Project Order

Proforma 2019

1. Short Project Title

Assessment of faults as potential connectivity pathways

Long Project Title	Assessment of faults as potential connectivity pathways
GISERA Project Number	W.19
Proposed Start Date	15/07/2019
Proposed End Date	31/12/2020
Project Leader	Matthias Raiber (co-leader Jorge Martinez)

2. GISERA Region

☐ Queensland ☒ **New South Wales** ☐ Northern Territory

☐ South Australia ☐ Western Australia ☐ Victoria

3. GISERA Research Program

☒ **Water Research** ☐ GHG Research ☐ Social & Economic Research

☐ Biodiversity Research ☐ Agricultural Land Management Research ☐ Health Research

4. Project Summary

Objective

Geological structures (e.g. faults) exist in most sedimentary basins around the world where coal or gas resources are developed, and the geometry and characteristics of fault zones have been a central aspect of petroleum geosciences and reservoir engineering for many decades (which traditionally focus on the deeper subsurface). From the hydrogeological perspective, the presence of faults alone does not mean that there is a potential issue or that there will be impacts on groundwater resources, but the emerging interest of the hydrogeological community (who traditionally focus on the upper approximately 200 m of the subsurface) into the role of faults in sedimentary basins throughout the last years highlights that the potential role of faults on groundwater dynamics in sedimentary basins is an aspect that is worthy of more research.

In the Narrabri region (NSW), there are conflicting views on whether faults extend to the surface in the Jurassic formations of the Surat Basin, and whether they can form seal bypass structures, which could potentially allow hydrogeological connectivity between deep coal seam gas target formations, Great Artesian Basin hydrogeological formations and shallow aquifers or surface water systems.

Some previous studies argue that faulting is largely absent in the Surat Basin strata in NSW. On the other hand, there are some indications that suggest that there may be fault-related displacements of Surat Basin strata that may extend to the surface within the proposed Narrabri Gas Project area (red outline in Figure 1), possibly reaching streams such as Bohena Creek and its associated alluvia where an inferred fault oriented sub-parallel to Bohena Creek has been mapped from DEM's (black dashed line in Figure 1 (Welsh et al., 2014). If its presence is confirmed, this would indicate that the fault likely extends to the surface (e.g. Raiber and Suckow (under review)), although it would still be unknown to which depth below the ground surface the fault extends to. There also appear to be significant regional-scale volcanic intrusions (dykes and sills) associated with Cenozoic tectonism in the wider Narrabri area. Seismic images confirm that these penetrate both Gunedah and Surat basins strata (Totterdell et al., 2009), and such intrusive features can sometimes be associated with regional structural weaknesses such as fault zones, where potential pathways for the upward migration of fluids or gas may exist.

In the Queensland part of the Surat and Bowen basins, where coal seam gas has been commercially developed since the mid 1990's (Bowen Basin since 1996; Surat Basin since 2006 (Australian Academy of Science, 2011)), faults have until recently not been considered by numerical groundwater model impact predictions.

The Underground Water Impact Report (UWIR), produced by the Queensland Office of Groundwater Impact Assessment (OGIA) to convey the results of the cumulative impact assessment of CSG activities into aquifers of the Surat and Bowen basins in Queensland, has been recently updated by OGIA (2019). This recent study included 32 regional faults into the geological model and groundwater flow model used for the groundwater impact assessment and future water balance predictions. As part of this assessment, OGIA found that although smaller faults may have the potential to locally increase hydraulic connectivity between the CSG target units and overlying aquifers, regional implications of faulting on the propagation of impacts are not anticipated. OGIA will continue to investigate the role of faults in the Surat Basin in Queensland and the continuous investiment in representing and assessing faults in the regional model, where 17 regional faults were considered in the UWIR 2016 and 32 in the UWIR 2019, indicates the iterative and evolving nature of these assessments where newly-acquired data can help to reduce the uncertainty of future impact predictions.

