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Hydrodynamics in the Queensland Sector of the Cooper/Eromanga Basins: Identifying Non-Conventional Exploration Plays Using Water Pressure and Chemistry Data

Webster M.A.*, Brew J., Grimison A.G.*

* Santos Ltd.

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Abstract

Analysis of water chemistry and pressure data from the Queensland sector of the Cooper and Eromanga Basins indicates that two regional fluid flow systems are operating within these basins. In the Eromanga Basin (Jurassic–Cretaceous) a southwestward and descending open flow system is evident, driven by the topographically induced Great Artesian Basin hydrodynamic regime. In the underlying Cooper Basin (Upper Carboniferous–Triassic) a closed system is reflected by overpressuring and ascending flow out of each of the major Permian troughs. Where the two systems interact and equilibrate, mixing of formation waters from Permian and Jurassic reservoirs is apparent in water chemistry data and potentiometric surface minima can be identified in vertical pressure profiles.

The water chemistry and pressure data have been used to identify hydraulic baffles within the Permian and Jurassic sequences. These barriers are likely to provide effective lateral or vertical seals and, once identified, can be targeted in regional mapping projects to identify potential stratigraphic traps. In addition to the potential exploration applications, regional hydrodynamic databases are also valuable in petrophysical evaluations, by providing estimates of water resistivity in areas with poor well control, and for estimating field limits when the only available pressure data are from hydrocarbon columns within crestal wells.

Introduction

Exploration programmes in the Cooper and Eromanga Basins have historically relied upon 2D, and more recently 3D, seismic data for the identification of potential structural traps. As exploration programmes in these basins mature and reserve additions from conventional plays reach a plateau, complementary or alternative techniques are required to identify new exploration plays and non-conventional traps and to provide insights into the petroleum systems operating within these basins. Hydrodynamics is one such technique by which water pressure and chemistry data can be used to identify flow barriers, which may reflect hydrocarbon traps, and flow conduits, which are likely migration fairways and areas of elevated seal risk. The technique provides a tool for evaluating the relative effectiveness of inter-formational and intra-formational sealing lithologies, which can then be applied in exploration risk assessment and particularly in the ranking of stratigraphic leads and prospects.

This paper summarises results of a review of water chemistry and pressure data from the most commercially significant reservoirs in the Eromanga and Cooper Basins in Southwest Queensland (Figs. 1 & 2). Water analyses are available for samples collected during drillstem tests or field production; these data have been screened to eliminate samples contaminated with drilling or completion fluids. Aquifer pressure measurements are available from drill stem test data or wireline (RFT or MDT) data; the pressure data have been screened to eliminate anomalies that are the result of hydrocarbon effects or sampling errors (supercharging, seal failures etc). The data have been mapped both areally and stratigraphically to identify directions and magnitude of fluid flow within and between major flow units.

Regional Setting

The Eromanga Basin is one of three Mesozoic basins that together make up the Great Artesian Basin (GAB), an active groundwater system that covers an area of approximately 1.7 million sq km, or one-fifth of the Australian continent (Fig. 1). The sedimentary sequence within the GAB is up to 3000m thick (Fig. 3). The Cooper Basin, a Permo-Triassic intra-cratonic basin, covers an area of approximately 153,000 sq km and underlies the Eromanga Basin in the central portion of the GAB (Fig. 1). The Permo-Triassic sequence is up to 1500m thick and includes numerous shales and coals, deposited in lacustrine and fluvio-deltaic settings, which provide effective capillary seals for multiple, stacked gas columns in many fields. Many of these units are potential seals for stratigraphic traps where they onlap intra-basinal basement highs or downlap regional unconformities. Hydrodynamics enables an assessment to be made of the relative quality and effectiveness of these units as hydraulic barriers.

The hydrogeology and hydrochemistry of the GAB have been described in numerous publications [1-6]. The basin comprises a multi-layered confined aquifer system, with aquifers in continental quartzose sandstones of Triassic, Jurassic and Cretaceous age. The major confining beds are Cretaceous marine mudstones of the Wallumbilla to Lower Mackunda Formations [1,7] (Fig. 3). There are two main aquifer systems: a Cretaceous aquifer, which includes sandstones within the Winton and Mackunda Formations, and a Jurassic–lower Cretaceous system, which includes sandstones in the Precipice, Hutton, Adori and Cadna-owie Formations (Figs. 3 -5). Waters enter these systems along the western slopes of the Great Dividing Range, where the aquifers crop out, and to a lesser degree along the western margin of the basin (Fig 4). The waters travel for distances of up to 1200 km before being discharged along the southwestern and southern margins from approximately 600 artesian springs that are associated with faulting and stratigraphic terminations in these areas. Flow velocities are in the order of 1 – 5 m/yr and residence time for the waters, calculated from the flow velocities and from isotope data, is between 10 000 and 1.4 million years [2,3]. The present hydrodynamic regime is interpreted to have been initiated in the early Cretaceous and modified during Plio-Pleistocene tectonism when the eastern margin was uplifted to form a broad syncline and the aquifers were elevated to their current position 500 – 700m above sea level (Fig. 5).

Previous hydrogeological work has focussed primarily on the water resources of the GAB, which have been exploited since 1878. Some 30,000 shallow water bores have been drilled into the Cretaceous aquifer system, and approximately 4700 into the Jurassic–lower Cretaceous system. The potentiometric surface of the Cretaceous system has always been below ground level, and wells tapping these aquifers are consequently non-flowing artesian bores that are usually equipped with windmill-operated pumps. The potentiometric surface of the deeper Jurassic-lower Cretaceous aquifer system is above ground level, hence wells drilled into these reservoirs are naturally flowing artesian bores [4]. The potential impact of the GAB hydrodynamic flow in the Eromanga Basin Petroleum System has been previously reviewed in terms of the implications for petroleum migration, tilted field contacts or flushing of oil accumulations within Jurassic and Cretaceous reservoirs [5,6]. Some interflow with underlying basins has been inferred from water chemistry data [6,8]. Toupin et al [9] published results of finite-element modelling of the hydrology of the Cooper and Eromanga Basins, focussing on the development of topography and compaction driven groundwater flow systems and their role in heat redistribution, petroleum generation and oil and brine migration during basin evolution. Their models indicate hydraulic communication between the Cooper and Eromanga basins over the southern portion of the Cooper basin and flushing of Cooper basin brines by topography driven flow during the Tertiary[9].

This paper presents data from oil and gas exploration, appraisal and development wells in Southwest Queensland that confirm the GAB hydrodynamic flow is transmitted into the underlying Cooper Basin. The results confirm that water chemistry and pressure data can be used to identify and map flow conduits and barriers within and between hydrocarbon reservoirs in these basins.

Water Chemistry

Approximately 630 water analyses are available for samples collected during drillstem tests and production in the reservoirs of interest (Patchawarra, Toolachee, Epsilon in the Cooper Basin and Precipice/Basal Jurassic and Hutton Formations in the Eromanga Basin, Fig. 3). These analyses have been subjected to a series of standard industry screening criteria [10] designed to identify erroneous laboratory data and contaminants derived from drilling fluids, water cushions, completion fluids, or condensation. Of this dataset, only 125 samples (25%) are interpreted to represent ‘clean’ formation waters, highlighting the issue of formation invasion during the drilling process and the difficulty in obtaining representative formation fluid samples. The range and average of Total Dissolved Solids (TDS) measurements for each reservoir are summarised as Table 1. Data can also be displayed as Stiff diagrams, which are used to characterise the chemical fingerprint of waters from each formation. Type Stiff diagrams for the Permian Patchawarra Formation and the Jurassic Hutton Formation are shown as Figure 6. The Eromanga waters are characterised by their low salinity (Na & Cl) and high HCO3 content, reflecting a component of meteoric waters. In contrast, Permian waters from the Patchawarra Formation are characterised by higher Na and Cl concentrations and low HCO3 content.

Hydrochemistry maps for the Hutton and Patchawarra Formations are included as Figures 7 & 8. The Hutton samples show consistent, low TDS profiles, particularly in the northeast where TDS levels are <1100 mg/l, and high HCO3 concentrations. Similarly, the Patchawarra Formation samples display a characteristic profile with higher Na and Cl concentrations but low HCO3. There are several anomalous samples in the Patchawarra dataset, including a sample from Wackett-8, in an area of significant faulting on the flank of the Wackett high.

The hydrochemistry map for the Toolachee Formation (Fig. 9) indicates Jurassic water signatures around the Central Ridge and on the flanks of the Nappamerri Trough; Patchawarra water signatures are apparent elsewhere in the Toolachee system. These data suggest some mixing of Jurassic and Permian waters where the Triassic seals are eroded and thin, or where the Permian and Jurassic reservoirs are in fault communication.

