Craven (2012), Custance (2012), Leaney et al. (2013) and Kretschmer and Wohling (2014).

The analysis and interpretation of groundwater level data in this study has confirmed previous interpretations by Varma (2012) and Keppel et al. (2019) of the scale and directions of groundwater flow in the province. In general, groundwater flow is from north to south-south-east. Temporal groundwater level data is sparse and there are large unpopulated areas across the Great Victoria Desert where groundwater exploration has not occurred and therefore no data exists. Nevertheless, the change in static groundwater level from north to south-south-east is ~350 m over a distance of 150 km, resulting in a hydraulic gradient of ~0.002. Recharge rates and fluxes are very low (i.e. <2 mm/yr) and groundwater residence times are long (i.e. a few thousand years). Furthermore, geological modelling and interpretation of AEM measurements have highlighted the heterogeneity of both bedrock topography and potential compartmentalisation of surficial cover by structure and possibly neotectonic activity. Together these would contribute to the development of rather complex or tortuous paths of groundwater flow in both the alluvial/colluvial and underlying palaeovalley cover. Neotectonism, involving the reactivation of basement fault systems perpendicular to primary orientation of the main trunk valleys, may also form hydraulic barriers within the pre-existing cover sediments, thereby adding additional complexity to the groundwater story.

A comparison of ^{2}H and ^{18}O data from groundwater, with that of Alice Springs precipitation, indicates that groundwater is depleted in recharge areas in the north of the province in and around outcropping crystalline basement and enriched with increasing distance to the south and south-east in discharge areas. The depleted isotopic composition confirms localised recharge as the dominant recharge process to bedrock and alluvial/colluvial aquifers in and around outcropping crystalline basement. A comparison of the isotopic composition to the amount-weighted mean monthly isotopic composition of Alice Springs precipitation, indicates that at least 40 mm of rainfall in a given month is required to overcome soil moisture deficits in this arid zone and generate groundwater recharge predominantly in outcropping bedrock and sandstone aquifers. However, at least 60 mm of rainfall in a given month is required to recharge the majority of the bedrock and alluvial/colluvial aquifers across the Musgrave Province.

Chlorofluorocarbons are only present in groundwater from recharge areas including bores in outcropping bedrock aquifers and bores in alluvial/colluvial aquifers either adjacent outcropping bedrock or along or near ephemeral drainage lines. Some groundwater from the alluvial/colluvial aquifers contains both measurable CFCs and radioactively decayed ^{14}C indicating a mixture of young and old water. These bores occur in the valleys and plains adjacent outcropping crystalline basement confirming the hydrological connectivity between the two aquifers as a result of localised discharge from bedrock aquifers into adjacent alluvial/colluvial aquifers. The mean annual recharge rate estimates derived from CFCs for both bedrock and alluvial/colluvial aquifers is an order of magnitude higher than estimates derived with both CMB and ^{14}C (alluvial/colluvial aquifer mean of 11 mm/yr, and bedrock aquifer mean of 20 mm/yr). This is not surprising given the short temporal scale (tens of years) that CFCs account for and the fact that they only represent the portion of recharge that comes from larger localised flood events in aquifer outcrops and near ephemeral drainage features, as opposed to long-term diffuse recharge out on the plains. However, the recharge rates estimated here using CFCs are consistent with those estimated for the northern Musgrave Province by Cresswell et al. (2002) when excluding two samples likely contaminated during field sampling.

Radiocarbon has been the most prominently sampled tracer in the Musgrave Province with a total of 80 bores sampled, though ^{13}C data was only available for 50 of these sites. Uncorrected mean residence time (MRT) for groundwater regardless of aquifer ranges from 0 to 16,000 years (± 500 years), though most samples range from 0 to 10,000 years with only three sites >10,000 years. The alluvial/colluvial aquifer has the largest range in MRT and highest median MRT of ~3500 years which is not surprising given the extensive cover of alluvial/colluvial material spanning an area of approximately 75,900 km^{2}. Mean residence times for both bedrock aquifers and alluvial/colluvial aquifers in recharge areas in the north of the province near the ranges have low MRTs ranging up to 500 years. Geochemical corrections were undertaken on the data from 14 groundwater sites, which resulted in several sites in recharge areas having much shorter MRT (0 to 500 years), although a number of samples further south in throughflow and discharge areas still having corrected MRT ranging up to 3000 years. Given the patchy nature of pedogenic calcrete horizons throughout the province, the lack of appropriate field and laboratory chemistry required to correct ^{14}C MRTs and no systematic trend in field pH corrections to, the large number of ^{14}C measurements was not possible. However, it is conclusive that where corrections were appropriate not enough mineral weathering has taken place given the patchy nature of the calcrete that groundwater with a MRT of several thousand years still occurs in throughflow and discharge areas. This finding is further confirmed by the presence of ^{4}He concentrations in groundwater above atmospheric equilibrium in the same throughflow and discharge areas (see below). Given that geochemical modelling demonstrated that not all ^{14}C require geochemical correction, uncorrected ^{14}C MRTs were used to derive the long-term (several thousand years) annual recharge rates for each aquifer.

Regardless of aquifer, the mean annual recharge rate derived using ^{14}C is very low (<2 mm/yr) though recharge rates for individual bores were higher (up to 14 mm/yr) in alluvial/colluvial aquifers adjacent outcropping crystalline basement. Overall, the recharge rates derived with uncorrected ^{14}C MRTs correlate well with those derived using CMB. Both the CMB and ^{14}C derived recharge rates are better suited for understanding the long-term annual recharge rates for aquifers and appear conceptually correct for an arid zone with a mean annual rainfall of <250 mm/yr and annual areal potential evapotranspiration >3000 mm/yr. In addition, the recharge rates derived with ^{14}C are an order of magnitude higher than those using the same method reported by Craven (2012) and Custance (2012). However, this study had access to a much larger number of samples collected from multiple aquifers over a much larger geographical area unlike the very low (<1 mm/yr) localised estimates derived by Craven (2012) and Custance (2012), which are also likely to be affected by diffusion.

Helium-4 concentrations in groundwater span over two and a half orders of magnitude, with a large proportion of the samples (~60%) having concentrations about one to one and a half orders of magnitude above atmospheric equilibrium. The highest concentrations of ^{4}He in groundwater occur well south of the ranges in discharge areas which are also samples with the lowest ^{14}C. Most of the samples with a ^{4}He concentration in groundwater at or close to atmospheric equilibrium occur in the recharge areas in the north of the province in and around the ranges. The noble gas sampling by both Leaney et al. (2013) and Kretschmer and Wohling (2014) was very useful for validating the ^{14}C data and thereby confirming the spatial trends in recharge and discharge areas.

The mean annual volume of recharge estimated for the two most important hydrogeological units in the Musgrave Province (fractured bedrock and alluvium/colluvium) is similar to those published by Kretschmer and Wohling (2014). Estimates derived in this study are slightly higher due to a combination of using a more stringent conceptual assumption with CMB as well as deriving estimates with ^{14}C which are spatially averaged recharge rates, a method not employed by Kretschmer and Wohling (2014). Regardless of the recharge volumes estimated, groundwater discharge estimates are currently unknown and would require further modelling to estimate. Nevertheless, recharge rates are very low across the province and long-term (decadal) groundwater extraction will have to be very carefully managed to ensure groundwater from aquifers is not mined.

Project publications

Munday T, Taylor A, Raiber M, Soerensen C, Peeters L, Krapf C, Cui T, Cahill K, Flinchum B, Smolanko N, Martinez J, Ibrahimi T and Gilfedder M (2020) Integrated regional hydrogeophysical conceptualisation of the Musgrave Province, South Australia. Technical Report Series No. 20/04, Goyder Institute for Water Research, Adelaide.

2.9 Conceptual model of regional groundwater recharge and flow

The combined geophysics and groundwater hydrology work in G-FLOWS Stage-3 builds on the earlier work in the region and confirms, in broad terms, some of the previous conceptual understanding of aquifers in the arid Musgrave Province. The conceptualisation of both the geology and hydrogeology have been previously presented in conceptual schematics by Munday (2013) and more recently by Gogoll (2016). In this study we have also considered findings from some localised work by Parsekian et al. (2014), and coupled them with findings in this study to subsequently adapt and refine conceptual schematics from Munday (2013) and Gogoll (2016) as shown in Figure 2-22.

