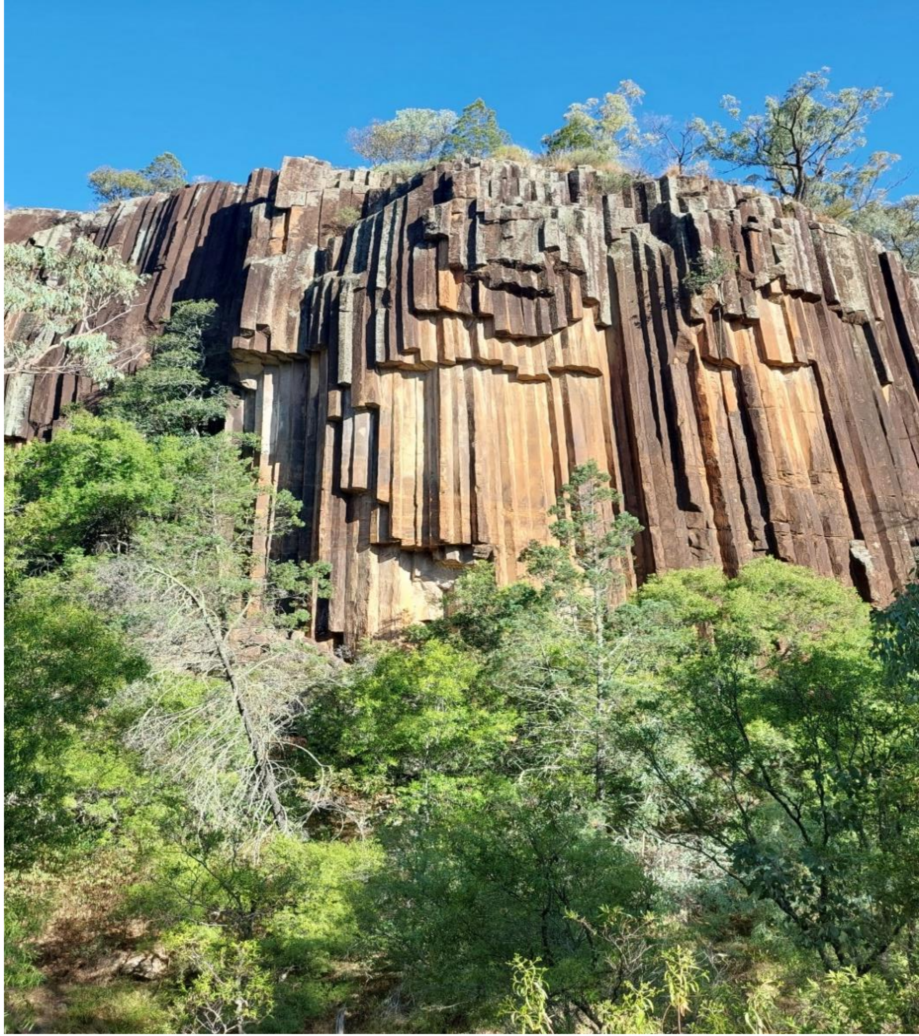
GISERA W28 – Airborne electromagnetic surveys, environmental tracers and geochemical modelling to refine the understanding of connectivity between coal seams and overlying aquifers


Sawn rocks north of Narrabri

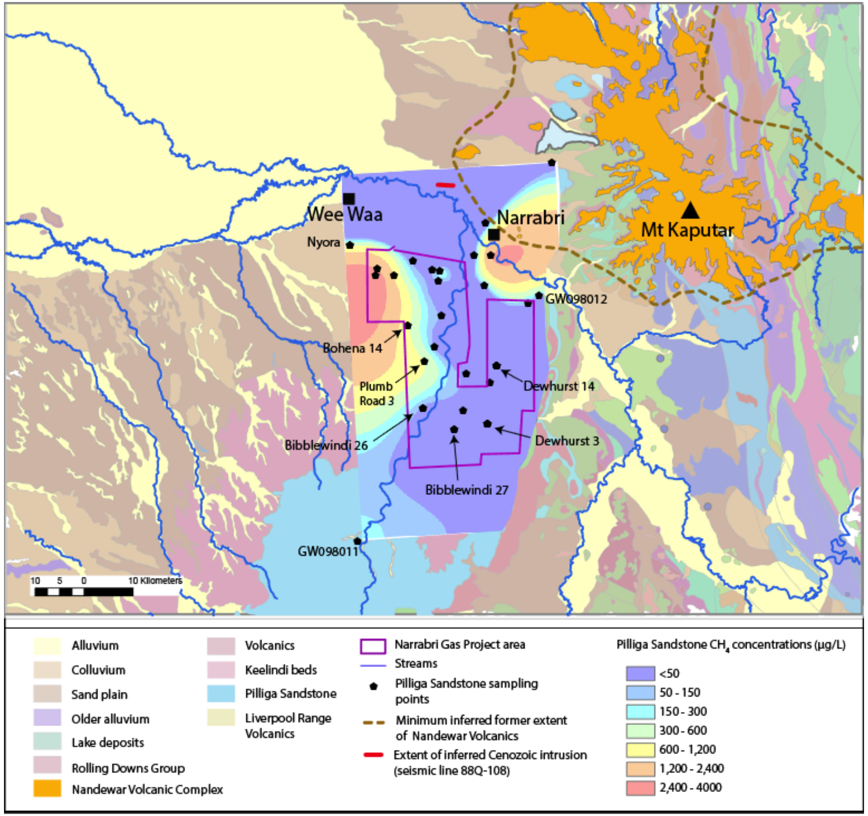
Australia's National Science Agency

Aims of GISERAW28 research

Build up on previous work to reduce uncertainties on potential hydrogeological connectivity pathways from Gunnedah Basin to Pilliga Sandstone.

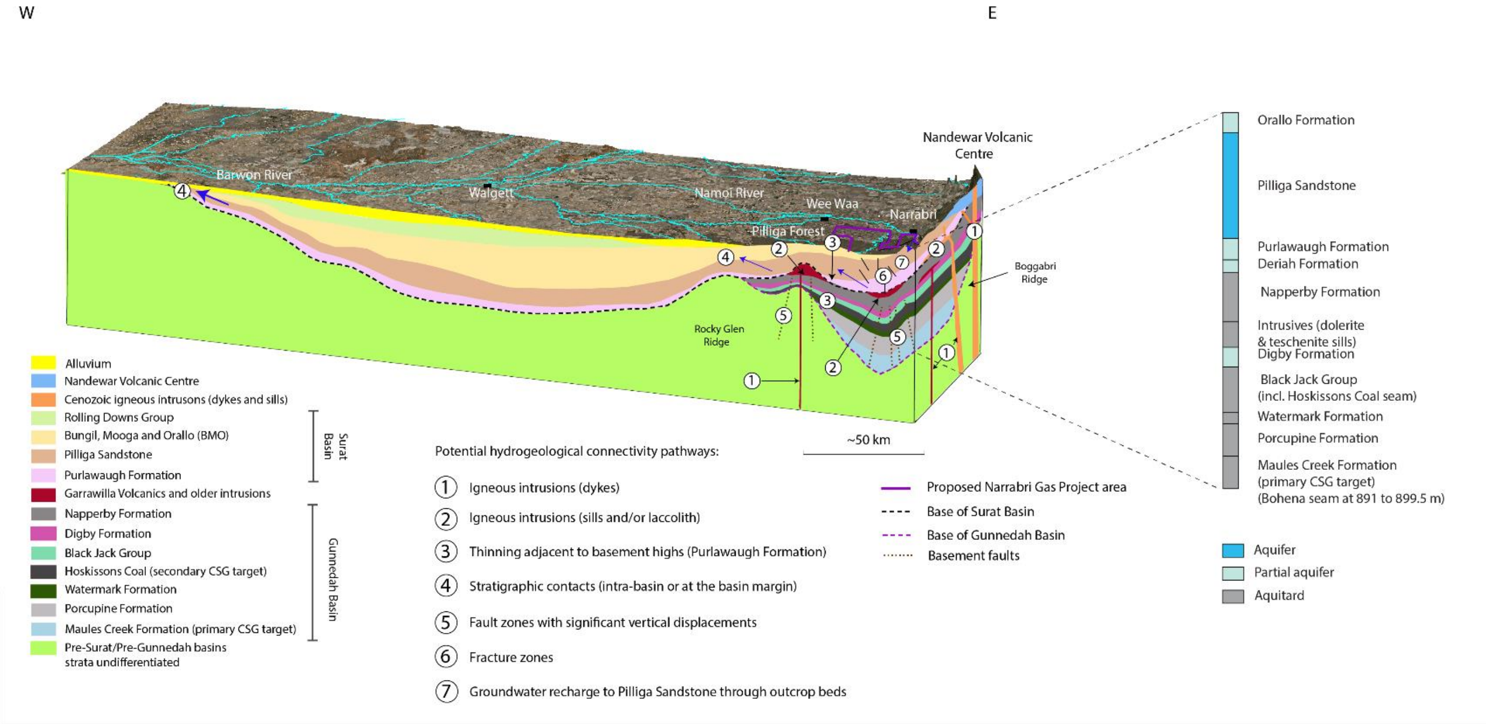
Open questions at end of GISERA project W19 'Assessment of faults as potential hydraulic seal bypasses in the Pilliga Forest area, NSW' were:

- What causes the increase in salinity, methane concentrations and other parameters from east towards north-west?
- What degree of connectivity is there at Plumb Road?
- Do intrusions form connectivity pathways?



Raiber et al (2022). Assessment of the influence of geological structures on aquifer connectivity in the Pilliga Forest area, NSW – an integrated hydrogeological, geophysical, hydrochemical and environmental tracer approach. CSIRO, Australia.

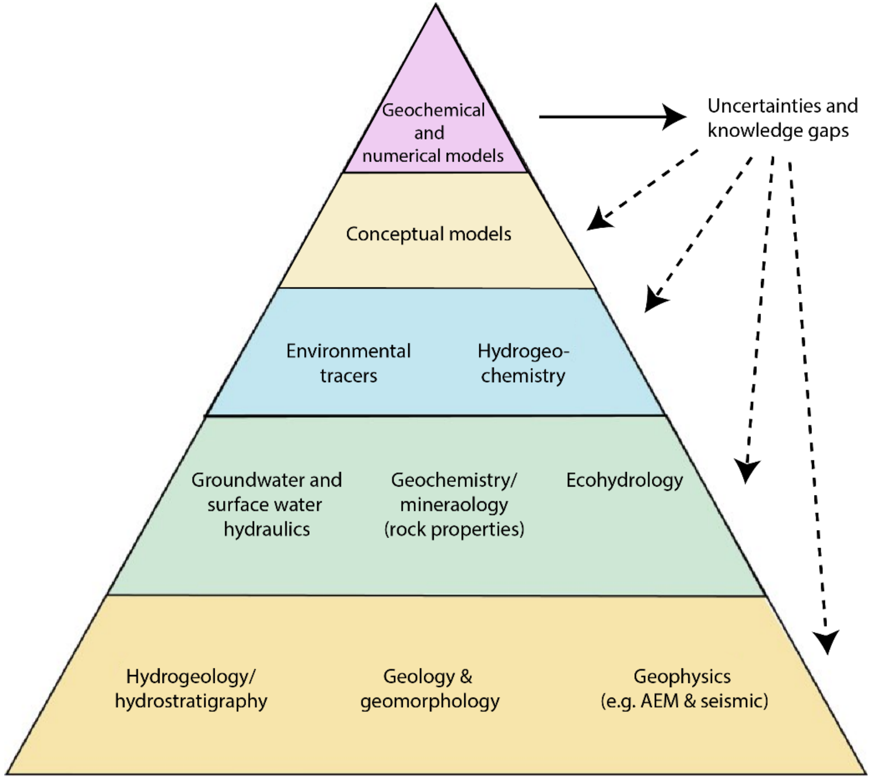
Potential hydrogeological connectivity pathways identified in GISERA W19 (2021 to 2022)



Raiber et al (2022). Assessment of the influence of geological structures on aquifer connectivity in the Pilliga Forest area, NSW – an integrated hydrogeological, geophysical, hydrochemical and environmental tracer approach. CSIRO, Australia.

GISERAW28 approach - Integration of multiple lines of evidence

- Conduct Airborne Electromagnetic (AEM) survey to obtain a more spatially continuous picture of upper 400 m of subsurface
- Characterise rocks (age of intrusions, XRD, XRF and $^{87}Sr/^{86}Sr$)
- Collect samples from new DPIE/Water NSW nested coal basin monitoring sites (comprehensive hydrochemistry and environmental tracer suite)
- Geochemical modelling to test conceptual models of hydrogeological connectivity pathways



Geological framework

Age		Basin	Major stratigraphic subdivision NSW		Stratigraphic subdivision/ stratigraphic equivalents Qld	Depositional environment	Generalised hydro-stratigraphy
Quaternary			Alluvium/Colluvium			Fluvial	Aquifer
Paleogene/ Neogene			Warrumbungle & Nandewar Volcanics		Main Range Volcanics	Volcanism	Aquifer
Cretaceous	Late	Surat Basin (Great Artesian Basin)	Rolling Downs Group		Griman Creek Formation	Coastal brackish/estuarine to freshwater fluviatile-lacustrine	Aquitard/ partial aquifer
					Surat Siltstone	Shallow marine/coastal swamp	
	Early				Wallumbilla Formation	Shallow marine	
			Drildool beds		Bungil Formation	Paralic	Partial aquifer
			Keelindi beds		Mooga Sandstone	Fluvial	Aquifer
					Orallo Formation	Flood plain	Partial aquifer
Jurassic	Late		Pilliga Sandstone		Gubberamunda Sandstone (Qld)	Fluvial (braided streams)	Aquifer
					Westbourne Formation (Qld)		Aquitard
					Springbok Sandstone (Qld)		Aquifer
	Middle		Purlawaugh Formation		Walloon Coal Measures (Qld)	Flood plain, overbank & meandering streams	Partial aquifer
	Early		Garrawilla Volcanics		Hutton Sandstone (Qld)		
Triassic	Middle	Gunnedah Basin	Napperby Formation			Lacustrine and prograding delta	Aquitard
	Early		Digby Formation			Alluvial Fan	Partial Aquifer
Permian	Late		Black Jack Group	Neah Subgroup	Trinkey Formation	Low-energy fluvial system	Aquitard
					Wallala Formation	High-energy fluvial system	
				Coogal Subgroup	Clare Sandstone	Fluvial	Partial Aquifer
					Benelarbi Formation	Low-energy fluvial system	Aquitard
					Hoskissons Coal	Peat Swamp, high-energy fluvial	CSG target
				Brothers Subgroup	Brigalow/Arkarula Fm.		Aquitard
					Pamboola Formation		
	Early		Millie Group		Watermark Formation	Marine shelf and delta	Aquitard
					Porcupine Formation	Marine shelf	Aquitard
			Bellata Group		Maules Creek Formation	Alluvial plain	Includes primary CSG target

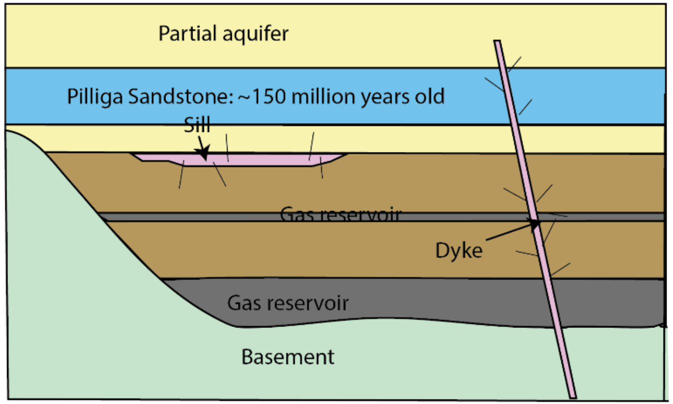
Timing of intrusive activity in Narrabri Gas Project area

Why is it important?

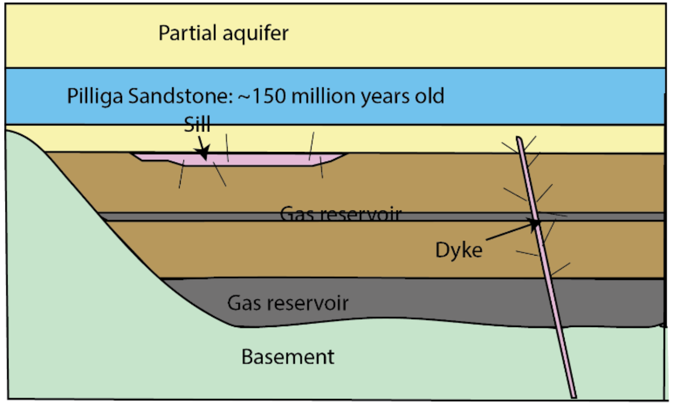
An intrusion that occurred for example 20 million years ago could extend into Pilliga Sandstone and could form potential connectivity pathway with coal seams.

An intrusion that occurred for example 180 million years ago is older than Pilliga Sandstone and cannot form connectivity pathway with coal seams.

Cenozoic intrusion (~20 million years ago)



Early Jurassic intrusion (~180 million years ago)

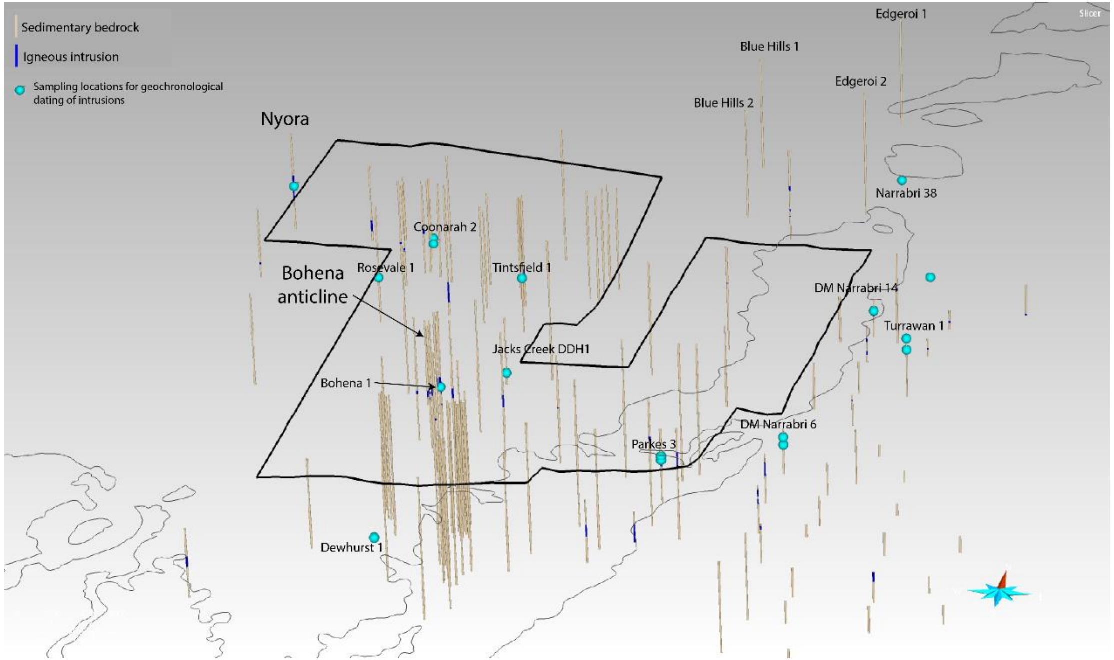


Timing of intrusive activity in Narrabri Gas Project area – spatial mapping of intrusions

In some publications, intrusions within Narrabri Gas Project area sometimes described as “Tertiary” (=“Cenozoic”).

