AGL Upstream Investments Pty Ltd

Hydrogeological Investigation of a Strike-slip Fault in the Northern Gloucester Basin

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PARSONS BRINCKERHOFF

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Glossary

Alluvium	Unconsolidated sediments (clays, sands, gravels and other materials) deposited by flowing water. Deposits can be made by streams on river beds, floodplains, and alluvial fans.
Ammonia	A compound of nitrogen and hydrogen (NH3) that is a common by-product of animal waste and landfills but is also found naturally in reduced environments. Ammonia readily converts to nitrate in soils and streams.
Anisotropy	The presence of a preferred orientation / directionally dependent.
Annulus	The void space between two strings of casing in a water bore or gas well.
Aquifer	Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water.
Aquifer properties	The characteristics of an aquifer that determine its hydraulic behaviour and its response to abstraction.
Aquifer, confined	An aquifer that is overlain by low permeability strata. The hydraulic conductivity of the confining bed is significantly lower than that of the aquifer.
Aquifer, semi-confined	An aquifer overlain by a low-permeability layer that permits water to slowly flow through it. During pumping, recharge to the aquifer can occur across the leaky confining layer – also known as a leaky artesian or leaky confined aquifer.
Aquifer, unconfined	Also known as a water table aquifer. An aquifer in which there are no confining beds between the zone of saturation and the surface. The water table is the upper boundary of an unconfined aquifer.
Aquitard	A low permeability unit that can store groundwater and also transmit it slowly from one formation to another. Aquitards retard but do not prevent the movement of water to or from adjacent aquifers.
Australian Height Datum (AHD)	The reference point (very close to mean sea level) for all elevation measurements, and used for correlating depths of aquifers and water levels in bores.
Background concentration	A natural concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources.
Barrier (boundary/fault)	When a geological unit has a contrastingly lower permeability than the formations adjacent to it, and it thus considered a hydraulic barrier.
Bedding plane	In sedimentary or stratified rocks, the division plane which separates the individual layers, beds or strata.
Beneficial aquifer	An aquifer with a water resource of sufficient quality and quantity to provide either ecosystem protection, raw water for drinking water supply, and agricultural or industrial water.

Bore	A structure drilled below the surface to obtain water from an aquifer or series of aquifers.
Boundary	A lateral discontinuity or change in the aquifer resulting in a significant change in hydraulic conductivity, storativity or recharge.
Carbon 13 (^{13}C)	A naturally occurring radioisotope of chlorine. It has a half-life of 301,000±2,000 years and is suitable for age dating groundwaters up to 1 million years old.
Claystone	A non-fissile rock of sedimentary origin composed primarily of clay-sized particles (less than 0.004 mm).
Coal	A sedimentary rock derived from the compaction and consolidation of vegetation or swamp deposits to form a fossilised carbonaceous rock.
Coal seam gas (CSG)	Coal seam gas is a form of natural gas (predominantly methane) that is extracted from coal seams.
Concentration	The amount or mass of a substance present in a given volume or mass of sample, usually expressed as microgram per litre (water sample) or micrograms per kilogram (sediment sample).
Conceptual model	A simplified and idealised representation (usually graphical) of the physical hydrogeologic setting and the hydrogeological understanding of the essential flow processes of the system. This includes the identification and description of the geologic and hydrologic framework, media type, hydraulic properties, sources and sinks, and important aquifer flow and surface-groundwater interaction processes.
Conductive boundary or fault	When a geological unit has a contrastingly higher permeability than the formations adjacent to it, and it thus considered a conduit.
Cone of depression	A depression of the water table or potentiometric surface that has the shape of an inverted cone, which develops around a production bore/gas well from which water is being drawn. It defines the radius of influence of a pumping test.
Confining layer	Low permeability strata that may be saturated but will not allow water to move through it under natural hydraulic gradients.
Datalogger	A digital recording instrument that is inserted in monitoring and pumping bores to record pressure measurements and water level variations.
Detection limit	The concentration below which a particular analytical method cannot determine, with a high degree of certainty, a concentration.
Deuterium (^{2}H)	Also called heavy hydrogen, a stable isotope of hydrogen with a natural abundance of one atom in 6,500 of hydrogen. The nucleus of deuterium, called a deuteron, contains one proton and one neutron, where a normal hydrogen nucleus has just one proton.
Dip	The inclination of a planar surface measured in the vertical plane perpendicular to its strike.

Dip - slip fault	A fault (either normal or reverse) where the relative movement (or slip) on the fault plane is vertical.
Discharge	The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.
Discharge area	An area in which there are upward or lateral components of flow in an aquifer.
Dissolution	Process of dissolving a substance into a liquid. If the saturation index is less than zero, the mineral is undersaturated with respect to the solution and the mineral might dissolve.
Drawdown	A lowering of the water table in an unconfined aquifer or the pressure surface of a confined aquifer caused by pumping of groundwater from bores and wells.
Dual permeability aquifer	An aquifer in which groundwater flow is through both the primary porosity of the rock matrix and the secondary porosity of fractures and fissures.
Electrical Conductivity (EC)	A measure of a fluid's ability to conduct an electrical current and is an estimation of the total ions dissolved. It is often used as a measure of water salinity.
Environmental isotapes	Also known as stable isotopes, they act as 'groundwater signatures' and can be used as natural groundwater tracers.
Falling head test	A hydraulic test on a monitoring bore that involves a sudden rise in water level (i.e. a volume of water is quickly added to the water column and the rate of water level decline is measured). Also called a slug test or slug-in test.
Fault	A fracture in rock along which there has been an observable amount of displacement. Faults are rarely single planar units; normally they occur as parallel to sub-parallel sets of planes along which movement has taken place to a greater or lesser extent. Such sets are called fault or fracture zones.
Fracture	Breakage in a rock or mineral along a direction or directions that are not cleavage or fissility directions.
Fractured rock aquifer	These occur in sedimentary, igneous and metamorphosed rocks which have been subjected to disturbance, deformation, or weathering, and which allow water to move through joints, bedding planes, fractures and faults. Although fractured rock aquifers are found over a wide area, they generally contain much less groundwater than alluvial and porous sedimentary rock aquifers.
Global Meteoric Water Line (GMWL)	A line that defines the relationship between oxygen-18 (^{18}O) and deuterium (^{2}H) in fresh surface waters and precipitation from a number of global reference sites.
Groundwater	The water contained in interconnected pores or fractures located below the water table in the saturated zone.
Groundwater age classification	Groundwater ages are commonly referred to as: ***Modern*** <100 years

	Sub-modern 100-1,000 years
	Old >1,000 years
Groundwater flow	The movement of water through openings in sediment and rock within the zone of saturation.
Groundwater system	A system that is hydrogeologically more similar than different in regard to geological province, hydraulic characteristics and water quality, and may consist of one or more geological formations.
Hydraulic conductivity	The rate at which water of a specified density and kinematic viscosity can move through a permeable medium (notionally equivalent to the permeability of an aquifer to fresh water).
Hydraulic gradient	The change in total hydraulic head with a change in distance in a given direction.
Hydraulic head	Is a specific measurement of water pressure above a datum. It is usually measured as a water surface elevation, expressed in units of length. In an aquifer, it can be calculated from the depth to water in a monitoring bore. The hydraulic head can be used to determine a hydraulic gradient between two or more points.
Hydrogeology	The study of the interrelationships of geologic materials and processes with water, especially groundwater.
Hydrology	The study of the occurrence, distribution, and chemistry of all surface waters.
Infiltration	The flow of water downward from the land surface into and through the upper soil layers.
Ion	An ion is an atom or molecule where the total number of electrons is not equal to the total number of protons, giving it a net positive or negative electrical charge.
Isotope	One of multiple forms of an element that has a different number of neutrons than other atoms of that element. Some elements have isotopes that are unstable or radioactive, while others have 'stable isotopes'.
Lithology	The study of rocks and their depositional or formational environment on a large specimen or outcrop scale.
Local Meteoric Water Line (LMWL)	A line that defines the local relationship between oxygen-18 (^{18}O) and deuterium (^{2}H) in fresh surface waters and precipitation. In this report the LMWL used is for coastal Brisbane.
Major ions	Constituents commonly present in concentrations exceeding 10 milligram per litre. Dissolved cations generally are calcium, magnesium, sodium, and potassium; the major anions are sulphate, chloride, fluoride, nitrate, and those contributing to alkalinity, most generally assumed to be bicarbonate and carbonate.

Meridional	Pertaining to the north – south.
Methane (CH_4)	An odourless, colourless, flammable gas, which is the major constituent of natural gas. It is used as a fuel and is an important source of hydrogen and a wide variety of organic compounds.
MicroSiemens per centimetre (µS/cm)	A measure of water salinity commonly referred to as EC (see also Electrical Conductivity). Most commonly measured in the field with calibrated field meters.
Monitoring bore	A non-pumping bore, is generally of small diameter that is used to measure the elevation of the water table and/or water quality. Bores generally have a short well screen against a single aquifer through which water can enter.
Normal faulting	A dip – slip fault where the fault plane is vertical or dips towards the downthrow side of a fault.
Numerical model	A model of groundwater flow in which the aquifer is described by numerical equations (with specified values for boundary conditions) that are usually solved in a computer program. In this approach, the continuous differential terms in the governing hydraulic flow equation are replaced by finite quantities. Computational power is used to solve the resulting algebraic equations by matrix arithmetic. In this way, problems with complex geometry, dynamic response effects and spatial and temporal variability may be solved accurately. This approach must be used in cases where the essential aquifer features form a complex system (i.e. high complexity models).
Oxidising conditions	Conditions in which a species loses electrons and is present in oxidised form.
Oxygen-18 (^{18}O)	A natural, stable isotope of oxygen and one of the environmental isotopes. It makes up about 0.2 % of all naturally-occurring oxygen on Earth.
Percent modern carbon (pMC)	The activity of ^{14}C is expressed as percent modern carbon (pMC) where 100 pMC corresponds to 95 % of the ^{14}C concentration of NBS oxalic acid standard (close to the activity of wood grown in 1890).
Permeability	The property or capacity of a porous rock, sediment, clay or soil to transmit a fluid. It is a measure of the relative ease of fluid flow under unequal pressure. The hydraulic conductivity is the permeability of a material for water at the prevailing temperature.
Permeable material	Material that permits water to move through it at perceptible rates under the hydraulic gradients normally present.
Permian	The last period of the Palaeozoic era that finished approximately 230 million years before present.
pH	Potential of Hydrogen; the logarithm of the reciprocal of hydrogen-ion concentration in gram atoms per litre; provides a measure on a scale from 0 to 14 of the acidity or alkalinity of a solution (where 7 is neutral, greater than 7 is alkaline and less than 7 is acidic).

Porosity	The proportion of open space within an aquifer, comprised of intergranular space, pores, vesicles and fractures.
Porosity, primary	The porosity that represents the original pore openings when a rock or sediment formed.
Porosity, secondary	The porosity caused by fractures or weathering in a rock or sediment after it has been formed.
Porous rock	The porosity caused by fractures or weathering in a rock or sediment after it has been formed.
Potentiometric surface	The potential level to which water will rise above the water level in an aquifer in a bore that penetrates a confined aquifer; if the potential level is higher than the land surface, the bore will overflow and is referred to as artesian..
Precipitation	(1) in meteorology and hydrology, rain, snow and other forms of water falling from the sky (2) the formation of a suspension of an insoluble compound by mixing two solutions. Positive values of saturation index (SI) indicate supersaturation and the tendency of the water to precipitate that mineral.
Produced water	Natural groundwater generated from coal seams during flow testing and production dewatering.
Pumping test	A test made by pumping a bore for a period of time and observing the change in hydraulic head in the aquifer. A pumping test may be used to determine the capacity of the bore and the hydraulic characteristics of the aquifer.
Quatemary	The most recent geological period extending from approximately 2.5 million years ago to the present day.
Quality assurance	Evaluation of quality-control data to allow quantitative determination of the quality of chemical data collected during a study. Techniques used to collect, process, and analyse water samples are evaluated.
Radioisotope	Radioisotopes undergo radioactive decay allowing for determination of residence times in aquifers and groundwater systems.
Recharge	The process which replenishes groundwater, usually by rainfall infiltrating from the ground surface to the water table and by river water reaching the water table or exposed aquifers. The addition of water to an aquifer.
Recharge area	A geographic area that directly receives infiltrated water from surface and in which there are downward components of hydraulic head in the aquifer. Recharge generally moves downward from the water table into the deeper parts of an aquifer then moves laterally and vertically to recharge other parts of the aquifer or deeper aquifer zones.
Recovery	The difference between the observed water level during the recovery period after cessation of pumping and the water level measured immediately before pumping stopped.