- Highly episodic runoff from the outcropping Musgrave, Mann and Tomkinson ranges;
- Highly episodic groundwater recharge predominantly at the ranges, where bedrock aquifers outcrop, but episodic recharge fluxes are also possible through ephemeral drainage lines traversing surficial alluvium and colluvium away from the ranges;
- Alluvial/colluvial and bedrock aquifers are hydraulically interconnected via localised bedrock discharge recharging the alluvium/colluvium surrounding the ranges and via throughflow from the alluvium/colluvium recharging underlying palaeovalley and compartmentialised bedrock aquifers;
- Intermediate to regional groundwater flow is ‘generally’ from north to south in both alluvial/colluvial and palaeovalley aquifers;
- Groundwater flow is controlled by highly episodic and low recharge fluxes occurring predominantly around the Musgrave and Mann ranges in the north of the province with flow proceeding and diminishing south towards the Officer Basin given very low hydraulic gradients;
- Intermediate to regional groundwater flow in alluvial/colluvial and palaeovally aquifers is also controlled by bedrock topography where small outcrops and shallow subcrops of crystalline basement sporadically interupt and create more tortuous flow paths from north to south;
- Structure compartmentalises the alluvial/colluvial fill in the palaeovalleys which may also influence the groundwater flow paths;
- The flow paths may also be interrupted by neotectonic activity resulting from the reactivation of basement structures and the formation of hydraulic barriers in the overlying sediment package;
- Groundwater discharge in alluvial/colluvial aquifers occurs via a combination of evapotransitaion and throughflow to both underlying palaeovally and bedrock aquifers, as well as southerly flow towards the Officer Basin;
- Groundwater discharge in bedrock aquifers occurs as evapotranspiration in aquifer outcrops and throughflow to adjacent alluvial/colluvial aquifers at the foot of the ranges;
- There is no hydraulic or hydrogeochemical evidence to support a hypothesis for intermediate to regional groundwater flow in bedrock aquifers in such a data sparse region. Evidence from airborne geophysics, lithological and stratigraphic logs, geological modelling, regional magnetics and high variability in both bore yields and groundwater salinity suggests the bedrock aquifers are highly compartmentalised but hydraulically interconnected at locations where they are overlain with palaeovalley and alluvial/colluvial aquifers.

Project publications

Macnae J, Xiuyan R and Munday T (2020a) Stripping induced polarization effects from airborne electromagnetics to improve 3D conductivity inversion of a narrow palaeovalley. *Geophysics* 85(5): B133–B139.

Munday T, Taylor A, Raiber M, Soerensen C, Peeters L, Krapf C, Cui T, Cahill K, Flinchum B, Smolanko N, Martinez J, Ibrahimi T and Gilfedder M (2020) Integrated regional hydrogeophysical conceptualisation of the Musgrave Province, South Australia. Technical Report Series No. 20/04, Goyder Institute for Water Research, Adelaide.

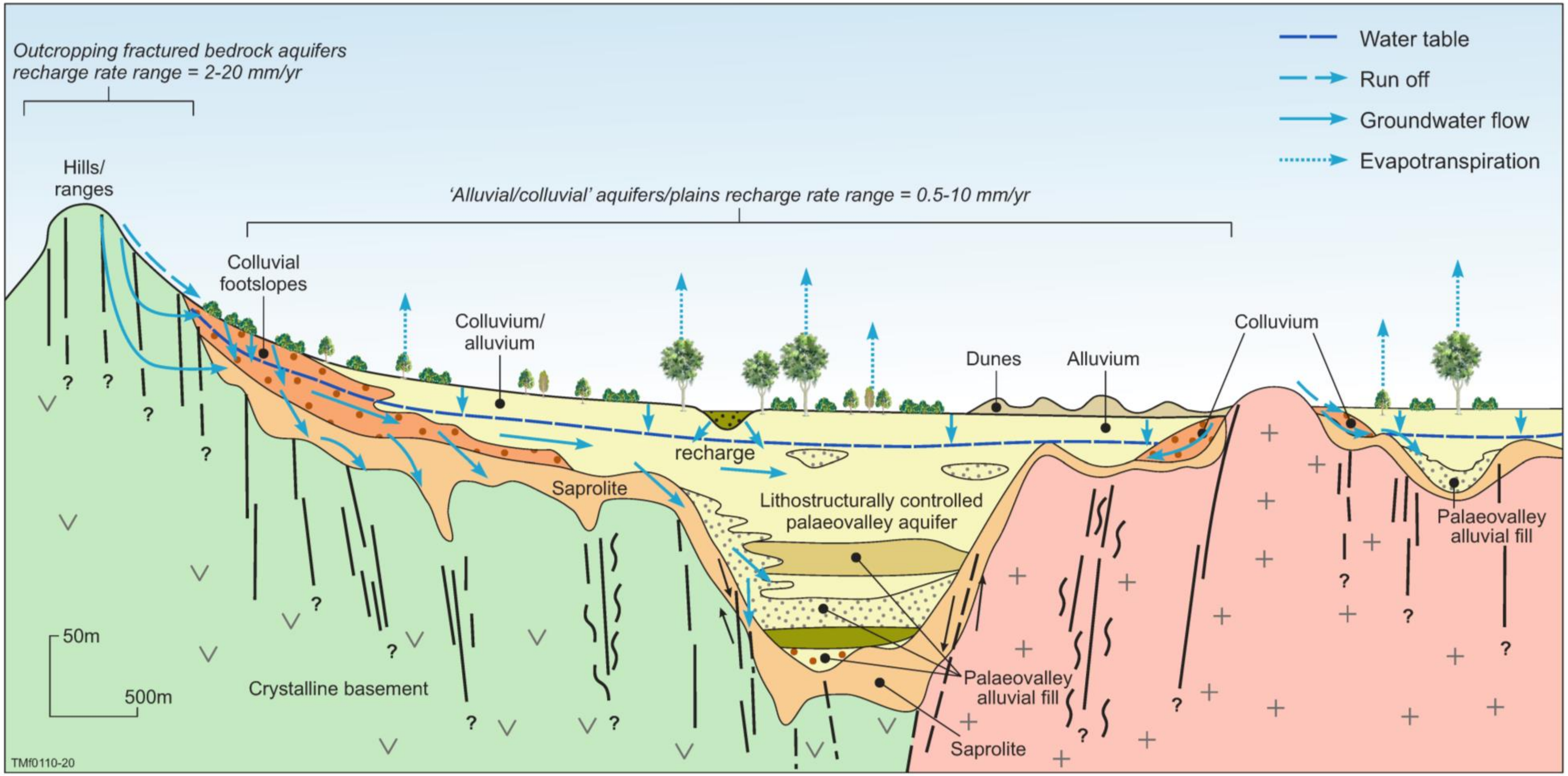


Figure 2-22. Schematic hydrogeological conceptual model showing a typical palaeovalley drainage system in the Musgrave Province. Figure adapted from Munday et al. (2013, 2020) and Gogoll (2016).

2.10 Numerical modelling of the Lindsay East Palaeovalley at the hydrogeological control site

Groundwater flow and age modelling were undertaken in order to test different plausible conceptual models of the groundwater regime within the palaeovalley to aid the understanding of the available resource. The purpose of modelling was to assess various conceptualisations of the system. This model is an initial attempt to model the palaeovalleys, however, it must be mentioned that further data collection would be required to provide more confidence and extend our results to obtain sustainability parameters.

The groundwater flow model was constructed as a two-dimensional vertical transect model. The model domain was aligned along the main trunk of the Lindsay East Palaeovalley, following the deepest recorded basement elevations based on the AEM conductivity depth profiles (Figure 2-23). The top elevation followed the ground surface. Overall, the selected model domain covers a flow distance of 17 km, originating at the prominent AEM feature in the north, where an east-west trending tectonic feature intersects the main trunk of the palaeovalley (Figure 2-23). The model extends south along the palaeovalley to the DH1 site. Based on the hydrogeological site characterisation and ^{14}C data at site DH1, a range of plausible conceptual models for the physical flow processes within the palaeovalley were formulated. These were translated into a corresponding numerical model using the USGS MODFLOW (Harbaugh 2005) model as the basis for the flow simulation, while the reactive transport model code PHT3D (Prommer et al. 2003) was applied for the simulation of groundwater age.

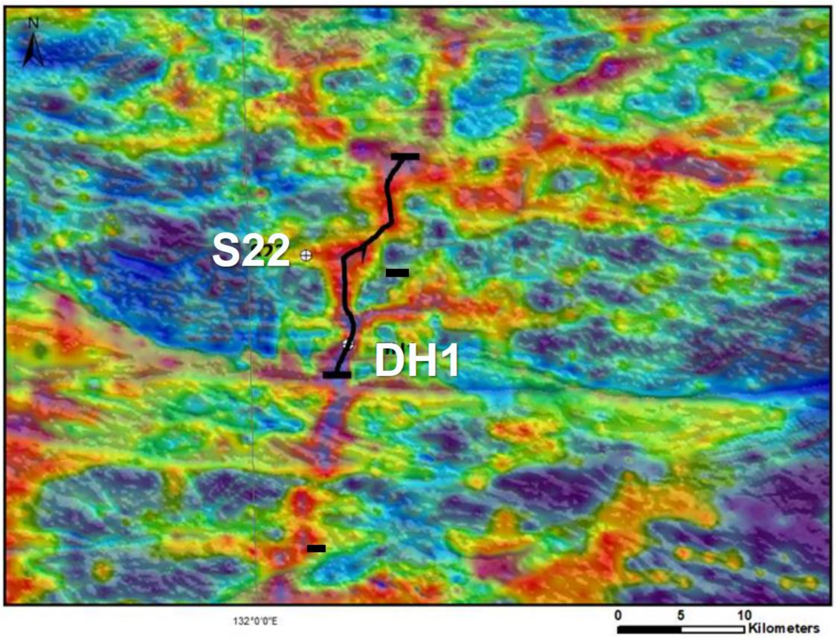


Figure 2-23. Location of the model profile across hydrogeological control sites DH1 and S22 including airborne electromagnetic depth slice 60-70 m below natural surface (colour) and total magnetic intensity (texture).