In this project, we assessed:

1) When did the intrusion occur?
2) Which formations are intersected by intrusions



Collection of rock samples from NSW core library

NSW WB Clark Geoscience Centre - Londonderry Drillcore Library

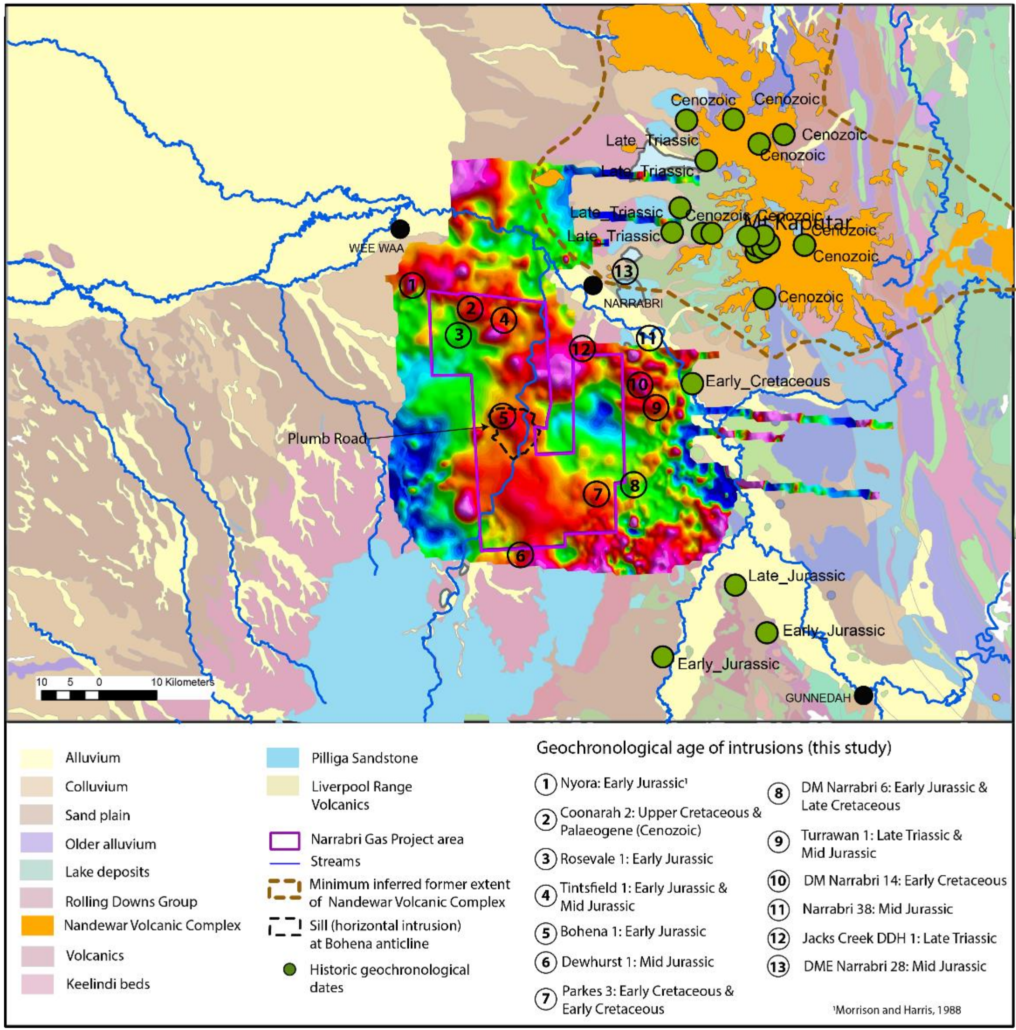
Core of dolerite intrusion at Rosevale 1 exploration well in the NSW WB Clark Geoscience Centre - Londonderry Drillcore Library

Timing of intrusions – K/Ar dating

Multiple periods of volcanic activity in Narrabri region:

- Cenozoic (~20 MA, not within Narrabri Gas Project area)
- Late Triassic/Early Jurassic (prior to deposition of Pilliga Sandstone)
- Mid Jurassic
- Cretaceous (after deposition of Pilliga Sandstone, but not observed within Pilliga Sst.)

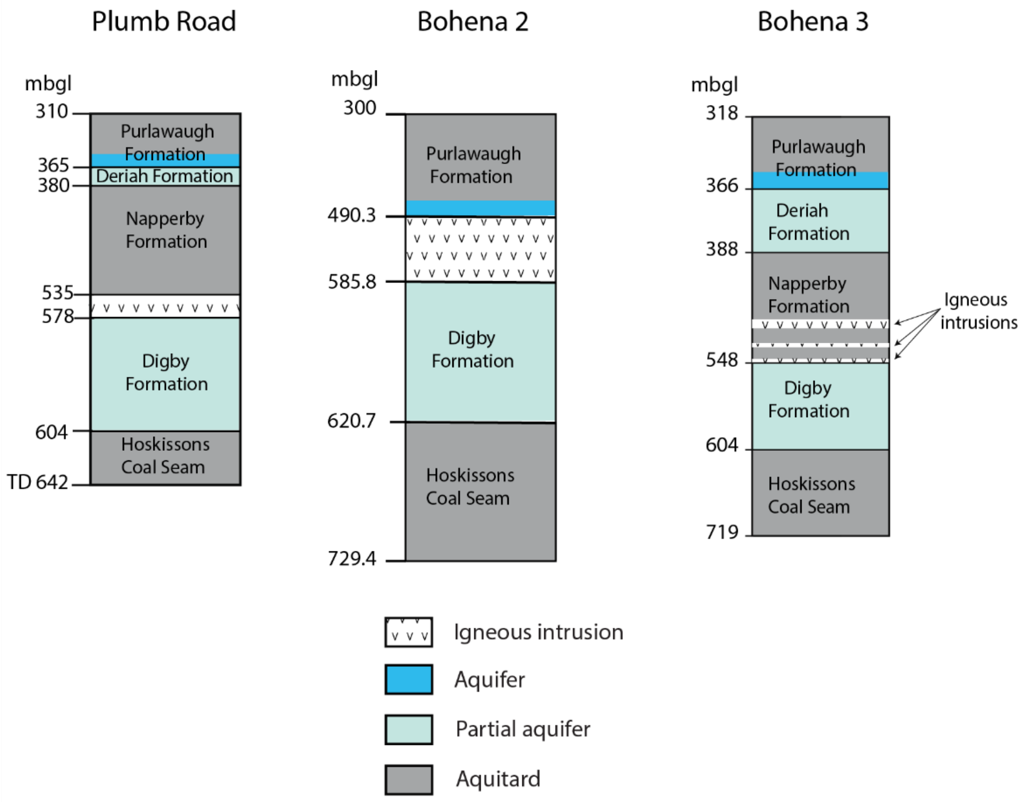
→ there are no Cenozoic volcanics in NGP area



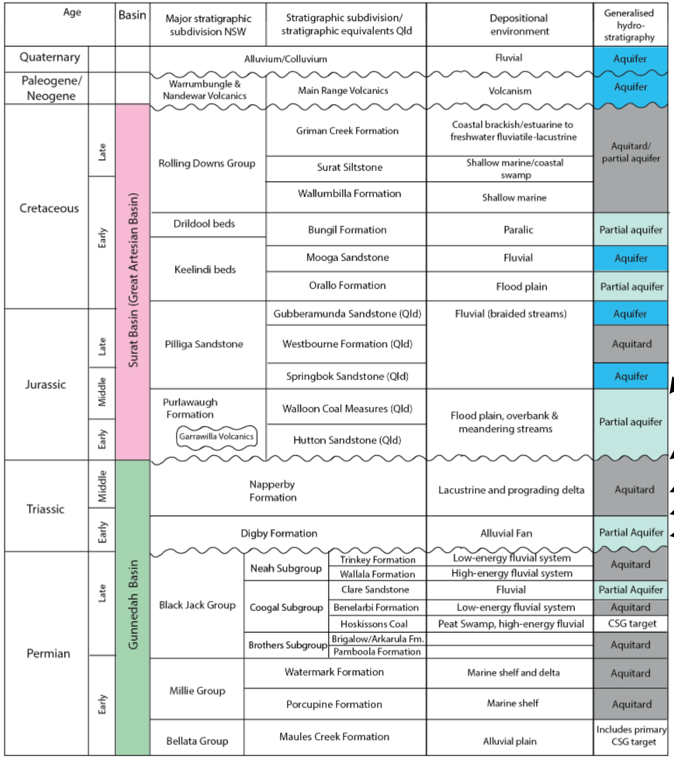
Timing of intrusive activity in Narrabri Gas Project area – spatial distribution of intrusions from stratigraphic logs

Which formations are intersected by intrusions?

In the central part of the Narrabri Gas Project area, an intrusion intersected different intervals of the uppermost Gunnedah Basin.



Intrusions observed in stratigraphic logs



Stratigraphic formation	Number of bores
Orallo Formation	N/A
Pilliga Sandstone	N/A
Interface Pilliga Sandstone - Digby Formation	1
Purlawaugh Formation	N/A
Garrawilla Volcanics	2
Deriah Formation	N/A
Interface Purlawaugh Formation - Napperby Formation	9
Interface Deriah Formation - Napperby Formation	1
Napperby Formation	12
Interface Napperby Formation - Digby Formation	7
Digby Formation	4
Black Jack Group	2
Porcupine Formation	2
Interface Porcupine Formation - Maules Creek Formation	1
Uncertain stratigraphy (within Gunnedah Basin)	17
Stratigraphic bores without intrusions	83

Most intrusions terminate at the interface of Purlawaugh – Napperby or within Napperby and Digby Fm

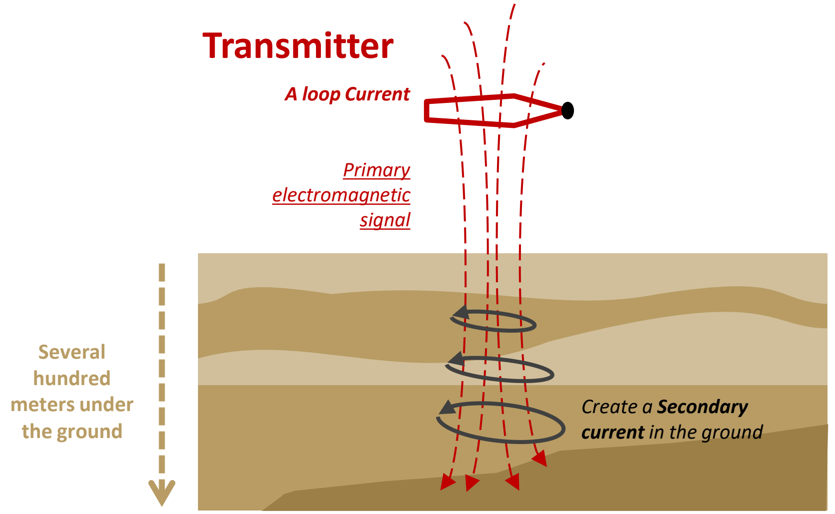
→ absence of faulting extending into Surat Basin and/or the higher thermal conductivity of siliciclastic sandstone and higher convective heat loss?

Geophysical and Geological Assessment..

Airborne ElectroMagnetic (AEM) Survey (conducted by SkyTEM)

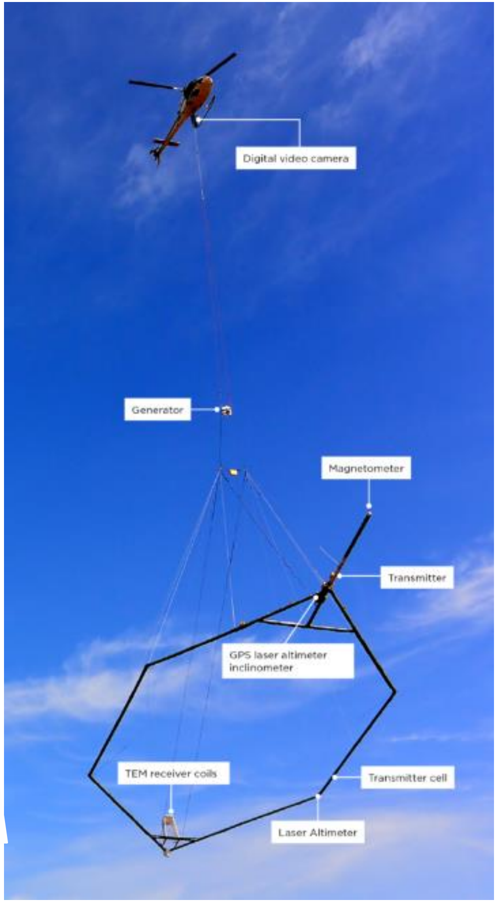
= **measures** natural variations in the **electrical properties** of soil, rocks and water

Aircraft with AEM instruments :

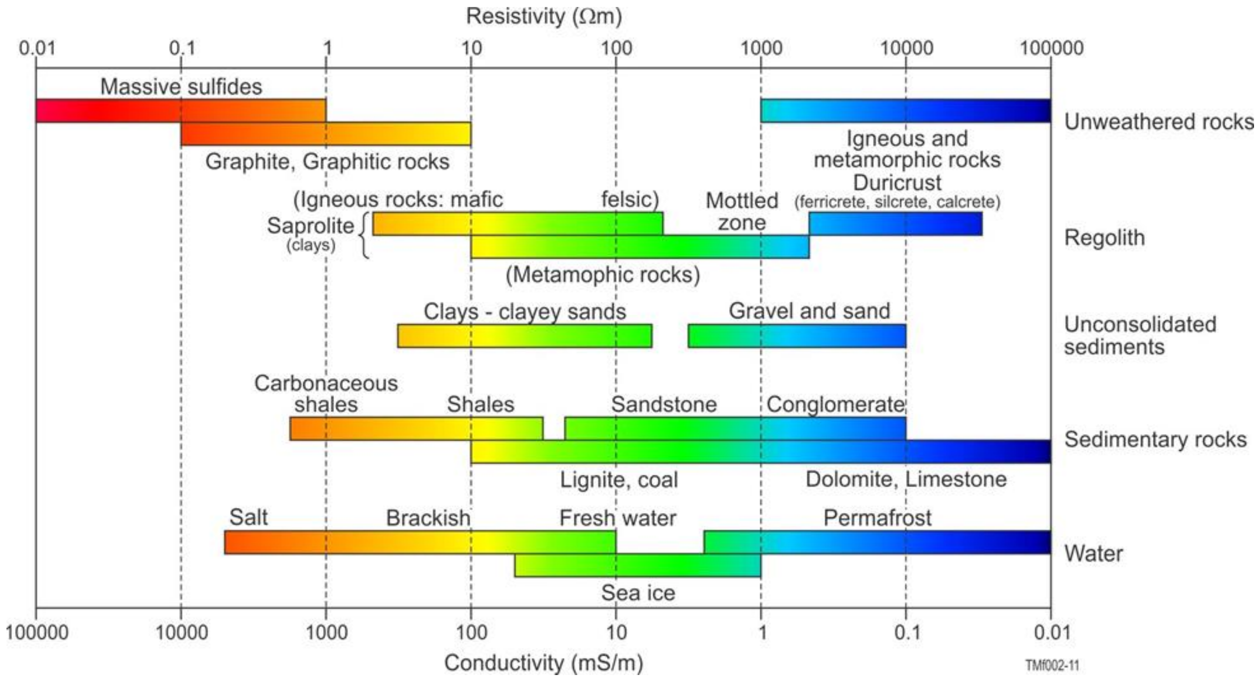


Stakeholder engagement with GISERA comms team

https://gisera.csiro.au/new-csiro-research-to-reveal-narrabri-from-400-metres-underground/



Different sediments or rocks and pore water compositions have different electromagnetic responses



Expected conductivity or resistivity of common earth materials. Overlapping values of conductivity show that the inverted conductivity values of the subsurface may not allow for unique determination of material (after Palacky 1983).

Airborne electromagnetic survey (SkyTEM)

Extensive stakeholder engagement with GISERA comms team led by Paul Cunningham and Melina Gillespie


April 16, 2024
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PROUDLY SERVING THE NARRABRI SHIRE SINCE 1913

SEARCH

NEWS SPORT SOCIAL BUSINESS COMMENT WEE WAA BOGGABRI REAL ESTATE FEATURES CLASSIFIEDS NORTH WEST

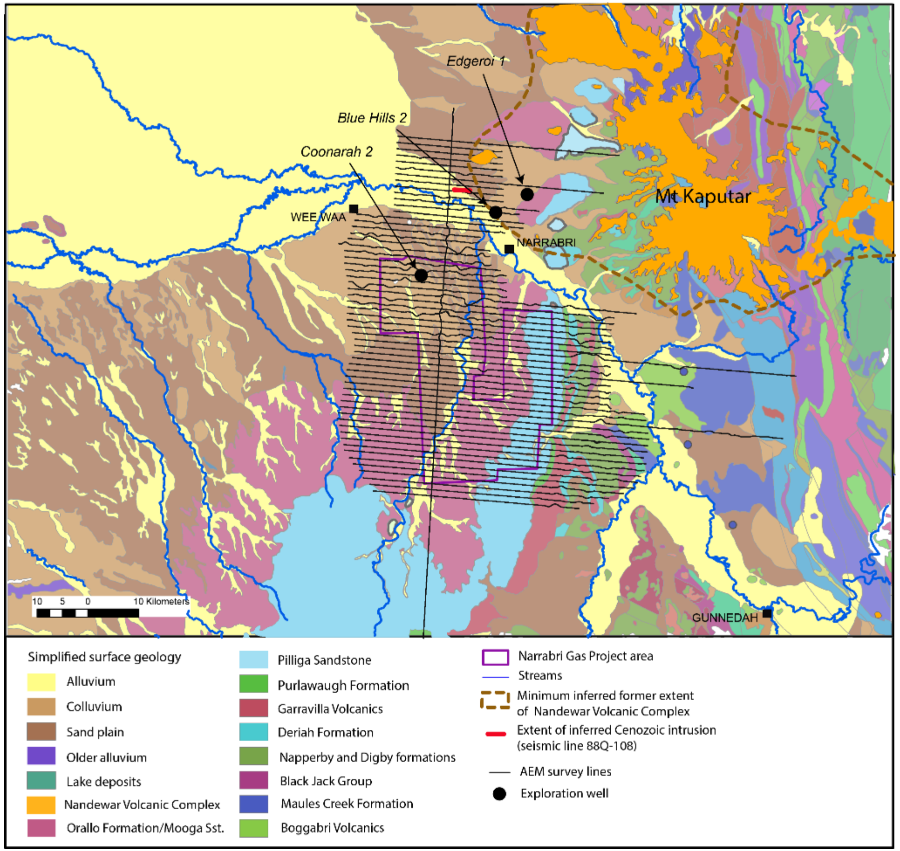
CSIRO

CSIRO Narrabri airborne electromagnetic survey

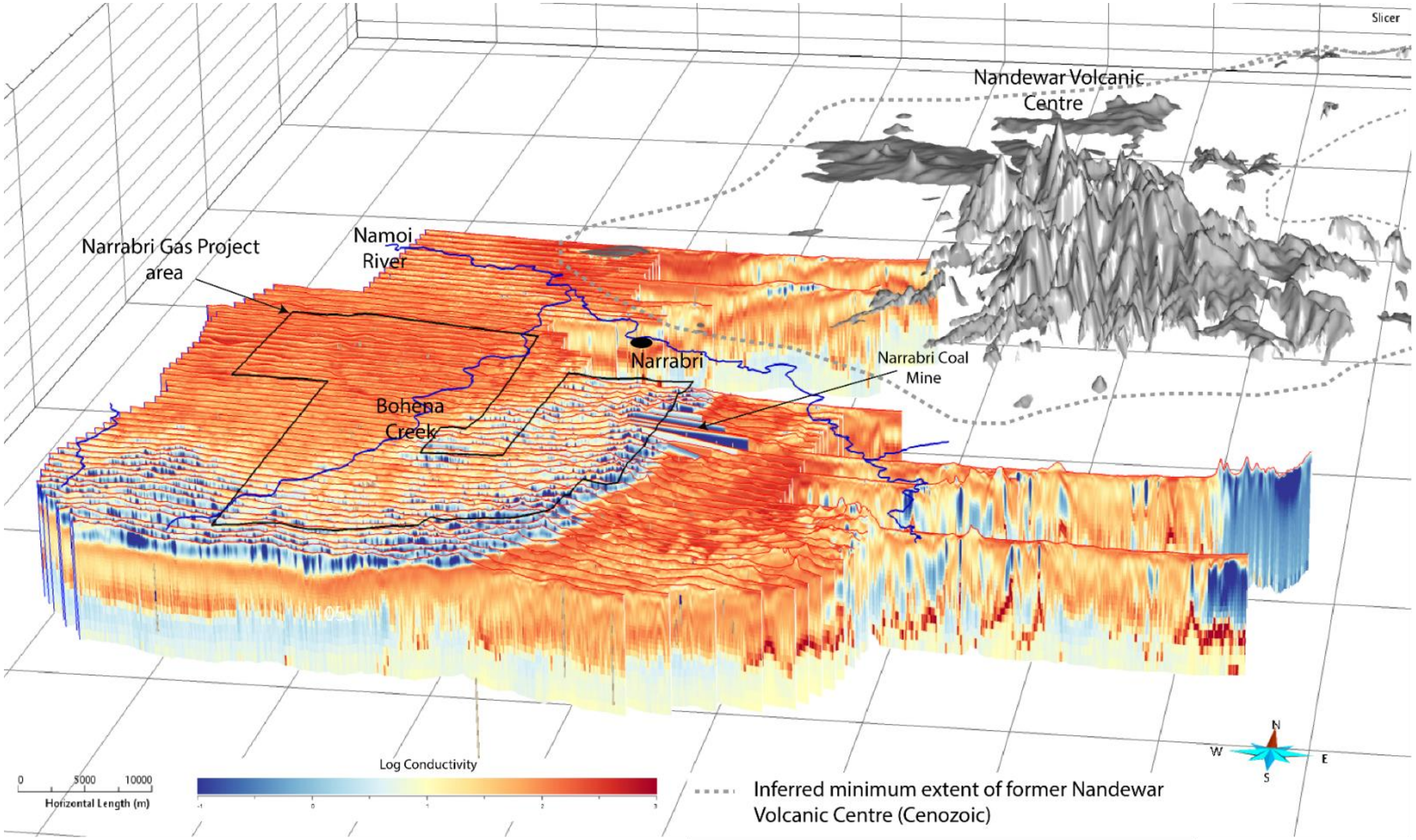
https://gisera.csiro.au/new-csiro-research-to-reveal-narrabri-from-400-metres-underground/