Recovery event	A monitoring event (in this case the download of dataloggers and the final water sampling program) completed after the pumping test.
Redox potential (ORP or Eh)	The redox potential is a measure (in volts) of the affinity of a substance for electrons – its electronegativity – compared with hydrogen (which is set at 0). Substances more strongly electronegative than (i.e. capable of oxidising) hydrogen have positive redox potentials. Substances less electronegative than (i.e. capable of reducing) hydrogen have negative redox potentials. Also known as oxidation-reduction potential and Eh.
Redox reaction	Redox reactions, or oxidation-reduction reactions, are a family of reactions that are concerned with the transfer of electrons between species, and are mediated by bacterial catalysis. Reduction and oxidation processes exert an important control on the distribution of species like O_2, Fe^{2+}, H_2S and CH_4 etc. in groundwater.
Reducing conditions	Conditions in which a species gains electrons and is present in reduced form.
Residence time	The time that groundwater spends in storage before moving to a different part of the hydrological cycle (i.e. it could be argued it is a rate of replenishment).
Reverse fault	A dip-slip fault in which the hangingwall (wall above the fault) moves upward relative to the footwall (wall beneath the fault).
RL	Reduced level or height, usually in metres above or below an arbitrary or standard datum.
Salinity	The concentration of dissolved salts in water, usually expressed in EC units or milligrams of total dissolved solids per litre (mg/L TDS).
Salinity classification	***Fresh water quality –*** water with a salinity <800 µS/cm. ***Marginal water quality –*** water that is more saline than freshwater and generally waters between 800 and 1,600 µS/cm. ***Brackish quality –*** water that is more saline than freshwater and generally waters between 1,600 and 4,800 µS/cm. ***Slightly saline quality –*** water that is more saline than brackish water and generally waters with a salinity between 4,800 and 10,000 µS/cm. ***Moderately saline quality*** – water that is more saline than brackish water and generally waters between 10,000 and 20,000 µS/cm. ***Saline quality*** – water that is almost as saline as seawater and generally waters with a salinity greater than 20,000 µS/cm. ***Seawater quality*** – water that is generally around 55,000 µS/cm.
Saturated zone	The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric pressure. The water table is the top of the saturated zone in an unconfined aquifer.
Sandstone	Sandstone is a sedimentary rock composed mainly of sand-sized minerals or rock grains (predominantly quartz).
Screen	A type of bore lining or casing of special construction, with apertures designed

	to permit the flow of water into a bore while preventing the entry of aquifer or filter pack material.
Sedimentary rock aquifer	These occur in consolidated sediments such as porous sandstones and conglomerates, in which water is stored in the intergranular pores, and limestone, in which water is stored in solution cavities and joints. These aquifers are generally located in sedimentary basins that are continuous over large areas and may be tens or hundreds of metres thick. In terms of quantity, they contain the largest volumes of groundwater.
Shale	A laminated sedimentary rock in which the constituent particles are predominantly of clay size.
Siltstone	A fine-grained rock of sedimentary origin composed mainly of silt-sized particles (0.004 to 0.06 mm).
Specific storage	Relating to the volume of water that is released from an aquifer following a unit change in the hydraulic head. Specific storage normally relates to confined aquifers.
Specific yield	The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil. Specific yield generally relates to unconfined aquifers. Gravity drainage may take many months to occur.
Stable isotope	Stable isotopes are atoms of the same element that have different masses due to differences in the number of neutrons they contain. Stable isotopes are not subject to radioactive decay, meaning they do not breakdown over time.
Standing water level (SWL)	The height to which groundwater rises in a bore after it is drilled and completed, and after a period of pumping when levels return to natural atmospheric or confined pressure levels.
Strike	The direction of a horizontal straight line constructed on an inclined planar surface, at the direction of 90^0 from the dip direction.
Storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to specific yield.
Stratigraphy	The depositional order of sedimentary rocks in layers.
Strike–slip fault	A fault where the displacement (or slip) is horizontal / parallel to the strike of the displacement plane.
Tertiary	Geologic time at the beginning of the Cainozoic era, 65 to 2.5 million years ago, after the Cretaceous and before the Quaternary.
Thrust fault	A reverse fault with a low angle of dip.
Total Dissolved Solids (TDS)	A measure of the salinity of water, usually expressed in milligrams per litre (mg/L). See also EC.

Trace element	An element found in only minor amounts (concentrations less than 10 milligram per litre) in water or sediment; includes heavy metals arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc.
Tracer	A stable, easily detected substance or a radioisotope added to a material to follow the location of the substance in the environment or to detect any physical or chemical changes it undergoes.
Transmissivity	The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.
Tritium (^3H)	A short-lived isotope of hydrogen with a half-life of 12.43 years. It is commonly used to identify the presence of modern recharge. Tritium is produced naturally in small amounts owing to the interaction of cosmic radiation with atmospheric oxygen and nitrogen in the troposphere, and is also produced by thermonuclear explosions.
Unsaturated zone	That part of an aquifer between the land surface and water table. It includes the root zone, intermediate zone and capillary fringe.
Water bearing zone	Geological strata that are saturated with groundwater but not of sufficient permeability to be called an aquifer.
Water quality	Term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.
Water quality data	Chemical, biological, and physical measurements or observations of the characteristics of surface and ground waters, atmospheric deposition, potable water, treated effluents, and waste water and of the immediate environment in which the water exists.
Water table	The top of an unconfined aquifer. It is at atmospheric pressure and indicates the level below which soil and rock are saturated with water.
Well	Pertaining to a gas exploration well or gas production well.

Units

^{o}C	degrees Celsius
L/s	litres per second
m	metres
m AHD	metres Australian Height Datum
mbgl	metres below ground level
mbtoc	metres below top of casing
meq/L	milliequivalents per litre
m/day	metres per day
m^3/day	cubic metres per day
m/year	metres per year
ML	megalitres
ML/day	megalitres per day
Mm	millimetres
µS/cm	microSiemens per centimetre
mg/L	milligrams per litre
mV	millivot
pMC	percent modern carbon
‰	per mil
TU	tritium unit

Executive summary

AGL Upstream Investments Pty Limited (AGL) is proposing to build the Gloucester Gas Project (GGP) which comprises several stages of development facilitating the extraction of coal seam gas (CSG) from the Gloucester Basin. Baseline groundwater investigations are required in advance of construction as part of the planning approvals process.

Following the referral of the Stage 1 GFDA to the Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) an extension of the baseline investigations requiring an assessment of the connectivity between faults, and the shallow and deep groundwater was initiated. This report presents the results of a field-based hydrogeological investigation of a strike-slip fault within the Stage 1 Gas Field Development Area (GFDA).

The Gloucester Basin is a structurally complex geological basin formed during the Permian period. The northern Gloucester Basin and the Stage 1 GFDA is dominated by west-dipping strata intersected by several westerly-dipping thrust faults and near-vertical to easterly-dipping oblique strike-slip faults. Seismic surveys clearly identify an easterly-dipping strike-slip fault in the study area which, in the upper 200 metres (m) appears to splinter into a number of related structures over a zone up to 300 m to 400 m wide. The surface projection of the fault zone corresponds to a visible NW-trending surface trace and a zone of anomalous conductivity. This fault structure and its surface trace provided an ideal target for the investigation.

The aim of this fault investigation is to develop a conceptual hydrogeological model of flow within the fault zone and surrounding area to assess the potential for enhanced vertical connectivity between the shallow fractured rock aquifers and the deeper coal seams. The hydraulic characteristics of the fault zone were investigated by inducing drawdown in both the fault zone (using a pumping test) and the deeper coal seam water bearing zones (gas well flow test) and monitoring the effects on the shallow groundwater system. Samples were collected and analysed for groundwater quality, dissolved methane content, isotopic composition and age. Test pumping (72 hour constant rate test) indicates that the fault zone is a broad zone of enhanced hydraulic conductivity within the shallow rock aquifer. The fault zone does not form a barrier to flow, nor cause strong preferred longitudinal flow, but may form heterogeneous, weakly transmissive zones in the near surface, relative to the adjacent unfractured shallow-rock domains.

Distinct hydrochemistry and (older) radiocarbon ages within the fault zone suggest that the fault forms a weak conduit that enhances discharge of deeper groundwater under natural conditions. However, the results of stable isotope analyses suggest that this connection is not strong and/or does not penetrate to the deeper coal seams which are significantly more depleted in terms of groundwater δ18O and δ2H

Depressurisation of deeper coal seams during the 29-day Stratford 4 flow test in September 2012 caused no apparent groundwater drawdown in some monitoring bores, while other bores show a slight declining trend that appears to start in early October 2012. It is not possible from the existing data to determine unequivocally the cause of the observed groundwater decline. However it appears to be more consistent with the regional decline in groundwater levels due to the very low rainfall conditions in late 2012, than due to the depressurisation effects.

Dissolved methane is ubiquitous in groundwater across the Gloucester Basin. Concentrations of methane are highly variable in all formations ranging from just above the laboratory LOR (10 µg/L) to concentrations above saturation (54,800 µg/L). The lowest concentrations of dissolved methane were measured in groundwater within a higher permeability zone associated with the fault, whereas methane concentrations above saturation are present at greater depths (>150 m), both within, and outside of the inferred fault zone.

The way in which methane migrates in and around faults is dependent on the characteristics and structure of the fault and the effects of faulting on the permeability of the strata. Faults can range between relatively permeable (open) structures to low permeability barriers to flow. The shallow, higher permeability zone of the inferred fault on the Tiedmans property is interpreted to be an open boundary, where dissolved methane concentrations are lower than in strata at equivalent depths outside this zone due to natural degassing of methane.

Compound specific isotope analysis of dissolved methane (carbon-13 (δ13C-CH4) and deuterium (δ2H-CH4)) indicates that dissolved methane in all strata is primarily of thermogenic origin and there is no apparent trend of isotopic composition with depth or concentration. Sampling of groundwater at multiple monitoring bores before and after the 29-day flow test indicates that dissolved methane decreased in concentration within the fault zone and there was no change in the isotopic signature of methane pre and post flow testing. This indicates that the depressurisation of deep coal seams at Stratford 4, did not result in any discernible vertical methane migration upwards along the fault during a 29-day flow testing period.

In conclusion, a comprehensive field based investigation was carried out to determine the hydraulic characteristics of one of several strike-slip faults in the Gloucester Basin and its control on groundwater flow and impacts under CSG development. Test pumping and isotopic analysis indicate that the fault zone is a broad and heterogeneous zone of increased hydraulic conductivity within the shallow rock aquifer and, under natural conditions, may form a weak conduit for discharge of older groundwater. However monitoring of groundwater levels and dissolved methane during the Stratford 4 gas flow test provide no clear evidence of enhanced connections between the deeper coal seams and shallow groundwater system.

1. Introduction

AGL Upstream Investments Pty Ltd (AGL) is proposing to build the Gloucester Gas Project (GGP) which comprises several stages of development facilitating the extraction of coal seam gas (CSG) from the Gloucester Basin. Concept Plan and Project Approval for the Stage 1 Gas Field Development Area (GFDA) was granted on 22 February 2011 under Part 3A of the *Environmental Planning and Assessment Act (1979) (EP&A Act)*. In addition the project received approval under the *Environment Protection and Biodiversity Conservation Act (1999) (EPBC Act)* on the 11 February 2013.

AGL also holds Petroleum Exploration Licence (PEL) 285, under the *Petroleum (Onshore) Act 1991*, covering the whole of the Gloucester Basin, approximately 100 km north of Newcastle, NSW. The Stage 1 GFDA in relation to the PEL boundaries is shown in Figure 1.1.

The GGP will involve the depressurising of deep groundwater and the extraction of gas from multiple coal seams within the Gloucester Coal Measures. Target coal seam depths will vary from site to site but are expected to range between 200 and 1,000 metres below ground level (mbgl). The collection and interpretation of groundwater and surface water level and quality data enhances and verifies the understanding of the conceptual (hydrogeological) model, and is the primary scientific data to determine whether there are any impacts resulting from CSG activities on groundwater and surface water systems.

The field based groundwater studies commenced with a comprehensive groundwater investigation, the Phase 2 Groundwater Investigation, which was commenced in late 2010 and completed in 2012 (Parsons Brinckerhoff 2012). This investigation confirmed the desktop based hydrogeological conceptual model for the Stage 1 GFDA (SRK 2010). The investigation established a dedicated water monitoring network, and enabled the collection of baseline water level, water quality and hydraulic conductivity data for each of the hydrogeological units represented across the groundwater system and the surface water systems.

Seismic surveys, undertaken by AGL in 2009 and 2010, identified a high angle strike–slip fault at the northern end of the Tiedman Property in the middle of the Stage 1 GFDA. Depending on the nature and degree of connectivity between the fault and the shallow and deep groundwater systems there is the potential for impacts to the shallow groundwater environment during the planned extraction of CSG.

Following referral of the GGP to the Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) under the EPBC Act an extension of the baseline investigation requiring an assessment of the connectivity between faults, and the shallow and deep groundwater systems was requested. This is reflected in Condition 17 a) (i) and (ii) of the recent EPBC approval.