Aquifer Pressures

Theory. The principles and applications of hydrodynamics in petroleum exploration are well documented in previous publications [11,12]. The underlying principle in hydrodynamics is that subsurface fluid movement occurs in response to potential energy differences, and that flow is directed from regions of high to low potential energy. The magnitude of the potential energy differential and the permeability of flow units (aquifers) and flow barriers (aquitards and aquicludes) control the rate of flow within and between flow units. The Potentiometric Surface Elevation (PSE) is an expression of the potential energy (or hydraulic head) at any point in the subsurface, and can be calculated from measured pore pressures as follows:

$$PSE = Z + P/Dw$$

where : PSE= Potentiometric Surface Elevation (ft)
Z= Elevation of Pressure Measurement (ft ss)
P= Measured Aquifer Pressure (psia)
Dw= Average Water Density Gradient (psi/ft)

Conversion factors are included as Table 2.

Pressure Data. Aquifer pressures have been derived from DST and RFT / MDT measurements in exploration, appraisal and development wells. The database in the area of interest comprises approximately 1200 DSTs in the reservoirs under review, of which around 145 are interpreted to be valid tests of water zones. RFT/MDT data in these reservoirs are available for approximately 110 wells. DST data were graded according to the difference between final shut-in pressure and extrapolated reservoir pressure; the pressures were cross-checked against the water chemistry database to ensure a pressure was derived for each valid water test. MDT data were similarly graded using mobility ratios, fluid gradients (where multiple pressures were acquired within a sand) and log response, to confirm the pressures did not reflect hydrocarbon effects. Pressure measurements from development wells, obtained for reservoir management and showing clear pressure depletion related to production, were excluded from the dataset. A summary Pressure / Elevation plot for Toolachee Formation reservoirs, plotted against a reference sea level hydrostatic reference gradient, is included as Figure 10. The plot illustrates the variation in pressure within the Toolachee Formation reservoirs at comparable depths, indicating a dynamic aquifer system.

Production Effects. As production effects will result in local aquifer depletion, which could be confused with hydrologic flow, cumulative production figures for each flow unit were plotted on a chronological series of maps and checked when selecting and interpreting pressure measurement. Oil production did not commence from Eromanga Basin fields in Southwest Queensland until 1984 and gas production from Cooper Basin reservoirs in this area has only been significant since 1994. MDT and DST data are available in most areas from wells drilled prior to and post production startup, and indicate that production-related pressure depletion is significant only in close proximity to fields. Most of the exploration and appraisal wells in the Queensland sector of the Cooper Basin were drilled prior to any production in the area and are thus unaffected.

Potentiometric Surface Calculations. A key assumption in the calculation of potentiometric surface elevations is the average density of water in the column, which requires knowledge of variations in water density, both areally and stratigraphically. Formation waters in the Cooper and lower Eromanga Basin reservoirs occupy a relatively narrow range of salinities but heat flow does vary significantly around the basins and impacts the density of waters at reservoir conditions (Fig. 11). Geothermal gradients, derived from extrapolated bottom hole temperature measurements and DST temperatures, have been used to correct measured water densities to subsurface conditions, from which a water gradient at reservoir conditions can be extracted.

There are three commonly applied alternatives used to calculate a Potentiometric Surface Elevation. A *Point Source Head* is calculated by extrapolating the water gradient at reservoir conditions to atmospheric conditions; this technique introduces a significant error because it fails to account for the role of temperature. A *Fresh Water Equivalent (FWE) Head* can be calculated by extrapolating a fresh water gradient from the point of measurement. An *Environmental Head* applies an integrated average of the water density variations through the water column and should be closest to the true head. For the purposes of regional PSE mapping, a freshwater head is generally accurate up to a salinity of 25,000 mg/l TDS and can be applied in basins where formation waters are relatively fresh [11].

For this review, both FWE and Environmental heads were calculated, in both instances corrected for temperature variations with depth. Results are very similar, as would be expected with the low water salinities, and it is concluded that for the purposes of identifying regional hydrodynamic trends, either a temperature-corrected FWE or environmental head is suitable in the Cooper / Eromanga Basins.

An example of an MDT dataset that clearly illustrates the hydrodynamic regime is provided by Wackett-8, an appraisal/exploration well drilled on the southern flank of the Wackett structure (Fig. 2) in 1997. Figure 12 is a summary of MDT pressure measurements in water zones in the well. The plot shows a distinct offset between points in the Jurassic Hutton sandstone and the Permian Toolachee reservoir, with a smaller offset between the Toolachee and deeper Epsilon and Patchawarra Formation reservoirs. A hydrostatic reference gradient, extrapolated from ground level, confirms that all reservoirs are overpressured relative to a hydrostatic regime, verifying the hydrodynamic regime. A plot of the PSE for each reservoir against depth (Fig. 13) clearly shows the offsets in PSE between the different aquifers and is valuable in visually identifying aquitards in the system. The Hutton PSE is substantiated by a DST pressure from Wackett-1, drilled in 1978, prior to any production in the area.

Figure 14 is an example of a hydraulic barrier identified from MDT profiles in one of the Cooper Basin gas fields. Two gas columns are present in this field, one in the Toolachee and upper Patchawarra reservoirs, and one in the lower Patchawarra reservoirs. An offset in water gradients is evident above and below an intra-formational coal/shale unit within the Patchawarra Formation, confirming this unit is an effective capillary and hydraulic barrier.

Maps of the PSE for the Hutton, Toolachee and Patchawarra Formations are included as Figures 15-17; similar maps have been constructed for other reservoirs in both the Eromanga and Cooper Basin sequences. The Hutton Formation map clearly reflects the Great Artesian Basin hydrodynamic flow regime, with a potentiometric gradient of approximately .001215 (1:825) across the area, and flow potential from the Northeast to Southwest. The orientation and magnitude of the potentiometric gradient in the Jurassic aquifer is in close agreement with published data derived from water bores[4]. Isopotential contours are evenly spaced in the north, indicating there are few barriers to flow. The isopotential contours converge south of the Central Ridge and mimic the form of the underlying Nappamerri Trough. PSE values indicate flow into the trough along the margins, suggesting hydraulic communication along the flanks where the Nappamerri Formation (the Triassic seal separating Permian and Jurassic reservoirs) is thin. Two potentiometric lows are evident in the Naccowlah and Pallano areas. These indicate convergent flow from surrounding areas and, to preserve material balance considerations, must be areas where fluids are exiting this flow unit [11]. Seismic data confirm the Nappamerri Group is thin or absent in these areas. These are therefore areas of hydraulic communication where Jurassic waters are entering the underlying Permian basin. Similarly, an enclosed potentiometric high in the Munkah area indicates flow into this unit from above or below (whichever has higher potential energy).

The PSE map for the Toolachee Formation (Fig. 16) reveals a similar gradient, with the PSE decreasing from approximately 1000 ft in the Northeast to less than 200 ft at the South Australia border. Enclosed potentiometric highs are apparent on the Central ridge at Yanda and Wackett, with a large potentiometric low in the Ballatt area. A fault to the northeast of Barrolka appears to be restricting flow but energy is retained in a narrow flow path extending to Karmona. Corridor-1 lies at the junction of these trends; a Toolachee water sample from this well shows no evidence of mixing (Fig. 9), suggesting the change in flow direction reflects a barrier in this flow unit. The PSE map indicates flow into the Nappamerri trough, as seen in the Hutton Formation.

In contrast, the map of the Patchawarra Formation (Fig 17) indicates flow is **out** of the Nappamerri Trough. Two potentiometric highs are apparent on the Central Ridge, at Wackett and Nockatunga. The Wackett anomaly is related to the fresh water recovery in the Patchawarra Formation (Fig. 8) and reflects downward flow from the Eromanga reservoirs. A very steep gradient is mapped into the Nappamerri trough, where data are available. This reflects regional overpressuring (in some areas more than 2000 psi in excess of hydrostatic) which is interpreted to be the consequence of volumetric expansion related to hydrocarbon generation and cracking in the deep low permeability environment.