AEM survey aims

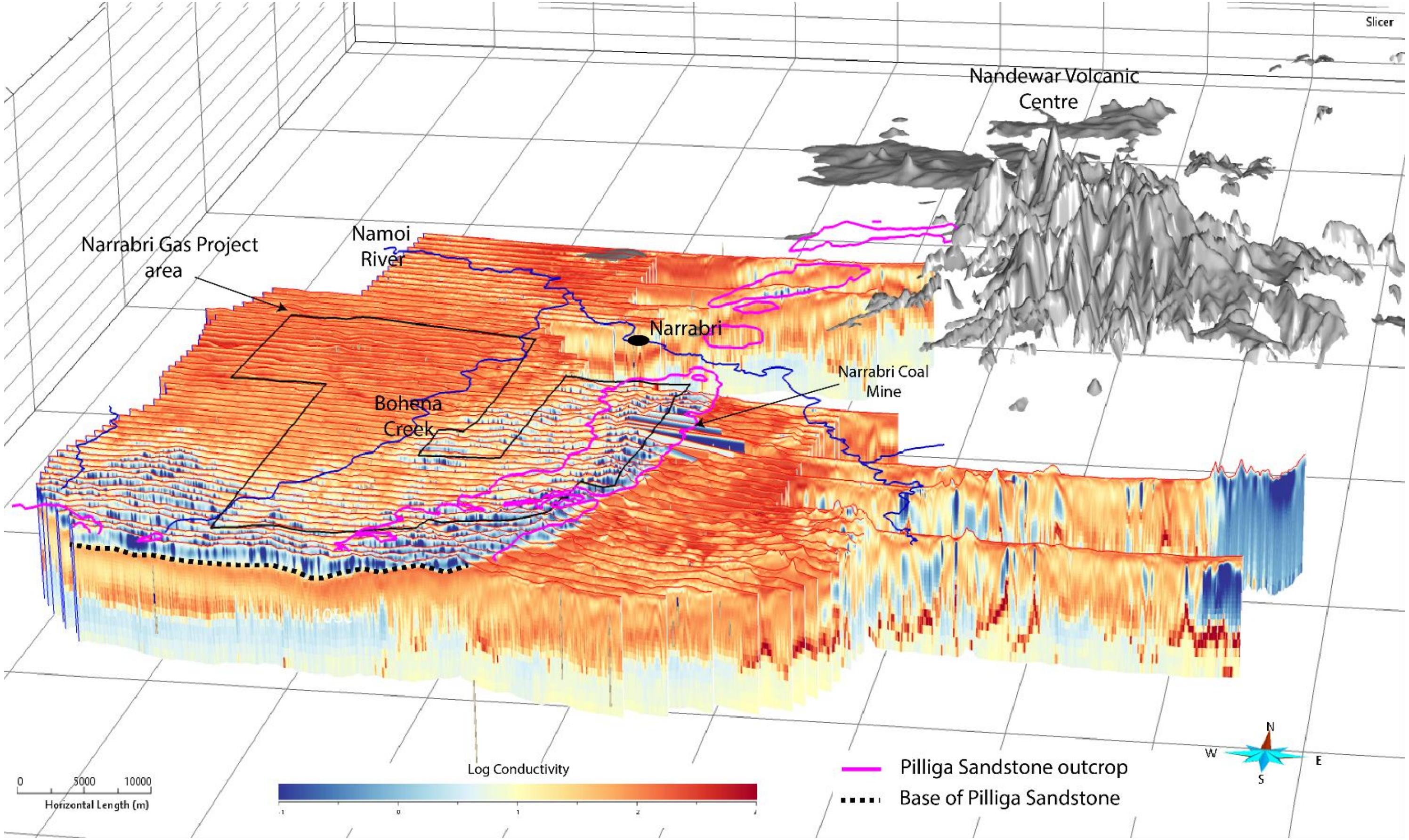
- Generating geophysical and geological mapping information to a total depth of at least 400 m
- Characterise boundaries between major formations, e.g. base of Cenozoic cover, Orallo Formation/Pilliga Sandstone, Pilliga Sandstone/Purlawaugh Formation, Purlawaugh Fm. and Napperby Fm.
- Providing insight into local geological structures (including underlying faults and intrusive igneous structures) to complement seismic surveys.



AEM survey lines

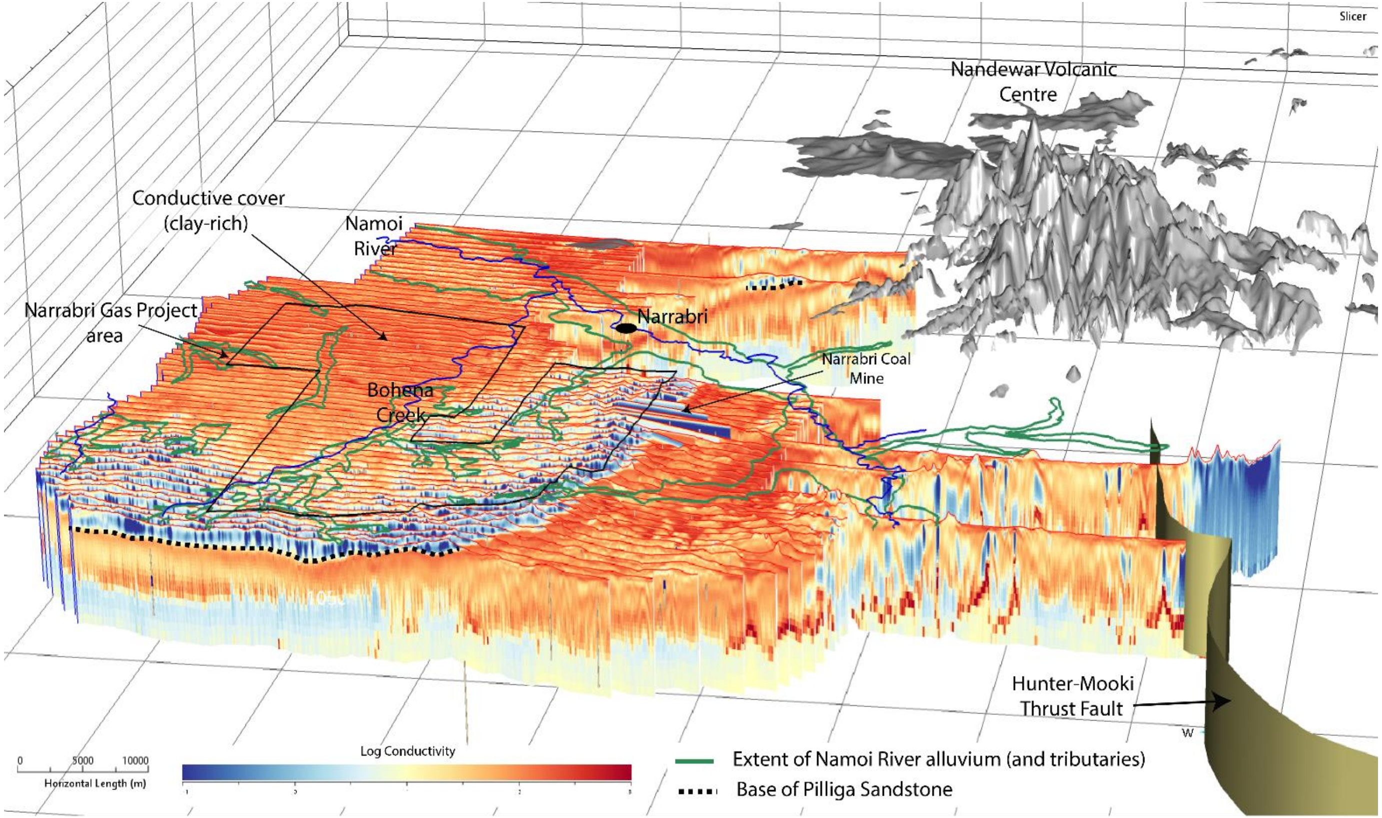


The total length of the AEM survey flown in this study was 2,765.7 km



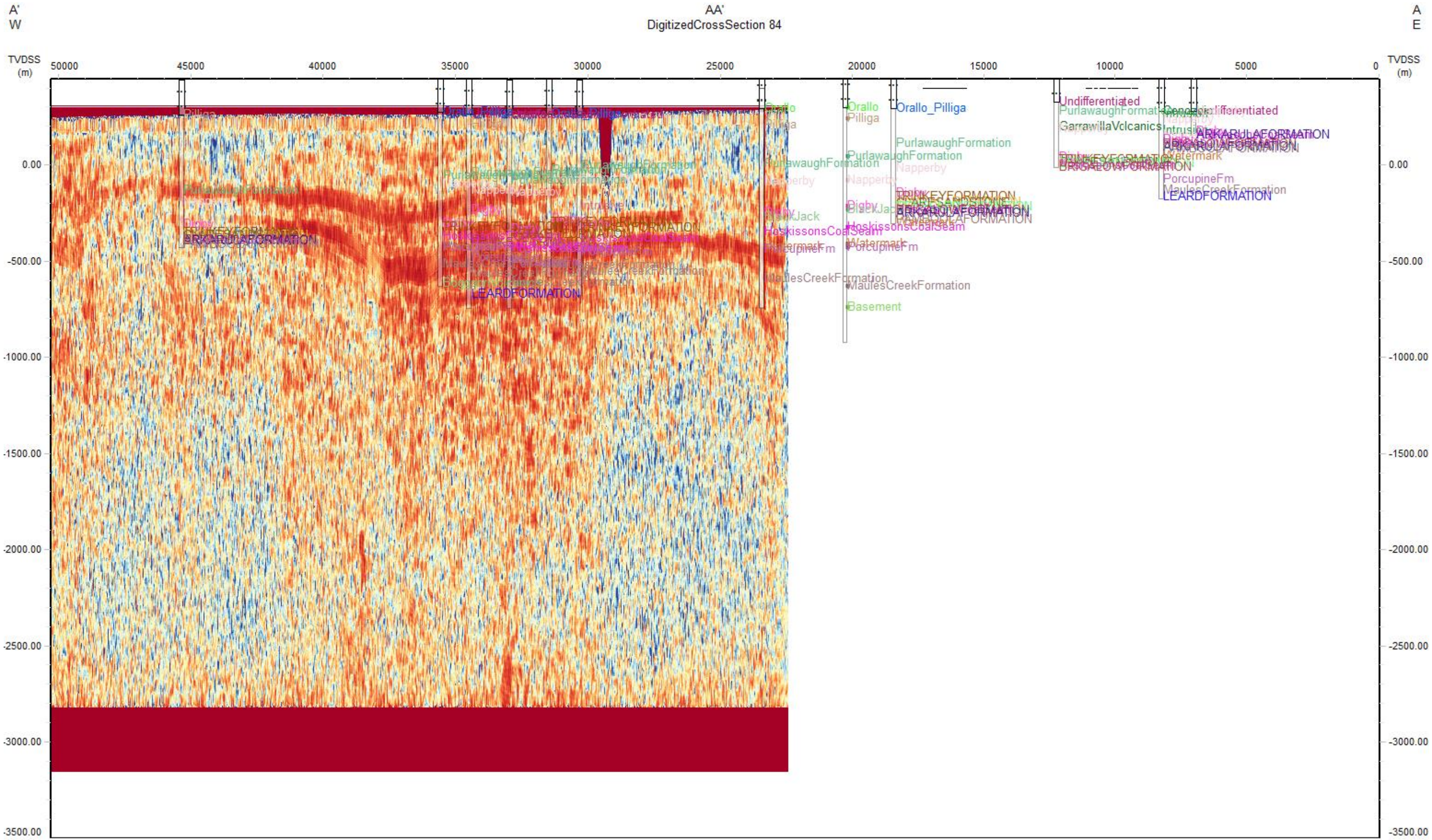
The geo-electrical response (a resistive blue-green pattern) of the Pilliga Sandstone in the outcrop beds (pink outline) suggest that the aquifer is dominated by a clean, sandy facies in this area.

Structural features

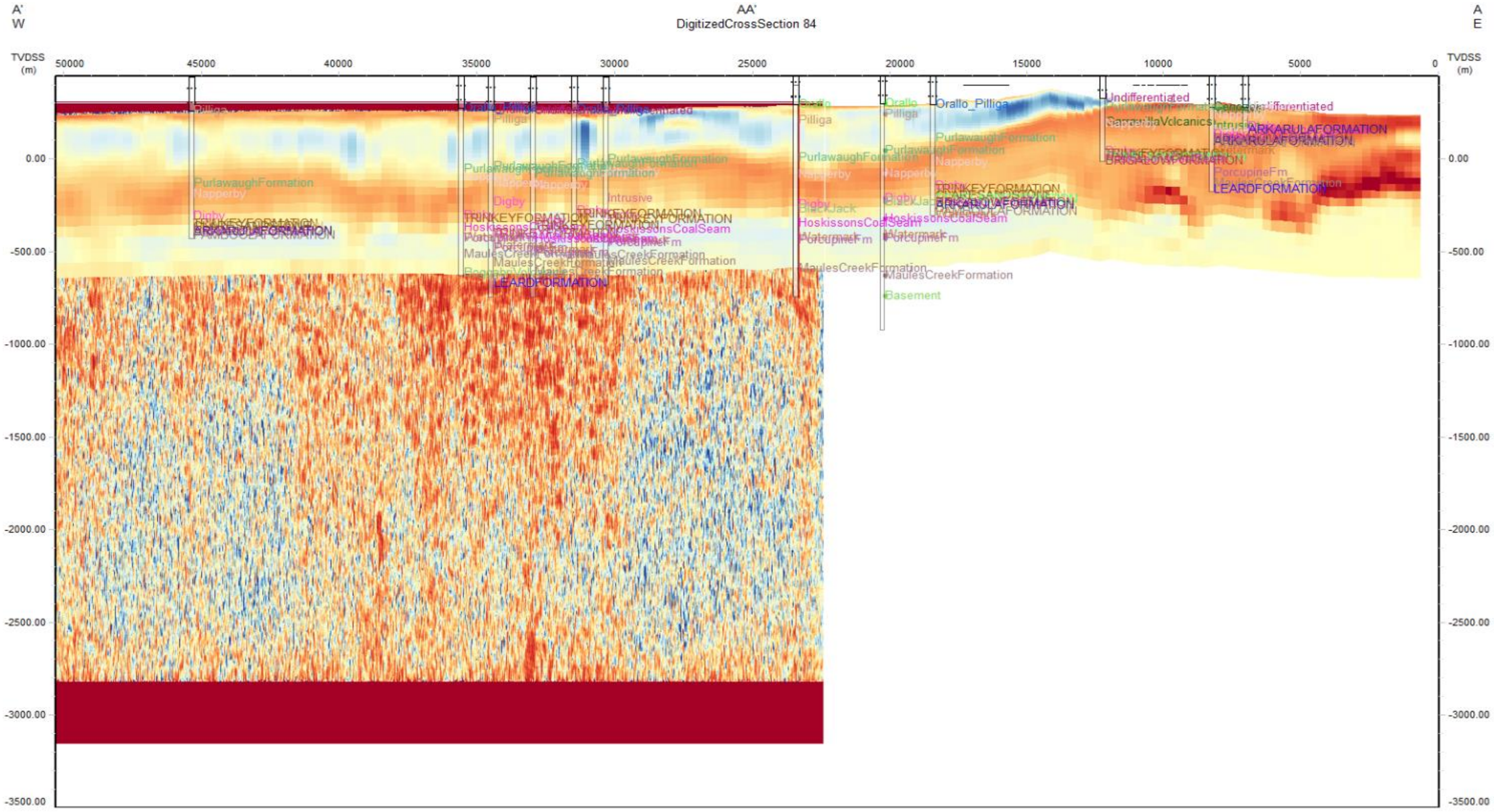


Structural features can be mapped from the AEM data: for example, the Hunter-Mooki Thrust Fault approximately 50 km east of the Narrabri Gas Project area can be clearly delineated.