This investigation provides additional information on permeability, groundwater flows and water quality in the vicinity of this strike-slip fault feature where there are existing gas wells and monitoring bores. The results have also been used to reconfirm the conceptual model for the groundwater systems of the Gloucester Basin (PB, 2013a).

PARSONS BRINCKERHOFF

HYDROGEOLOGICAL INVESTIGATION OF A STRIKE SLIP FAULT IN THE NORTHERN GLOUCESTER BASIN
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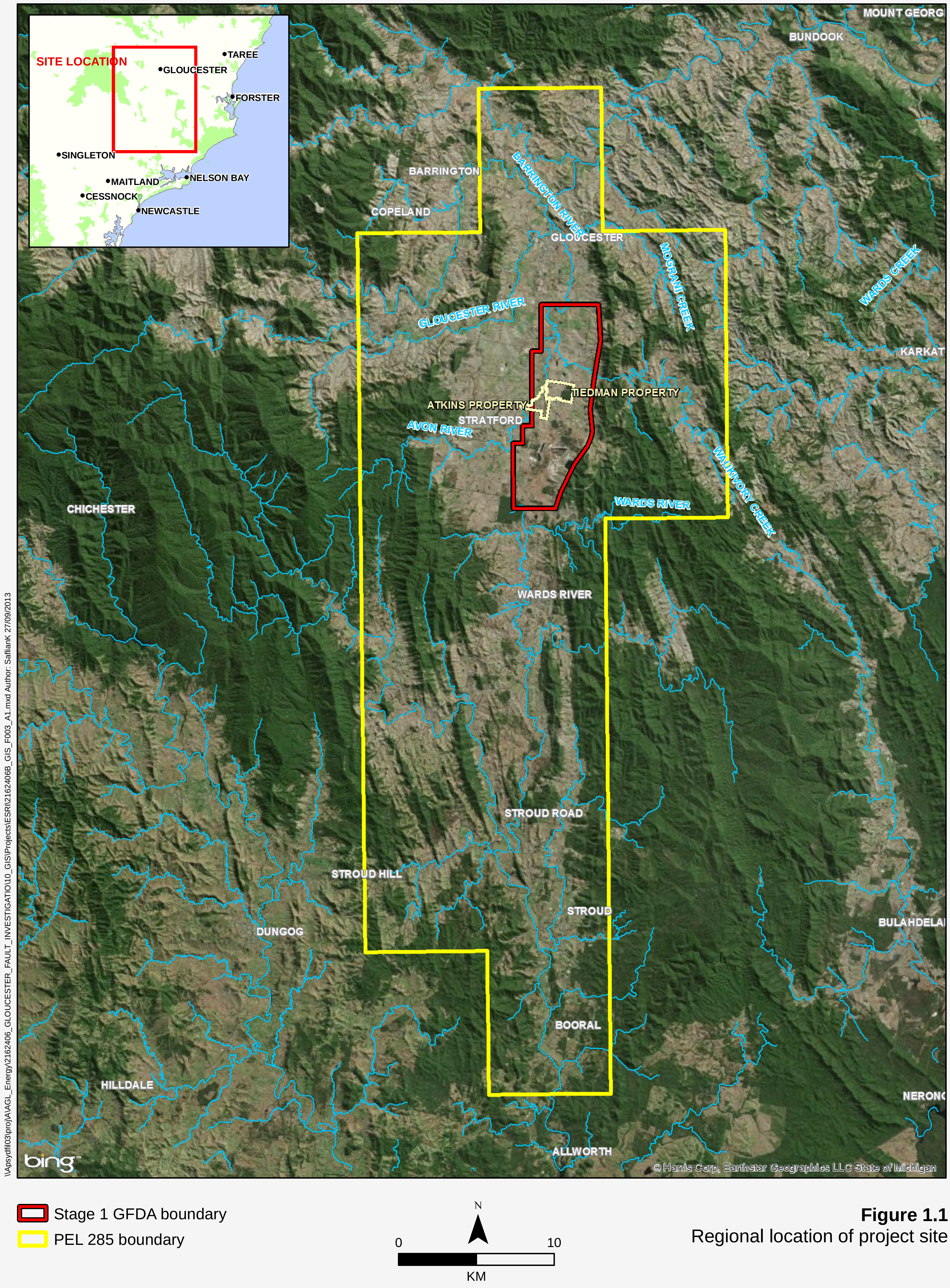

Figure 1.1
Regional location of project site

1.1 Objectives

The objectives of this fault investigation were to:

- Carry out a field-based investigation to assess the hydrogeological characteristics of a strike-slip fault within the Stage 1 GFDA. Field tests are designed to stress both the fault zone (using a pumping test) and the deeper coal seam water bearing zones (using a gas well flow test/pumping test), and monitor the effects on the shallow groundwater system.
- Develop a conceptual hydrogeological model of the fault zone and surrounding areas, and to assess the connectivity between the fault and shallow fractured rock aquifers and the deeper coal seams.
- Infer the potential impacts to the shallow and deep groundwater environment during the planned extraction of CSG.

Investigations were carried out using a surface geophysical survey, the construction of a test production bore into the fault zone and an associated groundwater monitoring network, and the completion of a three day, constant rate pumping test at the production bore (December 2011). In addition, after a pumping test was approved on the nearby Stratford 4 gas well, a 29 day, constant rate flow test was completed (September–October 2012).

1.2 Scope of works

The scope of works included the following:

- Undertake a desktop review of the geophysical data and relevant literature to assess local faults in the Gloucester Basin.
- Focussing an identified oblique strike-slip fault within the Stage 1 GFDA, undertake a Time Domain Electromagnetic (TEM) survey to confirm the position of the identified strike-slip fault.
- Undertake a drilling program involving the installation of a test production bore within the fault zone and three groundwater monitoring bores within and adjacent to the fault zone.
- Undertake three phases of hydraulic testing, including:
    - In-situ permeability tests (‘slug tests’) to determine the approximate hydraulic conductivities of water bearing formations adjacent to the screens at the three monitoring bores.
    - A three day, constant rate pumping test at the production bore TTPB in the fault zone to assess the connectivity between the fault and the shallow groundwater systems.
    - A 29 day, constant rate flow test (extraction of gas/water from unbroken deeper rock) at gas well Stratford 4 (intersecting the deeper coal seam water bearing zone) to assess the potential for groundwater to migrate in the nearby fault when deep coal seams are depressurised.
- Collate and interpret the pumping test and flow test groundwater level and quality data to refine the conceptual model and assess the potential for groundwater migration during coal seam depressurisation.

1.3 Report structure

This document provides a concise report detailing the steps and findings of the fault investigation. The structure of the report is as follows:

- Section 2: provides a contextual overview of the Gloucester Basin geology and hydrogeology.
- Section 3: details the investigative methodology and the phases of work.
- Section 4: provides the investigation results.
- Section 5: presents a discussion of the results.
- Section 6: presents the conclusions of the study.

This report presents the full results of the investigation and conclusions relating to the groundwater flow in a strike-slip fault zone and potential for gas migration.

2. Geology and hydrogeology

This chapter presents a summary of the geology and hydrogeology of the Stage 1 GFDA and the broader Gloucester Basin.

The geological and hydrogeological findings are based on field and desk top studies undertaken for the Phase 2 Groundwater Investigation (Parsons Brinckerhoff 2012), a hydrogeological conceptual model for the basin (Parsons Brinckerhoff 2013a), the Water Balance for the Gloucester Stage 1 GFDA (Parsons Brinckerhoff 2013b) and annual monitoring reviews. Information on the region's climate and rainfall, and further details on the geological and hydrogeological units can be found in these reports.

2.1 Geological setting

The Gloucester Basin represents a complex geological system formed by the interplay of extensional tectonic faulting and high rates of sedimentation. The Basin stratigraphy comprises a thick succession of Permian sedimentary rocks representing deposition in both terrestrial and marine environments during a complex period of subsidence, uplift and relative sea level change (marine transgression and regression).

The Basin is a synclinal intermontane structure formed in part of the New England Fold Belt between a major Permian plate margin and the Sydney-Gunnedah Basin (Lennox 2009). The north – south trending synclinal nature of the Gloucester Basin resulted from the collision between the East Australian and Pacific Plates.

Following a period of extension during the Early Permian the Gloucester Basin has undergone periods of normal and reverse faulting, with large scale tilting associated with late stage compressional movements towards the end of the Permian (Hughes 1995). Reverse faults dominate present day structure. A comparison with the contemporary horizontal stress field map (Hillis *et al* 1998) indicates the Basin is likely to be under compression in an east-west orientation.

The stratigraphy dips steeply (up to 90°) on the flanks of the Basin, dipping towards the north-south trending synclinal basin axis and flattening toward the centre of the Basin. Early Permian and Carboniferous hard resistive volcanics form the ridgelines of the Basin: the Mograni Range to the east; and the Gloucester and Barrington Tops to the west.

Overlying the Permian stratigraphy is a thin sequence of surficial Quaternary sediments. The Quaternary sediments are non-uniform in thickness, and comprise unconsolidated alluvial sediments (sand, gravel, silt and clay) along the drainage channels and colluvial deposits across the rest of the plain sourced from the surrounding outcropping Permian deposits.

2.1.1 Stratigraphy of the investigation area

2.1.1.1 Overview

The Gloucester Basin is divided into three major Permian stratigraphic units each representing a distinct depositional setting: the Gloucester Coal Measures, the Dewrang Group, and the Alum Mountain Volcanics. The generalised stratigraphy of the basin is summarised in Table 2.1. A geological map of the basin is shown in Figure 2.1.

Table 2.1 Stratigraphy of the Gloucester Basin

Period	Group	Sub-group	Formation	Approx. thickness (m)	Coal seam	Depositional environment	Tectonic events
Upper Permian	Gloucester Coal Measures	Craven	Crowthers Road Conglomerate	350		Marine regression, progradation of alluvial fans	Uplift to west of Gloucester Basin
			Leloma	585	Linden		
					JD		
					Bindaboo		
					Deards		
			Jilleon	175	Cloverdale		
					Roseville		
					Tereel/Fairbairns		
			Wards River Conglomerate	Variable			
			Wenham	23.9	Bowens Road		
					Bowens Road Lower		
		Speldon Formation				Marine transgression but also some progradation of alluvial fans in the west related to uplift	Extension (normal fault development) and regional subsidence. Uplift to west of Basin
		Avon	Dog Trap Creek	126	Glenview		
			Waukivory Creek	326	Avon		
					Triple		
					Rombo		
					Glen Road		
					Valley View		
					Parkers Road		
	Dewrang	Mammy Johnsons		300	Mammy Johnsons	Marine transgression, regression and further marine transgression	Extension (normal fault development) and regional subsidence
		Weismantel		20	Weismantel		
		Duralie Road		250			
Lower Permian	Alum Mountain Volcanics				Clareval	Arc-related rift	Rift?
					Basal		

Modified from AECOM, 2009; and SRK, 2005.

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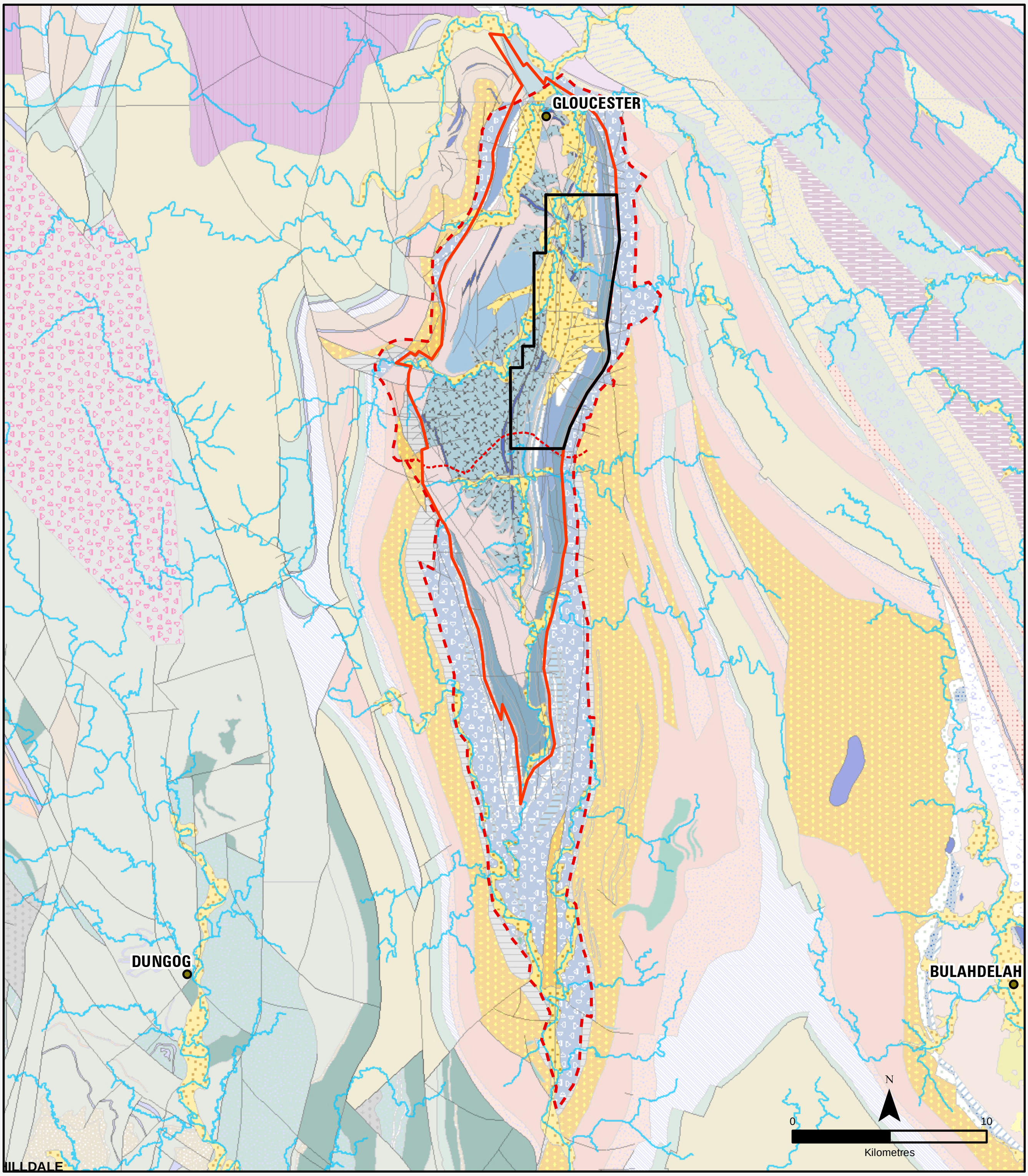
HYDROGEOLOGICAL INVESTIGATION OF A STRIKE SLIP FAULT IN THE NORTHERN GLOUCESTER BASIN