Interpretation. The PSE and water chemistry data are summarised as a regional cross section (Fig. 18) across the major troughs and structural highs in the basin (Fig. 2). The pressure data indicate a Southwestward and downward flow regime in the Eromanga basin sequence, driven by the Great Artesian Basin hydrodynamic regime. The highest potentiometric surface elevations within this sequence occur within the lower Cretaceous Namur Sandstone (Fig. 3). This open flow system is evident in many areas down to the Epsilon Formation, and in faulted areas down into the Patchawarra Formation. This is confirmed by widespread dilution (mixing) of the Toolachee Formation waters and by the recovery of fresh Jurassic waters from Patchawarra Formation reservoirs in some wells e.g. Wackett-8. A closed ascending flow system is apparent in the Patchawarra Formation in each of the Permian troughs and is interpreted to reflect overpressuring related to gas generation and cracking. A hydrostatic envelope is formed where these two systems equilibrate. This envelope occurs at various stratigraphic levels around the basin, and can be identified on MDT profiles in several wells.

Conclusions

Hydrodynamics is a valid exploration tool in the Cooper and Eromanga Basins. Water chemistry and aquifer pressure data indicate that two regional flow systems are operating in these basins: a southwestward and downward open flow system in the Eromanga basin, driven by the Great Artesian Basin regime, and an ascending closed system in the Patchawarra Formation in each of the major troughs. Flow barriers (seals) and flow conduits (migration pathways) can be identified using these data, improving our ability to identify and map subtle stratigraphic traps and rank exploration opportunities on the basis of their relative seal risk.

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Formation	TDS (mg/l) Clean Samples	
	Range	Average
Hutton	782 - 5523	2009
Basal Jurassic	1570 - 7300	3765
Toolachee	1920 - 11136	7514
Epsilon	5851 - 12306	9584
Patchawarra	4078 - 19243	14845

Table 1 : Water Salinity Data, Cooper / Eromanga Basins

To get	Multiply	By
m	ft	0.3048
kPa	psi/ft	22.5
psi/m	psi/ft	3.28
lb/gal	psi/ft	19.3