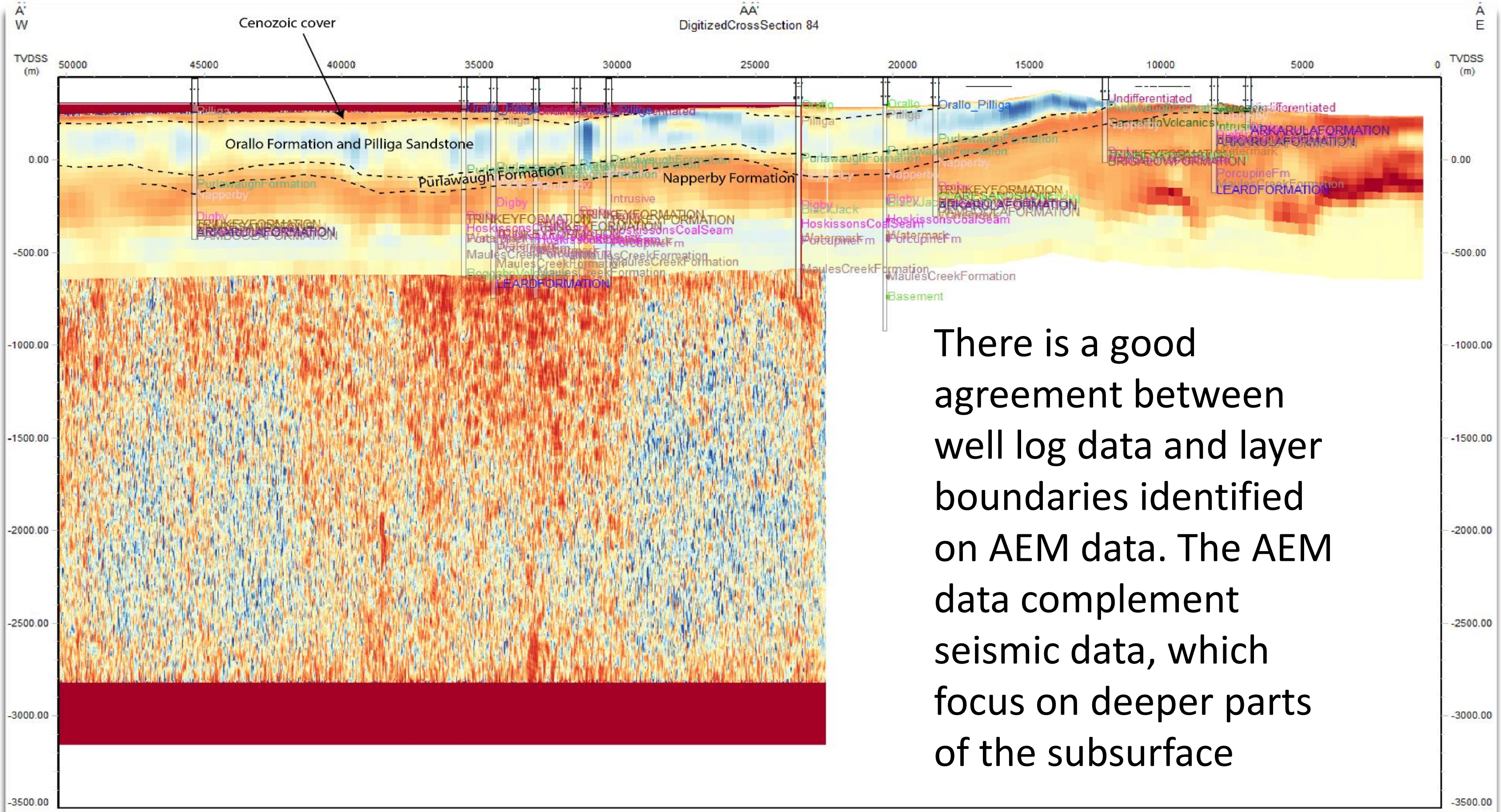
Comparison of stratigraphic logs, AEM and seismic lines



Comparison of stratigraphic logs, AEM and seismic lines

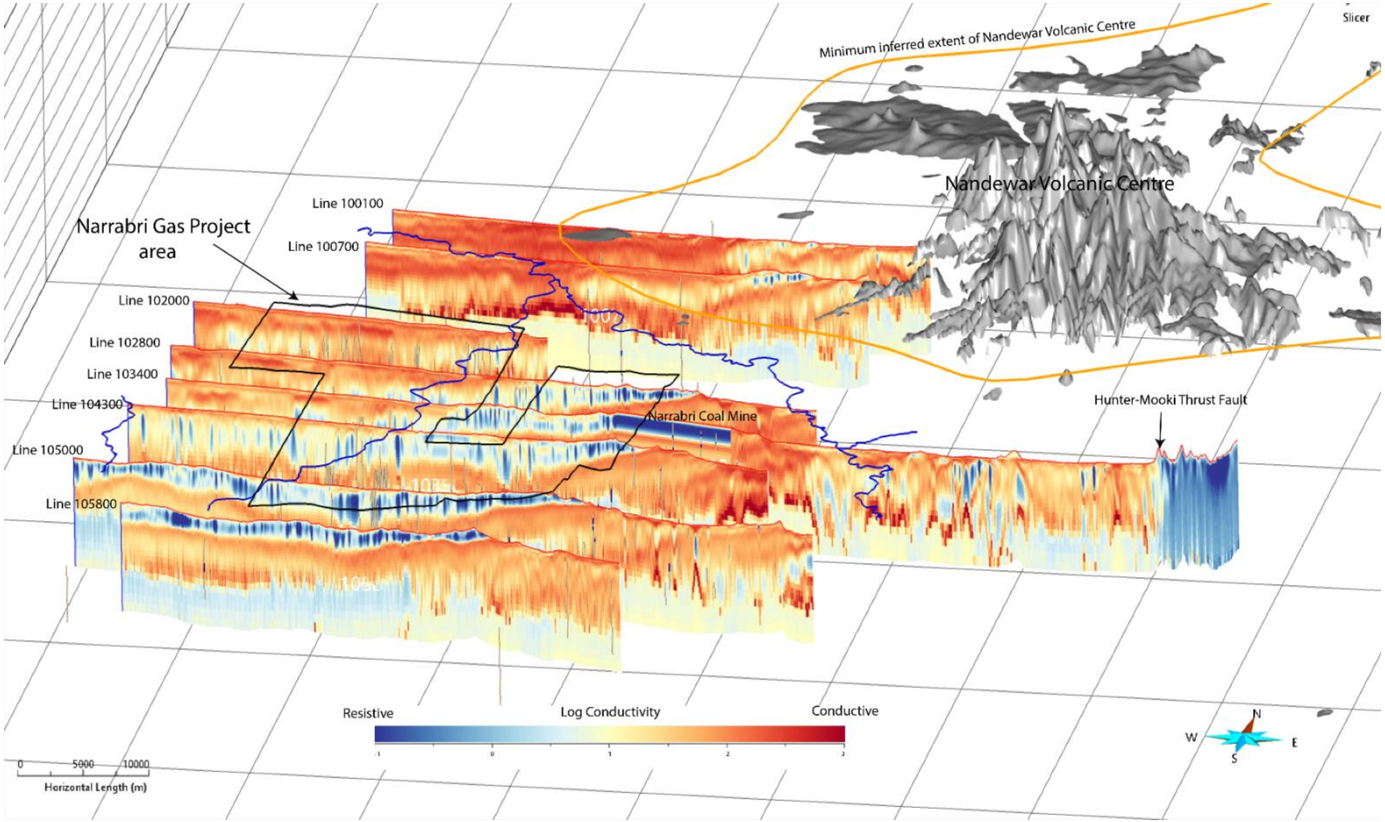


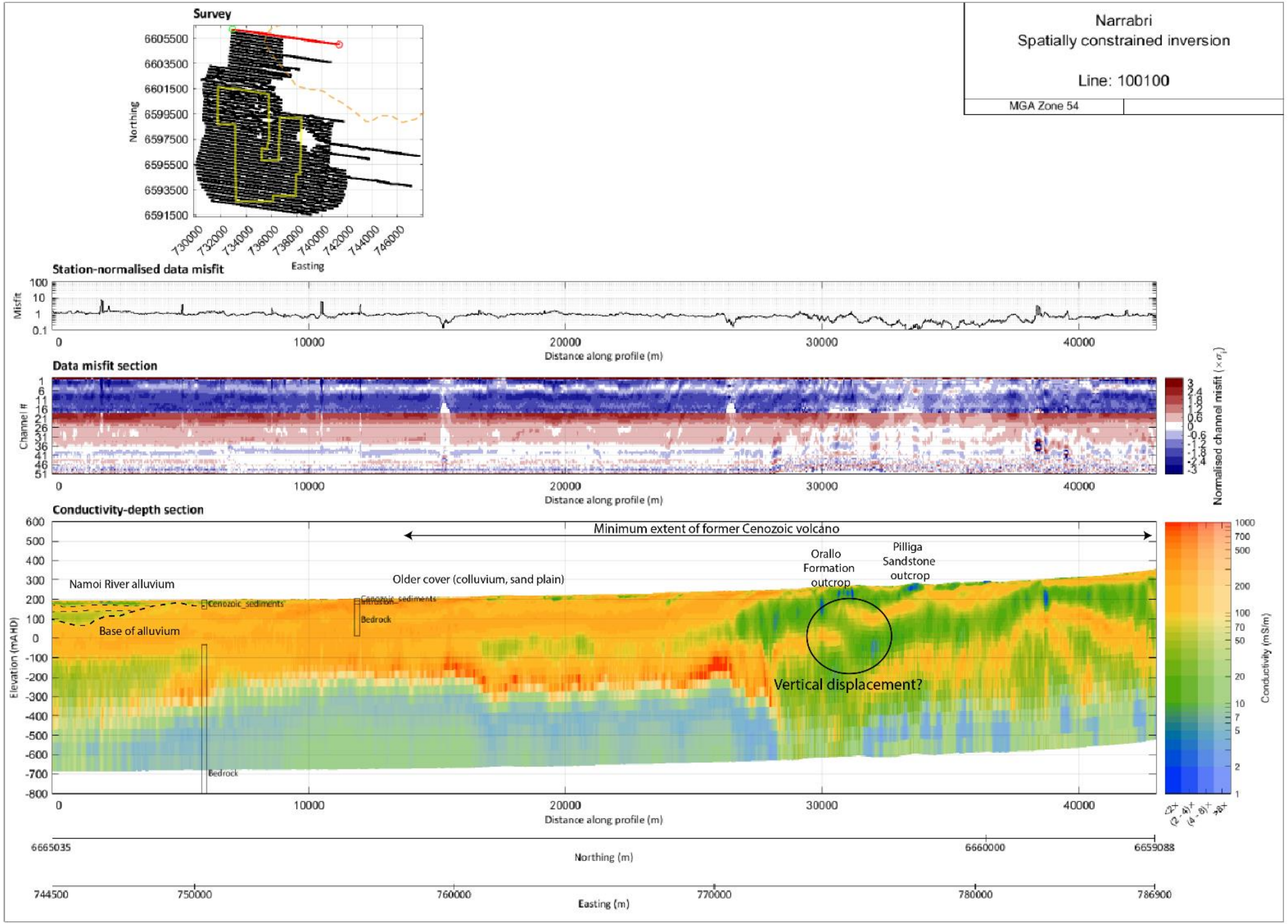
Comparison of stratigraphic logs, AEM and seismic lines



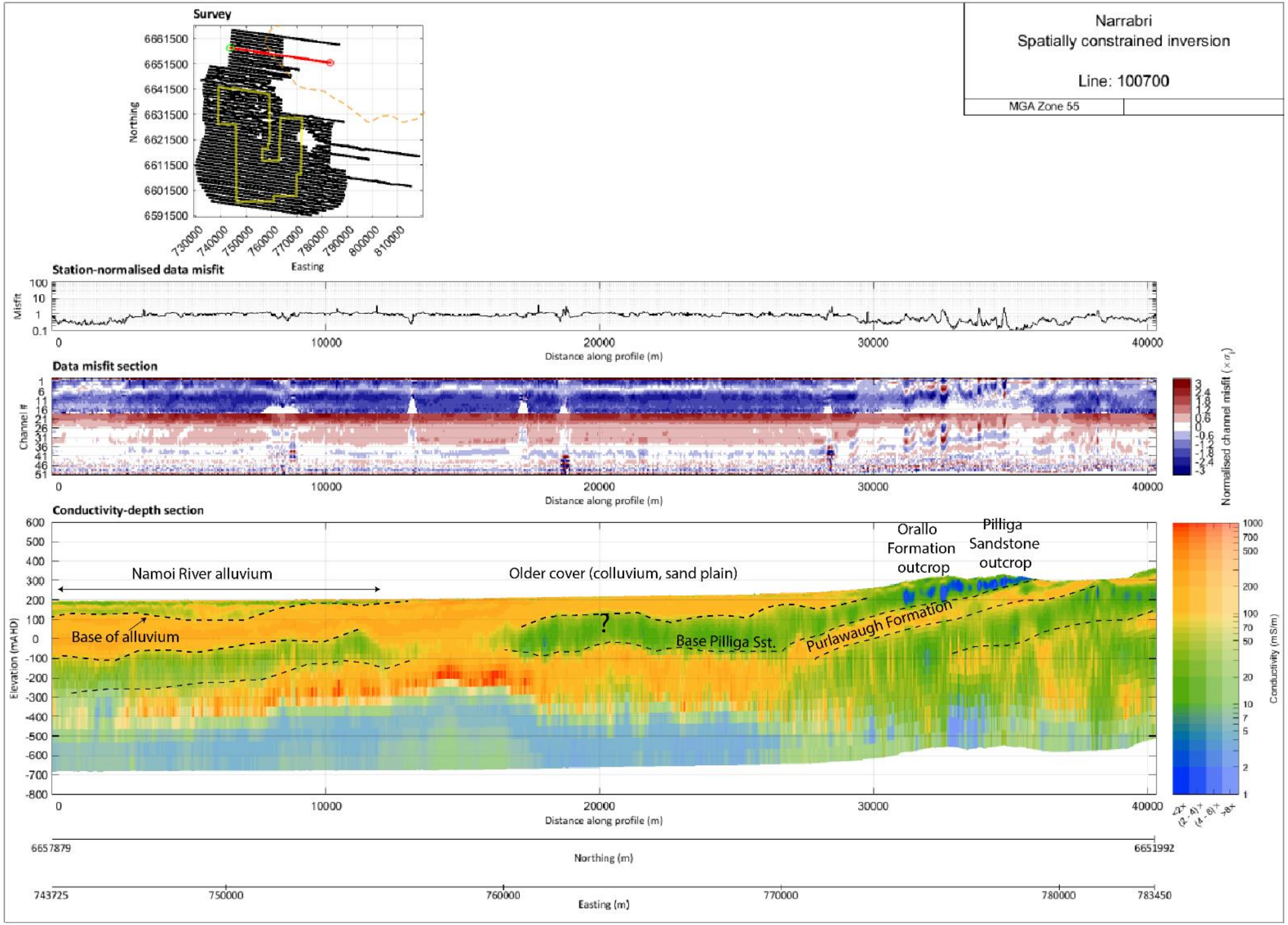
There is a good agreement between well log data and layer boundaries identified on AEM data. The AEM data complement seismic data, which focus on deeper parts of the subsurface

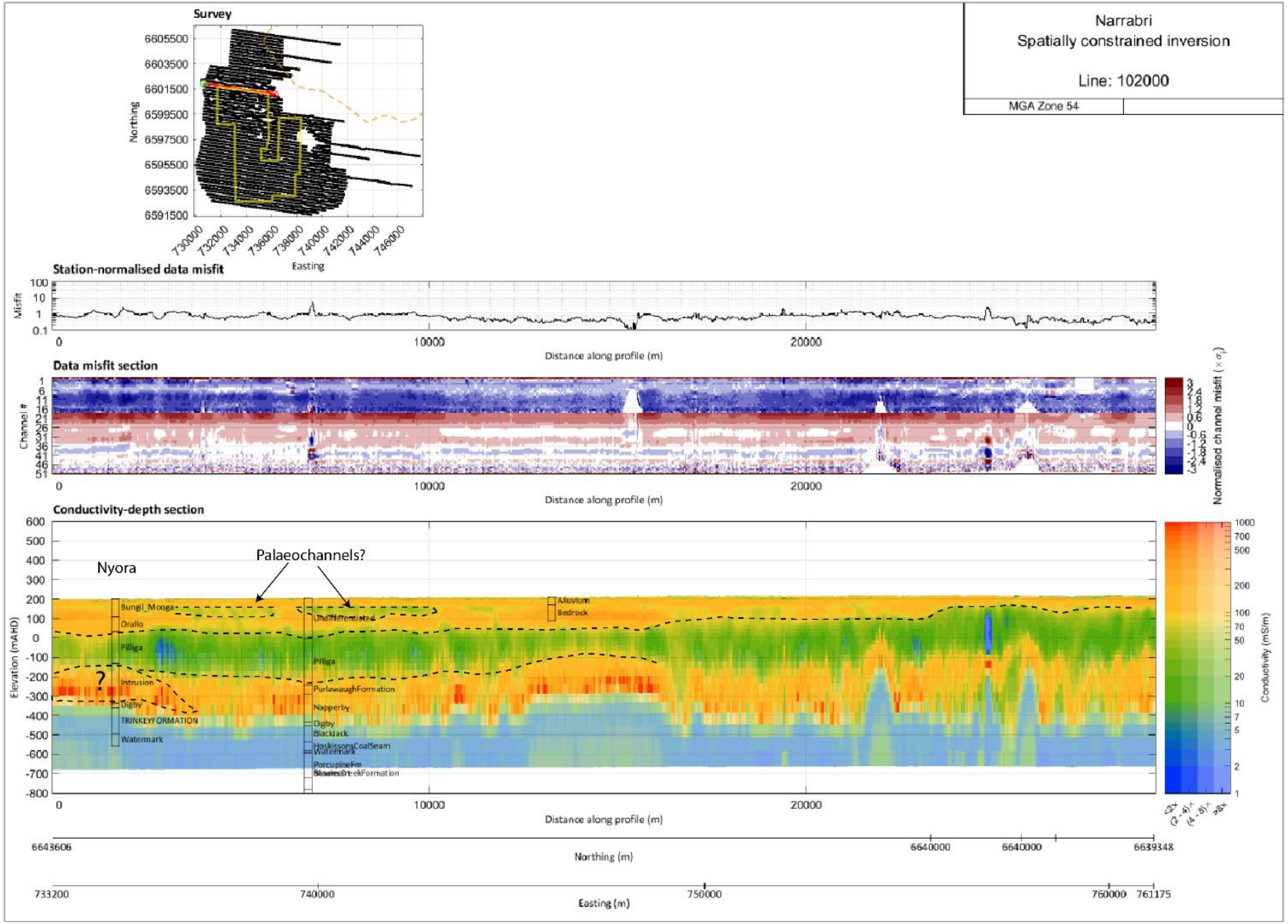
Selected AEM lines (shown in following slides)