AGL UPSTREAM INVESTMENTS PTY LTD



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- Alum Mountain Volcanics boundary
- Permian Coal Measures boundary
- Stage 1 GFDA boundary
- Rivers and streams

Gloucester Basin Geology

- Qa — Quaternary Alluvium
- G — Unnamed microgranite

Permian Geology

- Plc — Crowthers Rd Conglomerate
- Pll — Leloma Formation
- Pllj — Jo Doth Tuff Member
- Plo — Jilleon Formation
- Plw — Wards River Conglomerate
- Pla — Wards River Conglomerate
- Plgx — Gloucester Coal Measures
- Plh — Wenham Formation
- Plp — Speldon Formation
- Plt — Dog Trap Creek Formation
- Pli — Waukivory Creek Formation
- Pldy — Mammy Johnsons Formation
- Plde — Weismantels Formation
- Pldd — Duralie Road Formation
- Pea — Alum Mountain Volcanics
- Pear — Unnamed Rhyolite Member
- Peat — Unnamed Welded Tuff Member
- Peac — Unnamed Basal Sequence

Carboniferous geology

- Clo1 — Johnsons Creek Conglomerate
- Clkm — McInnes Formation
- Clr — Booral Formation
- Fault

Figure 2.1
Regional geology

2.1.2 Structural development

The tectonic development and structural setting of the Gloucester-Stroud Syncline is discussed by Roberts et al. (1991) based on regional geological mapping and seismic profile interpretation. Subsequent structural interpretations have been carried out by SRK (2005) and Lennox (2009). The following summary is based on those reports.

The Gloucester-Stroud Syncline is the largest structure in the surrounding region, being more than 55 km long and 24 km wide with steeply dipping limbs containing a stratigraphic section up to 8 km thick (Roberts et al, 1991). The syncline has a sinuous axial trace that trends generally northerly (355°) but that swings eastwards (022°) between Stratford and Gloucester. The syncline is doubly plunging, closing at both ends forming a tight canoe-like structure. The axial plane is inclined slightly to the east; bedding in the limbs of the syncline tends to dip steeply toward the axis at more than 60°, with some bedding sub-vertical or slightly overturned.

The syncline is a fault bounded trough, active during the Permian. Roberts et al, (1991) identify up to six deformation events that were important in the depositional and structural development of the Basin. SRK (2005) simplified the structural development into two main stages:

- Early – Middle Permian dextral tectonic margin, resulting in reactivation of NNW-striking faults as strike-slip dextral and formation of NE and EW striking normal faults, particularly around the margins of a circular basement feature (suspected deep intrusion) in the northern part of the Basin. The majority of the Coal Measures were deposited during this complex phase.
- Late Permian NE shortening during the early stages of the Hunter Bowen Orogeny, resulting in reverse and thrust faulting on NNW faults and some NNE faults.

Combining structural domains with the known distribution of stratigraphy, SRK (2005) divides the Basin into three structure/stratigraphic domains:

1. An eastern domain containing a number of coal seams in the Avon and Craven Sub-Groups.
2. A western domain where the surface mapping indicates sequences of Waukivory Formation and Wards River Conglomerate that mark periods of prograding fluvial systems that have significantly reduced the thickness of coal seams.
3. Major fault zones that separate the eastern and western domains.

In addition, SRK (2005) identifies a possible basement structure or intrusion overlapping with the northern part of the Basin that appears to have influenced the structural development of the Basin. The margin of that structure coincides with arcuate and east-west faulting in the mid part of the basin (e.g. west of Stratford) and may account for the contrasting deformation styles in the Carboniferous basement rocks to the north and south of this approximate line.

2.1.3 Faulting

Faulting in the Gloucester Basin is discussed by Roberts et al. (1991) who identify five distinct types or styles of faulting based on mapping and seismic interpretations:

1. Low-angle, west-dipping broadly meridional (N-S) thrust faults.
2. Sinistral strike slip (shears) zones striking between 300° and 350°.
3. Meridional reverse faults.
4. East-west striking normal faults.
5. Strike slip (shear) or normal faults striking between 040° and 060°.

These contrasting fault types reflect different episodes of deformation throughout the complex structural history of the Basin (Roberts et al. 1991), and the possible influence of basement structures (SRK, 2005). Lennox (2009) provided a spatial analysis of faults and other linear features based on air photo and seismic interpretations which follows a broadly similar classification (Figure 2.2).

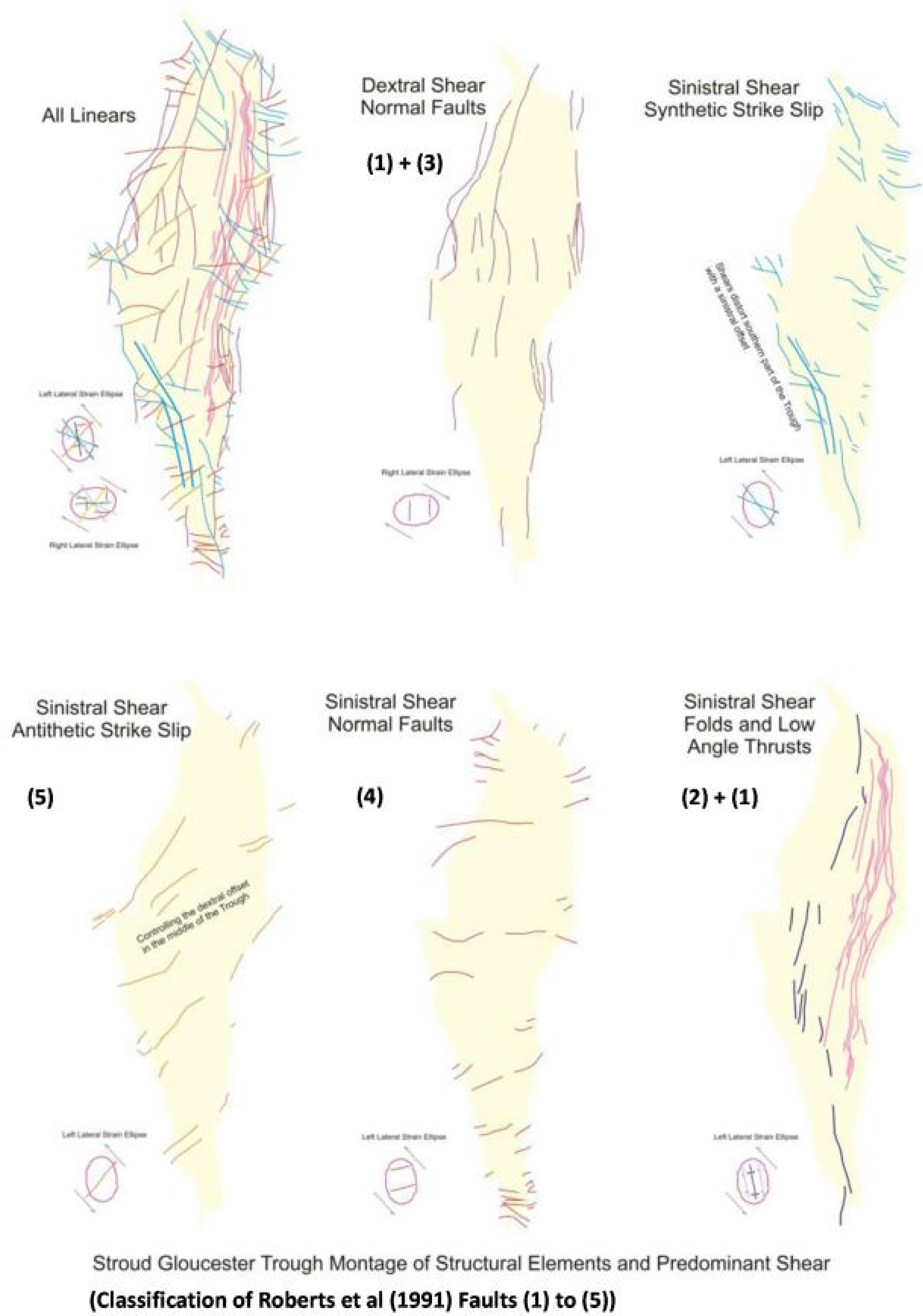


Figure 2.2 Major sets and styles of faulting in the Gloucester Basin (after Lennox, 2009)

Geological mapping of the Basin (Roberts et al. 1991) shows that, in the vicinity of the Stage 1 GFDA, the geological structure is dominated by moderately to steeply west-dipping strata intersected by near-vertical sinistral strike-slip faults with significant vertical components (Style 2, Figure 2.2) and westerly-dipping thrust faults (Style 1, Figure 2.2).

Recent seismic data acquired by AGL identify a number of westerly dipping thrust faults striking north-south, and north-south striking high angle oblique faults. The resolution of the vertical seismic profiles is good to depths of approximately 1 km, however the technique returns poor resolution in the top 200 m. This inhibits the ability to map these fault structures through the shallow surface rock and currently lineament traces can only be inferred. The resolution of the seismic data allows for identification of faults when displacement is greater than approximately 10 m.

The seismic section presented in Figure 2.3 shows the subsurface bedding and structure to depths of 1,900 mbgl beneath the Tiedman property in the centre of the Stage 1 GFDA. Figure 2.4 shows an east-west cross section through the Stratford Pilot area with four major westerly dipping thrust faults and two easterly dipping north-south trending strike-slip faults with minimal vertical offset.

Although regional geological mapping and seismic interpretation has identified numerous faults throughout the Basin, regolith and alluvial deposits tend to obscure the surface traces of many faults. Field reconnaissance and drilling carried out during the Phase 2 Groundwater Investigation for the Stage 1 GFDA identified the possible surface trace of one of the steeply dipping strike-slip faults noted in the seismic surveys crossing the northern boundary of the Tiedman property approximately 300 m east of the Stratford 4 Gas well. This location provided an opportunity to target and investigate the hydraulic properties of a fault zone in the near surface and in the vicinity of a gas test well. The delineation of this fault zone is described further in Section 4.