Table 2 : Conversion Factors

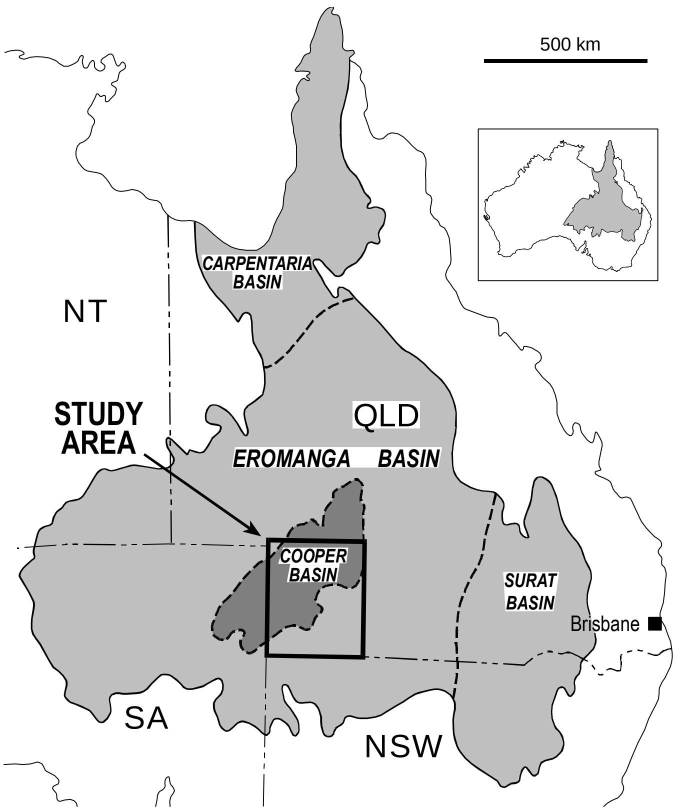


Figure 1 : Location Map, Great Artesian Basin

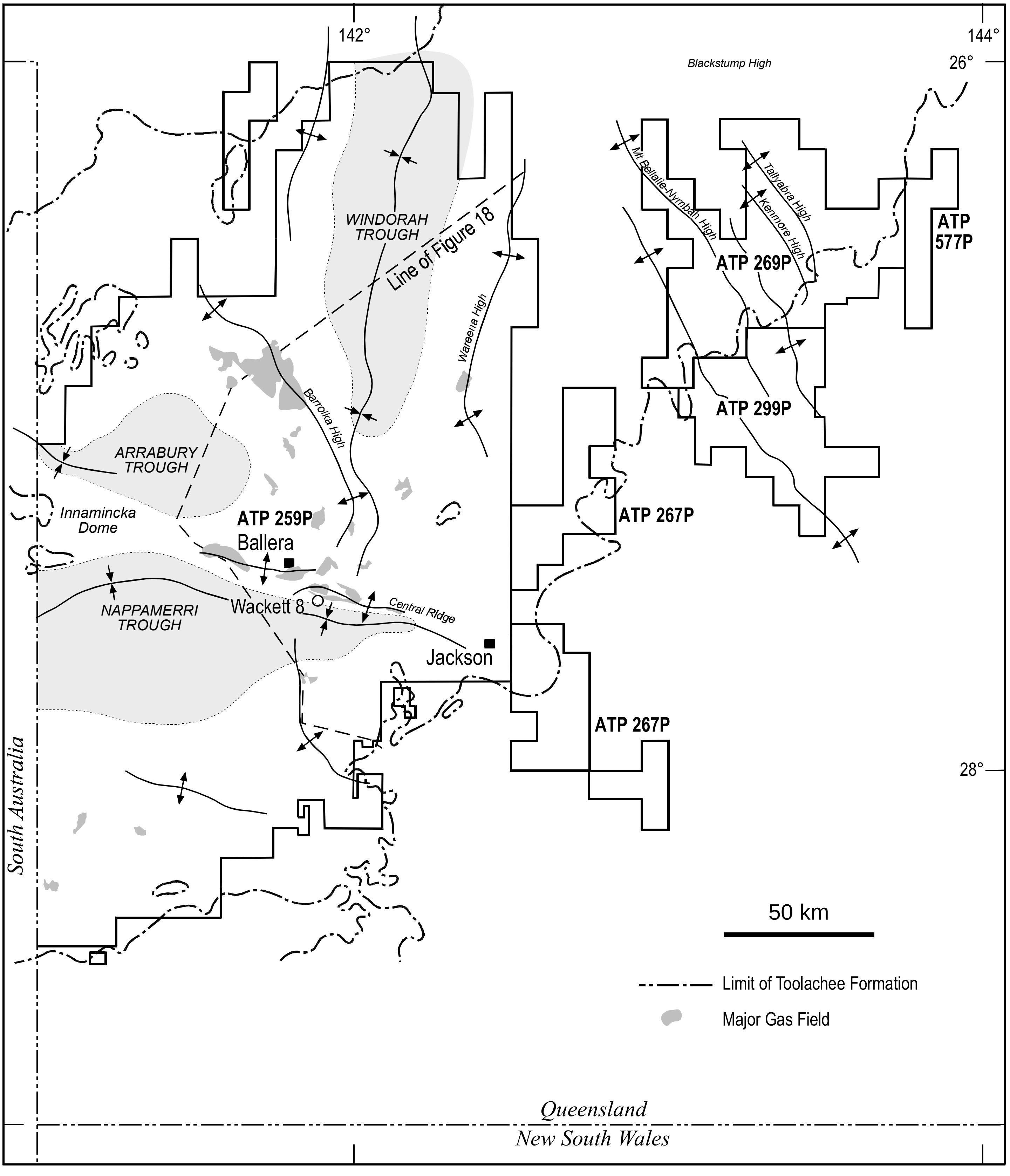


Figure 2 – Structural Elements, Queensland Sector, Cooper / Eromanga Basins

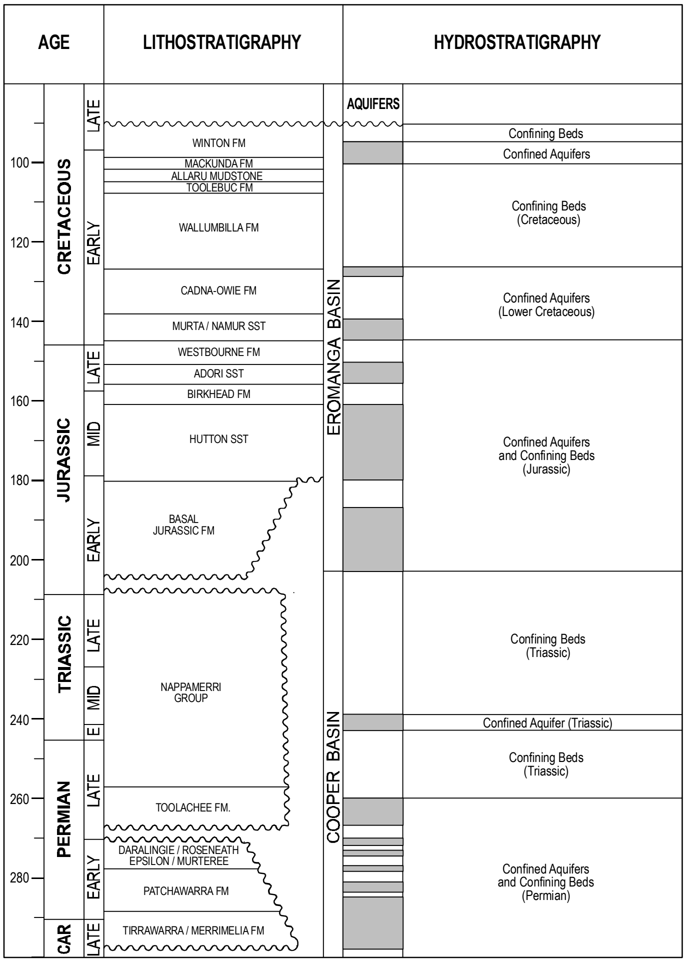


Figure 3 – Simplified Stratigraphic Column, Cooper / Eromanga Basin

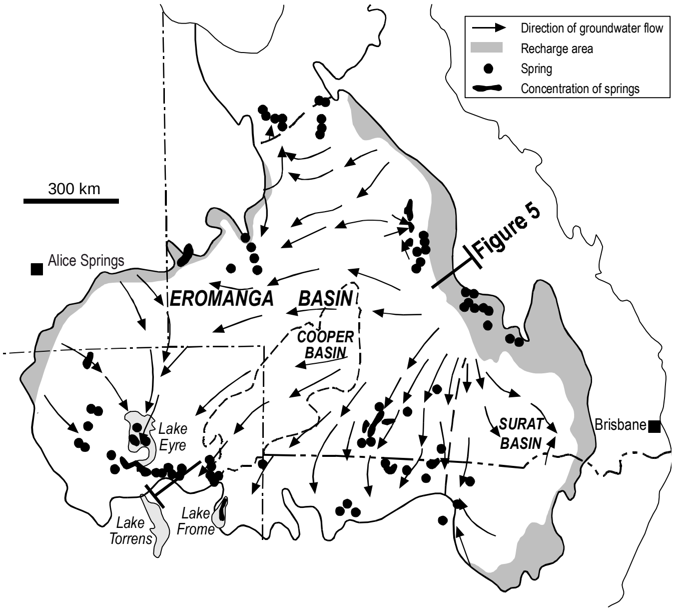


Figure 4 – Groundwater Flow, Great Artesian Basin (modified from Ref.3)

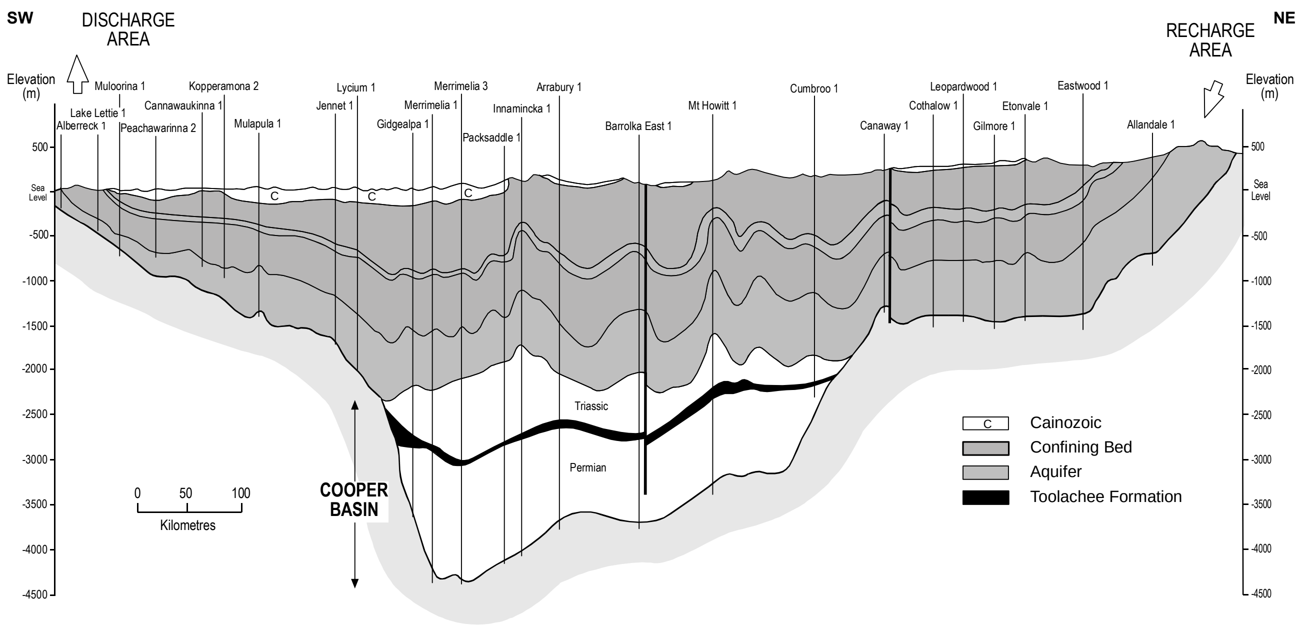
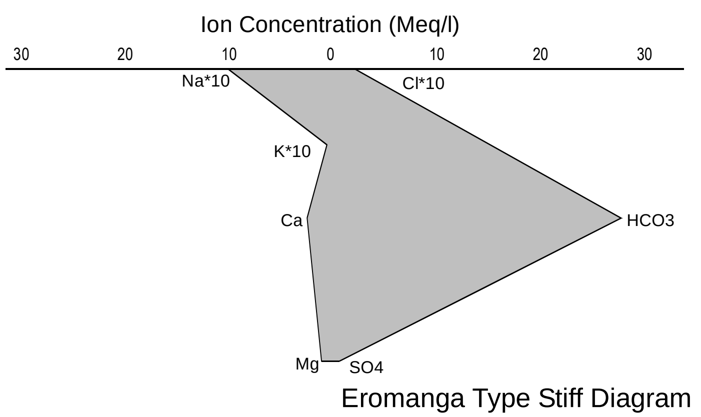


Figure 5 – Great Artesian Basin, Regional Cross Section (modified from Ref. 4)