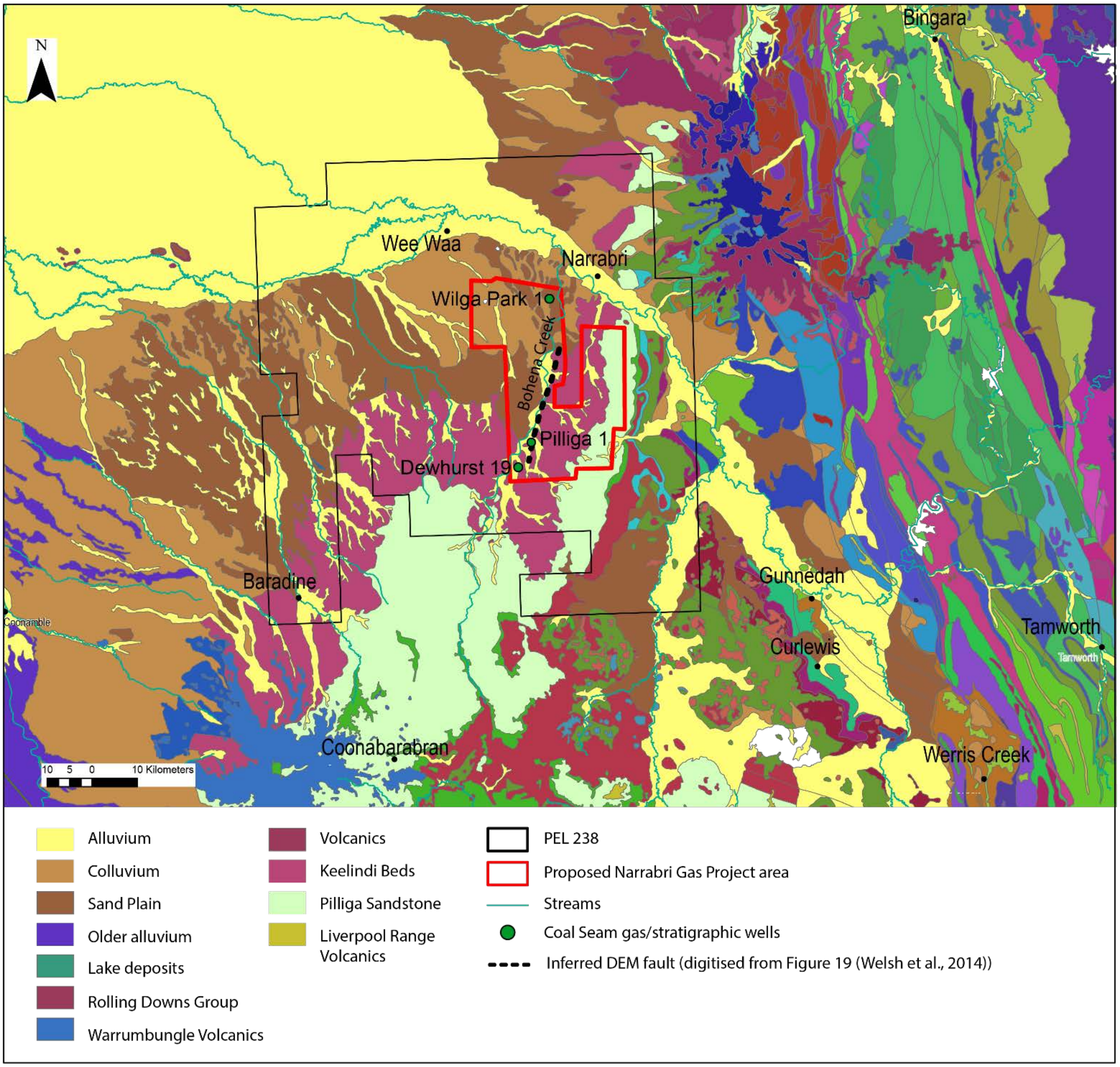

Figure 1 – Proposed Narrabri Gas Project area and inferred DEM fault parallel to Bohena Creek.

To determine if seal bypass structures compromise the continuity and performance of the seals/aquitards located between the shallow aquifers and the coal seams, and if they form actual pathways, integrated scientific approaches are required using aspects from both groundwater and petroleum system approaches (e.g. Mallants et al., 2018; Underschultz et al., 2016).

A previous study in the Namoi River catchment suggested that GAB water discharges into the alluvial aquifer in some locations (Iverach et al., 2017), although it is unknown if this is related to a possible presence of faults. Other studies suggest that it appears to be unlikely that faults have a significant influence on shallow groundwater systems in the Narrabri area. However, the on-going community concern and uncertainties relating to the presence of faults suggest that it is an issue worthy of more research.

Holland et al. (2019) described that the eastern side of the Namoi subregion is defined by the Hunter-Mooki Thrust Fault, which was assumed to be a zero-flow boundary in the numerical model used for the assessment of the potential impacts of CSG depressurisation on the GAB flux (GISERA, 2019). Indeed, geological structures were also not accounted for in an uncertainty analysis of CSG-induced GAB flux and water balance changes in the Narrabri Gas Project area (Janardhanan et al., 2018b). However, Janardhanan et al. (2018b) highlighted that further studies are required to quantify the effect of the faults presence on the flux changes induced by CSG development. These discussions prompted the development of the concept and design of the current proposal which aims to minimise the uncertainty on the potential of geological faulting to promote connectivity between CSG units and overlying aquifers.

In this project, we aim to build up on previous work (e.g. Creswell, 2014; CDM Smith, 2016; Iverach et al. 2017; Iverach et al., 2019; Janardhanan et al., 2018a; Janardhanan et al., 2018b; Holland et al., 2019; Raiber and Suckow, (under review); Suckow et al., (under review)) by focusing on specific areas where faults or igneous intrusions are likely to be present. We will use geophysical techniques to determine if these features extend to the shallow subsurface or surface and use selected environmental tracers that are sensitive to detect contribution from deeper aquifers to assess if there are any indications that suggest that connectivity between deep and shallow systems is likely to occur.

The NSW Government approvals process for the Narrabri Gas Project is not dependent on the outcome of this work. The outcomes of this work can be incorporated into future operating conditions at any time should that be necessary. This work will help to address public concerns and help to refine the understanding of faulting in the shallow subsurface. Different generations of groundwater models are usually developed throughout the life cycle of gas resource development projects, and the outcomes of this study can help to further reduce the uncertainty of future generation groundwater models in Narrabri area.

Description

In this project, we propose an integrated assessment that combines historical evidence, application of geophysical techniques and environmental tracers within and near the proposed Narrabri gas project development area south-west of Narrabri. The application of low-impact and non-intrusive geophysical techniques can greatly assist in producing high resolution images of the subsurface from the inference of spatial variation in physical properties of the rocks and associated structures. A combination of different geophysical methods is always recommended to develop conceptual models of faulted systems and reduce intrinsic uncertainties associated with each geophysical method. For the vertical mapping of fault zones and igneous intrusions that may act as potential pathways for fluid or gas migration from the target coal seams and the near surface receptors (within the upper 500 m of the subsurface in the Pilliga area), we propose the application of two independent geophysical methods.

In addition, we will use environmental tracers as an independent line of evidence to determine if there is any evidence for upwards flux of deep groundwater into shallow formations and surface water systems within the Bohena Creek sub-catchment, as previously suggested in the main channel of the Namoi River catchment (Iverach et al., 2017). The novel combination of high-resolution geophysical imaging with fast track environmental tracer techniques has been proven successful and effective for the investigation of fault-induced connectivity (e.g. Mallants et al., 2018).