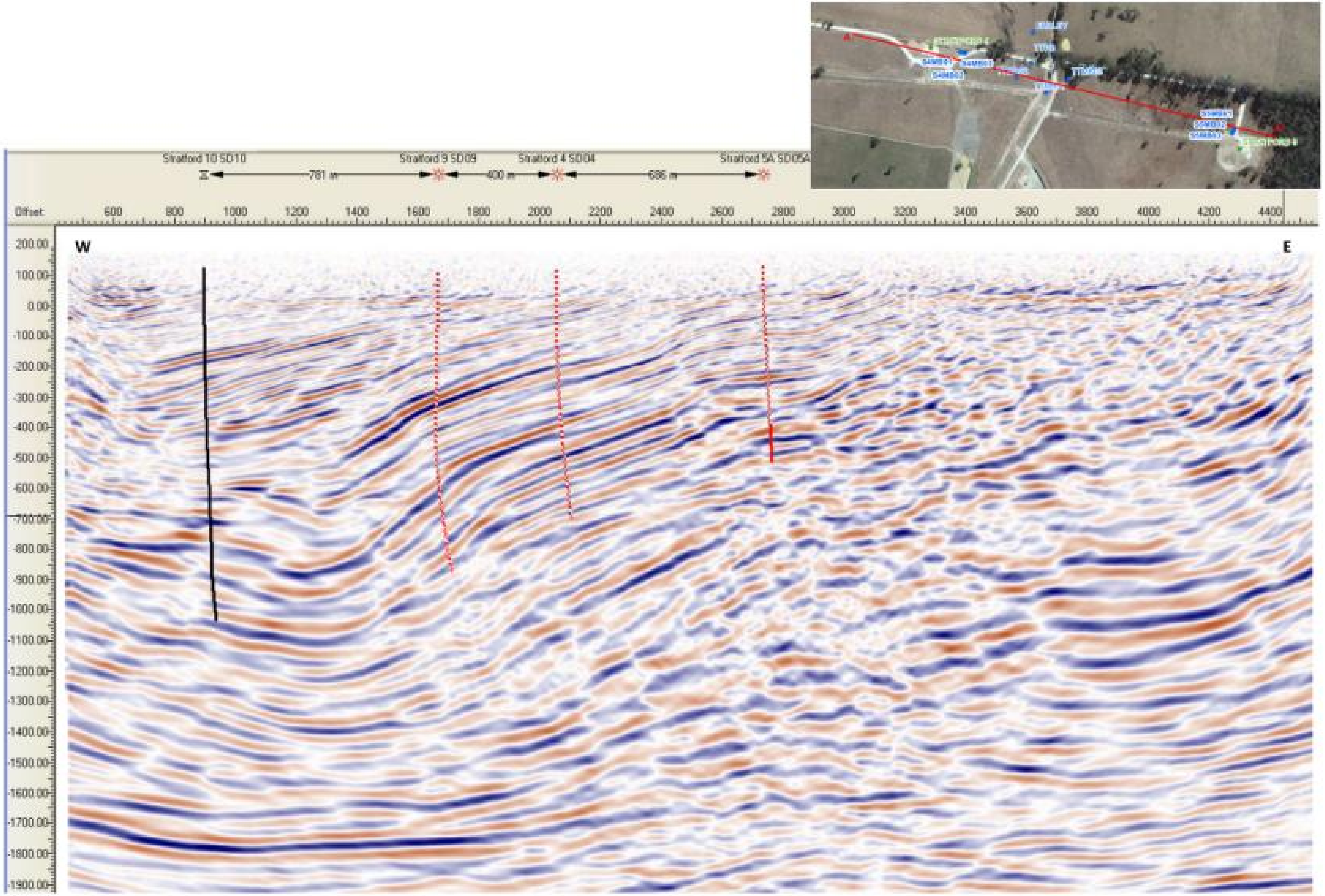


Figure 2.3 Seismic cross-section across the western part of the basin at the Tiedman Property, to a depth of 1,900 m

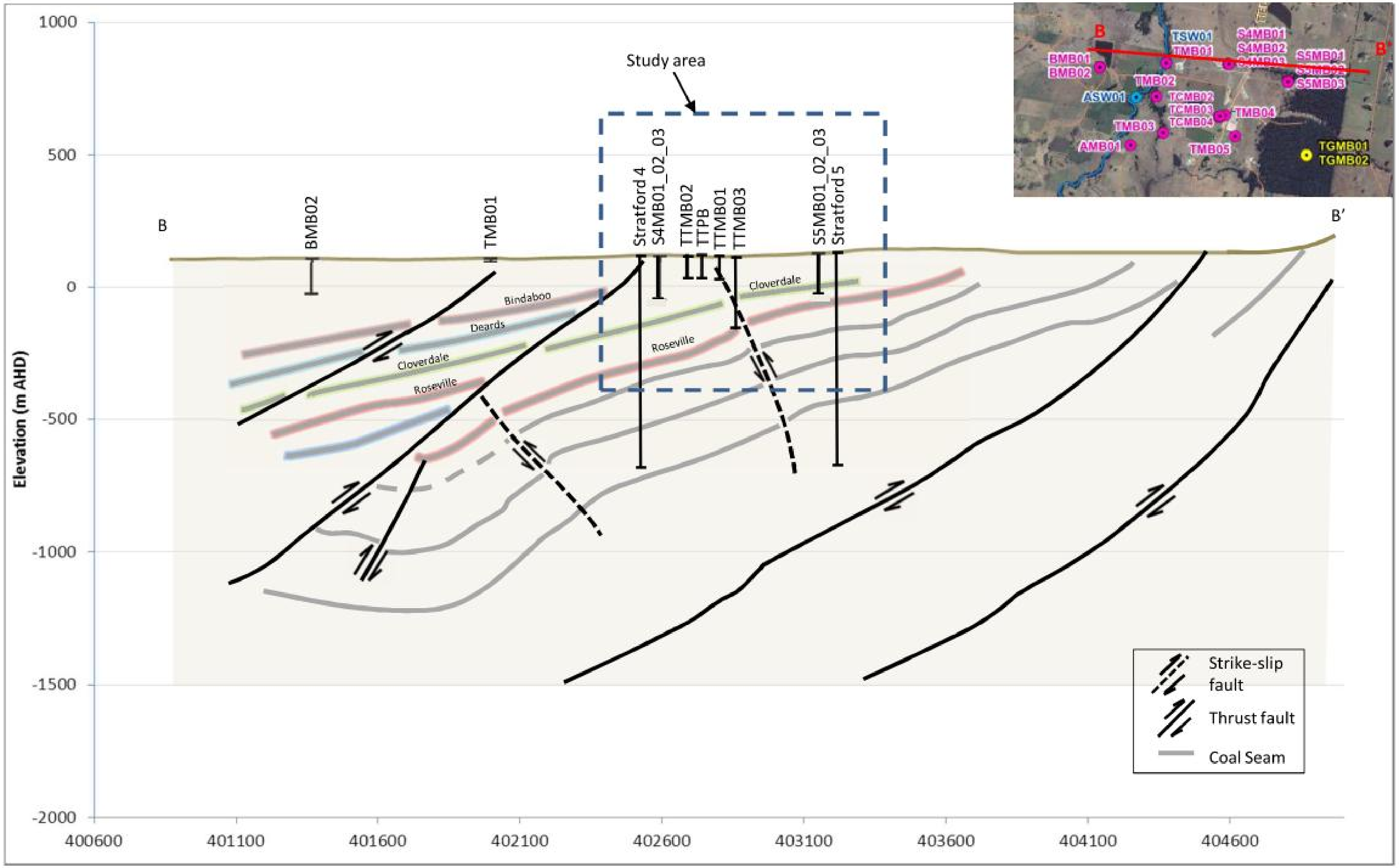


Figure 2.4 East-West schematic cross-section through the Stratford Pilot area

2.2 Hydrogeological units

Four broad hydrogeological units have been identified within the Gloucester Basin (Table 2.2). The permeability and groundwater flow characteristics of rocks within the Gloucester Basin are controlled by several factors including lithology, depth and the degree of fracturing and faulting. In this sense hydrogeological units and flow systems do not always correspond with defined geological boundaries.

Table 2.2 Four key hydrogeological units

Unit	Aquifer type	Formation name	General lithology	Hydraulic characteristics
Alluvium	Semi-confined, clay capped, porous, granular	Quaternary alluvium	Clay/mixed gravels	Heterogeneous, highly variable permeability associated with varying lithology
Shallow Rock (<150m)	Semi-confined, fractured rock	Upper Permian Coal Measures, Alum Mountain Volcanics	Interbedded sandstone/siltstone with bedding plane fractures	Heterogeneous, high and low permeability domains associated with fault zones and fracturing
Interburden	Confined, fractured rock	Upper Permian Coal Measures	Interbedded indurated sandstone/siltstone and claystone	Low permeability associated with sparse fractures, permeability decreases with depth
Coal Seams	Confined, fractured rock	Upper Permian Coal Measures	Coal/shale	Low permeability associated with cleating and fractures in coal seams, permeability decreases with depth

The four hydrogeological units are summarised as follows:

Alluvial deposits adjacent to major creeks and rivers comprising unconsolidated sand, gravel and clay. These systems are heterogeneous but generally permeable with rapid recharge, through-flow and discharge associated with interactions with streams, and to a lesser extent with the underlying less permeable shallow rock. Hydraulic conductivity measurements range from 0.3 to 300 metres per day (m/d), averaging around 10 m/d.

Shallow rock comprising variably weathered and fractured Permian rocks extending to approximately 150 m below the surface, across all sub-cropping Permian units. The shallow rock zone is highly heterogeneous with relatively impermeable domains separated by more permeable domains, but on the whole it is more permeable that the deeper coal measures. The domains of higher permeability domains are due to a higher density of fracturing associated with an irregular weathering profile and the near-surface expression of faulting. Groundwater flow within this zone is more strongly controlled by weathering and fracturing than the attitude of geological strata. Hydraulic conductivity of the shallow rock ranges from 10 m/d to 1×10^{-6} m/d at a depth of 150 m, but is typically in the order of 10^{-3} to 10^{-4} m/d.

Deep Coal Measures interburden. Sandstone and siltstone units that form interburden to coal seams are indurated and typically of very low permeability, forming aquitards and confining layers. Permeability of interburden decreases with depth such that, at the maximum depth of CSG production is likely to be in the order of 10^{-5} to 10^{-7} m/d, or less.

Coal seams. Coal seams tend to be slightly more permeable than interburden and commonly form weak water bearing zones. Permeability and storage are provided by small fractures and cleats in the coal. As with interburden, drill-stem tests clearly show that the permeability of coal seams generally decreases with depth. At the maximum depth of CSG production, the permeability of coal seams is very low (10^{-4} – 10^{-6} m/d), but may be an order of magnitude higher than the interburden.

The Alum Mountain Volcanics underlie the Permian Coal Measures, and form the impermeable base of the Gloucester Basin. The Alum Mountain Volcanics outcrop in the eastern and western boundaries of the basin, forming the elevated topography of the Gloucester and Barrington Tops to the west, and the Mograni Range to the east.

2.3 Role of faults

Folding and faulting of sedimentary rocks can give rise to complex hydrogeological systems. Fault zones can act as either barriers to groundwater flow or as groundwater conduits, or have negligible influence, depending on the nature of the fault zone and the material within it (Fetter, 2001). If the fault zone consists of finely ground rock and clay (fault gouge), the material may have very low hydraulic conductivity compared with the host rock and form a barrier to flow. Such low-permeability faults may be apparent from significant differences in groundwater level across the fault, or appear as hydraulic boundaries in aquifer (pumping) tests. Conversely, if a fault zone consists of one or more continuous open fractures, then it may act as a conduit. Under natural conditions, evidence for such conduit faults may be seen in geophysical surveys (contrasting conductivity), perturbations in groundwater levels, or the occurrence of fault related springs and discharge zones. When the groundwater system is pumped, such as in an aquifer test or dewatering well, a conduit fault may manifest as an apparent recharge boundary (source of recharge) and/or cause anomalous drawdown in monitoring bores connected to the fault. Any enhanced permeability of a fault zone will apply to the migration of gasses as well as water. These potential effects have been investigated in this study to assess the characteristics of a typical strike-slip fault within the Stage 1 GFDA.

On a regional (or basin) scale the influence of faulting on groundwater flow depends on numerous factors including the permeability of the fault(s) and their orientation with respect to the geological strata and dominant recharge and discharge zones (Tóth, 2009). The potential regional effects of faulting include:

- compartmentalisation of the regional flow (differences in groundwater level and/or flow direction between fault-bounded blocks)
- hydraulic sheltering; where quasi-stagnant zones of ‘no-flow’ are formed
- concentration of flow within fault zones which may enhance recharge or discharge, or form conduits, particularly where there are inclined or low-angle conduit faults within or between those zones
- anisotropy – faults or joints that have a dominant orientation can impart a preferred flow direction on groundwater systems
- may enhance vertical leakage in units assumed to be regional aquitards.

Where there are numerous faults of contrasting orientation and permeability, there may be insignificant influence on groundwater flow patterns on a regional or basin scale, or that influence may be difficult to identify because at that scale, the fracture network may approximate a continuous porous medium. Rushton (2009) notes that extensive faulting is present on the Sherwood Sandstone aquifer (United Kingdom), however analysis of hydrographs indicate that most faults have little influence on overall groundwater flow.

2.3.1 Role of faults in methane migration

Gas producibility from coal seams is controlled by the interaction between the following factors: coal distribution, rank, gas content, permeability, hydrogeology, depositional environment and structural setting. The way in which faults and their associated strain zones impose variations in the permeabilities and connectivities of coal seams and the surrounding strata, greatly affects the migration or retention of gas (Boardman and Rippon 1997).

Faults can act as both sealing and open boundaries for coal seam gas reservoirs. Sealing faults occur when the capillary pressure in the fault belts is greater than the gas reservoir pressure. Sealing mechanisms include the diagenetic cementation and deformation of rocks by crushing and shearing (cataclasis) (Xiangbo et al. 2005).