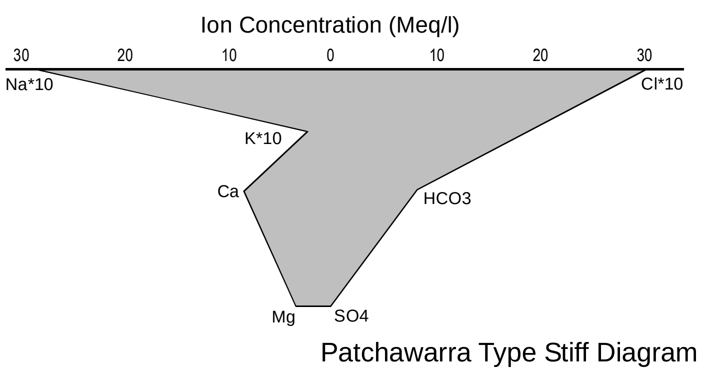


Figure 6 – Type Stiff Diagrams

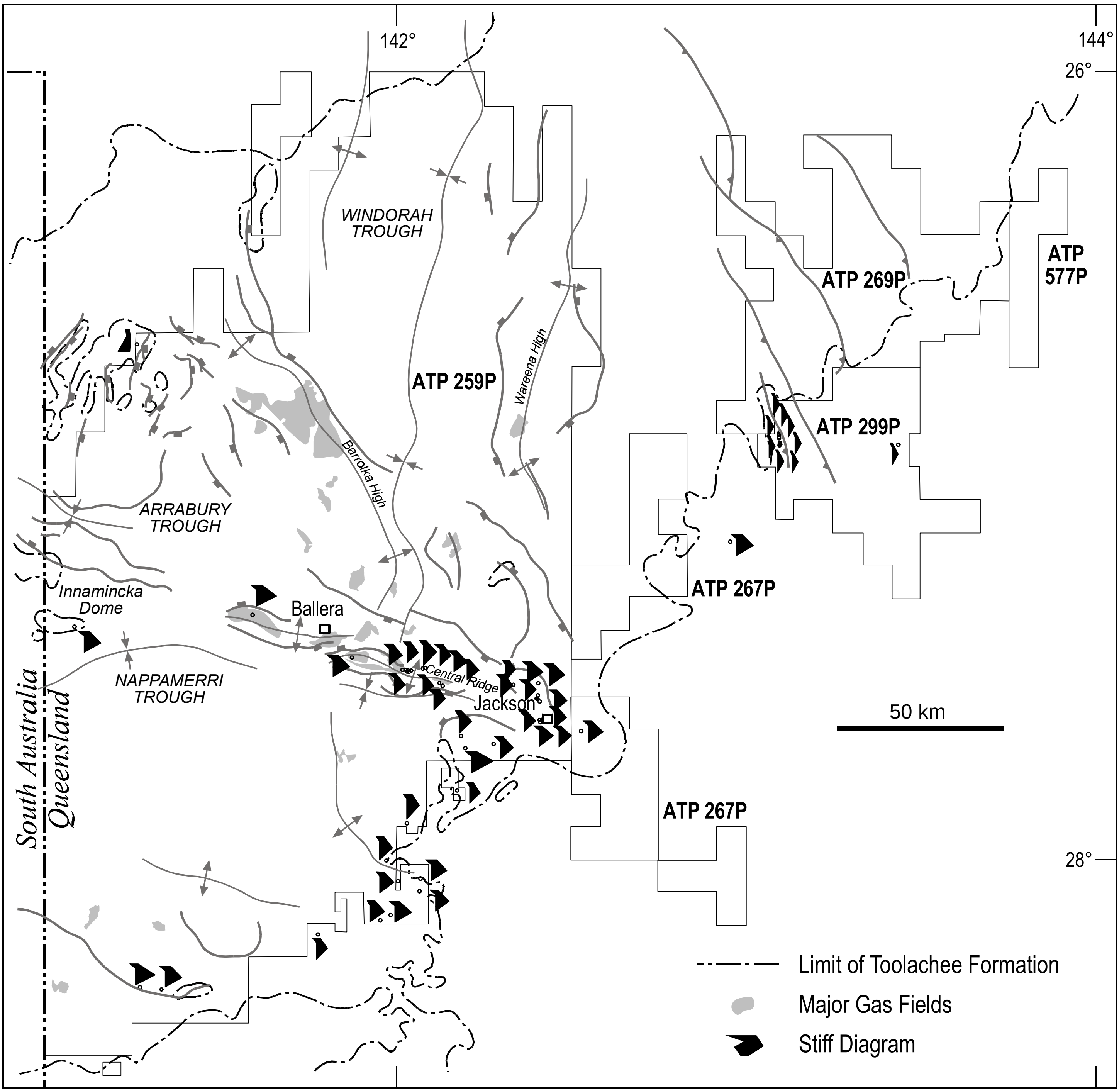


Figure 7 – Hydrochemistry Map, Hutton Formation

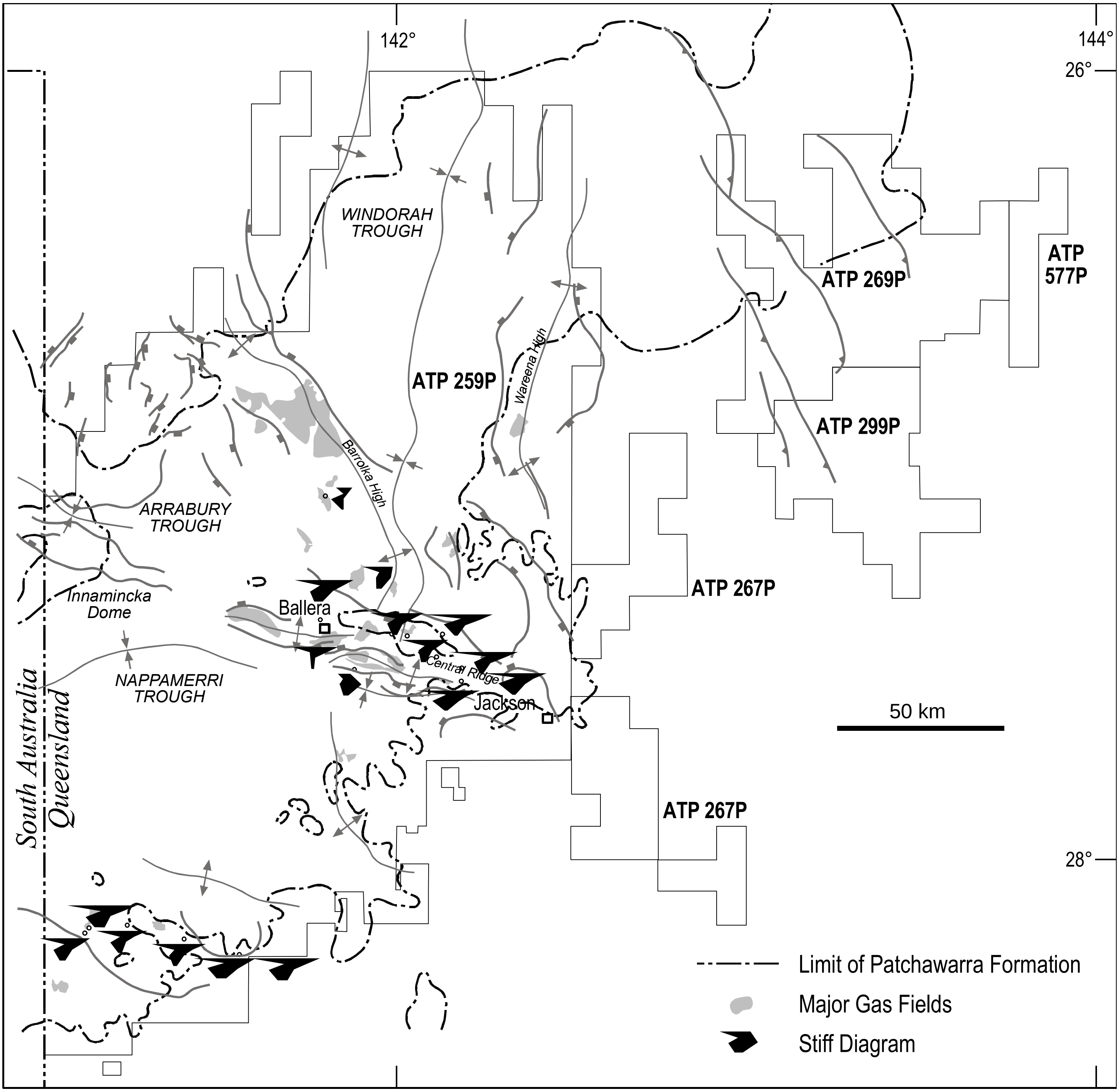


Figure 8 – Hydrochemistry Map, Patchawarra Formation

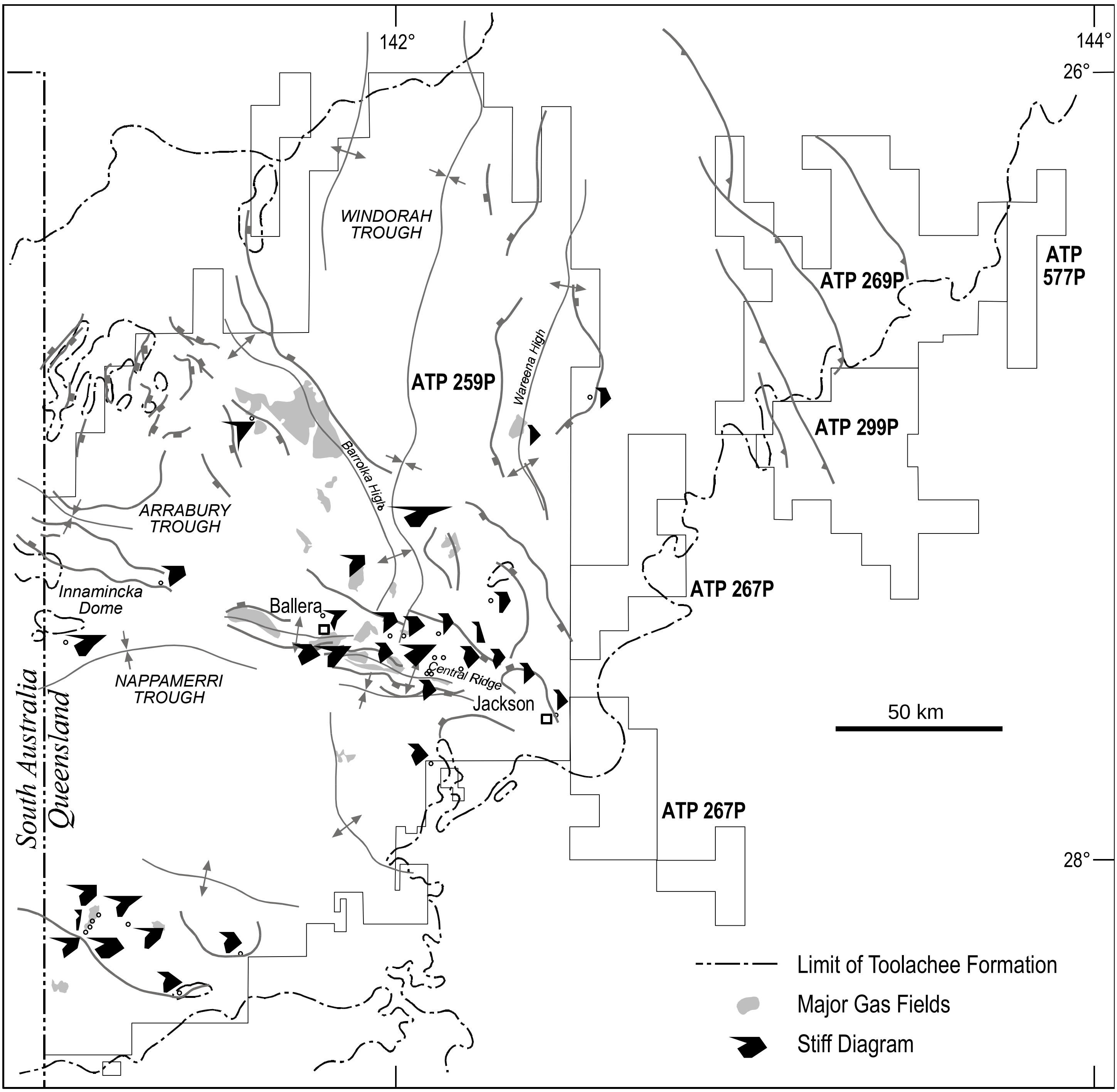