Need & Scope

This project in the Pilliga Forest region will help to refine the understanding of the shallow subsurface geometry, with irrefutable imagery supported by forensic environmental tracer data that will help to refine the understanding of the degree of hydraulic separation and the presence (or absence) of seal bypass systems in the Pilliga Forest area.

In studies where potential impacts of petroleum resource developments on water resources are assessed, understanding the role of subsurface architecture and geological structure is very important, especially the presence or absence of aquitards (or seals) and faults, the location of faults relative to the extraction wells, fault displacements, the hydraulic role of faults as either barriers or conduits to fluid migration and the composition and hydraulic properties of any fault-related infill material (Raiber et al., 2016). In particular, understanding the integrity and continuity of aquitards is paramount, and whether they form an effective seal depends on the presence and characteristics of fault zones and the geometry of the geological compartments defined by the faults or fractures. If aquitards are compromised by faults, the pressure change could be potentially transmitted at a higher velocity than the regional flow rate with potential impacts extending to the uppermost aquifers and surface water. Furthermore, it may be possible that prolonged depressurization may reactivate a fault zone, and thus create connections that were not active prior to the aquifer depressurization.

Current conceptual hydrogeological models developed for the Pilliga Forest region in NSW assume that faults do not significantly extend into, and displace, the Jurassic units of the Surat Basin. Likewise, existing 3D geological models and groundwater models developed for the Pilliga region have generally not represented faults (e.g. Janardhanan et al., 2018a; Turnadge et al. (2016)).

Although the investigations described above suggest that structural activity has affected mostly the Permian and Triassic strata in this region, there appears to be also evidence for post-Jurassic structural activity that deformed both Gunnedah and Surat basin strata, likely associated with Cenozoic volcanic activity. For instance, Short and Harris (1986) suggested that structural activity has occurred also throughout the Mesozoic, and that post-Jurassic structuring is evident. They have suggested that there are a series of north-south trending anticlines from seismic data, including the Wilga Park Anticline where displacements of both Gunnedah and Surat basin strata occurs. Due to the deformation of the Surat Basin strata, they suggested a minimum post-Mid-Jurassic age of structuring and related it to Cenozoic tectonics and volcanism.

Short and Harris (1986) also suggested that a Cenozoic intrusion penetrates the sedimentary bedrock sequences to the base of the Pilliga Sandstone. Volcanic features including dykes, sills and plugs are very common in the Gunnedah Basin (Welsh et al., 2014; Wellman and McDougall, 1974). South of Narrabri and south of the Wilga Park Anticline identified by Short and Harris (1986), a fault was inferred based on Digital Elevation Models (DEM's) (Figure 19 in Welsh et al., 2014); the orientation of this inferred fault coincides approximately with the southern part of the course of Bohena Creek (Figure 1). Furthermore, anomalous formation tops in stratigraphic and exploration wells in this area suggest that there may indeed be considerable geological structure (Raiber and Suckow, under review).

This continuing uncertainty on the presence and role of faults in this region is also highlighted by the advice from the independent Expert Scientific Committee (IESC), which emphasized the need to improve the characterization of the hydraulic role of faults (IESC, 2017). The IESC concluded: "Characterisation of fault displacements and provision of fault and geological/stratigraphic analyses and data to support the geological conceptualisation are required. Further consideration is needed with respect to the scale and extent of faulting in the region and the likely impact on groundwater during and post CSG extraction to justify excluding faulting from the groundwater model." Furthermore, in its advice, the IESC also identified impacts to landholder bores and GDEs utilising groundwater from the Namoi Alluvium, Pilliga Sandstone and the alluvium associated with Bohena Creek as key risks, and suggested that further field hydrogeological information including isotopes and the 'presence or absence of gas shows in the Jurassic Sequence' should be collected to increase confidence in the water balance, mixing processes and the conceptual hydrogeological and geological models (IESC, 2017).

In addition to the IESC advice, there is continuous community concern on the role of faulting, and potential impacts of faults on water resources.

For these reasons it has become important to contribute to this gap in knowledge and provide evidence to assuage any concerns or doubts on the existing conceptual understanding of the hydrogeology of the Narrabri area. As commonly observed in other CSG development areas (e.g. the Surat Basin in Qld where the first generations of groundwater models did not represent faults), new data collected throughout the life cycle of projects from exploration to appraisal to development ideally feed into new generations of groundwater models developed to predict potential impacts. The work can form one important line of evidence that will help to further reduce the uncertainty and close knowledge gaps on presence of faults in the shallow subsurface of the Narrabri area.

An information fact sheet outlining the objectives of this proposed project will be developed, aiming to inform landholders and other stakeholders on the aims of the geophysical survey and environmental tracer sampling campaign.

Recommendations from NSW Chief Scientist Independent Review of Coal Seam Gas Activities

(Refer to http://www.chiefscientist.nsw.gov.au/reports/coal-seam-gas-review)

The recommendations from the NSW Chief Scientist are not specific to any project or potential CSG development area. However, there are some general recommendations that can be partially met by our scope of work, which confirms the relevance and need for integrated multidisciplinary studies such as this project.

The role of faults as potential connectivity pathways is highlighted in multiple background papers commissioned to support the independent review from the NSW Chief Scientist. For example, a report on the groundwater resources in relation to coal seam gas production highlights that preferential flow paths through aquitards may be possible via joints, fractures and conductive faults (Anderson et al., 2013). A supporting report on the geology highlights that the Gunnedah and Bowen basins and the overlying Surat Basin are all hydraulically connected, but that there is limited knowledge about where hydraulic connections between deep and shallow formations occur (Ward and Kelly, 2013). Furthermore, the initial report of the NSW Chief Scientist highlights that ”the occurrence of natural methane leaks through fault lines raises the importance of both obtaining baseline measurements of methane over a period of time (to account for seasonal variations) and using sophisticated techniques to monitor an area, to be able to distinguish between natural sources of methane, methane being emitted through other bores, and CSG fugitive emissions” (O'Kane, 2013).