The palaeovalley aquifers, including a 20 m thick marine mud formation, were discretised into five model layers in order to obtain a sufficient vertical resolution of the lithology (see Figure 2-21). Thereby, layers 1 to 3 covered the upper 65 m thick fluvial sandstones, Layer 4 is the mud that overlies the base layer (Layer 5) and represents the basal fluvial sandstone aquifer (see Figure 2-21). The horizontal cell discretisation was homogeneous at 200 m cell width. Recharge was approximated to be 5 mm/year over the model domain. Influx via the northern boundary was allowed in model variants 2 and 6 via a general-head boundary in the upper fluvial sandstones (layers 1 to 3), while rainfall recharge was the sole influx for all other conceptual models. Outflow via model boundaries was allowed via the upper fluvial sandstone aquifer at the downstream southern extent of the model domain, implemented through a general-head boundary condition (Figure 2-24). Lateral groundwater flux perpendicular to the main trunk of the palaeovalley was considered negligible on the basis of the AEM depth profile at site DH1 and the ^{14}C age data at site S22, which indicated old water at the shallow margin of the palaeovalley, suggesting a limited hydraulic connectivity.

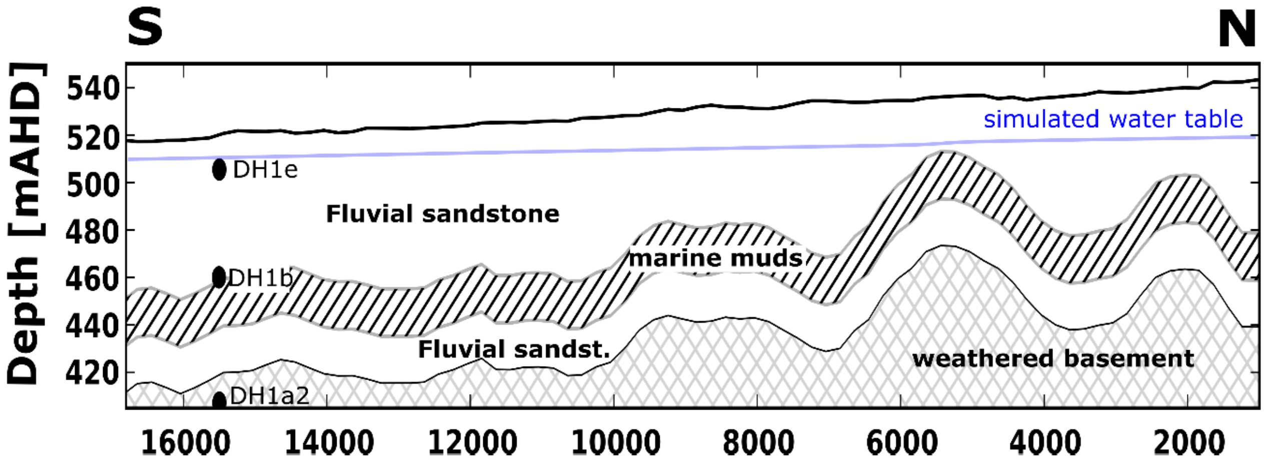


Figure 2-24. Dimension of model domain and spatial distribution of lithology along model transect from north–south.

A suite of six conceptual and numerical model variants for the sites groundwater flow regime were investigated. The flow and solute transport model head and groundwater age results were compared to measured groundwater heads and corrected ^{14}C groundwater ages at site DH1 and the regional head distribution for each scenario. The comparison between model simulation results and observations thereby allowed us to prioritise some conceptual models above others for their potential to represent a realistic flow regime and with that, aided in the understanding of the sustainability of the resource. At this stage, the numerical implementation of the palaeovalley geometry and lithology is idealised and based on depth records from site DH1, since more spatially distributed observation data is lacking. The available measured data along the profile is currently insufficient to constrain these conceptual models more tightly. The conceptual models could be verified in the future when additional age and water level data become available at various distances along the profile.

Based on the findings of model variants No. 1 to No. 5 in combination with the evidence from the discharge tests conducted at DH1, the most plausible conceptual model (model variant No. 6) recognises the hydraulic conductivities for the fluvial sandstones determined through aquifer testing (up to 25 m/day) and conceptualises the clay aquitard as discontinuous. This, in combination with the lateral influx of groundwater into the palaeovalley in addition to rainfall recharge, allows the regional head gradient, the vertical head gradient at DH1 and the observed 14C age distribution to be reasonably replicated (Figure 2-25).

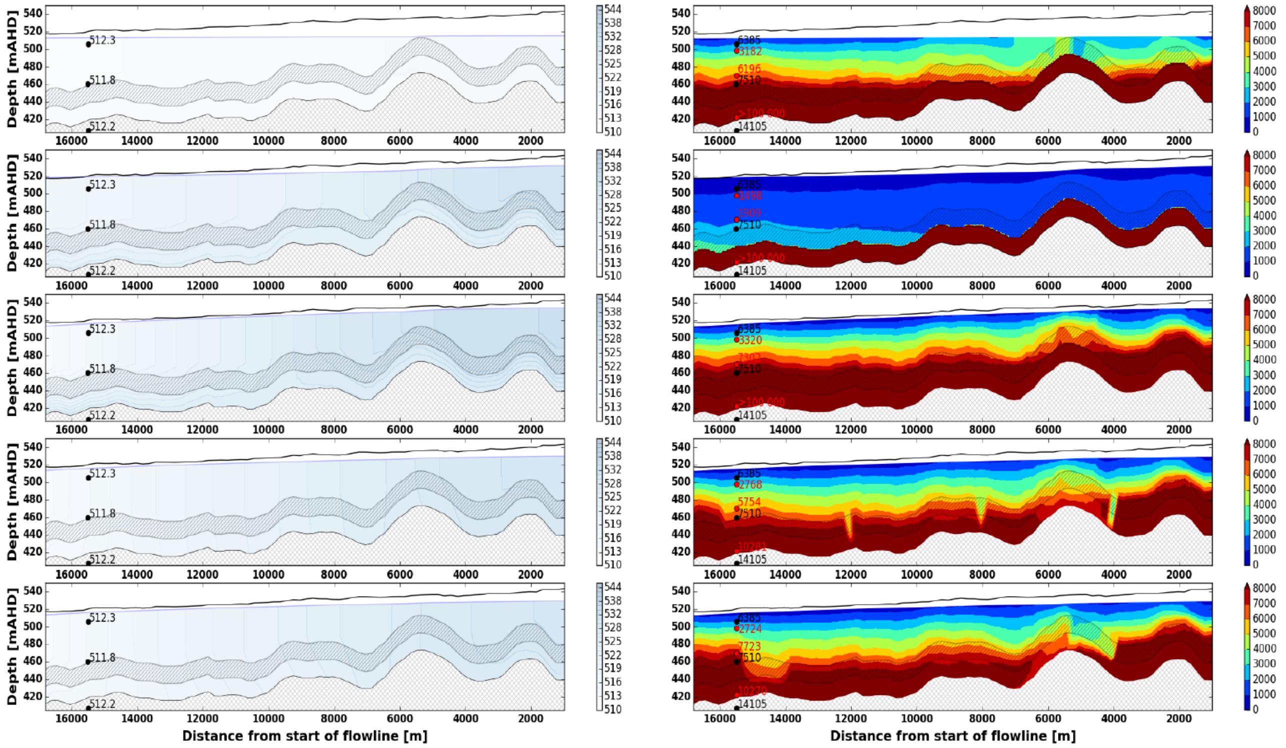


Figure 2-25. Simulated groundwater heads (mAHD) and groundwater age (years before present) for model variants No. 1 to No. 5. Observed groundwater age data based on ^{14}C measurements are marked in black for DH1e, DH1b and DH1a2, while the vertical simulated age distribution at site DH1 is provided in red for three depths.

Project publications

Love A, Costar A, Krapf C, Xie Y, Wallis I, Lane T, Keppel M, Inverarity K, Deng Z, Munday T and Robinson N (2020) G-FLOWS Stage 3: Hydrogeological conceptual understanding of the APY Lands groundwater system including the Lindsay East Palaeovalley. Goyder Institute for Water Research Technical Report Series No. 20/06, Goyder Institute for Water Research, Adelaide.

2.11 Hydrogeological conceptual understanding of the Anangu Pitjantjatjara Yankunytjatjara Lands groundwater system including the Lindsay East Palaeovalley

2.11.1 REGIONAL HYDROGEOLOGY

The hydrogeology of the region is complex in terms of both the hydrostratigraphy and the groundwater flow systems. Data is limited as it is a remote area which is difficult to access (special permits and permissions are required to enter the APY Lands), and as such, the understanding of hydrogeological processes are often general.

Most of the hydrogeological information comes from basic investigations into water supplies for the communities, road building and special research projects such as G-FLOWS. The occurrence and distribution of water wells is quite sparse throughout the vast area of the APY Lands and monitoring and maintenance of wells in this remote area is challenging.

Broad-scale geology and hydrogeology of the region has received some recent attention through investigations focused on small-scale localised water supplies for road building (Pawley and Krapf 2016), which has also delivered new insight into the hydrostratigraphy. Previous studies have suggested that the Musgrave Ranges and the headwaters of the drainage channels originating in the ranges, are important recharge areas (Leaney et al. 2013).