Figure 9 – Hydrochemistry Map, Toolachee Formation

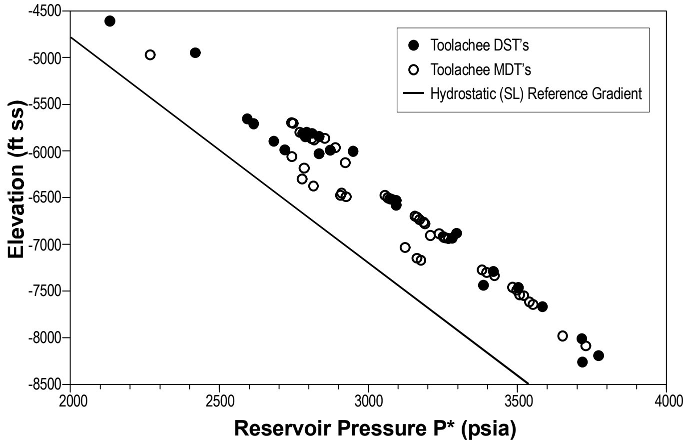


Figure 10 – Summary Pressure / Elevation Plot, Toolachee Formation

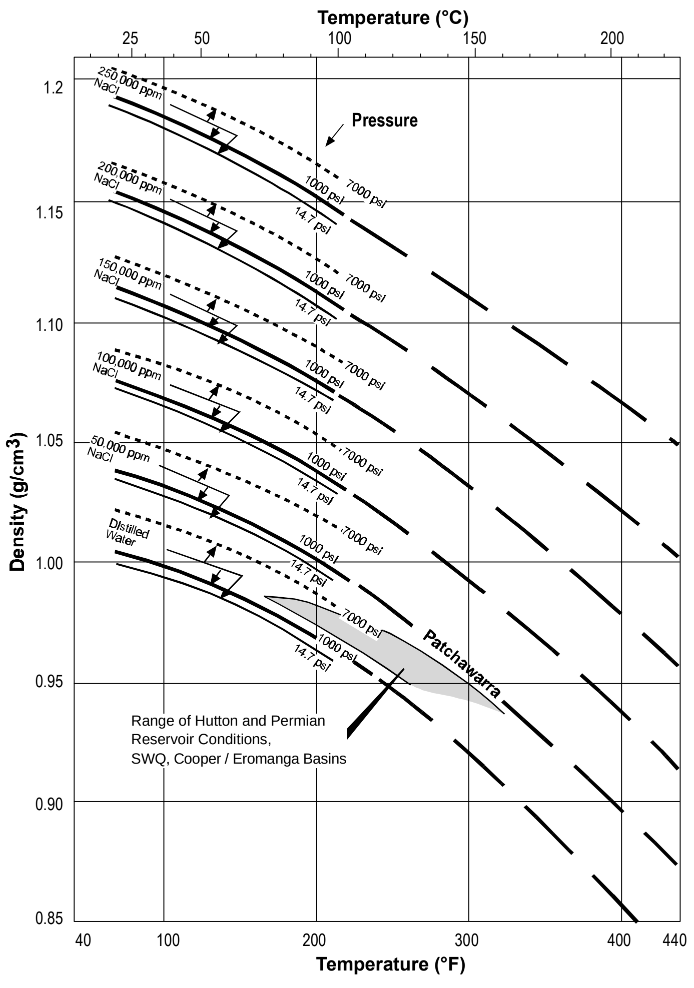


Figure 11 – Water Density Nomograph (modified from Ref. 13)