The way in which coal seam gas migrates in and around faults is dependent on the characteristics and structure of the fault and the effects of faulting on the permeability of the strata with respect to groundwater and gas. Strike-slip faults, which are the focus of this investigation at the Tiedman property, are complex and show considerable variation. They can vary from near-vertical fault planes, with minor displacement, to splaying strike-slip zones with significant dip slip displacement and fault plane dips at up to 45º. Due to the complexity of many strike slip zones and their variation, it is difficult to generalise their potential attributes with respect to fluid and gas migration (Boardman and Rippon 1997). Boardman and Rippon (1997) present a conceptual diagram based on Woodcock and Fischer (1986) showing strike-slip examples. They suggest that fault overlap zone may contain greater gas concentrations due to the combination of strained ground with no through-going structure (Figure 2.5). Depending on the depth of fracturing relative to the coal seams, Boardman and Rippon (1997) suggest zones adjacent to faults may also contain significant reserves of coal seam gas.

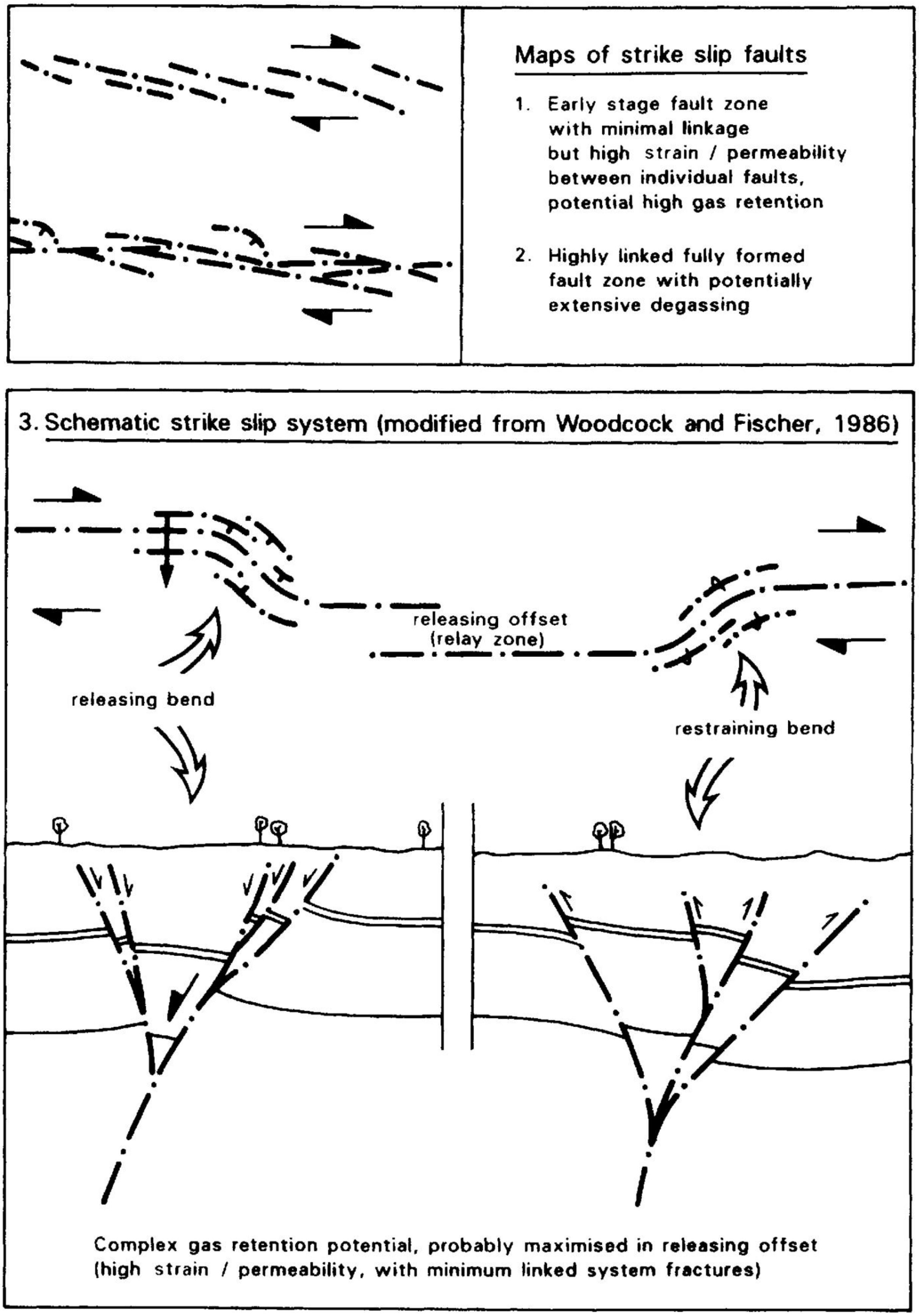


Figure 2.5 Strike slip fault examples illustrating the complex strain and permeability patterns (Woodcok & Fischer (1986) and Boardman and Rippon (1997).

2.3.2 Faulting in the Gloucester Basin

A large number of faults have been inferred to underlie the Stage 1 GFDA, many of which are not apparent at the surface or in logging of drill chips. There is currently little information concerning the hydraulic properties of these faults. The following observations have been made in previous studies:

- Pacific Power (1999, in SRK, 2010): An inferred normal fault, intersected at 325 mbgl in the Bowens Road Coal Seam of cored well PGSD3 provided a hydraulic conductivity of ~5.8×10^{-2} m/day, approximately one order of magnitude higher than those estimated for the coal seams at a similar depth (~8.6×10^{-3} – 1.2×10^{-2} m/day).
- Resource Strategies (2001) suggested that faulting locally caused compartmentalisation of groundwater flow (i.e. faults are of low permeability) (from URS, 2007, p14).
- Parsons Brinckerhoff (2010) observed that even though several monitoring bores in the Phase 2 Groundwater Investigation were located close to faults or straddle fault zones, initial data suggested that the faults do not affect the natural groundwater flow characteristics of shallow rock aquifers, interburden confining units or coal seam water bearing zones. Water quality and isotope data on the Tiedman site is less conclusive and may suggest near surface faults are enhanced recharge areas. The study concluded that faults are not major features with respect to natural groundwater flow pathways across the area.

2.3.3 Faulting and regional stress

In fractured or faulted rocks, the permeability of fracture networks and faults can be influenced by the regional stress regime (e.g. Morin and Savage, 2003), whereby fractures oriented parallel to the principal stress direction may dilate (increasing the permeability) whereas fractures oriented perpendicular to the principal stress direction are more likely to be closed (low permeability). The typically east-west principal stress direction in the Stage 1 GFDA would tend to result in closed fractures within the dominant meridional (N-S) faults and shear zones in the area.

2.4 Rainfall

The calculated mean annual rainfall for the Gloucester Basin ranges between 983.9 mm at the northern end of the basin (Gloucester Post Office, BoM Station 060015) and 1065.9 mm at the southern end of the basin (Gloucester Craven Station, BoM Station 060042). Historically, the period between July and September records the lowest monthly rainfall, while the period between January and March typically has the highest monthly rainfall.

The average actual evapotranspiration (the net transfer of water, as water vapour, to the atmosphere from both vegetated and clear land surfaces) for the Gloucester Basin is approximately 750 mm (Parsons Brinckerhoff 2013b).

2.4.1 Rainfall conditions during the investigation

Long term average monthly rainfall, actual monthly rainfall and cumulative deviation from the mean (representing discrete rainfall events as a continual trend over time) are presented in Figure 2.6. Comparison of the actual monthly rainfall and the average monthly rainfall during the period April 2011 to March 2012 indicates that actual rainfall was greater than the average rainfall, as confirmed by an upward sloping cumulative deviation trend. In contrast, the period between September 2012 and December 2012 shows a downward sloping cumulative deviation curve and thus the actual rainfall was lower than the average rainfall. Since January 2013 its again been above average.

The pumping test took place during a period of generally above average rainfall conditions whereas rainfall in the months during and following the Stratford 4 flow test was very low compared with the average monthly rainfall.

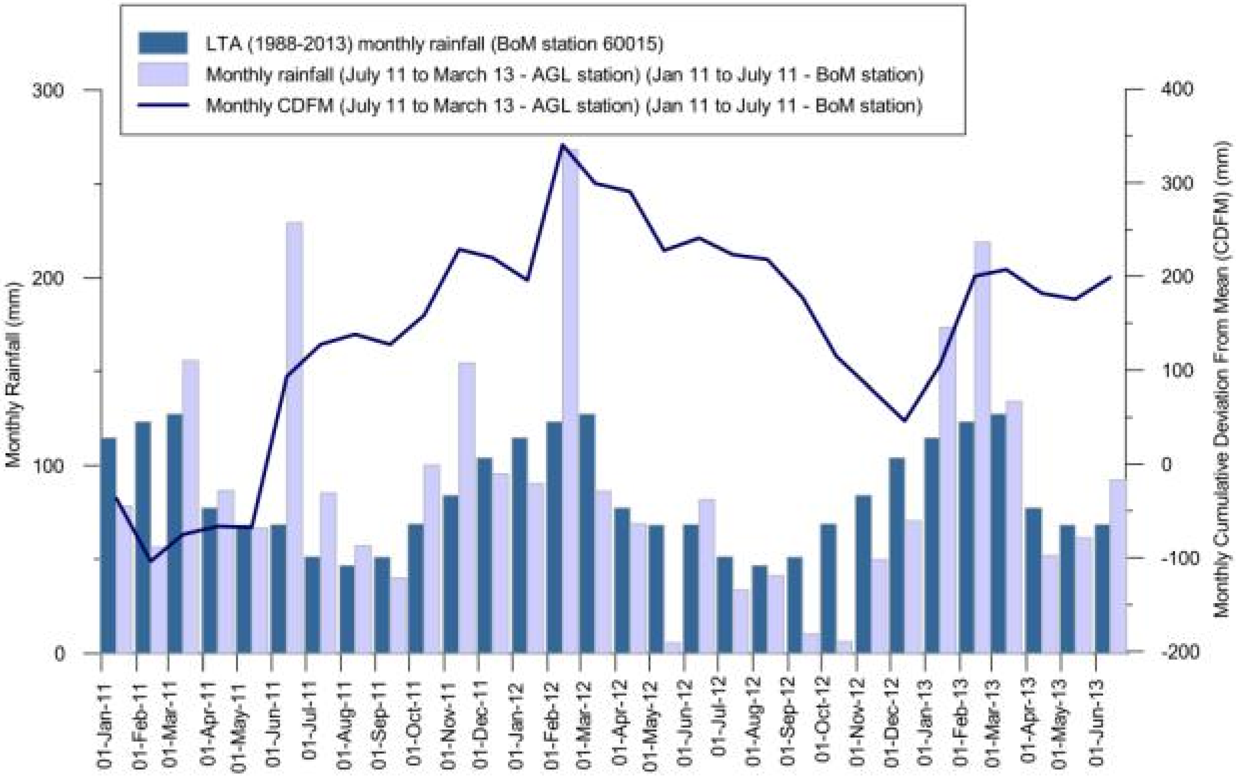


Figure 2.6 Monthly rainfall compared with monthly average rainfall at Gloucester, and the cumulative deviation from the monthly mean rainfall (CDFM)

3. Investigation methodology

3.1 Overview and rationale

Seven phases of work were carried out during the fault investigation program. The program was designed to progressively build on groundwater data gathered in previous investigations as outlined in Table 3.1.

Table 3.1 The fault investigation program

Phase	Description	Rationale	Report section
Desk-top review	Review of relevant structural interpretations of the Gloucester Basin; Review of the 2009 and 2010 3D and 2D seismic data.	To identify the target fault in the subsurface and its surface trace; to place the target fault in context of the overall basin structure	3.2
Geophysical Survey	Time Domain Electromagnetics (TEM) survey in the vicinity of the fault trace, undertaken in September 2011.	To confirm the position and extent of the fault zone in the near surface (<150 m depth) where seismic methods have poor resolution.	3.3
Drilling program	Drilling and installation of one production bore in the fault zone (TTPB) and three monitoring bores within (TTMB01), and adjacent to the fault zone (TTMB02 and TTMB03).	To expand the groundwater monitoring network to specifically monitor groundwater in an around the inferred fault zone.	3.4
Hydraulic conductivity (slug) testing	Slug testing of TTMB01, TTMB02 and TTMB03 (other bores were tested as in earlier investigations).	Measure the permeability of the rock mass in an around the inferred fault zone.	3.5.1
Pumping test	A three-day pumping test at TTPB test production bore in December 2011. Monitoring of groundwater levels and water quality at all monitoring bores in, and adjacent to the fault zone.	To assess groundwater drawdown and hydraulic character of the fault zone. To assess groundwater quality and age.	4.4
Flow test	A 29 day flow test, involving the extraction of a gas water mixture from gas well Stratford 4 (Sept-Oct 2012). Monitoring of groundwater levels and water quality at all monitoring bores in, and adjacent to the fault zone.	To assess changes in groundwater pressure, quality and age in and around the fault as a result of coal seam depressurisation at depth.	4.5
Methane isotopes	Concentration of dissolved methane in groundwater; carbon-13 ($\delta^{13}C-CH_4$) and deuterium ($\delta^{2}H-CH_4$) isotopes of dissolved methane	To determine the range in concentrations of methane in groundwater and the origin of dissolved methane.	4.5.2
Interpretation of results	Interpretation of all data and refinement of conceptual model for groundwater flow in the fault zone and in adjacent strata.	Implications for the role of faulting in groundwater flow and the potential for gas migration.	4.2 - 4.5

3.2 Review of seismic profile data and desk top data

In 2009 and 2010 AGL undertook a seismic survey to map thrust faults and normal faults across the Tiedman property and the other areas of the Stage 1 GFDA (Parsons Brinckerhoff 2012). Results of that review and analysis are incorporated into Figure 2.4, and discussed in subsequent sections. A strike-slip fault was identified as a suitable target for testing.