Faulting is widespread across the APY Lands and the region is known to be still tectonically active with evidence of many small-scale seismic events and earthquakes (Pawley and Krapf 2016). The specific impact of faulting on localised groundwater flow patterns within the study area is currently difficult to discern given the lack of data. However, given the prevalence of deformation, it is likely to be important. The general east-west trend of structural deformation, which is perpendicular to the north-south or northwest-southeast direction of the palaeovalley development, regional surface drainage and groundwater flow suggests that tectonic uplift or sagging is generally more important than the influence of shearing on the groundwater system.

Figure 2-20 displays the average depth weighted AEM horizontal slice from 45.3–53.8 m BNS) superimposed onto the total magnetic intensity (TMI). The red colour denotes zones of high conductivity while the blue zones denote zones of low conductivity and more resistive rock. Overlaying these two geophysical layers is an interpretation of potential east-west orientated faults in the region by Pawley and Krapf (2016). These faults can often correspond to rapid changes in the values of conductivity or magnetic intensity which is inferred to represent changes in lithology of the rocks, which often correspond to juxtaposing geological units.

While the AEM shows tributaries of the main palaeovalley drainage system are aligned east-west, the course of the main palaeovalley ‘channel’ is only affected in small area (where it actually crosses the east-west structures) and follows the natural topographic gradient from north to south (Krapf et al. 2019).

The potential influence of the east-west structural deformation on the groundwater flow systems can be observed in the AEM. This perpendicular relationship may also indicate a potential for localised development of lateral flow barriers, or preferential flow pathways (Krapf et al. 2019). Additionally, reactivation of older structures may have an important influence on the architecture of present-day drainage and palaeovalleys. Such an architecture is interpreted between Pukatja and Kaltjiti where the accumulation and thickness of Quaternary and Tertiary alluvial sediments appears to be impacted by dip-slip movement along east-west fault planes (Krapf et al. 2019).

The development of numerical models to simulate a system requires, in the first instance, an understanding or conceptualisation of the system. Conceptualising the hydrogeological processes in a groundwater system is an important step and includes some key elements which address characterisation of the system. These include, but are not limited to:

- Geological setting (including structural features and stratigraphy);
- Groundwater salinity and yield;
- Hydrostratigraphy – investigations that provide an understanding of the hydraulic nature of the system such as aquifer testing and measures of porosity; aquifer interconnectivity;
- Architecture – identification of aquifer systems (water bearing zones), their geometry, location within the landscape and their relationship with one another;
- Flow systems – establish groundwater flow direction(s) through various investigations including groundwater level measurements; and
- Recharge and discharge processes – where are these processes potentially located in the landscape and what are their recharge and discharge rates.

This project collated a number of different scientific tools which have been used to obtain a greater understanding of the system. These tools/datasets included AEM, surveying, geochemistry, environmental tracers and aquifer testing. It is important to understand that conceptualisation (and numerical modelling) is an iterative process meaning as new information and data becomes available there is a need to revisit the conceptualisation and update where necessary. However, the process of starting conceptualisation is extremely useful since it can identify knowledge gaps and therefore target investigations.

This chapter summarises the regional groundwater conceptualisation based on groundwater sampling undertaken in this project.

2.11.2 GROUNDWATER FIELD SAMPLING

Groundwater sampling was conducted during the drilling and airlifting phase (two samples – pre- and post-development) of the drilling program but was restricted to field measurements and major and minor solutes.

In November 2018 (3 months post drilling), a dedicated environmental tracer program was conducted. This involved collecting groundwater samples for the following environmental tracers:

- Tritium (^{3}H)
- Carbon isotopes (^{14}C and ^{13}C)
- Stable isotopes
- Major and minor solutes/elements

These samples were sent to laboratories (ANSTO, GNS Science (New Zealand) and CSIRO) for analysis in early January 2019 with results received in March to September 2019.

While G-FLOWS Stage-3 focused on the Lindsay East Palaeovalley, this sampling and analysis complemented the historical sampling mentioned in the previous sections.

2.11.3 HYDROGEOLOGICAL UNITS

Identification of the major hydrogeological units is well documented in Costar et al. (2019). Whilst specific groundwater quality assessments are required before it can be used for any specific purpose, they are dependent on the desired use of the water source. Salinity is a useful and preliminary water quality indicator that can be used to determine the potential for groundwater use. The well yield is also an important factor when considering the significance of a groundwater source.

The hydrogeological control site DH1 is located ~5 km southeast from Kaltjiti centred on the Lindsay East Palaeovalley. This was the first time that deep palaeovalley sediments have been used as water targets and drilled to investigate their potential as a suitable groundwater resource in the APY Lands. The sediments within the Lindsay East Palaeovalley can be divided broadly into four major units based on their hydrogeological characteristics:

- **Units 1a and 1b: Unconfined aquifer** (well DH1e, unit no. 5344-83). Encompasses the dune and underlying sandplain system (~30 m thick) beneath which lies the hydraulically connected fluvial palaeovalley fill sand deposit with an estimated thickness of 35 m (Krapf et al. 2019). Groundwater is encountered at ~8 m BNS. Salinities in the top 30 metres are ~1000–1500 mg/L and yields are estimated to be <1 L/s. However, for the target-water-bearing palaeovalley zone (55–65 m deep), salinities are lower ~870 mg/L, with much higher yields of 10–18 L/s (wells DH1b, DH1c, DH1d; unit no. 5344-89, 5344-80, 5344-82). Transmissivity values of ~120 m/day (Costar et al. 2020). Hydraulic parameters were estimated by conducting step drawdown tests and a constant rate discharge test (12 hour continuous pumping).
- **Unit 2: Confining bed.** Consists of a 20 m thick sequence of mud (silty clay).
- **Unit 3: Confined aquifer.** Represents the basal palaeovalley fill sediments (wells DH1a, DH1a2, unit no 5344-87, 5344-78; note DH1a has no screen interval and was replaced by DH1a2) consisting of sand but with a slightly higher salinity range (1200 mg/L). Yields are <2 L/s which is much less than that of the target-water-bearing palaeovalley zone. Thickness is ~10–15 m, grading into a weathered basement sequence at the bottom (which overlies fractured rock and a consolidated fresh basement).
- **Unit 4a: Weathered basement** (well DH1f, unit no. 5344-85). Located ~700 m to the west of the centre of the palaeovalley, yields are extremely low (<1 L/s) with salinities ~1000 mg/L. **Fresh basement forms Unit 4b** but has not been intersected in the drilling.

2.11.4 CONCEPTUALISATION

The hydrogeological conceptualisation developed from detailed drilling investigations at the scale of the palaeovalley (Figure 2-26) is consistent with that derived from primarily airborne and surface based geophysical information constrained by borehole logs (see Section 2.9). The ability to drill new groundwater wells that were study specific was a significant and crucial component in gathering groundwater data in the Lindsay East Palaeovalley at the local scale. While more drilling is required, historically, geological and hydrogeological interpretation has largely relied upon airborne datasets due to the difficulty in accessing the APY Lands due to the remoteness of the area and permissions.

Greater understanding of geological unit distribution across the study area (a subset of the APY Lands), as well as the evolution of the palaeovalleys has been achieved. In particular, the discovery of recurrent marine influences turned the Lindsay East Palaeovalley into an estuarine system during the Late Miocene – Early Pliocene and marine influence reached close to the foothills of the Musgrave Ranges more north than was previously observed and anticipated.

The geology of this region is extremely complex as the basement units contain highly metamorphosed rocks that have been intruded, folded and faulted, overlain by Adelaidean sediments that have also been influenced by subsequent deformation. In addition, erosion of and sedimentation onto the basement palaeosurface and the erosional and depositional processes that led to the evolution and preservation of the palaeovalley drainage system added to the complexity.

Converting geological information into a meaningful hydrogeological model and hence understanding is a difficult process. This is even more difficult in the APY Lands due to the complex nature of the geology as well as the overall data sparsity.