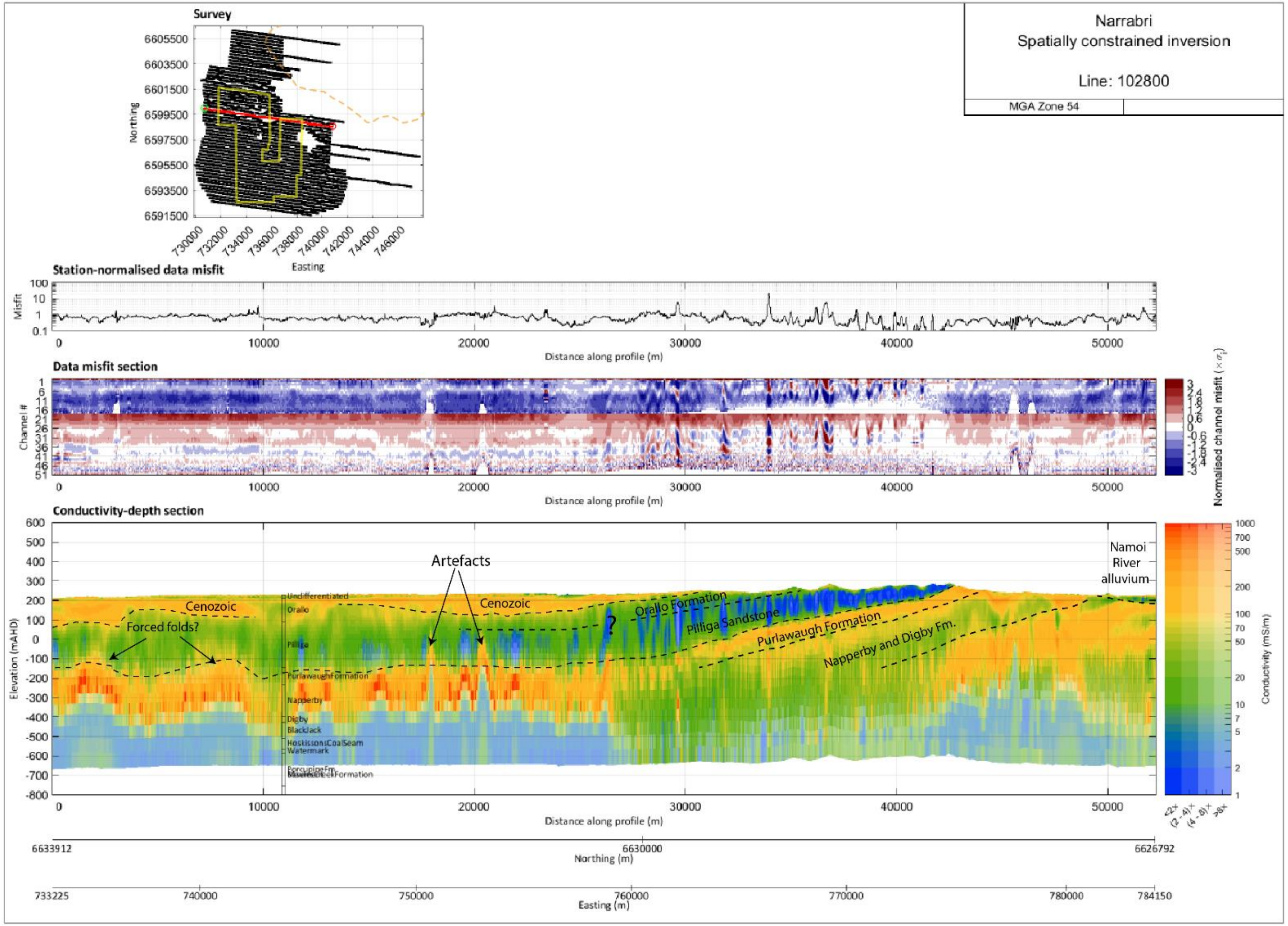


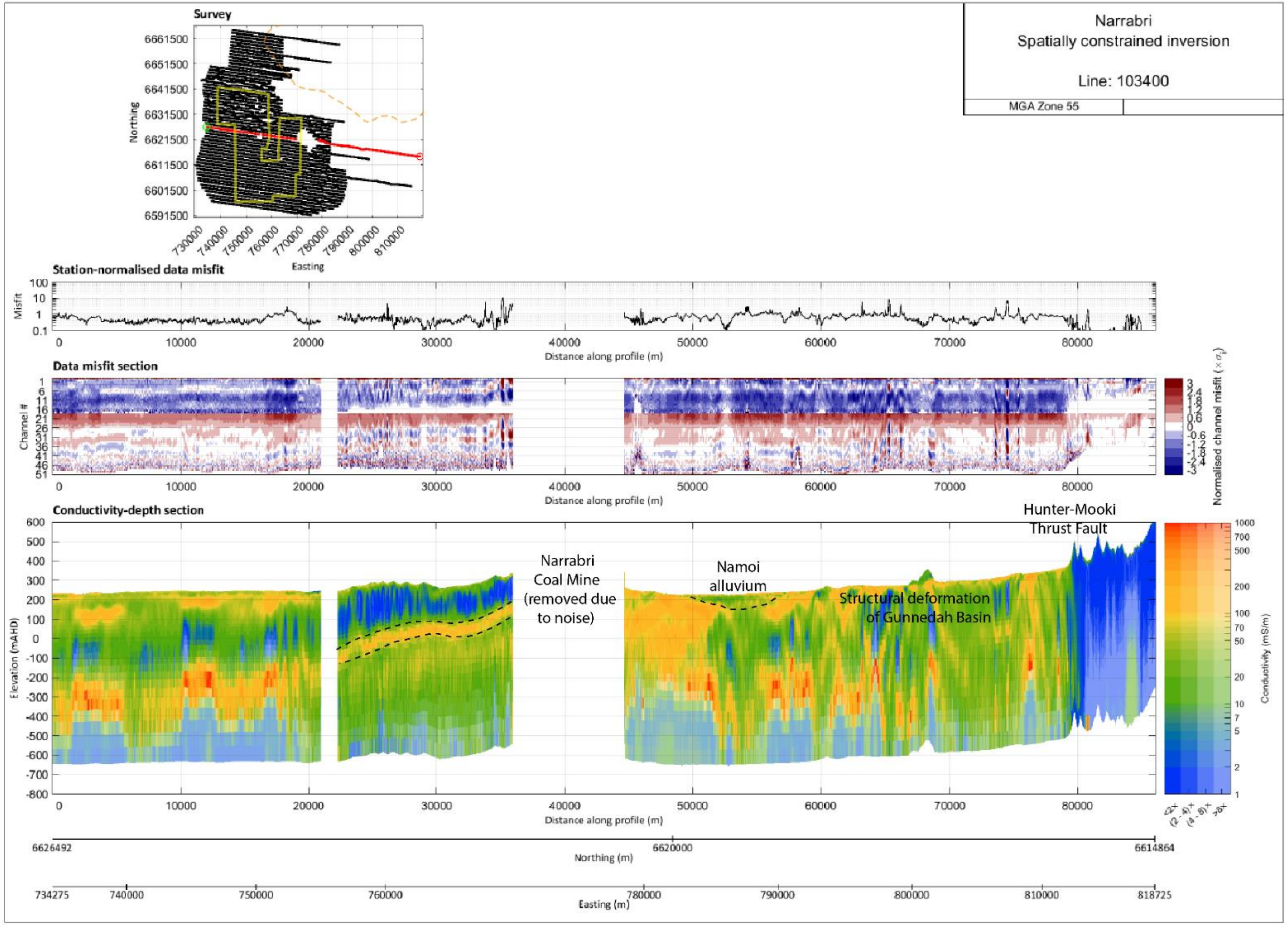
Narrabri
Spatially constrained inversion
Line: 100100
MGA Zone 54
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Minimum extent of former Cenozoic volcano
Namoi River alluvium
Older cover (colluvium, sand plain)
Orallo Formation outcrop
Pilliga Sandstone outcrop
Base of alluvium
Cenozoic_sediments
Bedrock
Vertical displacement?
Conductivity (mS/m)
Northing (m)
Easting (m)

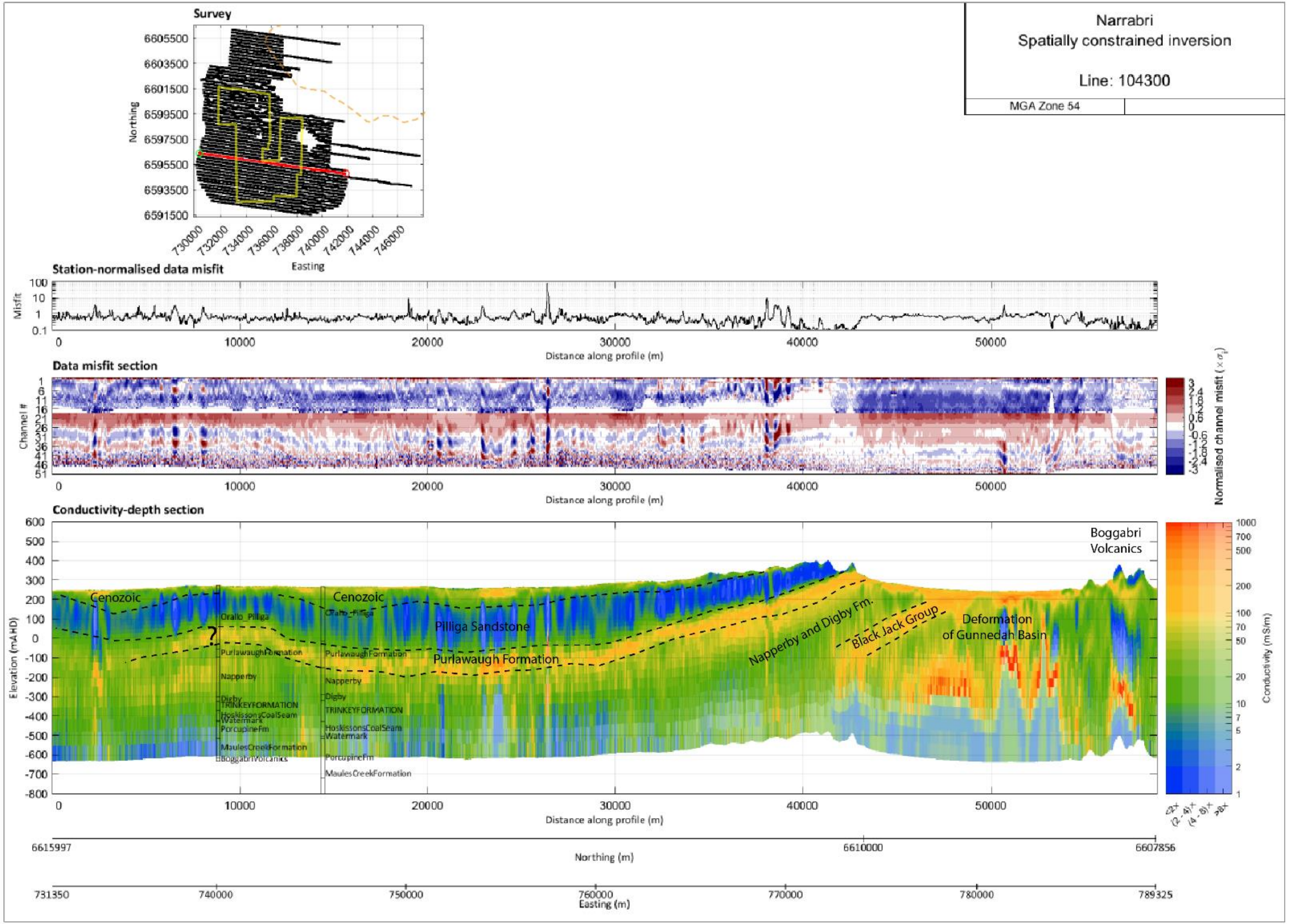

Narrabri
Spatially constrained inversion
Line: 100700
MGA Zone 55
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Namoi River alluvium
Older cover (colluvium, sand plain)
Orallo Formation outcrop
Pilliga Sandstone outcrop
Base of alluvium
Base Pilliga Sst.
Purlawaugh Formation
?
Elevation (mAHD)
Conductivity (mS/m)
Northing (m)
6657879
6651992
Easting (m)
743725
783450



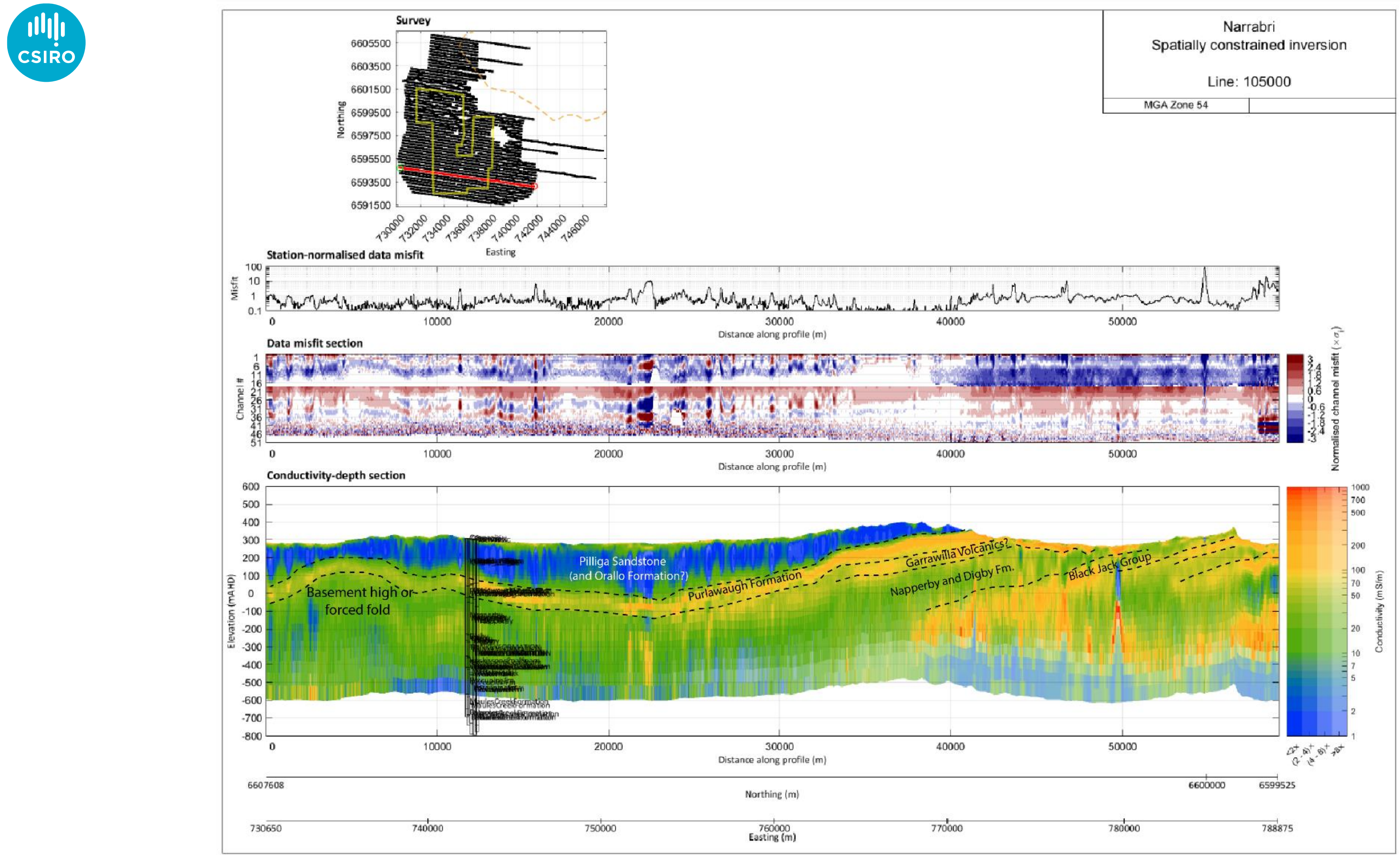
Narrabri
Spatially constrained inversion
Line: 102000
MGA Zone 54
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Conductivity (mS/m)
Nyora
Palaeochannels?
Bungil_Mooga
Orallo
Pilliga
Intrusion
Digby
TRINKEYFORMATION
Watermark
Undifferentiated
PurlawaughFormation
Napperby
Blackjack
HoskissonsCoalSeam
PorcupineFm
Alluvium
Bedrock
Northing (m)
Easting (m)

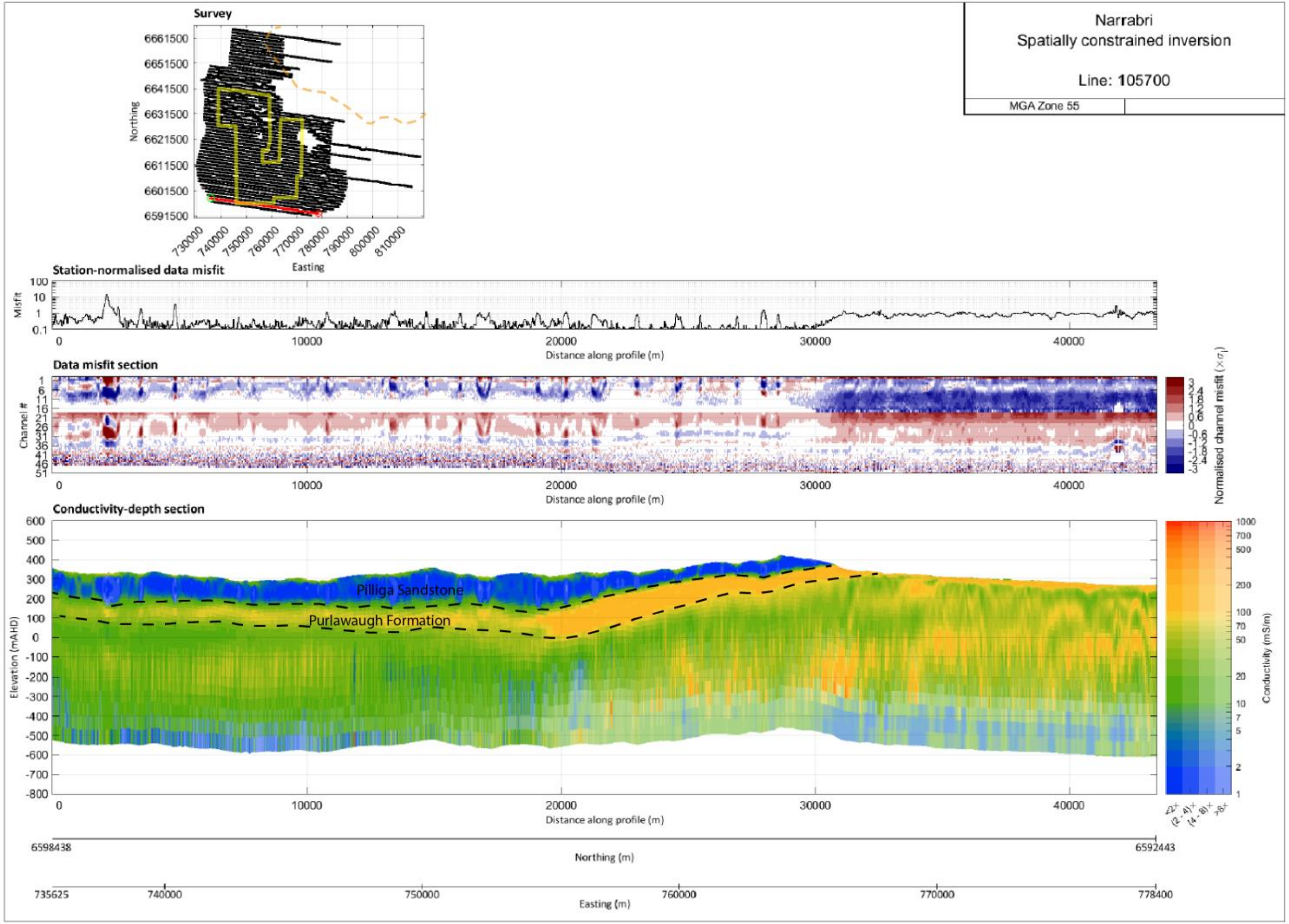

Narrabri
Spatially constrained inversion
Line: 102800
MGA Zone 54
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Conductivity (mS/m)
Artefacts
Cenozoic
Forced folds?
Orallo Formation
Pilliga Sandstone
Purlawaugh Formation
Napperby and Digby Fm.
Namoi
River
alluvium
Undifferentiated
Orallo
Pilliga
Purlawaugh Formation
Napperby
Digby
Blackjack
Hoskissons Coal Seam
Watermark
Porcupine Fm.
Northing (m)
Easting (m)


Narrabri
Spatially constrained inversion
Line: 103400
MGA Zone 55
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Conductivity (mS/m)
Narrabri
Coal Mine
(removed due
to noise)
Namoi
alluvium
Structural deformation
of Gunnedah Basin
Hunter-Mooki
Thrust Fault
Northing (m)
Easting (m)