3.3 Time domain electromagnetics

The resolution of the vertical seismic profiles is accurate to depths of approximately 1 km; however, such acquisition techniques return poor resolution data in the top 200 m of the geological profile. Therefore Alpha Geoscience were contracted by Parsons Brinckerhoff to undertake a Time Domain Electromagnetics (TEM) survey to locate any geophysical anomalies that may better define the position of the inferred strike-slip fault zone in the near surface. Their report is provided in Appendix B.

TEM surveys focus on depths between 50 and 150 mbgl, and were appropriate for investigating the fault in the near-surface environment. It was anticipated that the fault would be detected due to anomalously high conductivity in the fault zone as a result of enhanced weathering and groundwater flow, relative to the more resistive surrounding sandstone bedrock.

The TEM survey was conducted on 28 and 29 September 2011 using a TerraTEM system. The TEM survey was carried out over the suspected fault zone and in a 250 m line along the northern boundary of the Tiedman property to provide an extended cross section from the Avon River in the west to the centre of the Tiedman property.

TEM involves a current flowing in a transmitter loop that establishes a magnetic field, which when turned off induces eddy currents to flow into electrical conductors in the ground below. Such eddy currents can set up a secondary magnetic field which can be detected by a receiver loop as a time dependant decaying voltage. The decaying field is measured by recording the voltage produced in a receiver coil at various time gates (Alpha 2011).

The raw amplitude data was processed by Alpha using Templot software. The Spiker algorithm was applied to transform the surrounding data to model conductivity with depth and profiles of modelled conductivity were generated semi perpendicular to the strike of the fault to infer apparent earth conductivities (Alpha, 2011).

The TEM amplitude data, displayed in 3D autoCAD, provided to Parsons Brinckerhoff was gridded in 3D space in GoCAD 3D geology modelling software. The amplitude data was displayed in conjunction with the seismic section Morgrani 826 provided by AGL. Bore locations, geology and screen depths were also included in the GoCAD projection.

3.4 Groundwater monitoring network

3.4.1 Site selection

In order to further characterise the hydrogeology of the fault area and to carry out the pumping and flow tests, a test production bore and three monitoring bores were constructed on the Tiedman Property (in the Stage 1 GFDA area), in addition to the existing groundwater monitoring network constructed for the Phase 2 Groundwater Investigation.

The Phase 2 Groundwater Investigation of the Stage 1 GFDA identified the possible surface trace of a steep easterly-dipping strike-slip fault evident in seismic surveys carried out by AGL in 2009 and 2010, and is the target fault for this investigation crossing the northern boundary of the Tiedman property, approximately 300 m east of the Stratford 4 gas well. The linear feature is approximately 1 km long and characterised by an elongated topographic depression with vegetation differing to the surrounding area.

During November 2011 one test production bore (Tiedman test production bore - TTPB) and two monitoring bores (Tiedman test monitoring bores - TTMB01, TTMB02) were drilled and constructed at the northern end of the Tiedman property designed on the basis of the electromagnetic and seismic survey data to intersect the fault zone and provide monitoring of groundwater levels both inside and outside the fault zone. Bore depths ranged from 90 to 200 m depth. TTPB was located to intersect the inferred fault zone with TTMB01 located along strike within the fault zone and TTMB02 perpendicular to the strike of the fault zone within the assumed zone of enhanced permeability between the S4MB nested groundwater monitoring bores and TTPB.

During April/May 2012, following the completion of the pumping test but before the commencement of the flow test, an additional off-strike groundwater monitoring bore intersecting the interburden below the fault was constructed (TTMB03).

This local network of monitoring bores associated with the TTPB production test bore was drilled to both intersect and surround the inferred fault zone and was specifically designed to assess the hydraulic characteristics of the fault.

The groundwater monitoring bore construction details (including the survey coordinates) and geological logs are included in Appendix A. Table 3.2 lists the bores monitored for the fault investigation; the location of these bores is shown in Figure 3.1.

Table 3.2 Fault investigation groundwater monitoring bore network

Bore	Monitoring network	Construction and purpose	Total depth/ Screened interval) (mbgl)	Screened lithology	Hydrostratigraphic units
TTPB #	Fault investigation	150 mm steel test production bore intersecting fault zone	90 (76 – 88)	Leloma Formation: siltstone/ sandstone	Fault zone/shallow rock
TTMB01	Fault investigation	50 mm uPVC monitoring bore intersecting fault zone	90 (76 – 88)	Deards Coal Seam, Leloma Formation: siltstone/ sandstone	Fault zone/shallow rock
TTMB02	Fault investigation	50 mm uPVC monitoring bore adjacent to fault zone	90 (76 – 88)	Deards Coal Seam, Leloma Formation: siltstone/ sandstone	Shallow rock

Bore	Monitoring network	Construction and purpose	Total depth/ Screened interval) (mbgl)	Screened lithology	Hydrostratigraphic units
TTMB03	Fault investigation	50 mm steel monitoring bore adjacent to fault zone	200 (186 – 199)	Leloma Formation: siltstone/ sandstone	Fault zone/ interburden
S4MB01	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	66 (58 – 64)	Leloma Formation: sandstone	Shallow rock
S4MB02	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	97 (89 – 95)	Leloma Formation: siltstone/sandstone	Shallow rock
S4MB03	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	170 (162 – 168)	Jilleon Formation: Cloverdale Coal Seam	Coal seam
S5MB01	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	60 (52 – 58)	Jilleon Formation: siltstone/sandstone	Shallow rock
S5MB02	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	114 (110 – 102)	Jilleon Formation: siltstone/sandstone	Shallow rock
S5MB03	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	166 (158 – 164)	Jilleon Formation: Roseville Coal Seam	Coal seam
TCMB01	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	95 (87 – 93)	Leloma Formation: siltstone/sandstone	Shallow rock
TCMB02	Phase 2 Groundwater Investigation	50 mm uPVC monitoring bore	183 (175 – 181)	Leloma Formation: siltstone/sandstone	Interburden
TCMB03	Phase 2 Groundwater Investigation	50 mm steel monitoring bore	268 (260 – 266)	Jilleon Formation: Cloverdale Coal Seam: coal & sandstone	Coal seam
TCMB04	Phase 2 Groundwater Investigation	50 mm steel monitoring bore	334.7 (327 – 333)	Jilleon Formation: Roseville Coal Seam	Coal seam
Farley bore	Private landholder bore	Unknown construction, used as a monitoring bore	unknown	unknown	Shallow rock

(1) # note that an earlier PVC lined test production bore was drilled about 5 m away but it collapsed and had to be replaced.

3.4.2 Groundwater licences and approvals

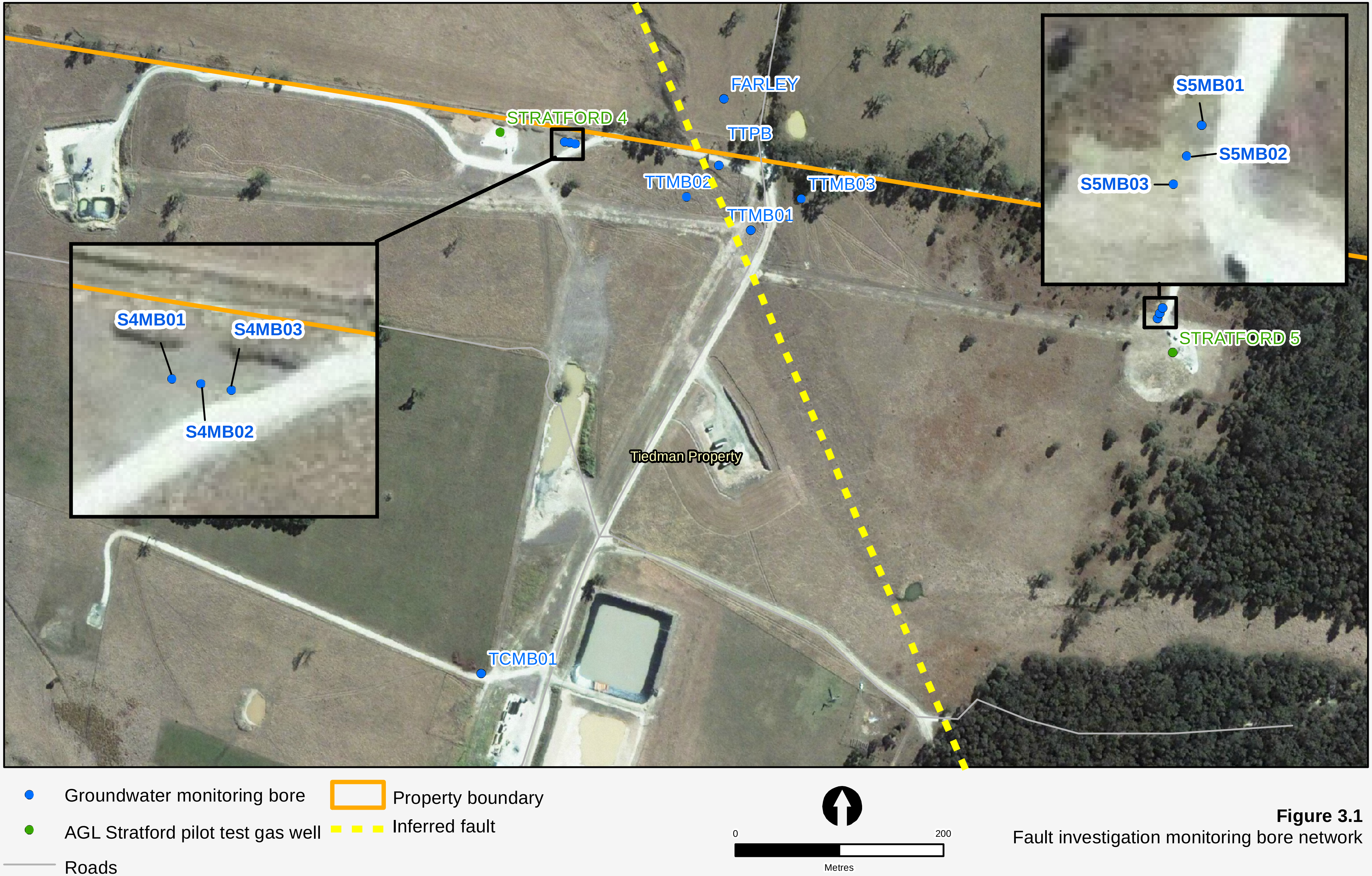
Test (monitoring bore) licences under the *Water Act 1912* were obtained by AGL prior to the groundwater monitoring bore drilling program. Drilling and completion of the bores was carried out in accordance with the NSW Office of Water (NOW) bore licence conditions and followed a detailed design and specification compliant with the:

Minimum Construction Requirements for Water Bores in Australia, Edition 2. (Land and Water Biodiversity Committee 2003).

Test bore licence (20BL172626) for the drilling and construction of test and monitoring bores were issued by NOW for Lot 85 DP 979859. Standard conditions for the construction of test and monitoring bores are attached to the licence. No other approvals were required to construct these bores. Licence details are summarised in Table 3.3. and a copy is provided in Appendix A.

Table 3.3 Fault investigation groundwater monitoring bore network

NOW Licence No.	No. of locations	Local bore ID	Site location (property)	Lot	DP	Bore type
20BL172626	3	TTMB01 TTMB02 TTMB03	Tiedman	85	979859	Monitoring bore
20BL172626	1	TTPB	Tiedman	85	979859	Test production bore



\\Apsydfil03\proj\A\AGL_Energy\2162406_GLOUCESTER_FAULT_INVESTIGATION\10_GIS\Projects\ESRI\2162406B_GIS_F005_A1.mxd // SaflianK // 19/02/2013

Figure 3.1
Fault investigation monitoring bore network

3.5 Hydraulic conductivity testing

3.5.1 Slug tests

Rising and falling head (‘slug’) tests are simple field procedures designed to calculate the approximate hydraulic conductivities of water bearing formations adjacent to monitoring bore screens. A falling head test is achieved by introducing a ‘slug’ to displace the water column within the monitoring bore causing the water level to instantaneously rise and flow from the bore into the aquifer via the well screen. A rising head test is the opposite, where a volume of water is instantaneously removed from the groundwater monitoring bore, causing the water level to fall, drawing water into the bore from the aquifer. Forcing the water out of and into the monitoring bore sometimes produces slightly different results and therefore by comparing the results for each test a degree of confidence in the accuracy of the test can be achieved.