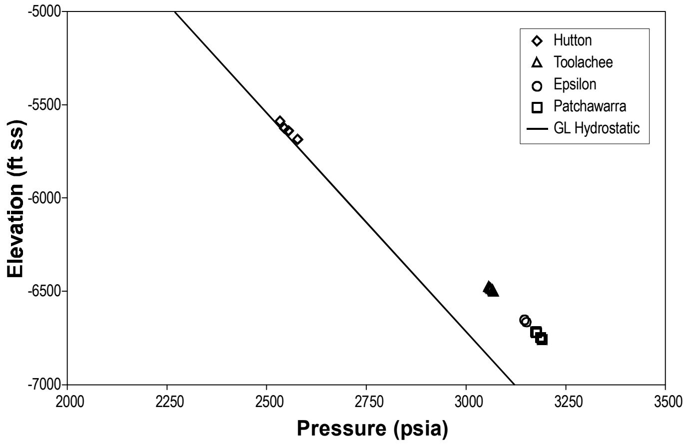


Figure 12 – Wackett-8 Summary MDT Data

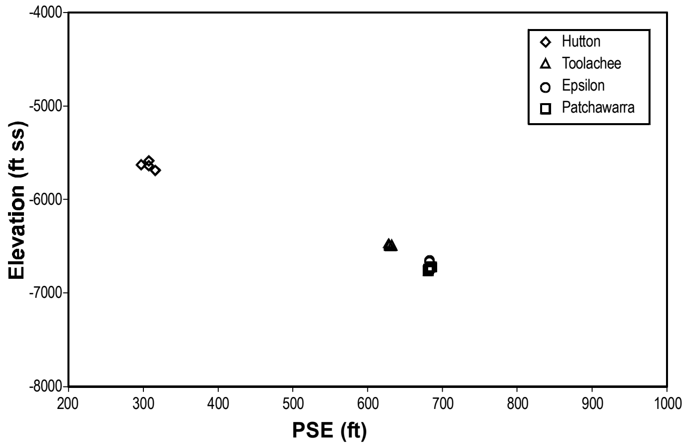


Figure 13 – Wackett-8 PSE Plot

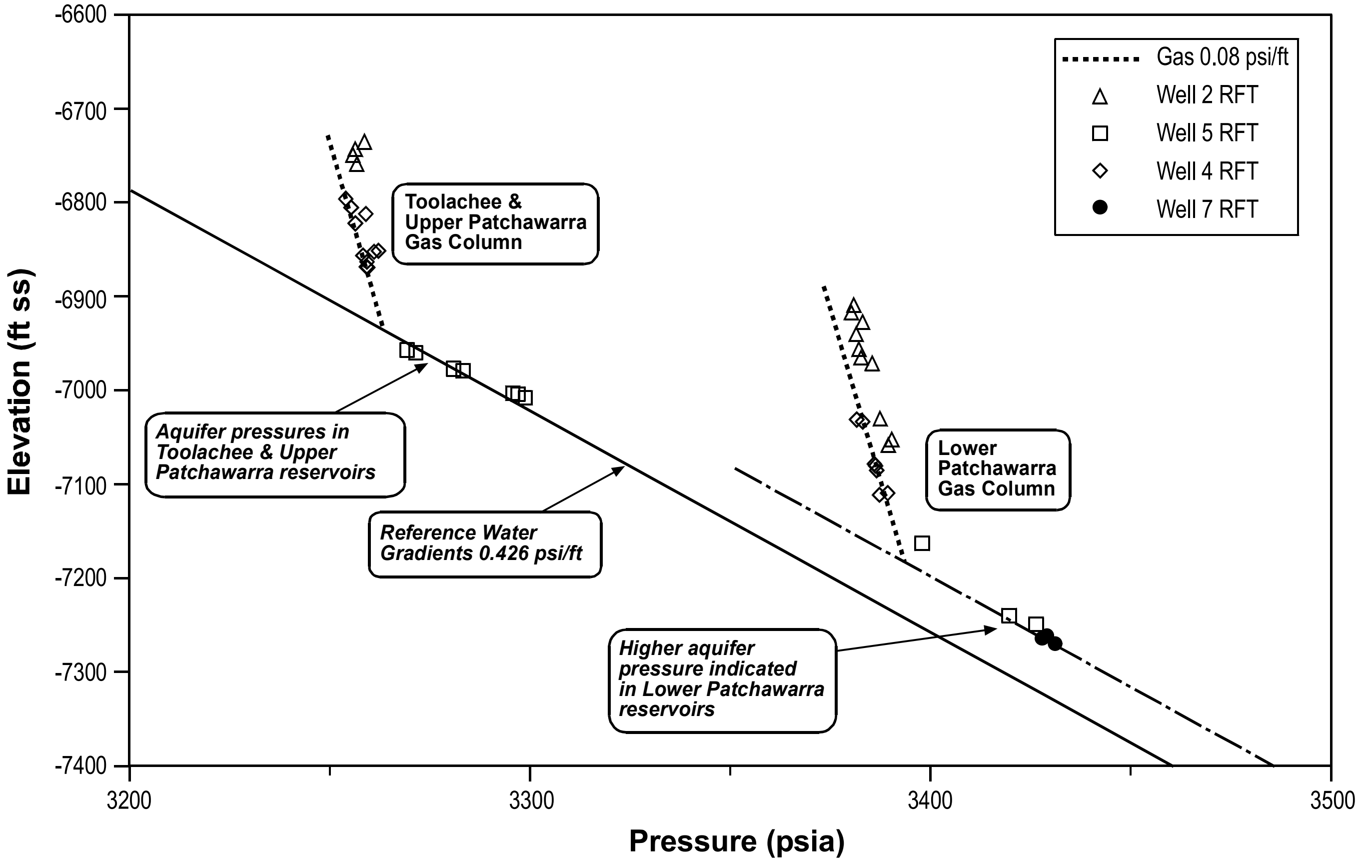


Figure 14 – Field Example of Hydraulic Barrier, Cooper Basin

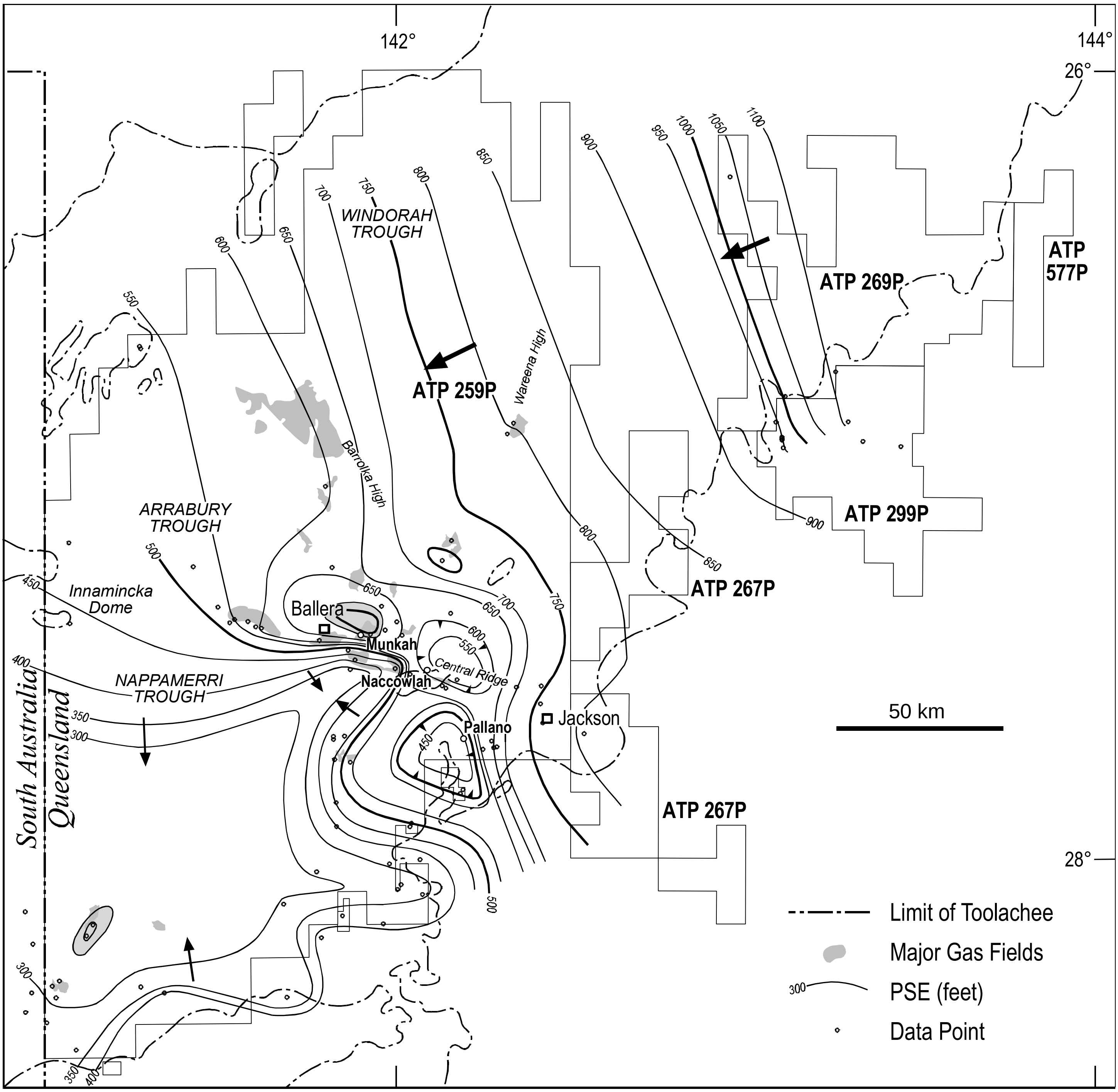


Figure 15 – Potentiometric Surface Elevation, Hutton Formation