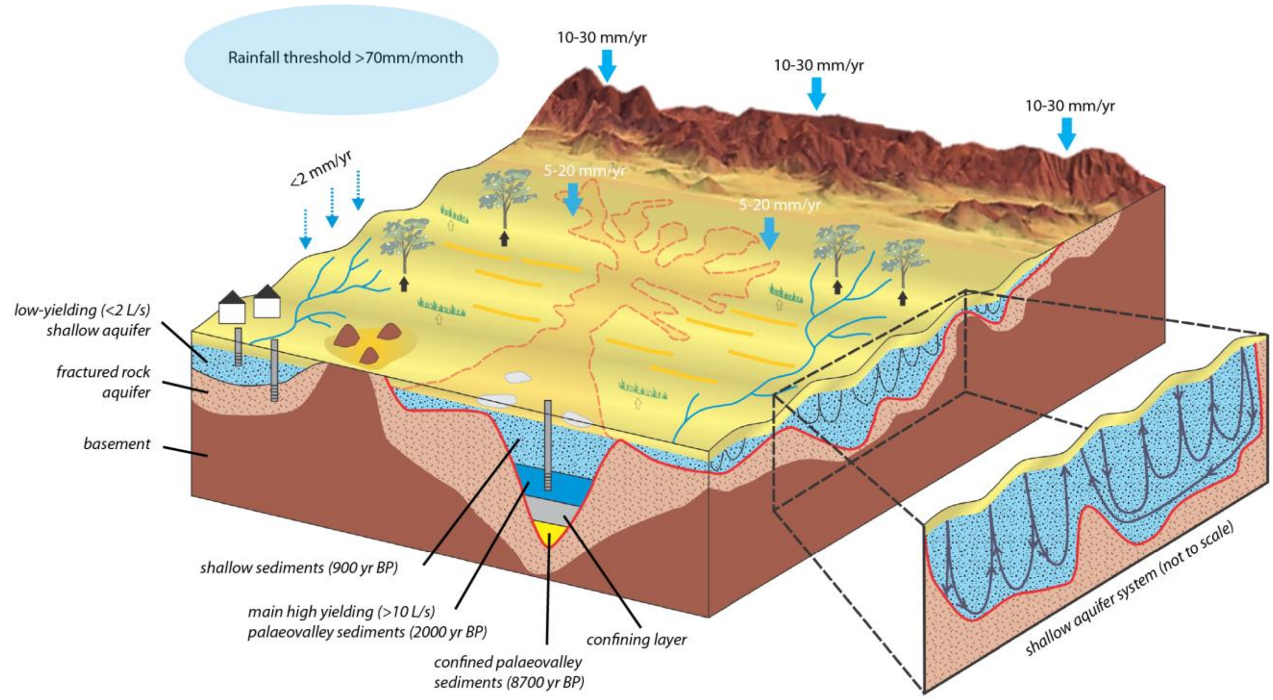


Figure 2-26. Schematic conceptual hydrogeological understanding in the Anangu Pitjantjatjara Yankunytjatjara Lands.

The watertable follows the topographic surface at a relatively shallow depth. Undulations of the watertable combined with relatively large aspect ratios result in cellular groundwater flow systems.

Groundwater flow systems of the APY region are dominated by local, and to a lesser extent, intermediate flow systems. There is no evidence for a regional flow system, nor that of groundwater recharge originating from the Musgrave Ranges to the flatter plains of the study area. Furthermore, first pass numerical modelling indicates that even small undulations of the watertable can drive local groundwater flow systems.

Groundwater recharge to the hydrogeological system occurs for monthly rainfall in excess of 70 mm/month. Rapid recharge to the aquifers occurs from monsoonal activity in the north of the continent that deposits intense rainfall events with depleted values of the stable isotopes of groundwater. This rapid recharge mechanism is also supported by modern radiocarbon as well as low Cl concentrations. High rates of groundwater recharge (~10-20 mm/year) occur in the Musgrave Ranges and are associated with fractured rock aquifers while the plains, and the source of community supply exhibit much lower recharge rates (<2 mm/year).

Diffuse discharge driven by evaporation appears to be minimal. Rather, groundwater discharge is dominated by transpiration from plants. These areas are located in low lying regions of the landscape.

The palaeovalley system exhibits both recharge and discharge zones.

Groundwater recharge to the Lindsay East Palaeovalley (~8–20 mm/year) occurs at the boundary of the fractured rock unit and the palaeovalley sedimentary fill. A good example of this occurs near the community of Umuwa.

The new watertable map shows a mixture of groundwater flow at different scales, i.e. local and intermediate. This includes a general gradient of the watertable towards the south, however, this is superimposed by several local groundwater flow cells as indicated by large and small scale watertable undulations. In these local areas groundwater will flow from high zones to low zones, which corresponds to zones of potential recharge and discharge.

The discovery of a new fresh groundwater resource (<1000 mg/L TDS) in the APY Lands has enormous potential for the future development of this remote region in outback South Australia. Availability of a high yielding groundwater resource within the Lindsay East Palaeovalley could unlock the potential for economic development in the region. However, it is vital to follow up with additional hydrogeological investigations to determine the size and sustainability of this groundwater resource.

2.11.5 FUTURE WORK

Future work is required to assess the full potential of these palaeovalley resources. This work includes drilling, aquifer testing and geochemical sampling, for both a greater understanding of the sustainability of the system as well as the potential targeting of new untapped greenfield water resources. Specifically:

- Deep drilling (<120 m BNS) along the course of the Lindsay East Palaeovalley i.e. to the north and south of the hydrogeological control site DH1, including establishment of nested piezometers.
- Shallow drilling (<20 m BNS) to map the watertable along the Lindsay East Palaeovalley thalweg.
- Long-term aquifer testing designed to assess pumping sustainability of the resource.
- Establishment of nested piezometers in recharge zones.
- Establishment of weather stations (i.e. rainfall) in the ranges and plains to assess the local climate.
- Hydrogeological and geological mapping of the land surface to assess any groundwater manifestations (i.e. what the landscape tells us about the groundwater flow).
- Drilling into other palaeovalley systems, such as the Lindsay West Palaeovalley to help determine the feasibility of other palaeovalleys as potential water targets and resources and verify characteristics of the wider palaeovalley drainage distribution across the APY Lands.
- Extend the groundwater environmental tracer suite to argon 39 and krypton 85 (100–3000 years BP) that is more conducive to the groundwater age windows within the APY Lands.
- Extension of the numerical modelling, once more data (temporal and spatial) is available.
- Mapping of recharge and discharge zones in combination with numerical modelling.

This research to uncover a palaeovalley drainage network in the APY Lands has identified the location of a potentially significant new water resource. Finding reliable water resources under cover in arid environments is challenging but by having a suitable water target, such as the palaeovalleys, ensures a greater probability of success.

A considerable amount of data and analysis has been achieved by this study/project to further understanding the groundwater system (in particular the palaeovalley system). More work and targeted investigations are required to add to the findings and to prove the groundwater resource for the region.

Project publications

Keppel M, Costar A, Love A and Krapf C (2019) G-FLOWS Stage 3 APY Lands Drilling Program, north-western South Australia. Technical Report Series 19/39, Goyder Institute for Water Research, Adelaide.

Krapf C, Costar A, Stoian L, Keppel M, Gordon G, Inverarity K, Love A and Munday T (2019) A sniff of the ocean in the Miocene at the foothills of the Musgrave Ranges – unravelling the evolution of the Lindsay East Palaeovalley. *MESA Journal* 90(2), 4–22.

Love A, Costar A, Krapf C, Xie Y, Wallis I, Lane T, Keppel M, Inverarity K, Deng Z, Munday T and Robinson N (2020) G-FLOWS Stage 3: Hydrogeological conceptual understanding of the APY Lands groundwater system including the Lindsay East Palaeovalley. Goyder Institute for Water Research Technical Report Series No. 20/06, Goyder Institute for Water Research, Adelaide.

2.12 Groundwater knowledge integration system

Water resources managers siting boreholes for long-term water supply in remote areas in the arid interior of Australia need regional scale information of groundwater prospectivity. The information and data available are often very limited and new information and data does not only change the prospectivity, it has the potential to change the conceptualisation of the system.

The objective of the Groundwater Knowledge Integration System (GKIS) is to develop a framework for groundwater prospectivity mapping that (i) accounts for uncertainty due to limited data availability and (ii) allows to update prospectivity where and when new information becomes available.

The methodology starts with an explicit definition of sustainable groundwater extraction, which is a function of the minimal required pumping rate, minimal period the pumping rate needs to be sustained, the maximum allowed drawdown and groundwater quality requirements (such as maximal salinity levels). Stochastically generated grids of hydraulic properties and salinity are evaluated to obtain probability distributions of maximal pumping rate (Theis Equation), available volume and salinity. Groundwater prospectivity is expressed as the joint probability that all requirements for sustainable development are satisfied (Peeters et al., 2020). The stochastic grids of hydraulic properties and salinity can be iteratively updated as new information becomes available and alternative conceptualisations are developed.

The methodology was applied to groundwater exploration in the APY Lands. In this arid region, a crystalline basement is covered with regolith and a vast system of palaeovalleys that are filled with sediments. Both the regolith and the palaeovalley systems are known to host aquifer systems.

Figure 2-27 shows the evolution of the conceptualisation of the system in function of the data available. The initial desktop mapping based on a high-resolution digital elevation model identified three hydrostratigraphic units (HSU). For each HSU, a prior distribution for the hydraulic properties and salinity is established, based on the available data and knowledge. The probability of finding a water source that can sustain 30 m^3/d of pumping for ten years without causing a drawdown of more than 5% of the saturated thickness and has a salinity of less than 5000 mg/L in this conceptualisation is 0.11 for the palaeovalley HSU, 0.07 for the colluvium and 0.03 for the bedrock HSU.