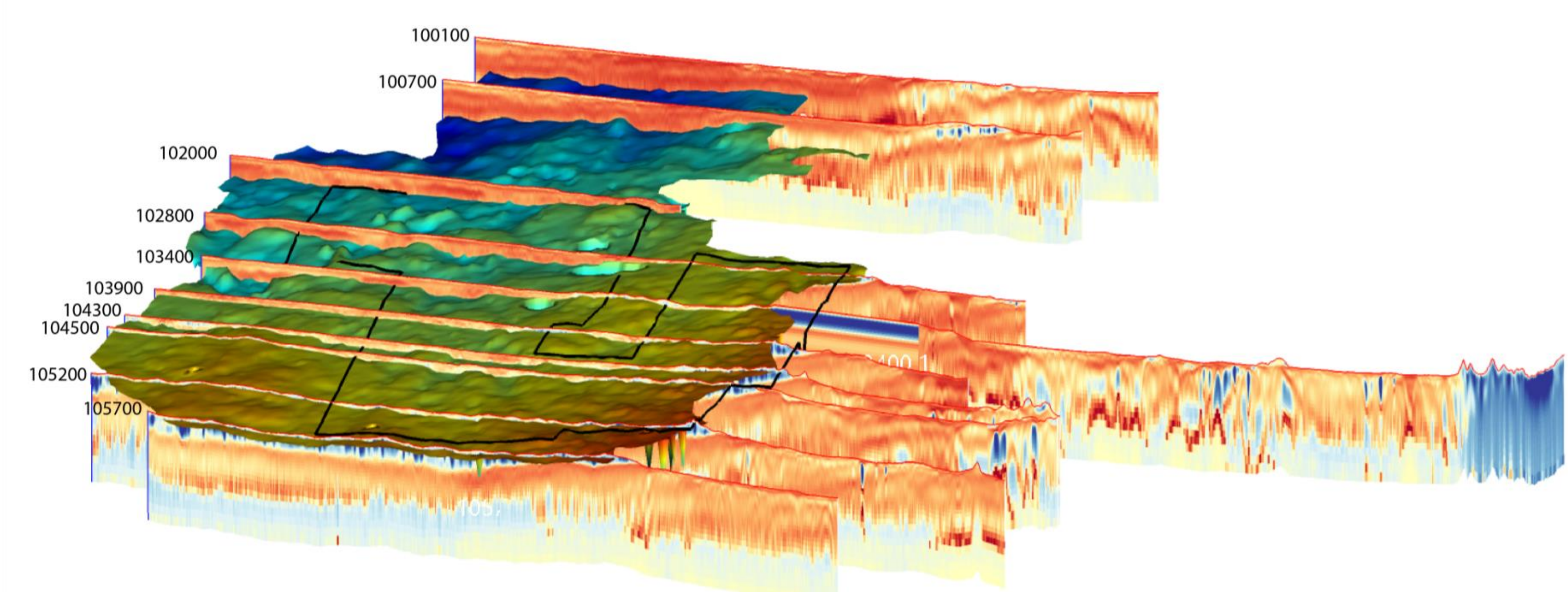
Narrabri
Spatially constrained inversion
Line: 104300
MGA Zone 54
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Cenozoic
Pilliga Sandstone
Purlawaugh Formation
Napperby and Digby Fm.
Black Jack Group
Deformation of Gunnedah Basin
Boggabri Volcanics
Conductivity (mS/m)
Northing (m)
Easting (m)


CSIRO
Narrabri
Spatially constrained inversion
Line: 105000
MGA Zone 54
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Pilliga Sandstone
(and Orallo Formation?)
Basement high or
forced fold
Purlawaugh Formation
Garrawilla Volcanics?
Napperby and Digby Fm.
Black Jack Group
Conductivity (mS/m)
Northing (m)
Easting (m)



Narrabri
Spatially constrained inversion
Line: 105700
MGA Zone 55
Survey
Northing
Easting
Station-normalised data misfit
Misfit
Distance along profile (m)
Data misfit section
Channel #
Normalised channel misfit
Conductivity-depth section
Elevation (mAHD)
Pilliga Sandstone
Purlawaugh Formation
Conductivity (mS/m)
Northing (m)
6598438
6592443
Easting (m)
735625
778400

Base of Cenozoic surface



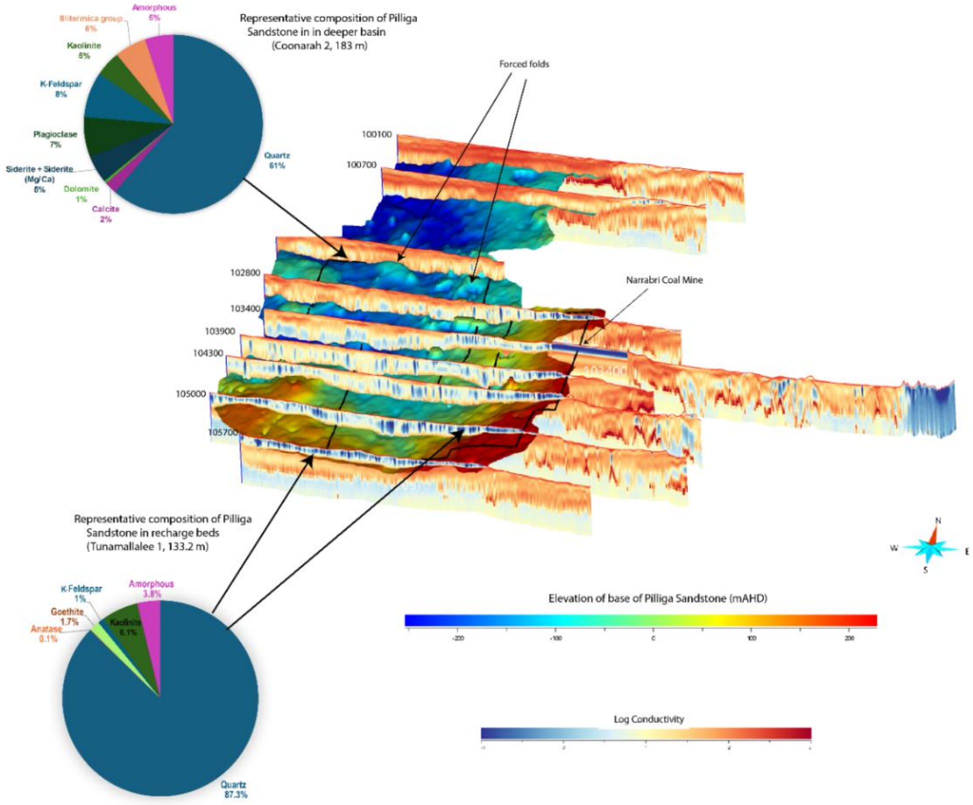
The thickness of the Cenozoic cover thins towards south and east

Spatial variability of Pilliga Sandstone

<u>Pilliga Sandstone in recharge beds:</u>
geo-electrical response of the Pilliga Sandstone suggest that the aquifer is dominated by a clean, sandy facies.

<u>Pilliga Sandstone in deeper basins:</u>
geo-electrical response of the Pilliga Sandstone becomes more conductive due to presence of a higher proportion of finer-grained material ‘smearing’ the electrical response of the material.

<u>The interface between the Pilliga Sandstone and Orallo Formation is difficult to identify</u>



Summary of AEM survey

- The thickness of the Cenozoic cover significantly decreases from north to south and from east to west.
- There is a significant variability in the geo-electrical response of the Pilliga Sandstone from north to south and east to west.
- Within the Narrabri Gas Project area, the geometry of conductive sedimentary bedrock layers (e.g. the Purlawaugh Formation) suggests that there are some low-amplitude or forced folds. These are typically characterized by gentle undulations rather than by sharp or steep bends, often creating dome-like or flat-topped structures.
- To the north of the Narrabri Gas Project area (close to the Nandewar Volcanic Centre) and to the east (close to the Hunter-Mooki Thrust fault), significantly more deformation of sedimentary bedrock conductors is visible in the AEM conductivity-depth sections.

Summary of geological and geophysical assessment of potential hydrogeological connectivity pathways

- Age dating of intrusions and stratigraphic assessment indicate that many intrusions occurred prior to depositions of Pilliga Sandstone and cannot form direct connectivity pathway from coal seams into the Pilliga Sandstone;

- Generally little evidence from AEM for structure in upper ~400 m of the subsurface in south and east of the Narrabri Gas Project area;

- Possible structure (forced folds/doming) in north-western part of Narrabri Gas Project area agrees with findings from previous seismic surveys;

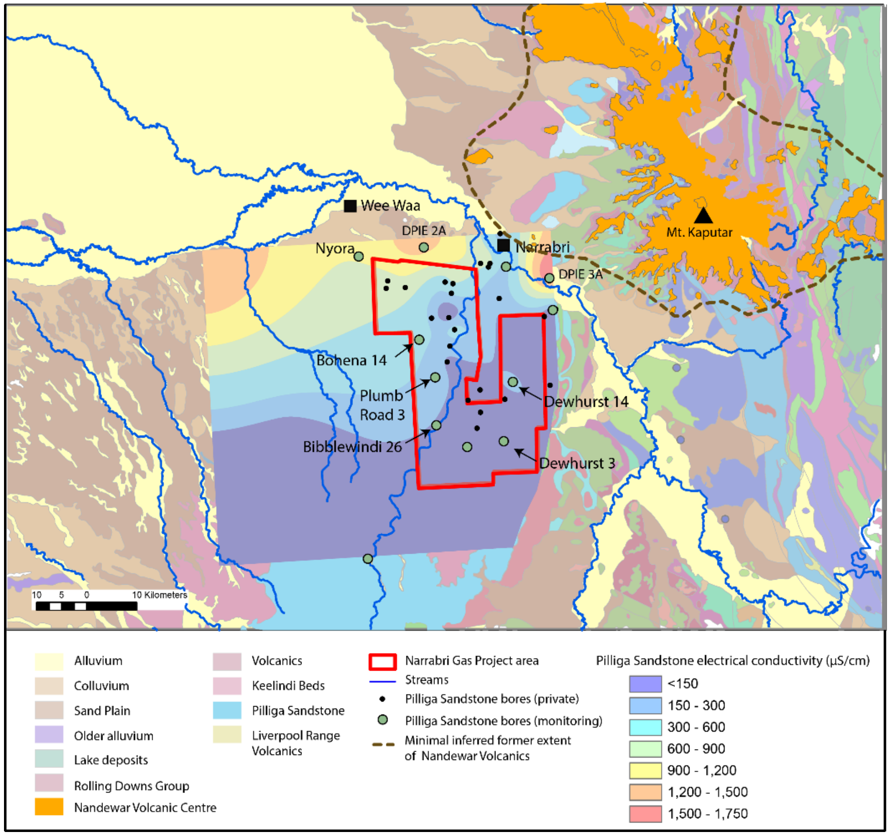
- Higher level of deformation in far easter part of the AEM survey area;

- No clear contrast between Orallo Formation and Pilliga Sandstone in some parts of the survey area.

Hydrochemistry and environmental tracers: are potential connectivity pathways actual pathways?

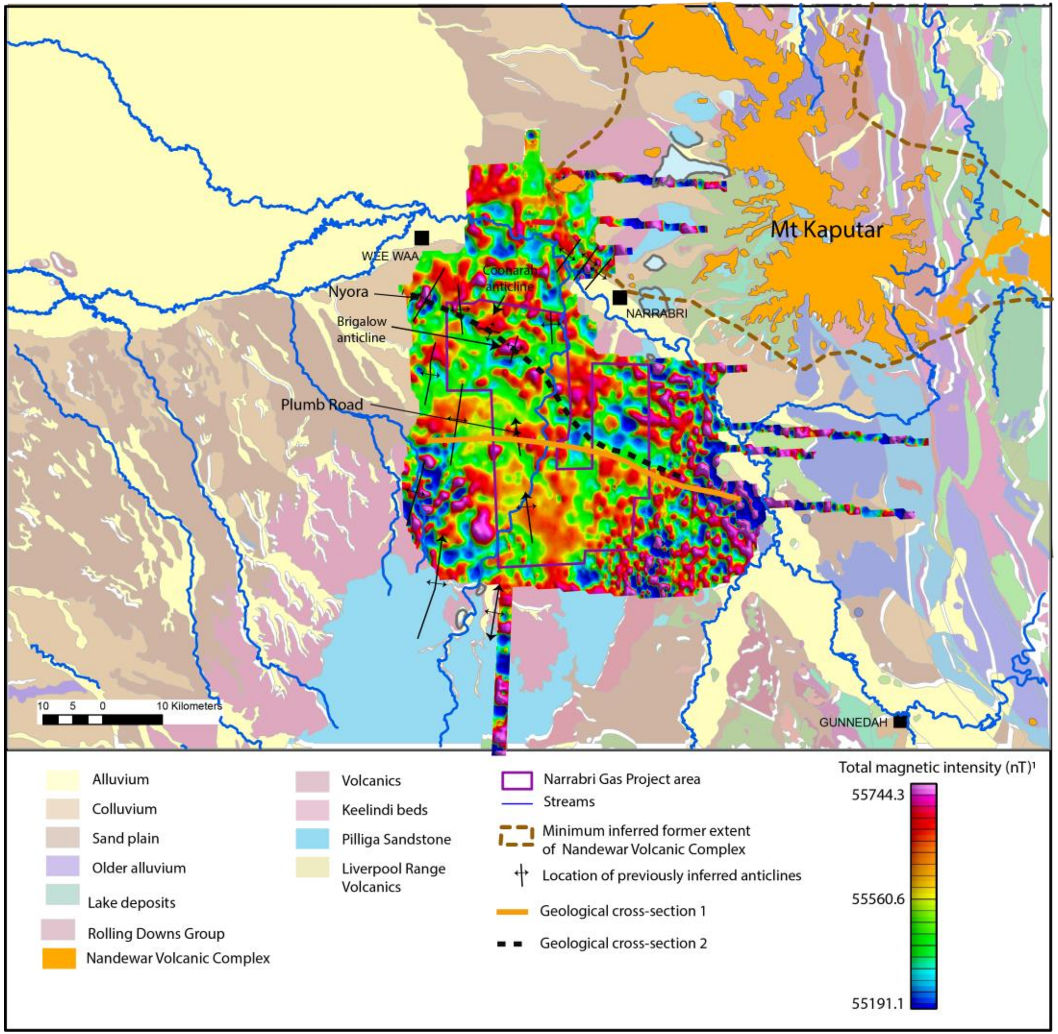
Spatial distribution of electrical conductivity in Pilliga Sandstone

- Very low salinity in the centre, south and south-east
- Increase of salinity towards north and north-west (although still relatively low salinity), starting approximately at Plumb Road
- Interaction with over- or underlying formation likely as Pilliga Sandstone is considered as a clean, quartzose sandstone?



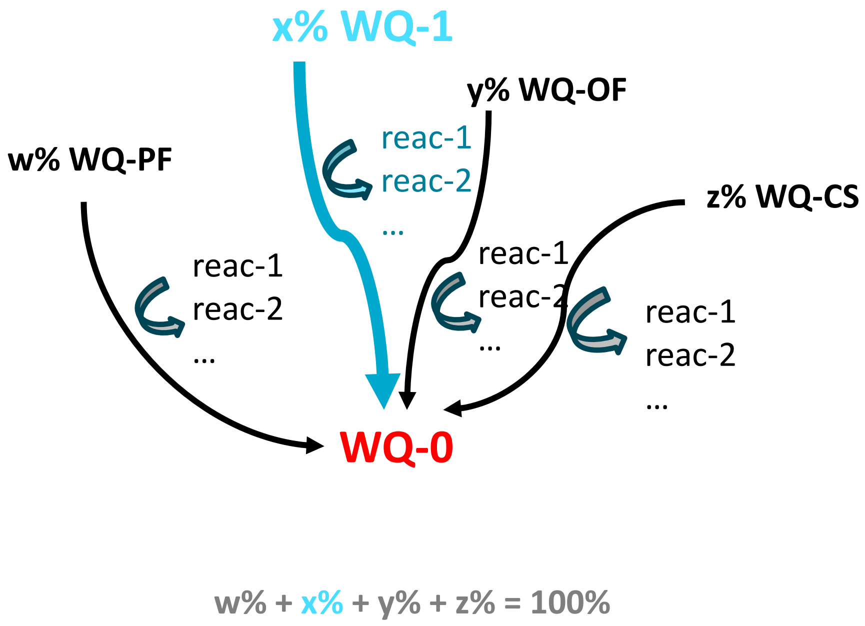
Raiber et al. (2022)

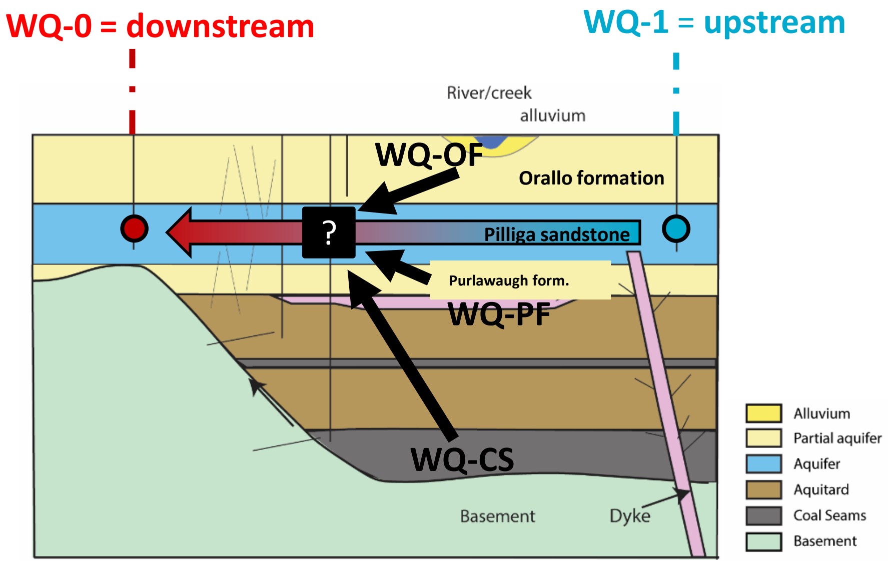
Geochemical mixing calculations along two cross-sections



Inverse Geochemical Modelling

Inverse modelling capabilities of PHREEQC allow to test **possible conceptual models** of hydrochemical evolution



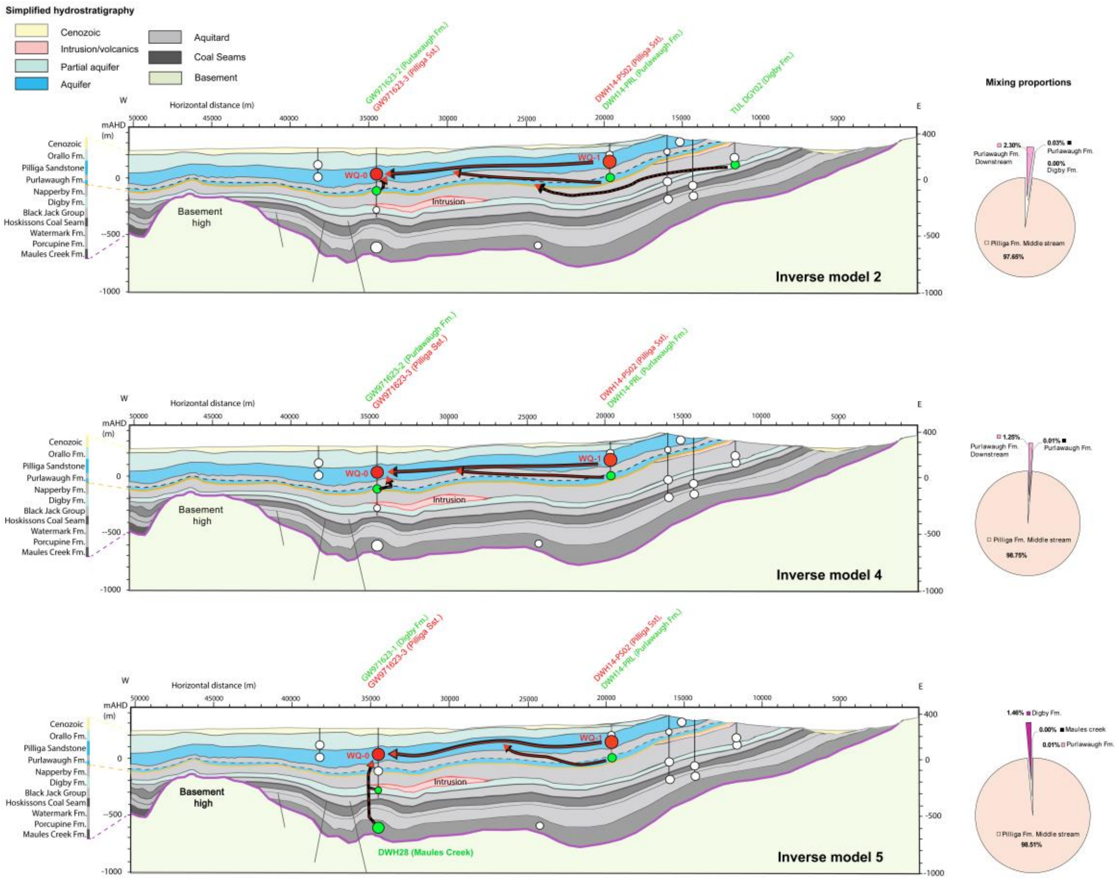


Observation and characterisation data serve as joint constraints for the inverse model

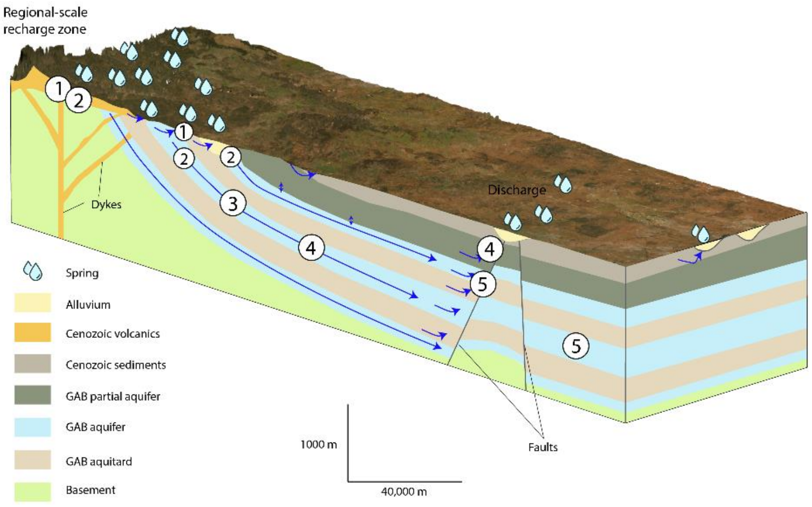
- **Rock composition** (Mineralogy, etc)
- **Groundwater** (Major ions, ^{87}Sr, ^{18}O, ^{2}H, etc.)
- **Age tracers** (^{36}Cl, ^{14}C, etc.)