In the Information paper on fracture stimulation activities (O'Kane, 2014), the Chief Scientist reinforces the role of geological factors influencing the use of fracture stimulation and highlights that NSW CSG resources differ from QLD basins particularly due to the “occurrence of faults extending throughout the basins and the complicated nature of groundwater interactions…”. More importantly, the Chief Scientist stresses that groundwater-surface water relationship could be disrupted at a local level potentially due the occurrence of faults and the need to apply “high quality diagnostics to a greater extent than could be expected in the more uniform basins such as the Surat or Powder River”. Finally, O'Kane (2014) clearly indicates that conceptual subsurface modelling should be represented in 3D and represent “hydrostratigraphic layers for flow models, map pathways of connectivity and map fault planes and fracture networks”. The document refers to the report produced by Ward and Kelly (2013) which notes that 3D geological models taking into account faults and fracture networks for proposed CSG sites in NSW were limited at that point in time.

The final report from the Chief Scientist highlights that “more detailed knowledge of the structure and composition (especially regarding hydrogeology) of the sedimentary basins is needed to enhance productivity for the CSG industry through more precise resource characterisation and better subsurface and surface environmental management” (O'Kane, 2014). Furthermore, it emphasises the need for commissioning of ‘formal scientific characterisation of sedimentary basins starting with the East Coast basins and concentrating initially on integration of groundwater with the geological, geophysical and hydrological context. Viewing these integrated systems in models and in interpretation could be described as a ‘Glass Earth’ approach to understanding the dynamics of activities and impacts in the basins’ (O'Kane, 2014).

Methodology

Existing evidence

In the first phase of the project, existing evidence for the presence of seal bypass systems in the region will be evaluated together with anecdotal evidence of methane occurrences in groundwater and surface water in the Pilliga region.

Currently, data from more than 2600 km of 2D geophysical seismic survey lines are publicly available through the Geological Survey of NSW website (DIGS). Although this is an extremely useful scientific resource, it is well known that these existing data collected as part of hydrocarbon exploration surveys have been acquired under specific field set ups designed to characterise the geometry of deeper oil and gas zones in the Gunnedah Basin, which generally exceeds 500 m in depth. As a result, geological structures within the interval from the surface to an approximate depth of 500 m are often neglected and the data are not processed for the elimination of data noise and enhancement of structures that are important for the impact assessment and identification of possible connectivity pathways. In order to fill such gaps, it is proposed that the data from a representative subset of 2D seismic lines covering approximately 30 linear kilometres in the vicinity of Bohena Creek are reinterpreted and integrated with the newly acquired electromagnetic datasets. This subset of data will be revisited to eliminate noise and enhance possible geological structures present within the top 500 m of the geological profile

As described above, the existing seismic data will be compiled and evaluated to inform the design of the geophysical field surveys.

Field reconnaissance

During the early stage of this project (task 2), we will conduct a field reconnaissance trip with experts on the geology and hydrogeology of the region, including industry representatives, government agencies, scientific experts and local representatives from the farming community. During this field trip, we will visit specific sites in the Narrabri region where existing evidence suggests that deep-seated faults may extend to the surface, forming potential connectivity pathways. As part of this trip, we aim to identify the most suitable sites for the surface-based geophysical surveys.

Surface-based geophysical survey

Following this initial phase of the project, we will conduct the surface-based geophysical survey combining two methods for the mapping of underground geological structures that may form connectivity pathways from the CSG target strata to the near surface environmental assets.

The main geophysical method is the high-resolution resistivity sounding, also known as Controlled Source Audio-frequency Magnetotellurics (CSAMT), which has been extensively used in hydrocarbon, mineral, geothermal and groundwater exploration since the late 1970's.

The CSAMT measures electric and magnetic fields that are used to estimate the resistivity structure of the subsurface along continuous cross-sections. Variation in rock and sediment porosity, pore fluid and the presence of fluids or sealed intervals along faults zones, weathering and anomalous fractures patterns within intrusive structures (e.g. dykes) are primary factors affecting resistivity of the subsurface.

The complimentary method is the Transient Electromagnetics (TEM), which is also used for vertical resistivity sounding and can greatly assist in refining the high-resolution images produced by the CSAMT. The TEM method was successfully applied by Mallants et al. (2018) in the Gloucester Basin to confirm that deep seated faults mapped by deep seismic surveys extended through the top 100 m of the geological profile and act as potential fluid migration pathways.

The data from both methods can be collected with a small field crew during a single field campaign.

Water sampling

A targeted water sampling campaign is proposed to focus on shallow hydrostratigraphic units, including the Bohena Creek alluvium. The sampling program will also involve a synoptic surface water sampling survey of Bohena Creek (subject to flow conditions). This will complement existing tracer data (Cresswell, 2014) and data from a recent CSIRO sampling campaign (Task 4 within the GISERA project 'Impacts of CSG depressurisation on the Great Artesian Basin flux') which focussed on the wider regional patterns of recharge to the Pilliga Sandstone. As part of this recent assessment of recharge, only very few samples were collected from the Pilliga Sandstone within the proposed CSG development area and no samples were collected from the coal seams within the proposed CSG development area or from shallow aquifers such as the Namoi River and Bohena Creek alluvia.