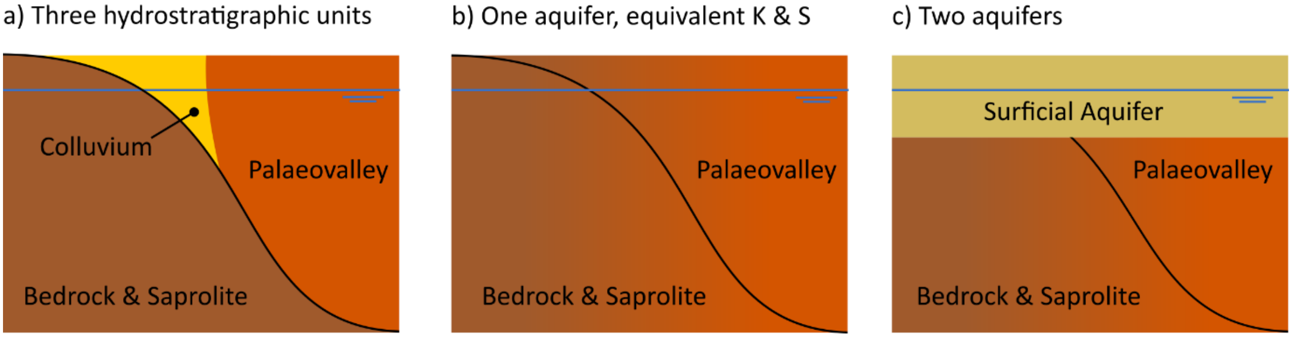


Figure 2-27 Evolution of conceptualisation with increasing data availability: a) three hydrostratigraphic units based on DEM mapping, b) single aquifer with equivalent properties based on saprolite - palaeovalley interface from airborne electromagnetic survey, c) two aquifer system based on interpretation of borehole data.

The 2016 airborne electromagnetic (AEM) survey (Soerensen et al. 2018) allowed the identification of the interface between bedrock/saprolite and palaeovalley sediments. The results of the AEM survey were combined with borehole data and geological mapping with the Cover Thickness Uncertainty Mapper algorithm (Visser and Markov 2019) to generate an ensemble of 1020 surfaces, all consistent with the available data and knowledge. The conceptualisation was changed to a single aquifer system with equivalent properties based on the position of the interface between bedrock/saprolite and palaeovalley sediments (Peeters and Visser 2019) and the position of the watertable. The latter was created using Bayesian Data Fusion of kriged groundwater level observations and a MODFLOW groundwater model (Peeters et al. 2010). This resulted in a spatially variable probability map, with probabilities ranging from less than 0.01 to 0.25.

The hydrostratigraphic interpretation of a 116 m cored borehole drilled in 2018 in combination with the on-ground geophysics resulted in another revisit of the conceptualisation (Figure 2-27c). The top 30 m of the system is now considered to be a continuous surficial aquifer system with the hydraulic properties and salinity previously assigned to the colluvium HSU. Figure 2-28 shows the combined probability of finding a sustainable water source in either the surficial aquifer or in the underlying bedrock/palaeovalley system aquifer. The maximum probability increased to 0.30 and the spatial distribution of the palaeovalleys as most prospective regions is apparent. Note the area in Figure 2-28 for which prospectivity is calculated extends beyond the area covered by the AEM survey as the GKIS methodology is able to extrapolate findings from data rich areas to data poor areas.

The stochastic framework for groundwater prospectivity mapping based on an explicit definition of sustainability requirements allows iterative updating of conceptualisation as new information becomes available. The level of confidence in the prospectivity estimate is expressed as a probability of success.

For the case study in the APY Lands, the most attractive regions for groundwater production are associated with palaeovalley systems. Outside the palaeovalley systems, prospectivity can also be high, provided drilling targets both the surficial and deeper aquifer. The datasets of the G-FLOWS Stage-3 proved to be an ideal testbed for the development of machine learning approaches in palaeovalley mapping (Jiang et al. 2019) and watertable mapping (Cui et al. 2019).

Project publications

Cui T, Pagendam D, Peeters LJM, Siade AJ, Gilfedder M, Janardhanan S (2019) Gaussian process machine learning for groundwater system characterisation and modelling. Abstract presented at AGU Fall Meeting 2019.

Jiang Z, Mallants D, Peeters L, Gao L, Soerensen C, Mariethoz G (2019) High-resolution paleovalley classification from airborne electromagnetic imaging and deep neural network training using digital elevation model data. *Hydrology and Earth System Sciences* **23**: 2561–2580.

Peeters L (2018) Sensitivity analysis and value of information in groundwater exploration: a case study from the APY lands, South Australia. In: AGCC 2018 - Australian Geoscience Council Convention; 14-18 October 2018; Adelaide, Australia. Abstract 469.

Peeters LJM and Munday T (2020) Iterative updating of conceptualisation in probabilistic groundwater prospectivity mapping. Extended abstract accepted for presentation at Computational Methods in Water Resources, June 2020, Stanford, USA

Peeters LJM and Visser G (2019) Probabilistic data assimilation for cover thickness mapping in the APY Lands. Jupyter Notebook. CSIRO.

Peeters LJM, Mallants D, Cui T, Taylor A, Pickett T, Gilfedder M, Munday T (2019a) Stochastic knowledge integration for groundwater exploration in data scarce areas. Abstract presented at IAH2019, 22-27 September 2019, Malaga, Spain.

Peeters L, Mallants D, Cui T, Taylor A, Pickett T, Gilfedder M, Munday T (2019b) Stochastic knowledge integration for groundwater exploration in data scarce areas (396). Abstract presented at NCGRT/IAH Australasian Groundwater Conference 2019, Brisbane November 24-27.

Peeters LJM, Cui T, Pickett T, Gilfedder M, Mallants D, Taylor A, Jiang Z, Flinchum B, Cahill K, Munday T (2020) Groundwater Knowledge Integration System (GKIS): Probabilistic groundwater prospectivity mapping with iterative updating of conceptualisation. Technical Report Series No. 20/01, Goyder Institute for Water Research, Adelaide.

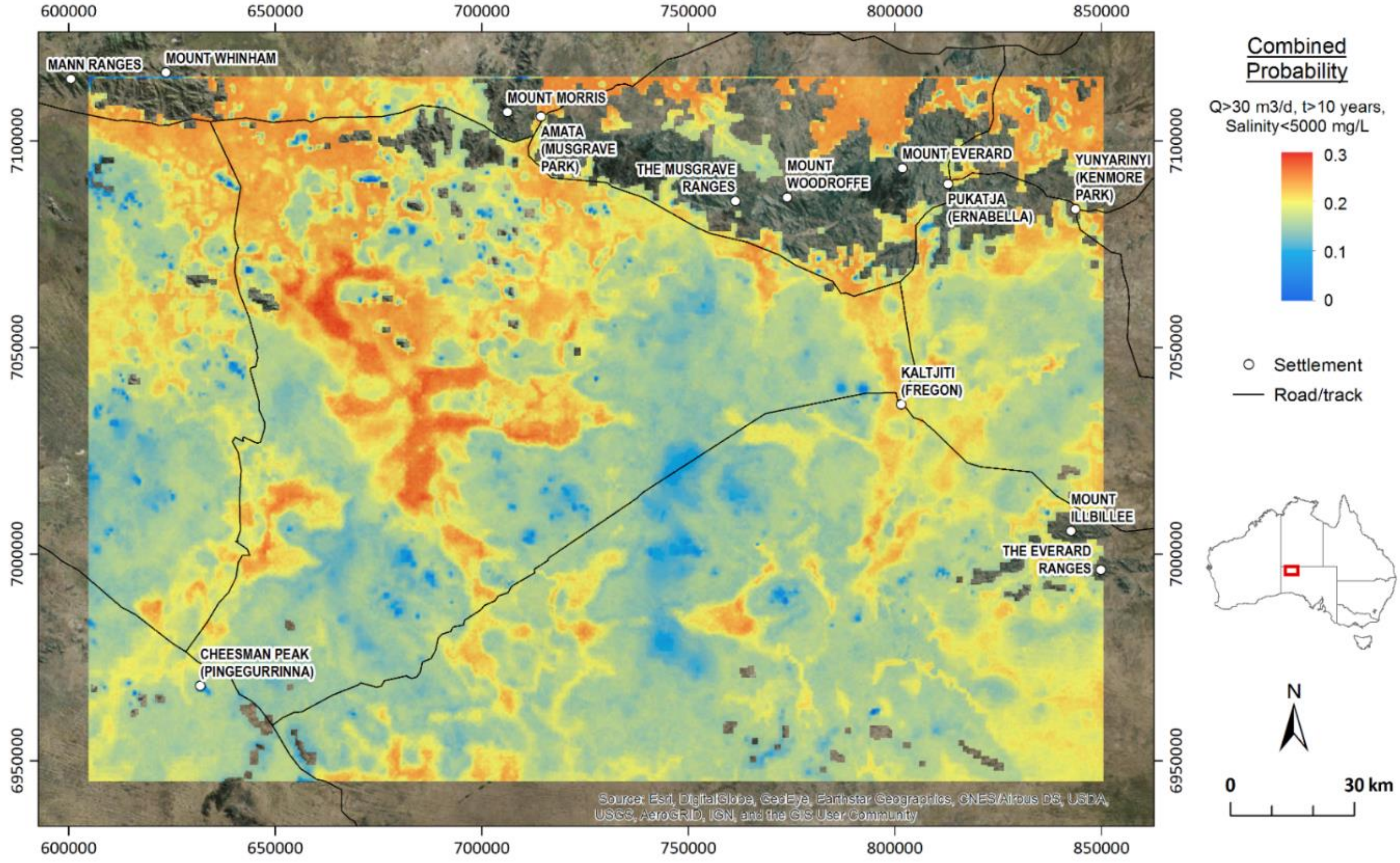


Figure 2-28. Probability of sustaining a pumping rate of 30m^3/d for 10 years with a salinity less than 5000 mg/L.