Examples of geochemical mixing models

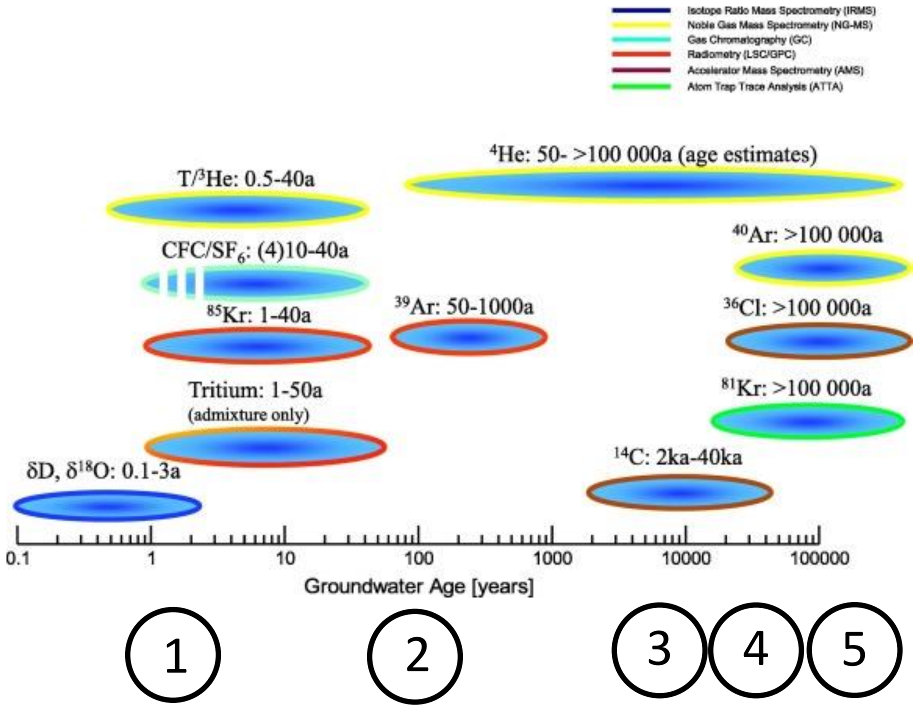
- Many mixing models were developed to test potential hydrogeological connectivity pathways
- The results were compared to other lines of evidence (e.g. environmental tracers)



Groundwater age tracers as connectivity indicators



Our initial conceptual understanding



Raiber et al (2022) Assessing recharge processes and flow dynamics using environmental tracers in the Great Artesian Basin. CSIRO, Australia.

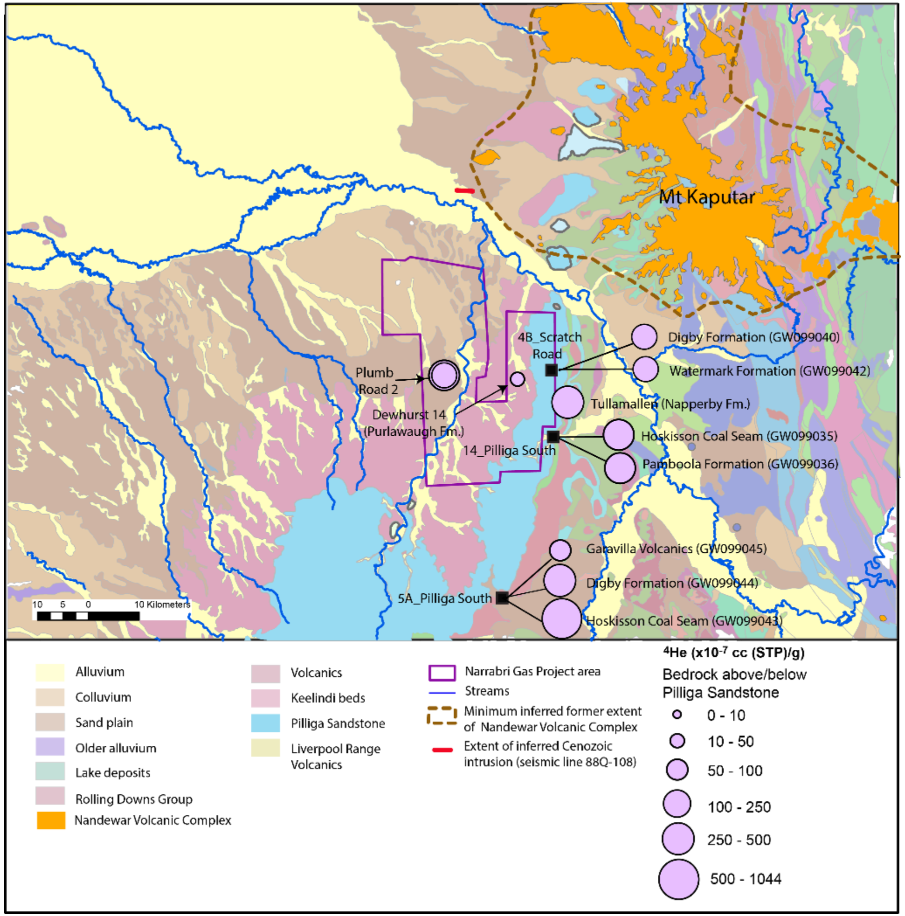
Suckow A (2014) The age of groundwater – definitions, models and why we do not need this term. Applied Geochemistry 50, 222–230.

Helium 4 – bedrock above/below Pilliga Sst.

Helium-4 increases with time

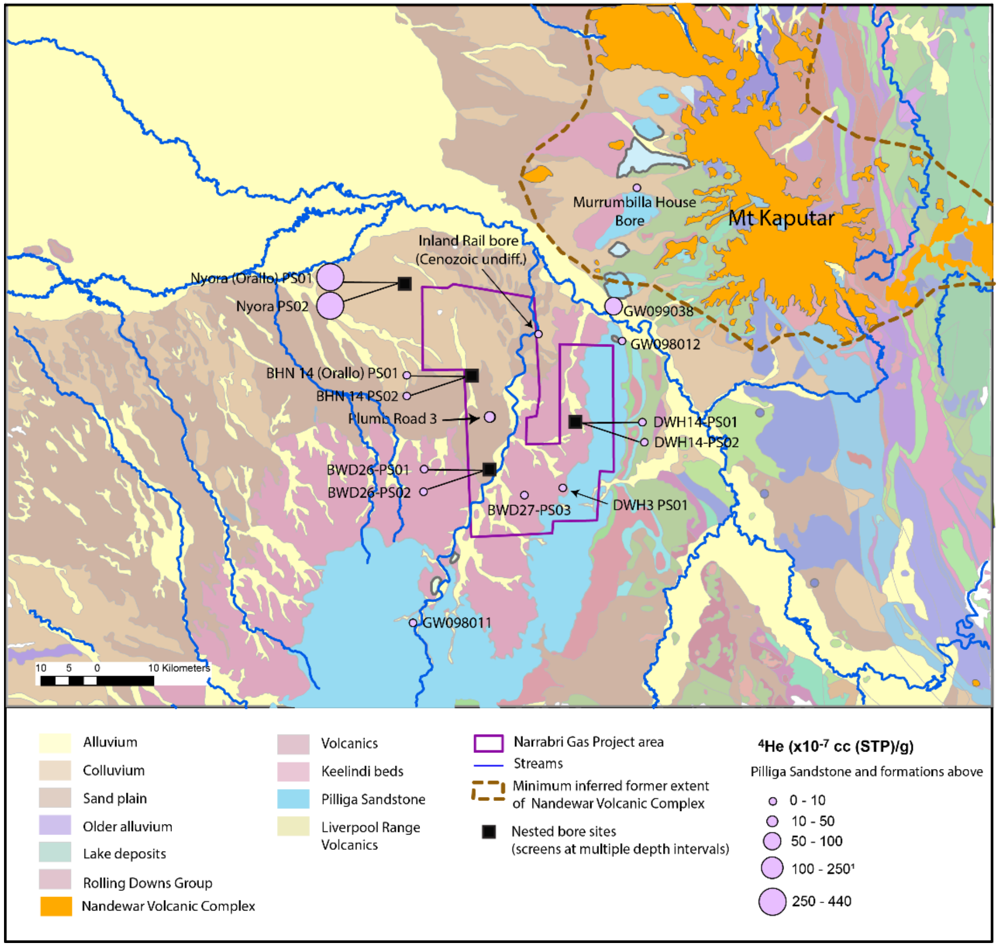
Very high values in Gunnedah Basin formations

→ <u>very old groundwater</u>



Helium-4 – Pilliga Sandstone

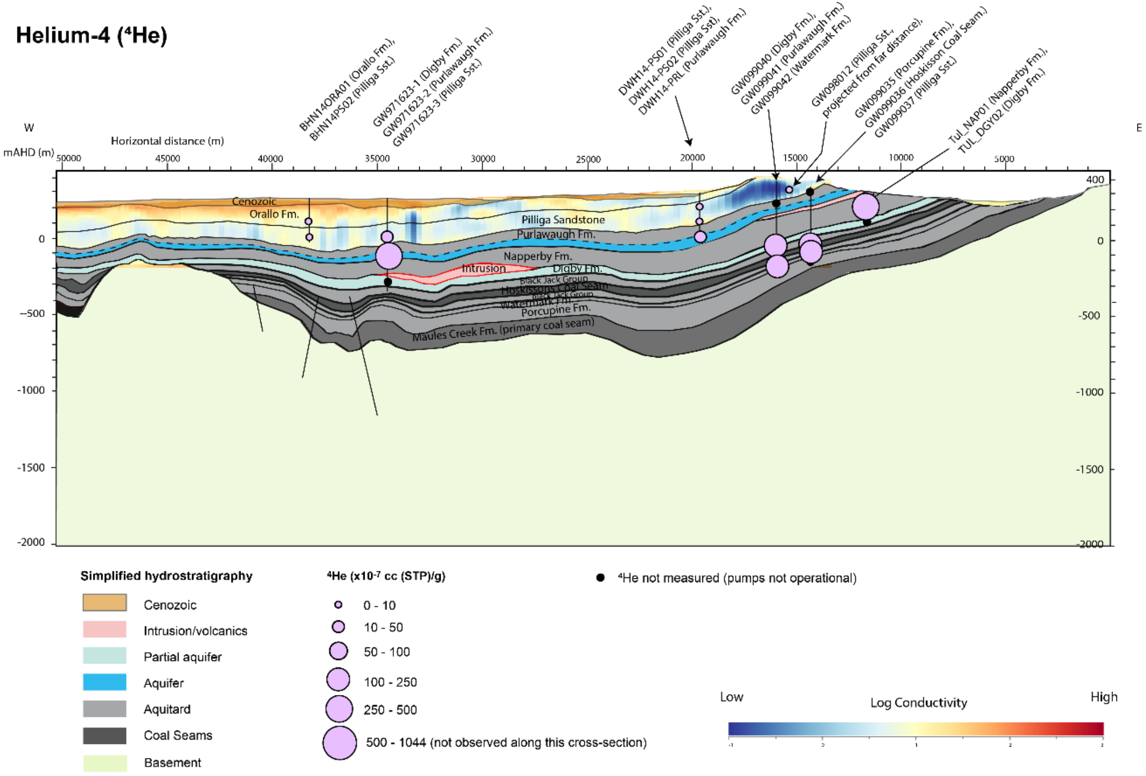
- ^4He concentrations in Pilliga Sandstone within NGP area are very low → competent seals
- High values at Nyora PS02 → stagnant flow, lithological variability or a possible contribution from below (e.g. through thinning of Purlawaugh Fm.)



Helium-4 – Pilliga Sandstone

Along cross-section 1, there are generally high values of ^{4}He in Gunnedah Basin, indicating very old groundwater (hundreds of thousands to > 1 million years old).

Values in the Pilliga Sandstone are orders of magnitude smaller, indicating younger groundwater.

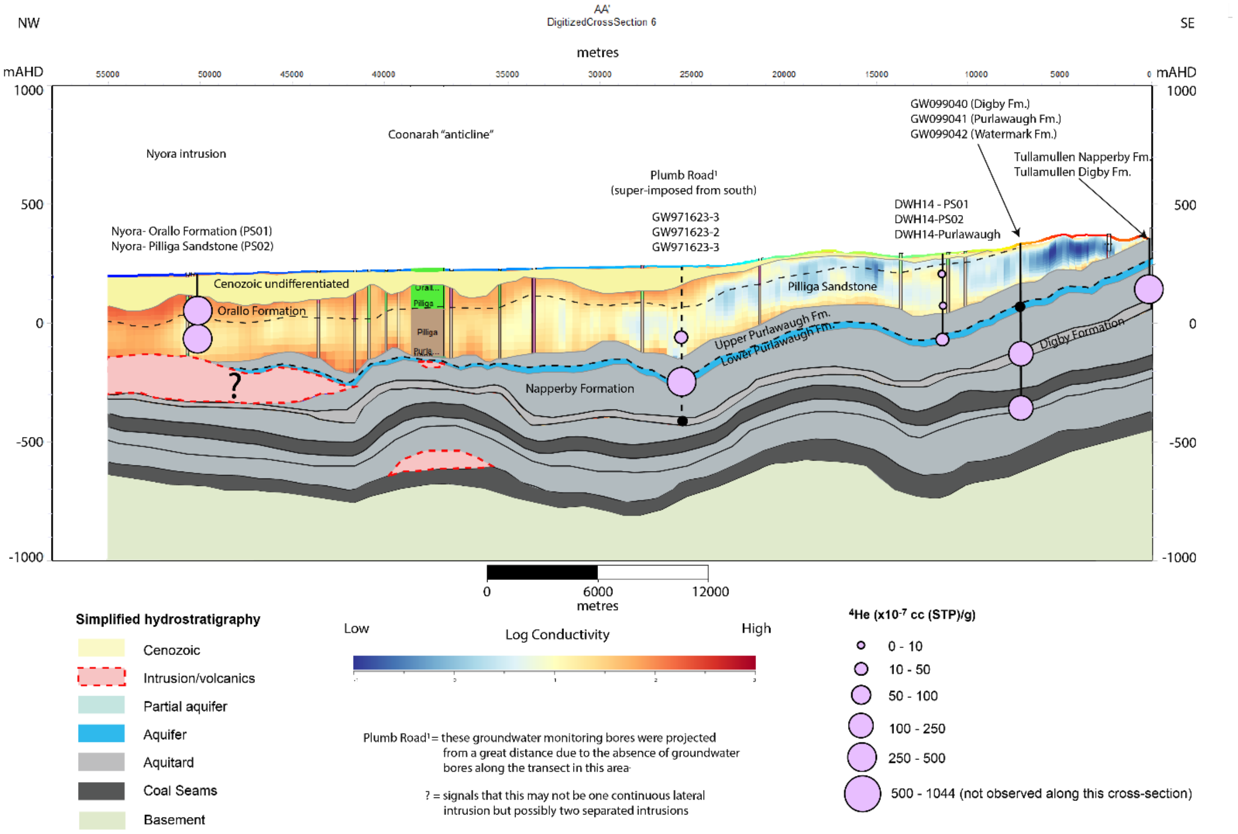


Helium-4 – Pilliga Sandstone

Along cross-section 2, values are generally high in the Gunnedah Basin

Low values in Pilliga Sandstone, but there is an increase towards the north-west.

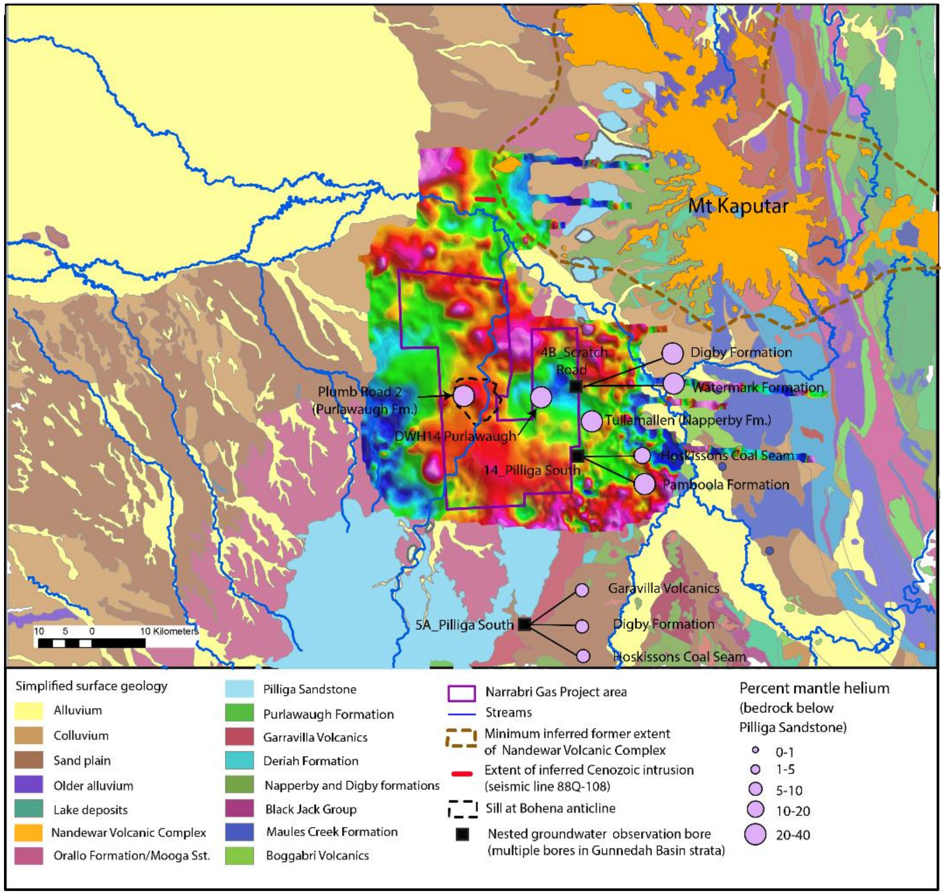
This increase is likely associated with the change in lithological properties of the Pilliga Sandstone from east to west



Are potential connectivity pathways actual connectivity pathways?