Environmental tracers

To further verify the degree of hydraulic connection or separation between deeper and shallow formations, we propose to analyse water samples for a range of expedite environmental tracers, with a focus on those analytes that are sensitive to detect upward fluid migration (e.g. helium, ^{222}Rn and methane). The detection limit of major or minor ions towards influx of groundwater from deeper formations via fractures and faults or aquitard leakage is in the range of 5-10% admixture of deep water (e.g. fluoride concentration in the Maules Creek Formation range from 6-12 mg/L and below detection limit to 1.5 mg/L in the Pilliga Sandstone) (Cresswell, 2014; Iverach et al., 2017). Helium in contrast can indicate admixtures in the per mil range because deeper formations (e.g. Hoskissons Coal within the Black Jack Group and Maules Creek Formation) – if indeed containing much older groundwater – contain up to a factor 1000 more helium than the shallower aquifers (e.g. Pilliga Sandstone, Orallo Formation, alluvium and surface water). Helium therefore is a much more sensitive parameter for detection of upward flowing groundwater in shallow strata and streams, and will provide more robust indications of cross formational flow (Raiber and Suckow, 2019 (under review)).

The integrated analysis of methane concentrations and stable isotopes (δ^2H and $\delta^{13}C$ of methane), noble gases (e.g. helium and ^{222}Rn), hydrochemistry and trace element concentrations will help to better understand the origin of the gas and possible diffusive and advective pathways for gases from CSG target units (coal seams of the Gunnedah Basin) to overlying shallow hydrological systems in the Pilliga region in the Namoi River catchment in NSW.

Noble gases have been identified as ideal tracers to examine the diffusive and advective transport pathways due to their non-reactive nature and well-characterised isotopic compositions (Darrah et al., 2014; Harkness et al., 2017).

The environmental tracer component will greatly add a robust line of evidence to the visual high-resolution images expected to be produced by the electromagnetic geophysical surveys and improve the understanding of regional gas migration pathways and the degree of hydraulic isolation between coal seams and overlying aquifers (in particular Pilliga Sandstone and the alluvial aquifers of Bohena Creek). It will also address multiple knowledge gaps in relation to the proposed gas projects and collect additional field hydrogeological and isotopic data to increase confidence in existing hydrogeological conceptual models, as recommended by the IESC (2017).

5. Project Inputs

Research

The knowledge gap on the presence and role of faults as potential connectivity pathways between CSG target formations and shallow aquifers and surface water systems continues to represent considerable uncertainty in the Narrabri region in NSW, as highlighted by the IESC advice (IESC, 2017) and ongoing community concerns on security of water quantity and quality. This project aims to address this knowledge gap by conducting new research that will build up on previous work conducted in the Namoi region, including previous GISERA and Bioregional Assessment projects in the Narrabri region (e.g. Janardhanan et al., 2018; Raiber and Suckow, under review, Suckow et al., under review), Office of Water Sciences projects (Turnadge et al., 2016), industry-funded work (e.g. Cresswell et al. (2014)), UNSW and ANSTO work (e.g. Iverach et al., 2017) and NSW government agency studies.

This project was developed by researchers of the CSIRO Water Resources Management Programme (Matthias Raiber, Jorge Martinez, Axel Suckow and Dirk Mallants). Throughout the project development, multiple stakeholders from NSW government (NSW Department of Industry Lands and Water) and federal government agencies/research organisations (Geoscience Australia and ANSTO) and universities (University of New South Wales and University of Queensland) were consulted to ensure that this project takes into account the currently available expert knowledge. As part of Task 2 of the project (Site reconnaissance and synoptic river sampling), further opportunities for consultation with experts and local stakeholders will arise.

Resources and collaborations

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Matthias Raiber	15 days	Geology and hydrogeology	15	CSIRO
Jorge Martinez	22 days	Geology, geophysics and hydrogeology	15	CSIRO
Axel Suckow	20 days	Environmental tracers	25	CSIRO
Alec Deslandes	15 days	Environmental tracers	10	CSIRO

Subcontractors (clause 9.5(a)(i))	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Simon Mann	N/A	Geophysics	12	Zonge Engineering and Research Organization
Dioni Cendón	N/A	Environmental tracers and geochemistry	20	ANSTO

Budget Summary

Source of Cash Contributions	2018/19	2019/20	2020/21	% of Contribution	Total
GISERA	$0	$137,170	$23,278	75%	$160,448
- Federal Government	$0	$109,736	$18,622	60%	$128,358
- NSW Government	$0	$18,289	$3,104	10%	$21,393
- Santos	$0	$9,145	$1,552	5%	$10,697
Total Cash Contributions	**$0**	**$137,170**	**$23,278**	**75%**	**$160,448**

Source of In-Kind Contribution	2018/19	2019/20	2020/21	% of Contribution	Total
CSIRO	$0	$45,723	$7,759	25%	$53,482
Total In-Kind Contribution	**$0**	**$45,723**	**$7,759**	**25%**	**$53,482**

6. Project Impact Pathway

Activities	Outputs	Short term Outcomes	Long term outcomes	Impact
Compilation of historic data and reinterpretation of existing seismic surveys	Compiled historic evidence on presence of faults to inform the following tasks	The potential role of faults as pathways that connect CSG target formations and shallow aquifers or surface water continues to raise community concerns. In addition, recommendation by the NSW Chief Scientist and advice by the IESC (2017) highlight the need to improve the understanding of subsurface structures. This project will provide invaluable information on the subsurface geometry and potential fault-induced connectivity. In addition, it will provide valuable publicly-available baseline concentration of various parameters in shallow aquifers and surface water for future assessments of potential impacts of CSG activities.	Communities will have high quality trusted information on the role of faults as connectivity pathways between different formations. Regulatory agencies will be able to use knowledge generated on shallow geophysical surveys, water chemistry and environmental tracers to inform regulatory decision making. Regulatory agencies and industry will be able to use this information to decide on most suitable and representative sites for the installation of groundwater monitoring infrastructure.	Greater community knowledge on potential impacts of gas development in the Gunnedah Basin in NSW. This project will add to the better understanding of risks on quantity and quality of shallow water resources. It will help to determine if there are any areas subjected to a higher risk due to the presence of faults, and it will provide advice for regulatory agencies and industry alike with improved knowledge and measures for preventing and mitigating outcomes from undesirable events, reducing societal concerns, environmental impacts and improved organisational management.
Site reconnaissance and synoptic river sampling	Decide on most suitable locations for geophysical surveys and collect surface water samples for environmental tracers in communication with local experts and land holder representatives			
Surface geophysical survey and groundwater sampling	Groundwater samples collected; geophysical surveys conducted			
Environmental tracer laboratory analysis	Groundwater samples analysed and conducted initial interpretation of results			
Data interpretation, integration and report writing (including peer reviews)	Integration of all data, refinement of conceptual hydrogeological models and knowledge transfer by communicating results to GISERA stakeholders according to standard GISERA project procedures, including workshops, technical reports and journal publications			