3 Recommendations

G-FLOWS Stage-3 has clearly shown the benefits from the application of AEM surveys for providing an up-scaled understanding of the hydrogeology at the regional scale. For the Musgrave Province this includes spatial mapping of key hydrogeological units including alluvium/colluvium, palaeovalleys and outcropping/sub-cropping bedrock across the region. It also provides the additional benefit of mapping the spatial extent and thickness of both alluvium/colluvium and palaeovalleys which are key targets for water resource exploration. Furthermore, while localised drilling and ground-based geophysical investigations such as those conducted on the Lindsay East Palaeovalley have further characterised the hydrostratigraphy and nature of the groundwater present, the AEM survey provides increased confidence that these findings can potentially be extrapolated to other areas of alluvium/colluvium and palaeovalleys, such as the Lindsay West Palaeovalley.

While the project has demonstrated the potential of different hydrogeophysical techniques to elucidate the hydrostratigraphy and nature of the groundwater present in the Lindsay East Palaeovalley system, the value of more systematic studies such as this will only be realised through further hydrological investigations of the aquifers, and through additional combined analysis of the geophysical data. For example, it is possible to constrain inversions of electromagnetic data with information provided by seismic data. Similarly, the joint inversion of borehole and surface EM data can also be undertaken. Potentially these approaches will yield more robust models for subsurface properties.

The Groundwater Knowledge Integration System (GKIS) provides a systematic and transparent framework to integrate the available information into quantities relevant to water resource management. The prospectivity maps can easily be updated as new information becomes available and allows to extrapolate to data poor areas. It is recommended that the prospectivity maps continue to be updated as new information becomes available and the hydrogeological conceptualisation further evolves.

As additional ground-based geophysical results become available, the existing 3D geological model could be further enhanced by representing additional layers and through development of a 3D sedimentary facies model for sections of the palaeovalley systems (e.g. the Lindsay East Palaeovalley system near Kaltjiti/Fregon). This would enhance the characterisation of the hydraulic properties (e.g. identification of high conductivity layers) within the palaeovalley systems, help to further improve the hydrogeological conceptualisation and form the framework for development of a numerical groundwater model.

The regional AEM coverage also provides spatial context for previous drilling and aquifer testing undertaken in the assessment of groundwater resource, to support local community and industry. The opportunity remains to reassess that information in light of these data to better constrain the hydrogeological conceptualisation. These technologies have seen application (post G-FLOWS Stage-1) in arid parts of WA and the NT where knowledge about aquifer systems and groundwater remains limited. In the SA context there is opportunity to further develop an understanding of groundwater resources along the Braemar Corridor and also along the coast west of Ceduna.

Undertaking further detailed testing of bores employing multi-level slug tests (MLST), dipole-flow tests, and/or well bore flow (WBF) logging would be beneficial, and would provide a basis for deriving calibration values for the nuclear magnetic resonance (NMR) data. This would then permit the spatial extension of boreole NMR logging to other parts of the region to derive more representative information on the hydraulic properties of the alluvial aquifer systems present.

References

Auken E, Christiansen AV, Kirkegaard C, Fiandaca G, Schamper C, Behroozmand AA, Binley A, Nielsen E, Effersø F, Christensen NB, Sørensen K, Foged N and Vignoli G (2015) An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data. *Exploration Geophysics* 46: 223–235.

Bell JG, Kilgour PL, English PM, Woodgate MF, Lewis SJ and Wischusen JDH (compilers) (2012) WASANT Palaeovalley Map – Distribution of Palaeovalleys in Arid and Semi-arid WA-SA-NT (First Edition), scale: 1:4 500 000. Geoscience Australia Thematic Map (Geocat № 73980) – hard-copy and digital data publication: http://www.ga.gov.au/cedda/maps/96

Brown RJS and Gamson BW (1960) Nuclear magnetism logging. *Petroleum Trans., AIME* 219: 201–209.

Coates GR, Xiao L and Prammer MG (1999) NMR Logging Principles and Applications. Halliburton Energy Services, Houston.

Costar A, Howles S and Love A (2020). G-FLOWS Stage 3, APY Lands Aquifer Testing, northwestern South Australia. Unpublished report.

Craven CB (2012) Sustainability of regolith hosted aquifers in the Musgrave Province: Northern South Australia. Honours Thesis. Flinders University of South Australia.

Custance HE (2012) Hydrochemistry of shallow regolith hosted aquifers in the eastern Musgrave Province of South Australia. Honours Thesis. Flinders University of South Australia.

Dodds AR, Hostetler S and Jacobson G (2001) Community Water Supplies in the Anangu Pitjantjatjara Lands, South Australia: Sustainability of Groundwater Resources. Bureau of Rural Sciences, Canberra.

Dunn K-J, Bergman DJ and Latorraca GA (2002) Nuclear Magnetic Resonance Petrophysical and Logging Applications. Oxford, United Kingdom: Elsevier Science.

Gilfedder M and Munday T (2013) Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-1) Final Report. Goyder Institute for Water Research Technical Report Series No. 13/13, Adelaide, South Australia. ISSN: 1839-2725

Gilfedder M, Munday T, Bestland E, Cahill K, Davies PJ, Davis A, Heinson G, Ibrahimi T, Lamontagne S, Ley-Cooper Y, Love A, Olifent V, Pichler M, Robinson N, Smith S, Sørensen C, Suckow A, Taylor AR, Thompson J and Annetts D (2015) Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-2) Final Report. Goyder Institute for Water Research Technical Report Series No. 15/49, Adelaide, South Australia. ISSN: 1839-2725

Gogoll M (2016) Challenges targeting potable groundwater in the APY Lands, SA. Presentation at SA-NRM Science Conference 2016, University of Adelaide 13-15 April 2016. Day 3 Session 8.

Gulbrandsen ML, Cordua KS, Bach T and Hansen TM (2017) Smart Interpretation – automatic geological interpretations based on supervised statistical models. *Computational Geosciences* 21: 427–440.

Harbaugh AW, Banta ER, Hill MC and McDonald MG (2000) MODFLOW–2000, the U.S. Geological Survey Modular Ground-Water Model—User guide to modularization concepts and the Ground-Water Flow Process. U.S. Geological Survey Open-File Report 00–92, 121 p.

Keppel M, Costar A, Love A and Krapf C (2019) G-FLOWS Stage 3 APY Lands Drilling Program, north-western South Australia. Technical Report Series 19/39, Goyder Institute for Water Research, Adelaide.

Krapf C, Costar A, Stoian L, Keppel M, Gordon G, Inverarity K, Love A and Munday T (2019) A sniff of the ocean in the Miocene at the foothills of the Musgrave Ranges – unravelling the evolution of the Lindsay East Palaeovalley. *MESA Journal* 90(2): 4–22.

Krapf CBE, Costar A, Munday T, Irvine JA, Ibrahimi T (2020) Palaeovalley map of the Anangu Pitjantjatjara Yankunytjatjara Lands (1st Edition), 1:500 000 scale. Department for Energy and Mining.

Kretschmer P and Wohling D (2014) Groundwater recharge in the Anangu Pitjantjatjara Yankunytjatjara Lands, South Australia. DEWNR Technical Report 2014/06, Government of South Australia, through the Department of Environment, Water and Natural Resources, Adelaide.

Leaney FW, Taylor AR, Jolly ID and Davies PJ (2013) Facilitating Long Term Out-Back Water Solutions (G-FLOWS) Task 6: Groundwater recharge characteristics across key priority areas. Goyder Institute for Water Research Technical Report Series No. 13/6, Adelaide, South Australia.

Munday TJ (2013) The role of airborne geophysics in facilitating long-term outback water solutions to support mining in South Australia. 23rd Geophysical Conference, ASEG, Extended Abstracts, http://dx.doi.org/10.1071/ASEG2013ab189.

Parsekian A, Grombacher D, Davis A, Flinchum B, Munday TJ and Cahill K (2014) Near-surface geophysics for informed water-management decisions in the Anangu Pitjantjatjara Yankunytjatjara (APY) lands of South Australia. *The Leading Edge* 33(12): 1342–1347.

Pawley MJ and Krapf CBE (2016) Investigating the potential for bedrock aquifers in the APY Lands. Report Book 2016/00021. Department of State Development, South Australia, Adelaide.

Peeters L, Fasbender D, Batelaan O and Dassargues A (2010) Bayesian data fusion for water table interpolation: Incorporating a hydrogeological conceptual model in kriging. *Water Resources Research* 46(8): W08532.

Prommer H, Barry DA and Zheng C (2003) MODFLOW/MT3DMS Based Reactive Multicomponent Transport Modelling. *Groundwater* 41(2): 247–257.

Soerensen CC, Munday TJ, Ibrahimi T, Cahill K and Gilfedder M (2018) Musgrave Province, South Australia: Processing and inversion of airborne electromagnetic (AEM) data. Technical Report Series 18/06, Goyder Institute for Water Research, Adelaide.