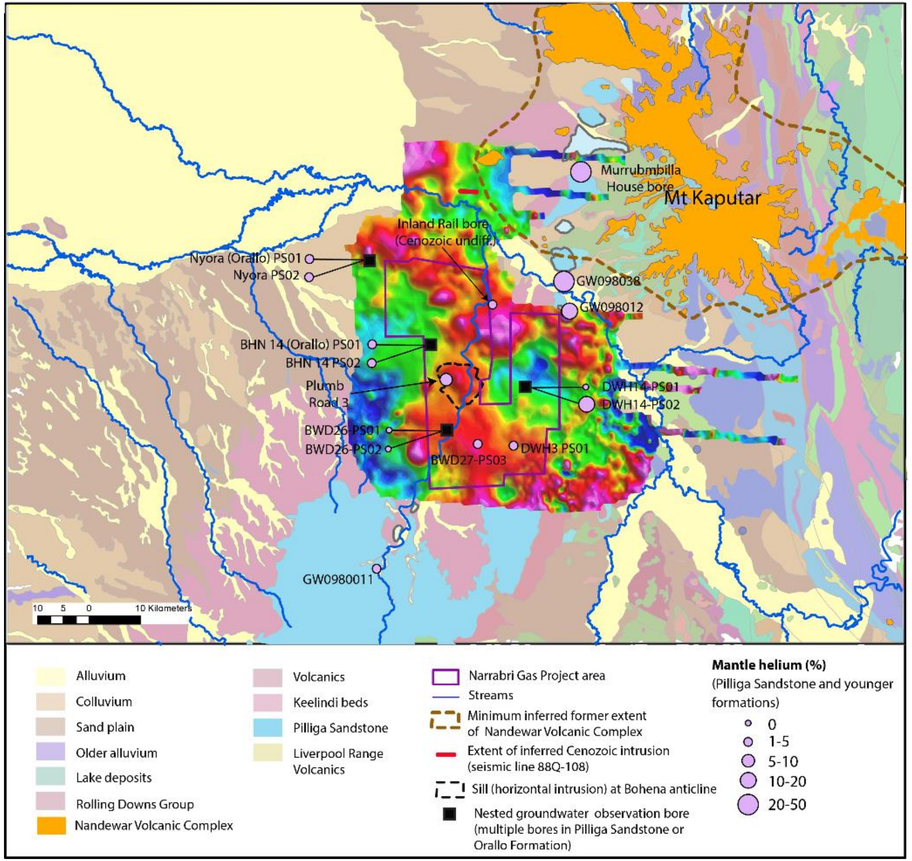
Mantle helium is a good connectivity indicator

Elevated $^3He/^4He$ ratios in Gunnedah Basin formations and Purlawaugh Formation indicate deep mantle helium source (“primordial” = existing since the formation of the earth) →related to intrusions



Noble gases as connectivity indicator - Pilliga Sandstone

- High $^3He/^4He$ ratios within or near extent of former Nandewar Volcanic centre related to Cenozoic intrusions;
- Low values of mantle helium ($^3He/^4He$ ratios) within Narrabri Gas Project area → competent seals and intrusions terminating below Pilliga Sandstone;
- Some mantle helium at Plumb Road 3, probably related to extensive sill;

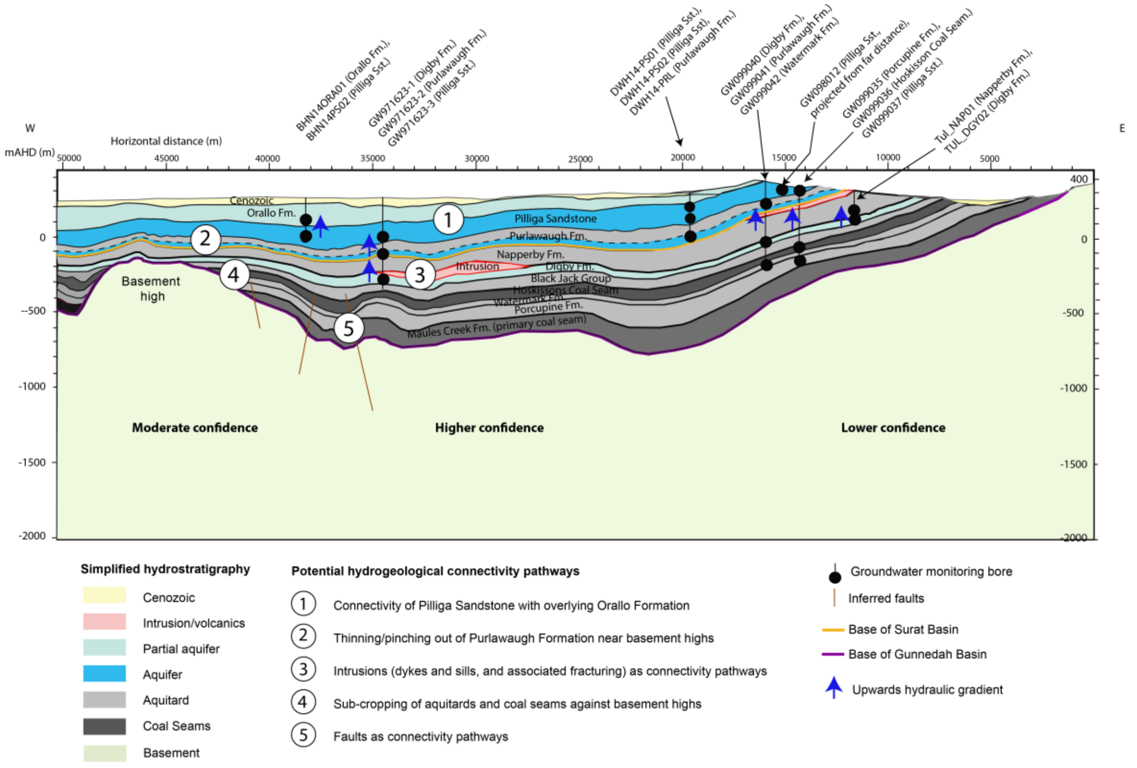


Integration of hydraulic and tracer data through numerical modelling

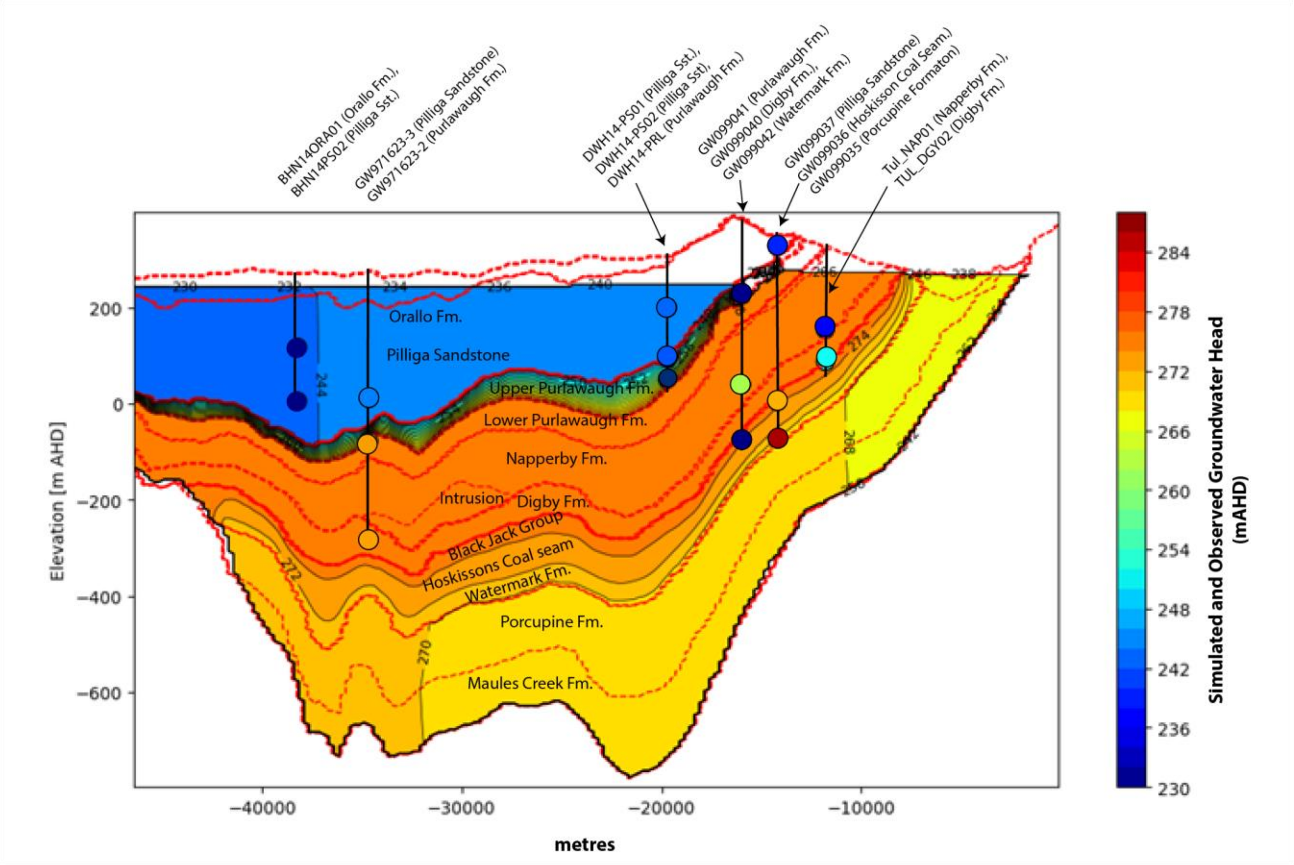
Flow and solute transport and geochemical models were developed to integrate and interpret field and laboratory observations:

- Geophysical and stratigraphic data were used to define a high-resolution (MODFLOW) groundwater flow model for a transect along the primary flow direction
- The simulated groundwater flow was used to drive a solute transport model that simulates 'groundwater age' (MT3DMS)
- Observed hydraulic heads and groundwater ages estimated from age tracer data (^{14}C, ^{36}Cl and ^{4}He) were used as joint model calibration constraints
- Inverse geochemical modelling was used as a secondary line of evidence to confirm/reject the proposed conceptual/numerical model that determines flowpaths and solute transport rates along the selected transect

Interpreted Stratigraphy for E-W Transect

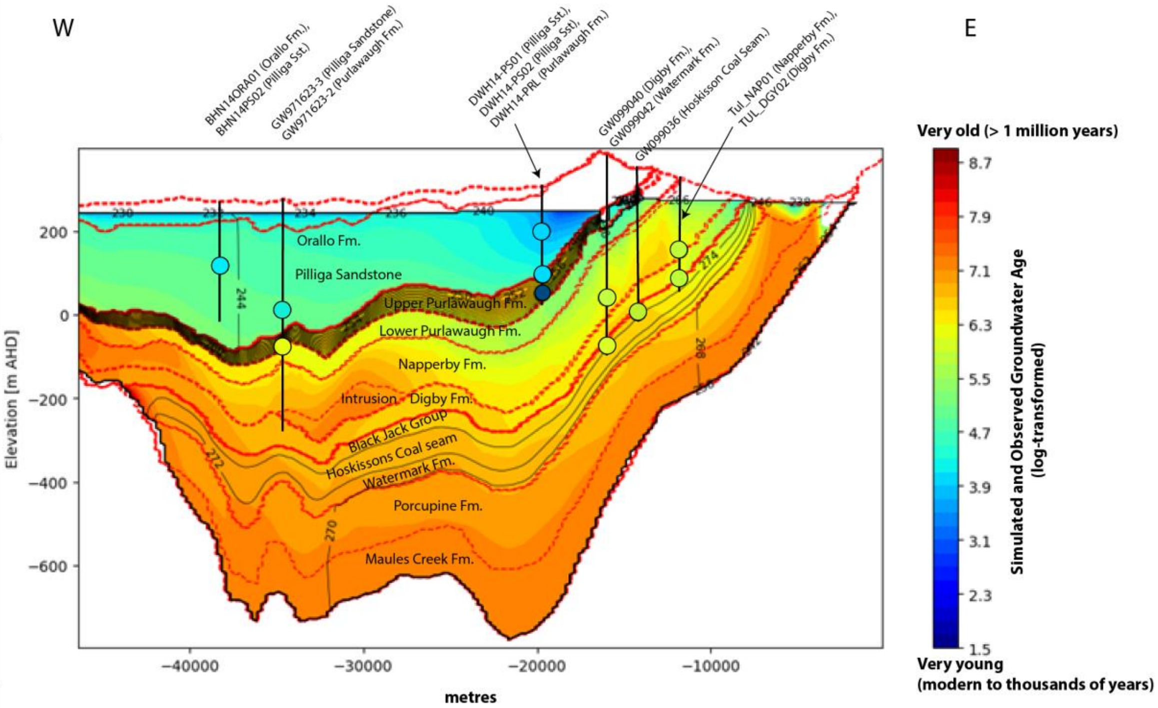


Groundwater Flow E-W Transect



Upper, tight section of Purlawaugh Formation acts as an effective seal that causes significant head drops over short vertical distances

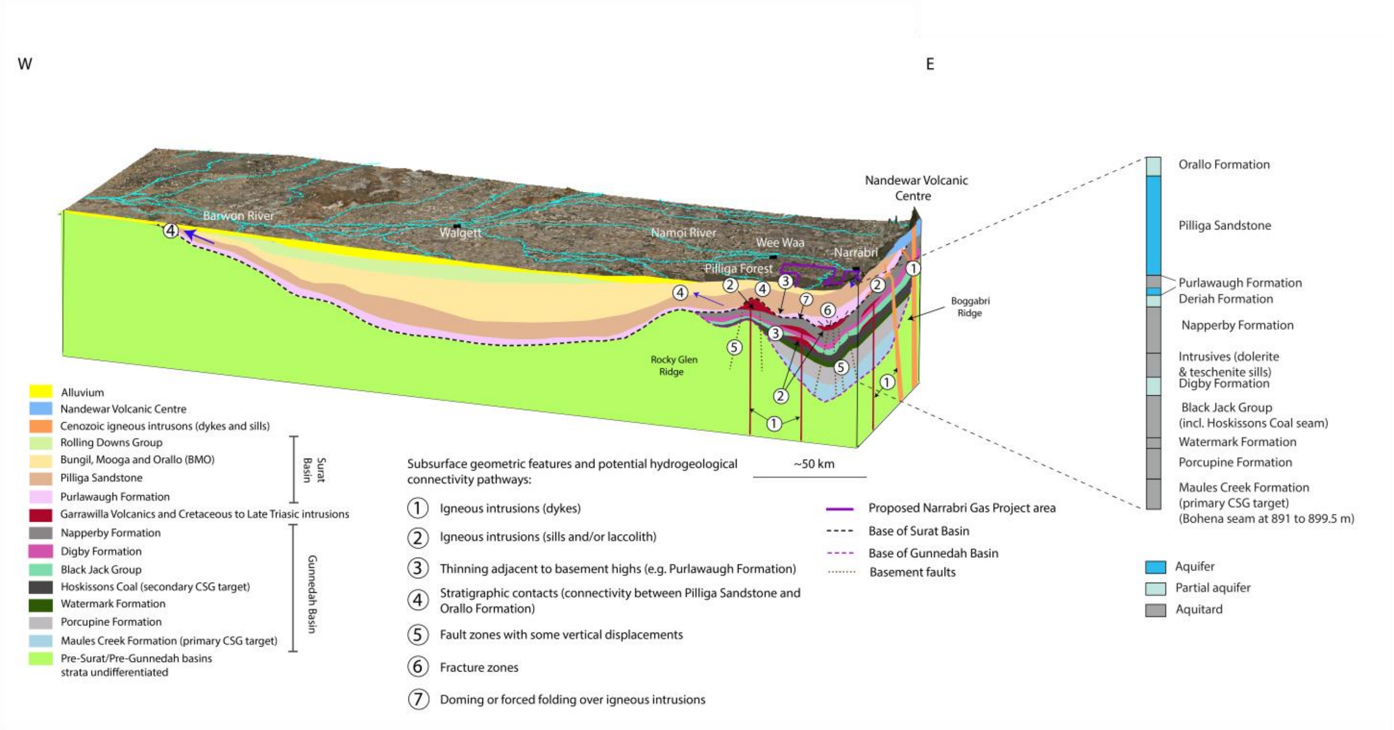
Simulated Ages for E-W Transect



- 'Younger' water (<10000 years) is present in the Orallo Formation and Pilliga Sandstone along cross-section 1
- Lower, permeable section of the Purlawaugh Formation still contains relatively young water in east
- Old to very old water (>1Ma) at depth

New conceptual hydrogeological model and potential connectivity pathways in the wider Narrabri region

The conceptual model of potential hydrogeological connectivity pathways has been further refined.

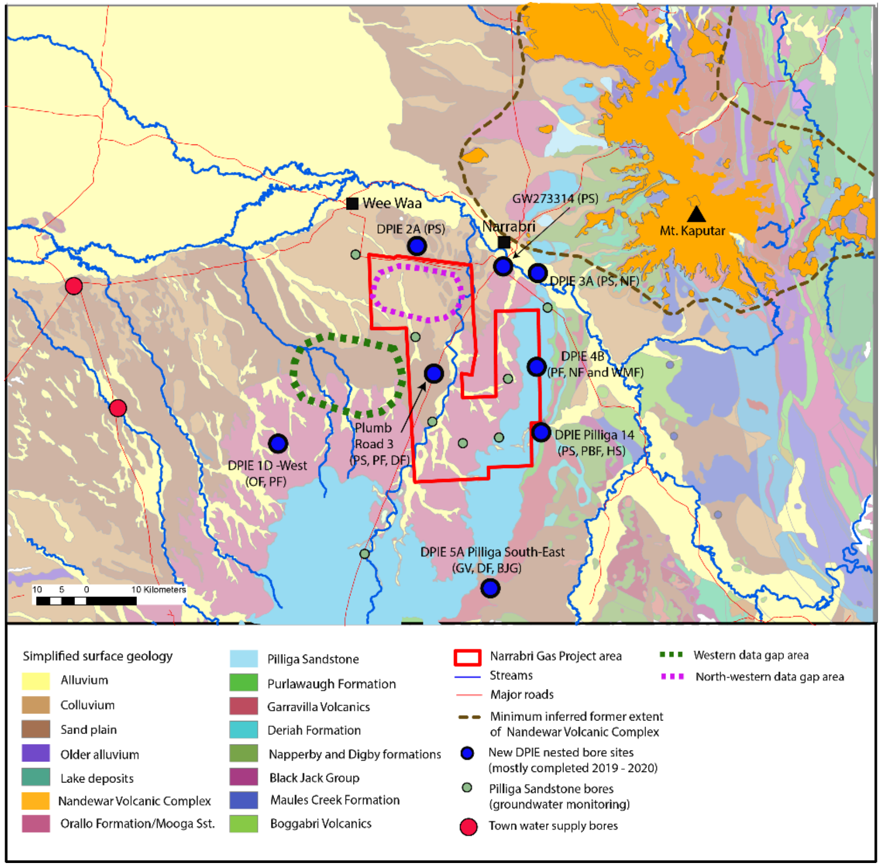


Conclusions

- The geophysical and geological assessment indicates that intrusions are the major potential connectivity pathway, but their occurrence is mostly limited to below Pilliga Sandstone in Narrabri Gas Project area
- Hydrochemistry and tracers (e.g. highly mobile parameters such as $^{3}He/^{4}He$, ^{4}He and methane) indicate that aquitards limit vertical connectivity throughout the east and south of the proposed CSG development area
- Hydrochemistry and tracers indicate that some geological structures (dykes or sills and thinning/terminating of Purlawaugh Formation and Napperby Fm. against intrusion) may form local connectivity pathways at Plumb Road (likely between uppermost Gunnedah Basin and Purlawaugh Formation). Mixing calculations confirm that it is unlikely that there is a contribution from the Maules Creek Formation.
- Noble gas tracers suggest that it is less likely that there is significant connection in north-west of NGP area.

Opportunities for further research

- Collect samples for hydrochemistry and environmental tracer suite for additional Gunnedah Basin bores that could not be sampled in this project due to issues with installed pumps (e.g. Digby Fm. at Plumb Road)
- Sample new Santos bores (Napperby/ Digby formations)
- Integrate seismic with AEM data
- Refine existing 3D geological models
- Close spatial data gaps in west and north-west



Thank you

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