7. Project Plan

Project Schedule

ID	Activities / Task Title (should match activities in impact pathway section)	Task Leader	Scheduled Start	Scheduled Finish	Predecessor
Task 1	Compilation of historic data and reinterpretation of existing seismic surveys	Matthias Raiber	15/07/2019	31/12/2019	
Task 2	Site reconnaissance and synoptic river sampling, including planning	Jorge Martinez	15/07/2019	31/10/2019	1
Task 3	Surface geophysical survey and groundwater sampling, including planning	Jorge Martinez	01/10/2019	31/03/2020	1, 2
Task 4	Environmental tracer laboratory analysis	Axel Suckow	01/10/2019	30/08/2020	1,2,3
Task 5	Data interpretation, integration and report writing (including peer reviews)	Matthias Raiber	01/07/2020	31/12/2020	1,2,3,4

Task description

Task 1

TASK NAME: Compilation of historic geological mapping, geological structural and hydrochemical data and reinterpretation of existing seismic surveys

TASK LEADER: Matthias Raiber

OVERALL TIMEFRAME: July 2019 – December 2019

BACKGROUND: This task builds up on previous work, including the studies by Cresswell (2014), Raiber and Suckow (under review)) and Suckow et al. (under review)). The various hydrochemical datasets will be integrated with the geological mapping, 3D geological models and current structural framework to support the development of a preliminary conceptual model of the region and identification of potential anomalies in the datasets. The anomalies may indicate the occurrence of preferential flow pathways in areas where geological faults are expected to be present.

A subset of the approximately 2600 km of 2D geophysical seismic data that is publically available will be reinterpreted. Existing seismic surveys were run as part of petroleum exploration studies. These studies focus on the deep subsurface, and as a result, these seismic surveys may lack resolution in the shallow subsurface. The raw data of a selected subset of seismic survey will be reprocessed to filter noise and enhance possible structural features positioned in the top 500 m of the geological profile.

TASK OBJECTIVES: The main purpose of this task is the identification of gaps in the current knowledge of faults and their role to potential fluid transport from the coal seams to near surface environmental assets and the selection of sites for further field investigations. A preliminary conceptual model of the groundwater system will be developed using existing geological and water geochemical data, including dissolved methane concentration associated with different hydrostratigraphic units.

The hydrochemical datasets will be interpreted in the context of the geological framework available for the region with a focus on the proximity to geological structures such as fault zones and lineaments to be further confirmed by the reinterpretation of the seismic survey data to identify the tendency for the occurrence of faults that extend to near surface.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: A preliminary conceptual model to support the selection of sites for field shallow geophysical survey and selection of existing bores for groundwater sampling will be developed.

Task 2

TASK NAME: Site reconnaissance trip and synoptic river sampling

TASK LEADER: Jorge Martinez

OVERALL TIMEFRAME: July 2019 – October 2019

BACKGROUND: Although previous work was conducted in relation to geology and water chemistry in this region, much of that work focussed on the deeper compartments of the subsurface. However, evidence exists that suggests that faults are present in the shallow subsurface and there is therefore a need to better characterise the geometry and potential fault-induced connectivity pathways. It is generally accepted that a multidisciplinary approach that considers independent lines of evidence is required to identify potential environmental assets that may be impacted by CSG activities in the vicinity of the potential faulting zones. Furthermore, it is critical to integrate existing expert knowledge into the planning of fieldwork and conceptualisation of the aquifer/aquitard systems.

This reconnaissance trip will allow us to engage with experts on the geology and hydrogeology of the Narrabri area. We will invite experts from industry, academia (UNSW), state and federal government agencies (e.g. NSW Department of Industry Lands and Water, Geoscience Australia and ANSTO) and a representative from private land holders to join us in the field and visit the area where previous work suggested that there may be geological structures present. This will include visiting important geological features as well as environmental assets (e.g. Bohena Creek). Together with the experts and with the information from Task 1, we will identify the most appropriate locations for the geophysical field surveys (Task 3). As part of this reconnaissance trip, we will also collect surface water samples from Bohena Creek (subject to flow conditions) for a suite of hydrochemical and environmental tracers, with a focus on those parameters (e.g. dissolved methane, ^{222}Rn and noble gases) that are sensitive for detection of a contribution of upwards flux from deeper formations.

TASK OBJECTIVES: Undertake a field reconnaissance trip and engage with local experts to identify most suitable areas for geophysical surveys. Collect surface water samples from Bohena Creek at approximately six sites for environmental tracer analysis (subject to flow conditions).

TASK OUTPUTS AND SPECIFIC DELIVERABLES: A memorandum summarizing expert views on geological structures, preliminary site selection for geophysical surveys and sampling of surface water of Bohena Creek.