Stapf S and Han S-I (eds) (2006) NMR Imaging in Chemical Engineering, Wiley-VCH, Weinheim.

Trofimczyk K, Downey M, Hopper T, Neville T and Birt B (2018) Continuous Hydrogeological Characterisation in Iron Ore Deposits Using Borehole Magnetic Resonance. *ASEG Extended Abstracts 2018*: 1–6.

Varma S (2012) Hydrogeological review of the Musgrave Province, South Australia. Goyder Institute for Water Research Technical Report Series No. 12/8, Goyder Institute for Water Research, Adelaide.

Vignoli G, Sapia V, Menghini A and Viezzoli A (2017) Examples of improved inversion of different airborne electromagnetic datasets via sharp regularization. *Journal of Environmental and Engineering Geophysics* 22(1): 51–61.

Visser G and Markov J (2019) Cover thickness uncertainty mapping using Bayesian estimate fusion: leveraging domain knowledge. *Geophysical Journal International* 219(3): 1474–1490.

Walsh D, Turner P, Grunewald E, Zhang H, Butler JJ jr, Reboulet E, Knobbe S, Christy T, Lane JW jr, Johnson CD, Munday T and Fitzpatrick A (2013) A Small-Diameter NMR Logging Tool for Groundwater Investigations. *Groundwater* 51: 914–926.

Appendix A – G-FLOWS stage-3 publications to date

Journal Paper

Costar A, Love A, Krapf C, Keppel M, Munday T, Inverarity K, Wallis I and Soerensen C (2019) Hidden water in remote areas – using innovative exploration to uncover the past in the Anangu Pitjantjatjara Yankunytjatjara Lands. *Mesa Journal* 90(2): 23–35.

Jiang Z, Mallants D, Peeters L, Gao L, Soerensen C, Mariethoz G (2019) High-resolution paleovalley classification from airborne electromagnetic imaging and deep neural network training using digital elevation model data. *Hydrology and Earth System Sciences* 23: 2561–2580.

Krapf C, Costar A, Stoian L, Keppel M, Gordon G, Inverarity K, Love A and Munday T (2019) A sniff of the ocean in the Miocene at the foothills of the Musgrave Ranges – unravelling the evolution of the Lindsay East Palaeovalley. *MESA Journal* 90(2): 4–22.

Macnae J, Xiuyan R and Munday T (2020a) Stripping induced polarization effects from airborne electromagnetics to improve 3D conductivity inversion of a narrow palaeovalley. *Geophysics* 85(5): B133–B139.

Macnae J, Munday T and Soerensen C (2020b) Estimation and geologic interpretation of regolith chargeability and superparamagnetic susceptibility in airborne electromagnetic data. *Geophysics* 85(5): E153–E162.

Technical Report

Davis A, Flinchum B, Munday T, Cahill K, Peeters L, Martinez J, Blaikie T, Gilfedder M and Ibrahimi T (2020) Characterisation of a palaeovalley system in Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of South Australia using ground-based hydrogeophysical methods. Technical Report Series 20/05, Goyder Institute for Water Research, Adelaide.

Keppel M, Costar A, Love A and Krapf C (2019) G-FLOWS Stage 3 APY Lands Drilling Program, north-western South Australia. Technical Report Series 19/39, Goyder Institute for Water Research, Adelaide.

Love A, Costar A, Krapf C, Xie Y, Wallis I, Lane T, Keppel M, Inverarity K, Deng Z, Munday T and Robinson N (2020) G-FLOWS Stage 3: Hydrogeological conceptual understanding of the APY Lands groundwater system including the Lindsay East Palaeovalley. Goyder Institute for Water Research Technical Report Series No. 20/06, Goyder Institute for Water Research, Adelaide.

Munday T, Taylor A, Raiber M, Soerensen C, Peeters L, Krapf C, Cui T, Cahill K, Flinchum B, Smolanko N, Martinez J, Ibrahimi T and Gilfedder M (2020) Integrated regional hydrogeophysical conceptualisation of the Musgrave Province, South Australia. Technical Report Series No. 20/04, Goyder Institute for Water Research, Adelaide.

Peeters LJM, Cui T, Pickett T, Gilfedder M, Mallants D, Taylor A, Jiang Z, Flinchum B, Cahill K and Munday T (2020) Groundwater Knowledge Integration System (GKIS): Probabilistic groundwater prospectivity mapping with iterative updating of conceptualisation. Technical Report Series 20/01, Goyder Institute for Water Research, Adelaide.

Soerensen CC, Munday TJ, Ibrahimi T, Cahill K and Gilfedder M (2018) Musgrave Province, South Australia: Processing and inversion of airborne electromagnetic (AEM) data. Technical Report Series 18/06, Goyder Institute for Water Research, Adelaide.

Conference

Costar A and Keppel M (2018) G-FLOWS – Hidden water, innovation exploration. Conference Proceedings ARGA 2018, 8-11 April 2018, Wallaroo, South Australia, p. 59.

Costar A, Krapf C, Keppel M, Love A, Inverarity K, Munday T and Soerensen C (2018) G-FLOWS S3 – Drilling for community in the APY Lands. In: Reid A (ed.) Geological Survey of South Australia Discovery Day 2018: Presentation abstracts and posters, Report Book 2018/00034. Department for Energy and Mining, South Australia, Adelaide, pp 4-7.

Costar A, Love A, Krapf C, Keppel M and Munday T (2019) Hidden water in remote areas - using innovative exploration to uncover the past. Abstract presented *at NCGRT/IAH Australasian Groundwater Conference 2019*, Brisbane November 24-27.

Cui T, Pagendam D, Peeters LJM, Siade AJ, Gilfedder M and Janardhanan S (2019) Gaussian process machine learning for groundwater system characterisation and modelling. Abstract presented at *AGU Fall Meeting 2019*.

Gogoll M (2017) New understanding, challenges and opportunities for targeting potable Groundwater in the remote APY Lands, SA. *OZWater 2017 Conference*, Sydney

Gordon G, Krapf C, Costar A (2019) Hydrated mineralogy – mapping the palaeovalleys in the Musgrave Province. Abstract presented at NIR2019, 15-20 September 2019, Gold Coast, Australia.

Krapf C, Costar A, Keppel M, Love A, Inverarity K, Munday T and Soerensen C (2018) AEM applications for landscape evolution and groundwater exploration in the Musgrave Province. In: Reid A (ed.) Geological Survey of South Australia Discovery Day 2018: Presentation abstracts and posters, Report Book 2018/00034. Department for Energy and Mining, South Australia, Adelaide, p 35.

Krapf C, Costar A, Keppel M, Inverarity K, Love A, Stoian L, Gordon G, Soerensen C and Munday T (2019) Backing up the AEM – unravelling a palaeovalley fill for groundwater exploration in the APY Lands, *ASEG Extended Abstracts 2019*: 1–6, DOI: 10.1080/22020586.2019.12073103

Munday T, Sørensen C and Gulbrandsen ML (2018) Peeling back the cover on an ancient landscape – AEM in the Musgrave Province, South Australia. AEM 2018 7th International Workshop on Airborne Electromagnetics, June 17-20 Kolding Denmark. pp4.

Peeters L (2018) Sensitivity analysis and value of information in groundwater exploration: a case study from the APY lands, South Australia. In: *AGCC 2018 - Australian Geoscience Council Convention*; 14-18 October 2018; Adelaide, Australia. Abstract 469.

Peeters L, Mallants D, Cui T, Taylor A, Pickett T, Gilfedder M and Munday T (2019) Stochastic knowledge integration for groundwater exploration in data scarce areas (396). Abstract presented at *NCGRT/IAH Australasian Groundwater Conference 2019*, Brisbane November 24-27.

Peeters LJM, Mallants D, Cui T, Taylor A, Pickett T, Gilfedder M and Munday T (2019) Stochastic knowledge integration for groundwater exploration in data scarce areas. *Abstract presented at IAH2019*, 22-27 September 2019, Malaga, Spain.

Soerensen C, Munday T, Krapf C, Love A, Costar A, Inverarity K, Gogoll M and Gilfedder M (2018a) Uncovering the Musgrave Province in South Australia using airborne EM: *ASEG Extended Abstracts 2018,* 1-5. DOI: 10.1071/ASEG2018abT5_3H

Soerensen C, Munday T, Raiber M, Gilfedder M, Krapf C, Costar A, Keppel M, Gogoll M, Love A, Gulbrandsen ML and Pallesen TM (2018b) Uncovering an ancient landscape and helping the exploration for groundwater and minerals – The Musgrave province, South Australia. Abstract presented at AGCC Conference, Adelaide Oct 2018.

Soerensen C and Munday T (2018) The Musgrave Province – the untold story about Airborne IP. AEM 2018 / 7th International Workshop on Airborne Electromagnetics, June 17-20 2018 , Kolding Denmark, pp4.

Data product

Krapf CBE, Costar A, Munday T, Irvine JA and Ibrahimi T (2020) Palaeovalley map of the Aṉangu Pitjantjatjara Yankunytjatjara Lands (1st Edition), 1:500 000 scale. Department for Energy and Mining.

Peeters LJM and Visser G (2019) Probabilistic data assimilation for cover thickness mapping in the APY Lands. Jupyter Notebook. CSIRO.