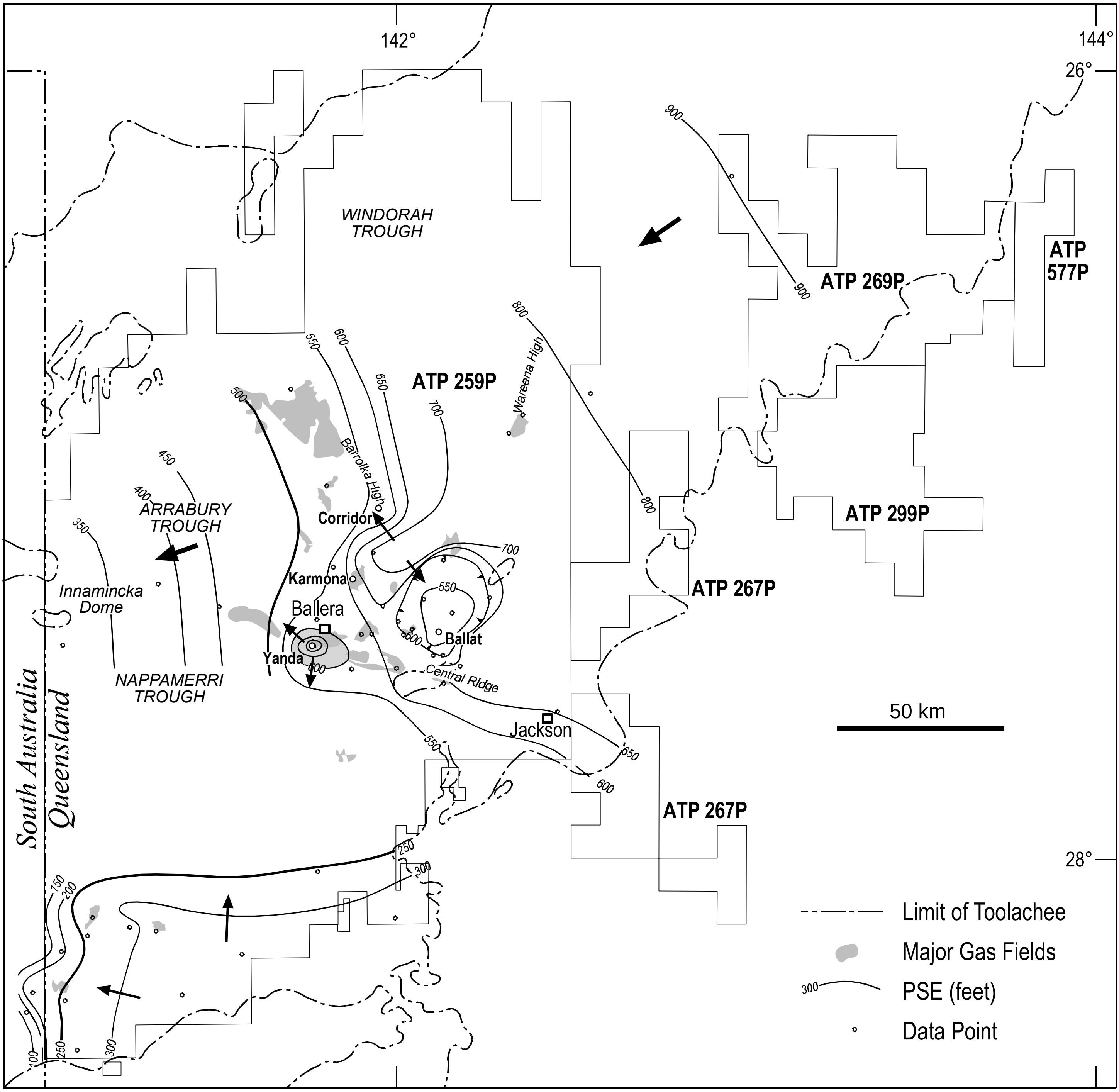


Figure 16 – Potentiometric Surface Elevation, Toolachee Formation

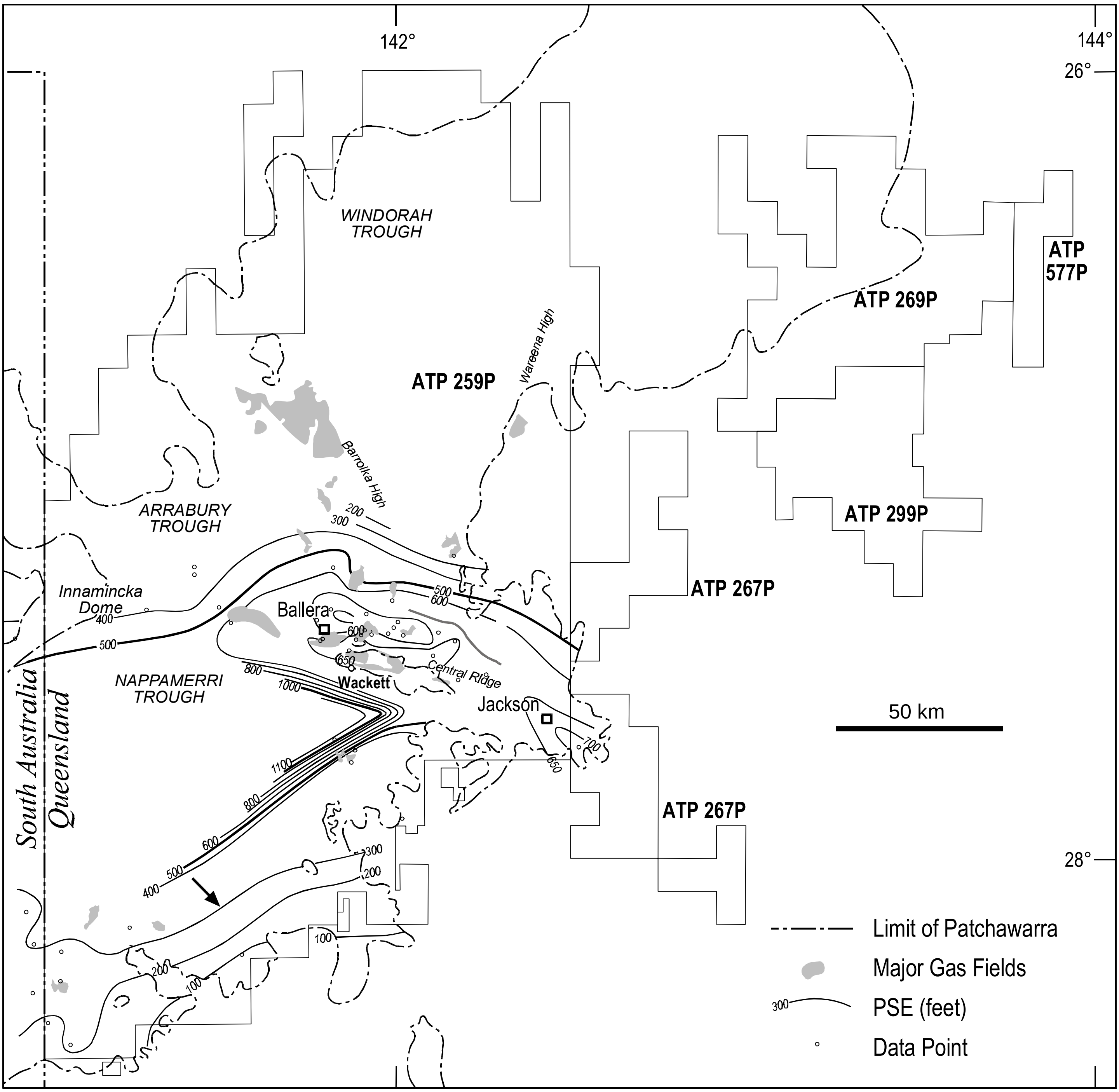


Figure 17 – Potentiometric Surface Elevation, Patchawarra Formation

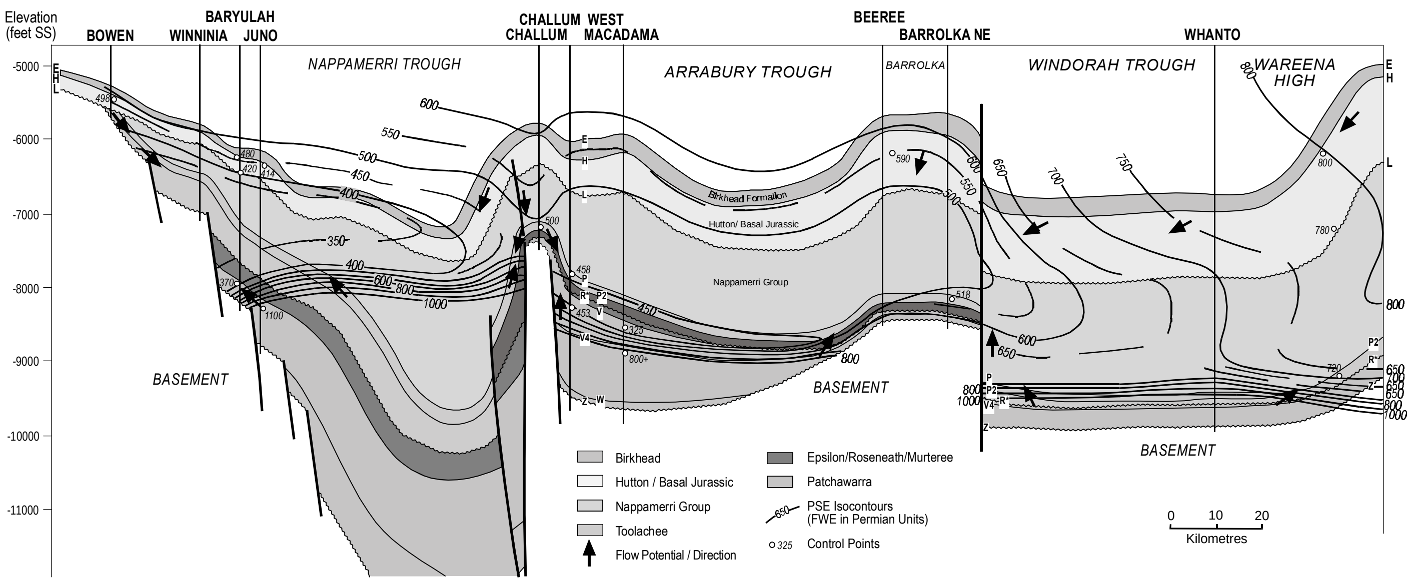


Figure 18 – Summary Cross Section Illustrating Regional Flow Systems (refer to Figure 2 for location)