Task 3

TASK NAME: Surface geophysical survey and groundwater sampling

TASK LEADER: Jorge Martinez

OVERALL TIMEFRAME: October 2019 – March 2020

BACKGROUND: The expression of geological faults in the shallow subsurface or at the surface can be initially inferred from the interpretation of the regional geomorphology using aerial photographs, existing LiDAR data, existing 3D geological models and satellite images. An initial assessment of aerial images of the proposed study area suggests that reaches of Bohena Creek are relatively straight lines over several km's, and these very closely follow the orientation of mapped structural lineaments that are likely associated with deep seated faults. Furthermore, irregular formation tops in stratigraphic and exploration wells have been observed underneath Bohena Creek.

The predominant high resolution geophysical method proposed in this study is the CSAMT, which has been extensively employed in mineral exploration (Hu et al., 2013), environmental, engineering problems (He et al., 2006) and groundwater investigation (Fu et al., 2013; Yan-ling et al., 2018). This method presents many logistical advantages when compared to other resistivity methods, resulting in extended field survey areas with relatively short periods of time by using a multi-channel receiver. TEM will also be used as a complementary tool to the CSAMT, particularly to assist in reducing the uncertainty of data collected by the primary method.

Groundwater sampling at approximately eight selected bores will be performed for laboratory analysis of parameters as described in task 4. The sites selection will be based on the findings from this task combined with information gathered during task 2 and existing data compiled under task 1.

TASK OBJECTIVES: The main objectives of the high-resolution geophysical investigation is to confirm the position of geological structures within the 500 m interval, characterise their geometry (azimuth and dip) and extent in a series of 2D sections. The proposed geophysical methods will provide valuable evidence on whether identified structures correspond to an extension of deep seated faults and their likelihood to connect near the surface environmental assets (groundwater dependent ecosystems and shallow groundwater private bores) to the deep coal seams that may potentially correspond to environmental stressors following gas development activities. It is important to highlight that the geophysical survey comprises one line of evidence that is expected to be combined and supported by the findings of the environmental tracers. The latter will help to ascertain if geological structures are likely to be conductive to flow migration.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: The outputs of both geophysical investigation methods will be presented as 2D vertical sections of interpolated values of ground resistivity. The preliminary findings from the geophysical survey together with historic evidence will be presented in a brief memorandum.

Task 4

TASK NAME: Environmental tracer laboratory analysis

TASK LEADER: Axel Suckow

OVERALL TIMEFRAME: October 2019 to August 2020

BACKGROUND: To further verify if connectivity between deeper and shallow formations occurs in the Narrabri region, groundwater samples from shallow bores (i.e. bores screened within the alluvial aquifer or the shallow parts of the Pilliga Sandstone) will be analysed for parameters such as helium and dissolved methane. Some of the methods previously used for identification of connectivity are limited. For example, detection limit of major or minor ions towards influx of groundwater from deeper formations via fractures and faults or aquitard leakage is in the range of 5-10% admixture of deep water (e.g. fluoride concentration in the Maules Creek Formation range from 6-12 mg/L and below detection limit to 1.5 mg/L in the Pilliga Sandstone; Raiber and Suckow, 2019). In contrast, helium can indicate admixtures in the per mil range because deeper aquifers (e.g. Black Jack Group and Maules Creek Formation) are likely to contain up to a factor 1000 more helium than the shallower aquifers (e.g. Pilliga Sandstone, Orallo Formation and alluvium). Helium therefore is a much more sensitive parameter for upward flowing groundwater and will provide more robust indications of cross formational flow.

TASK OBJECTIVES: Laboratory analysis of noble gas (He, Ne, Ar, Kr, Xe including $^{3}He/^{4}He$), ^{222}Rn, dissolved methane (concentrations and isotopes), other selected hydrochemical and isotopic tracers, including stable isotopes of water and strontium, tritium and carbon-14.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Analytical results of noble gases and other selected environmental tracers will be obtained, providing new evidence on the potential hydrogeological connectivity between deep and shallow aquifers.

Task 5

TASK NAME: Data interpretation and integration and conceptual hydrogeological model refinement

TASK LEADER: Matthias Raiber

OVERALL TIMEFRAME: July 2020 to December 2020

BACKGROUND: This last task of the proposed project will integrate all evidence from previous tasks to test and refine the conceptual hydrogeological model(s) of the Narrabri region. The geophysical evidence will allow us to assess if there is any indication that deep-seated faults extend from the Gunnedah Basin into the Surat Basin and reach the shallow subsurface or surface. In addition, the environmental tracers will allow us to identify whether potential faults are conductive to fluid or gas migration. Once combined, these complimentary techniques are expected to determine whether the current hydrogeological conceptual models are appropriate, or if alternative conceptual hydrogeological models that describe potential interactions between formations need to be developed.

TASK OBJECTIVES: Test the current conceptual hydrogeological model with focus on potential connectivity pathways from the CSG units to near surface environmental assets. Develop new conceptual models representing likely hydrogeological connections between deep and shallow systems from the newly conducted geophysical survey and reinterpretation from existing seismic data. New alternative conceptualisation of the hydrogeological system may be proposed if the newly acquired evidence shows that the present conceptual models are not accurate representations of the regional hydrogeological system.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: An improved conceptual hydrogeological model based on the integrated datasets from this study and previous studies. The project output will increase the confidence into the understanding of hydrogeological dynamics of the region and in particular the interaction between deep and shallow formations. Two dimensional cross-sections will be used to represent the local geology, hydrostratigraphic layers, presence of faults and associated offsets resulted from the geophysical surveys and the spatial distribution of environmental tracers, which may correspond to anomalies where in proximity and under the influence of geological structures.

The integration of all results from previous tasks will be presented in a technical report and a journal paper demonstrating the benefits of a methodology that combines innovative geophysical techniques with environmental tracers.

A stakeholder knowledge transfer workshop will be conducted.

Project Gantt Chart

	2019						2020											
Task	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Compilation of historic data and reinterpretation of existing seismic survey	■	■	■	■	■	■												
Site reconnaissance and synoptic river sampling, including planning	■	■	■	■														
Near surface geophysical survey and groundwater sampling, including planning				■	■	■	■	■	■									
Environmental tracer laboratory analysis and reporting				■	■	■	■	■	■	■	■	■	■	■				
Data interpretation and report writing, including peer reviews													■	■	■	■	■	■

8. Technical Reference Group

- Associate Professor Bryce Kelly (University of New South Wales)
- Representatives from NSW Department of Industry, Lands and Water
- Professor Jim Underschultz (University of Queensland)
- Dr. Dirk Mallants, CSIRO Land and Water, Adelaide

9. Communications Plan

Stakeholder	**Objective**	**Channel** (e.g. meetings/media/factsheets)	**Timeframe** (Before, during at completion)
Government and Industry	To facilitate a deeper understanding of research findings and implications for policy, programs, planning, and other initiatives	This will be achieved through the reconnaissance field trip, knowledge transfer sessions and a stakeholder engagement workshop	From the commencement of project and with updates as they become available
Regional Community/Wider Public/Traditional Owners	To communicate project objectives and key messages from the research, obtain land access approvals for geophysical survey and sampling, gather local knowledge on the natural system and hydrogeological features of interest	Through participation of a community representative in the reconnaissance field trip Participation in a community workshop where the community engagement will be assessed by the application of surveys prior and after the event. The objective of the survey is to gather an indication of the level of understanding of the wider public on the complexities of the subsurface physical environment, general limitations of groundwater studies such as this and whether the key messages have been attained through the communication protocol adopted by the research team. Fact sheet development that will explain the objective of this project and distributed to the wider public through a community representative to attend the reconnaissance field trip and GISERA website. Project progress reported on GISERA website to ensure transparency for all for all stakeholders including regional communities	From commencement of project, updates as they become available and near the completion of the project

Scientific community	To ensure that the proposed project integrates expert scientific knowledge and to communicate scientific findings	This will be achieved through reconnaissance field trip with science representatives (UNSW and ANSTO), technical reports and journal publication	On-going throughout project and at completion

10. Budget Summary

Expenditure	2018/19	2019/20	2020/21	Total
Labour	$0	$92,797	$29,037	$121,834
Operating	$0	$12,000	$2,000	$14,000
Subcontractors	$0	$78,096	$0	$78,096
Total Expenditure	**$0**	**$182,893**	**$31,037**	**$213,930**

Expenditure per Task	2018/19	2019/20	2020/21	Total
Task 1	$0	$37,024	$0	$37,024
Task 2	$0	$23,892	$0	$23,892
Task 3	$0	$66,802	$0	$66,802
Task 4	$0	$55,175	$6,324	$61,500
Task 5	$0	$0	$24,713	$24,713
Total Expenditure	**$0**	**$182,893**	**$31,037**	**$213,930**

Source of Cash Contributions	2018/19	2019/20	2020/21	Total
Federal Government (60%)	$0	$109,736	$18,622	$128,358
NSW Government (10%)	$0	$18,289	$3,104	$21,393
Santos (5%)	$0	$9,145	$1,552	$10,697
Total Cash Contributions	**$0**	**$137,170**	**$23,278**	**$160,448**

In-Kind Contributions	2018/19	2019/20	2020/21	Total
CSIRO (25%)	$0	$45,723	$7,759	$53,482
Total In-Kind Contributions	**$0**	**$45,723**	**$7,759**	**$53,482**

	Total funding over all years	Percentage of Total Budget
Federal Government investment	$128,358	60%
NSW Government investment	$21,393	10%
Santos investment	$10,697	5%
CSIRO investment	$53,482	25%
TOTAL	**$213,930**	**100%**

Task	Milestone Number	Milestone Description	Funded by	Start Date (mm-yy)	Delivery Date (mm-yy)	Fiscal Year Completed	Payment $ (excluding CSIRO contribution)
Task 1	1.1	Compilation of historic data and reinterpretation of existing seismic surveys	GISERA	Jul-2019	Dec-2019	2019/20	$27,768.00
Task 2	2.1	Site reconnaissance and synoptic river sampling, including planning	GISERA	Jul-2019	Oct-2019	2019/20	$17,919.00
Task 3	3.1	Surface geophysical survey and groundwater sampling, including planning	GISERA	Oct-2019	Mar-2020	2020/21	$50,101.50
Task 4	4.1	Environmental tracer laboratory analysis	GISERA	Oct-2019	Aug-2020	2020/21	$46,124.25
Task 5	5.1	Data interpretation, integration and report writing (including peer reviews)	GISERA	Jul-2020	Dec-2020	2020/21	$18,534.75

11. Intellectual Property and Confidentiality

<table>
<tr><td rowspan="3">Background IP (clause 11.1, 11.2)</td><td>Party</td><td>Description of Background IP</td><td>Restrictions on use (if any)</td><td>Value</td></tr>
<tr><td></td><td></td><td></td><td>$</td></tr>
<tr><td></td><td></td><td></td><td>$</td></tr>
<tr><td>Ownership of Non-Derivative IP (clause 12.3)</td><td colspan="4">CSIRO</td></tr>
<tr><td>Confidentiality of Project Results (clause 15.6)</td><td colspan="4">Project Results are not confidential.</td></tr>
<tr><td>Additional Commercialisation requirements (clause 13.1)</td><td colspan="4">Not Applicable</td></tr>
<tr><td>Distribution of Commercialisation Income
(clause 13.4)</td><td colspan="4">Not Applicable</td></tr>
<tr><td rowspan="3">Commercialisation Interest (clause 1.1)</td><td colspan="2">Party</td><td colspan="2">Commercialisation Interest</td></tr>
<tr><td colspan="2">CSIRO</td><td colspan="2">Not Applicable</td></tr>
<tr><td colspan="2">Santos</td><td colspan="2">Not Applicable</td></tr>
</table>

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