Slug tests were carried out using the following general method:

- At the commencement of the testing, the standing water level (SWL) of the groundwater were measured from a fixed reference point at the top of casing and the datalogger programmed to either 1 or 5 second intervals to measure the groundwater level changes.
- A falling head test was the first of the three tests to be performed. The slug was placed rapidly into the water column. The change in the water level was recorded manually and electronically as the water level recovered to the SWL.
- After the water level had returned to the SWL, a rising head test was performed by removing the slug. Again the change in water level was recorded manually and electronically as it recovered to the SWL.
- Finally, a second falling head test was performed.

The slug consists of a sealed concrete filled conjugate tube (1.6 m long) used to displace the water in the groundwater monitoring bores. Hydraulic conductivity testing was undertaken at the Tiedman test monitoring bores TTMB01 and TMB02 during November 2011, and at TTMB03 during June 2012. Slug tests were carried out at the groundwater monitoring bores comprising the existing monitoring network in April 2011 as part of the Phase 2 Groundwater Investigation (Parsons Brinkerhoff 2012).

Test data were processed and analysed using the appropriate Bouwer and Rice (Bouwer 1989), or Butler (1988) method with AQTESOLV Version 4.5. Results are presented in Appendix C as estimates of hydraulic conductivity (as m/day) for the bores tested.

3.5.2 Pumping test of fault zone

3.5.2.1 Methodology

A three day, constant rate pumping test was carried out at TTPB, on the Tiedman property, in December 2011. The pumping test aimed to stress the fault zone and to assess the connection between the fault zone, and the surrounding aquifer and coal seam water bearing zones. During the pumping test and the recovery period the groundwater level response was monitored in the fourteen bores comprising the fault monitoring network (see Table 3.2 and Figure 3.1).

Groundwater level monitoring during the drawdown and recovery phase of the pumping test was achieved using Solinst™ pressure transducers (dataloggers) suspended from a galvanised steel wire in the water column. Dataloggers were programmed to record a groundwater level (or standing water level (SWL)) measurement at intervals of between 20 seconds and 2 hours, depending on the predicted rate of drawdown. To calibrate the level recorded by the dataloggers, manual measurements were recorded daily using an electronic dip meter. A barometric logger installed above the water table at S4MB01 records changes in atmospheric pressure. Data from this logger are used to correct for the effects of changing barometric pressure on groundwater levels.

An electro-submersible Grundfos pump (SP 3A) was used for the pumping test, and was installed by Gloucester Rural Supplies (CRT). The pump intake was set at 75.7 mbgl, 1.15 m above the top of the screen. The flow rate was monitored with a 50 mm ISO 40-64 flow meter, also installed by CRT. The produced water was pumped via a PVC conduit to the Tiedman south dam, which is used specifically for the storage of produced water.

A step drawdown test was initially carried out at TTPB to determine a sustainable pumping rate for the constant rate test. The step drawdown test was carried out on 19 December 2011 and involved three, 100 minute steps of increasing flow rate: 0.5 L/s, 0.7 L/s and 0.9 L/s. While the aim is to keep the rates constant, in practice, small changes in flow rate in the order of +/- 10% can occur.

Following 100% water level recovery from the step test, the constant rate test commenced at 7 am on 20 December 2011, pumping at a constant rate of 0.8 L/s for a planned 72 hours. However, after 2.4 days of pumping, the pumping rate had to be slightly reduced to approximately 0.77 L/s to avoid the water level dropping below the pump inlet. The unexpected increase in drawdown implies a non-linear increase in s/Q (where s is drawdown and Q is pumping rate) which may be due to dewatering of a high-yielding fracture during pumping. The pump was switched off at 7 am on 23 December 2011 and the 'recovery' phase of the pumping test commenced.

Drawdown and recovery data collected during the pumping tests were analysed qualitatively, using standard graphical approaches, to identify groundwater system characteristics and hydraulic boundaries, and also quantitatively to determine key hydraulic parameters (e.g. permeability and storage coefficients.

3.5.2.2 Pumping test groundwater quality sampling

Groundwater quality samples were collected from TTPB and were analysed to assess the characteristics of the groundwater and to monitor any changes as the pumping test progressed. Groundwater samples were collected in a rinsed bucket from a discharge tap at the headworks.

During the second step of the step test, and half an hour before the end of the pumping test, groundwater samples were collected for laboratory analysis. The analysis of groundwater samples collected at the beginning and end of pumping allows for a temporal comparison of the results and thus further insight into the connectivity of hydrogeological environment. The groundwater samples collected in the field were analysed for a broad chemical suite detailed in Table 3.4.

Table 3.4 Laboratory chemical and isotope analytical suite

Category	Parameters	
Field parameters	Electrical conductivity pH Total dissolved solids	Temperature Oxidation reduction potential Dissolved oxygen
Major ions	*Cations* calcium magnesium sodium potassium	*Anions* chloride bicarbonate sulphate dissolved silica alkalinity
Metals and minor/trace elements	aluminium arsenic barium boron beryllium bromine cadmium cobalt copper iron	manganese molybdenum nickel lead selenium strontium uranium vanadium zinc
Nutrients	ammonia phosphorus (total) phosphorus (reactive)	nitrate nitrite Total organic carbon (TOC)
Hydrocarbons	Phenol compounds Polycyclic aromatic hydrocarbons (PAH)	Total petroleum hydrocarbons (TPH) Benzene, toluene, ethyl benzene and xylenes (BTEX)
Dissolved gases	Methane	
Isotopes	oxygen-18 deuterium $\delta^{13}C\text{-}CH_4$ and $\delta^{2}H\text{-}CH_4$	Radiocarbon (^{13}C and ^{14}C) Tritium

Groundwater samples for laboratory analysis were collected in the sample bottles specified by the laboratory, with appropriate preservation when required. Samples undergoing dissolved metal analysis were filtered through 0.45 µm filters in the field prior to collection.

Samples were sent to the following laboratories under appropriate chain-of-custody protocols (documentation and laboratory results are provided in Appendix F, G and H).

- Australian Laboratory Service (ALS) Environmental Pty Ltd, Smithfield, Sydney – chemistry analysis. NATA certified laboratory (Appendix F).
- GNS Stable Isotope Laboratory, Lower Hutt, New Zealand – oxygen-18 and deuterium analysis (Appendix G).
- Rafter Radiocarbon Laboratory, Lower Hutt, New Zealand – carbon-13 and carbon-14 analysis (Appendix H).

- UC Davis Stable Isotope Facility, California, United States – carbon-13 of DIC, carbon-13 of methane and deuterium of methane (Appendix I).
- ANSTO – Tritium in groundwater for determination of groundwater age (Appendix J).

The groundwater quality results have been compared against the ANZECC (2000) guidelines for freshwater ecosystems (south-east Australia – lowland rivers) as the rivers are the ultimate receiving waters for both surface water runoff and groundwater discharge. However, these water guidelines are often naturally exceeded in catchments with rocks deposited in marine environments, hence they are only guidelines and not strict criteria that should be used to evaluate individual results.

The laboratories conduct their own internal QA/QC program to assess the repeatability of the analytical procedures and instrument accuracy. These programs include analysis of laboratory sample duplicates, spike samples, certified reference standards, surrogate standards/spikes and laboratory blanks.

3.5.3 Flow test adjacent to fault zone

A 29 day flow test was conducted at gas production well Stratford 4 in September and October 2012, which is approximately 300 m due west of TTPB and west of the inferred strike-slip fault. The groundwater level response was monitored in all nearby monitoring bores to assess the impact of depressurising the deep coal seams intersected by Stratford 4.

Prior to the commencement of the flow test an addendum to the 2007 Stratford Pilot testing REF was approved. AGL has an (irrigation and industrial) bore licence for Stratford 4 (20BL172557) issued under the Water Act (1912).

AGL was responsible for facilitating the flow test, this involved setting up, installing and testing the: downhole pump, headworks, gas/water separator, pipework and flare controls, and this occurred in August 2012. The pump intake was 788 mbgl. Parsons Brinckerhoff undertook the water level and water quality monitoring.

Stratford 4 was constructed in October 2007 to a total depth of 846.3 m, with a 200 mm ID production casing. A total of 29 m of casing was perforated over 10 intervals to intersect coal seams (including the Bowens Road, Glenview, Avon and Triple Coal Seams) between 515 to 739 mbgl (Lucas Energy 2008).

Before the flow test could begin Stratford 4 had to be ‘killed’ (where kill mud, a relatively heavy fluid, is pumped down the well to supress the pressure of formation fluids) and the gas purged. Once the produced gas/water mixture had flown through the separator the gas was flared in the flare tank while the produced water flowed, via an inline pipe, to the Tiedman North dam. Two EC in line dataloggers were used during the test, one was installed in the headworks at the discharge line and the second also in the headworks between the separator and water gathering lines. The EC dataloggers recorded a salinity measurement hourly, these data are used to monitor changes in salinity and thus infer the extent of the dewatering of coal seams.

The flow test at Stratford 4 commenced on 4 September 2012, however, the gas well was shut down the following day due to high bush fire danger. The test recommenced on 11 September 2012; Stratford 4 was pumped for 29 days until 9 October 2012. The recovery phase therefore commenced on 9 October 2012.

3.5.3.1 Flow test groundwater quality sampling

A baseline sampling event, prior to the commencement of the flow test, and a recovery sampling event, during the recovery phase of the flow test, was undertaken at the dedicated groundwater monitoring bores to assess possible changes to groundwater quality. Baseline sampling was undertaken during June, July and August 2012, while the recovery sampling was undertaken on 15 and 16 October 2012 (4/5 days after shutting down the flow test).

Groundwater samples were collected using a variety of low flow and no-purge techniques, including: micro-purge™, snap sampler and a discrete depth sampler (double check bailer). The micro-purge™ and snap sampler systems allow groundwater to be drawn into the pump intake directly from the screened portion of the aquifer, while the double check bailer 'grabs' a sample from the screen section. Low flow sampling techniques collect a water sample from the screen interval and thus eliminate the need to purge relatively large volumes of groundwater from the sampled bores. In addition, low flow sampling techniques are preferable as the hydrogeological units sampled (shallow rock, interburden and coal seams) have relatively low hydrologic conductivities and these methods are also preferable for sampling gases.

In addition to the baseline and recovery groundwater sampling programs, samples of produced water were collected from Stratford 4 on days 6, 15 and 28 of the flow test. The produced water samples were collected in a rinsed bucket from a tap installed after the gas/water separator.

As with the pumping test, the analysis of groundwater samples collected before, during and after the flow test allows for a temporal comparison of the results and thus further insight into the vertical migration of groundwater and the possible connectivity of hydrogeological environment. The analytical suite, laboratories used and the laboratory QA program undertaken for the flow test were the same as the pumping test, with the addition of the following dissolved gas analytes: ethene, ethane, propene, butane, and tritium (Appendix I).

4. Investigation results

4.1 Definition of the fault

The Phase 2 Groundwater Investigation of the Stage 1 GFDA identified the possible surface trace of a steep easterly-dipping strike-slip fault evident in seismic surveys carried out by AGL in 2009 and 2010, and is the target fault for this investigation crossing the northern boundary of the Tiedman property, approximately 300 m east of the Stratford 4 gas well. The linear feature is approximately 1 km long and characterised by an elongated topographic depression with vegetation differing to the surrounding area (Figure 3.1).

The resolution of the seismic surveys is poor in the upper 200 m, however apparent displacements in some key reflectors suggests that the fault splays in to several branches within a broad ‘splinter zone’ in the upper 200 to 250 m (Figure 4.1). In order to better define the fault zone in the near-surface, an electromagnetic (TEM) survey was carried out. The results of that survey (Appendix B) indicate that there is a distinct zone of enhanced conductivity corresponding with, but offset slightly to the west of, the apparent fault surface trace. The anomaly is consistent with enhanced weathering and possibly also the presence of groundwater associated with a fault or shear zone (Figure 4.1 and also Appendix B). The TEM survey also identified anomalous zones of conductivity to the west of the S4 monitoring bores that may correspond to enhanced weathering associated with other mapped faults and shears (Figure 4.2). The zone of red and yellow on Figure 4.2 corresponds to high hydraulic conductivity associated with the fault zone, the blue and green colouring corresponds to a zone of lower hydraulic conductivity.

The test production bore and monitoring bores for the fault investigation were designed on the basis of the electromagnetic and seismic survey data to intersect the fault zone and provide monitoring of groundwater levels both inside and outside the fault zone.

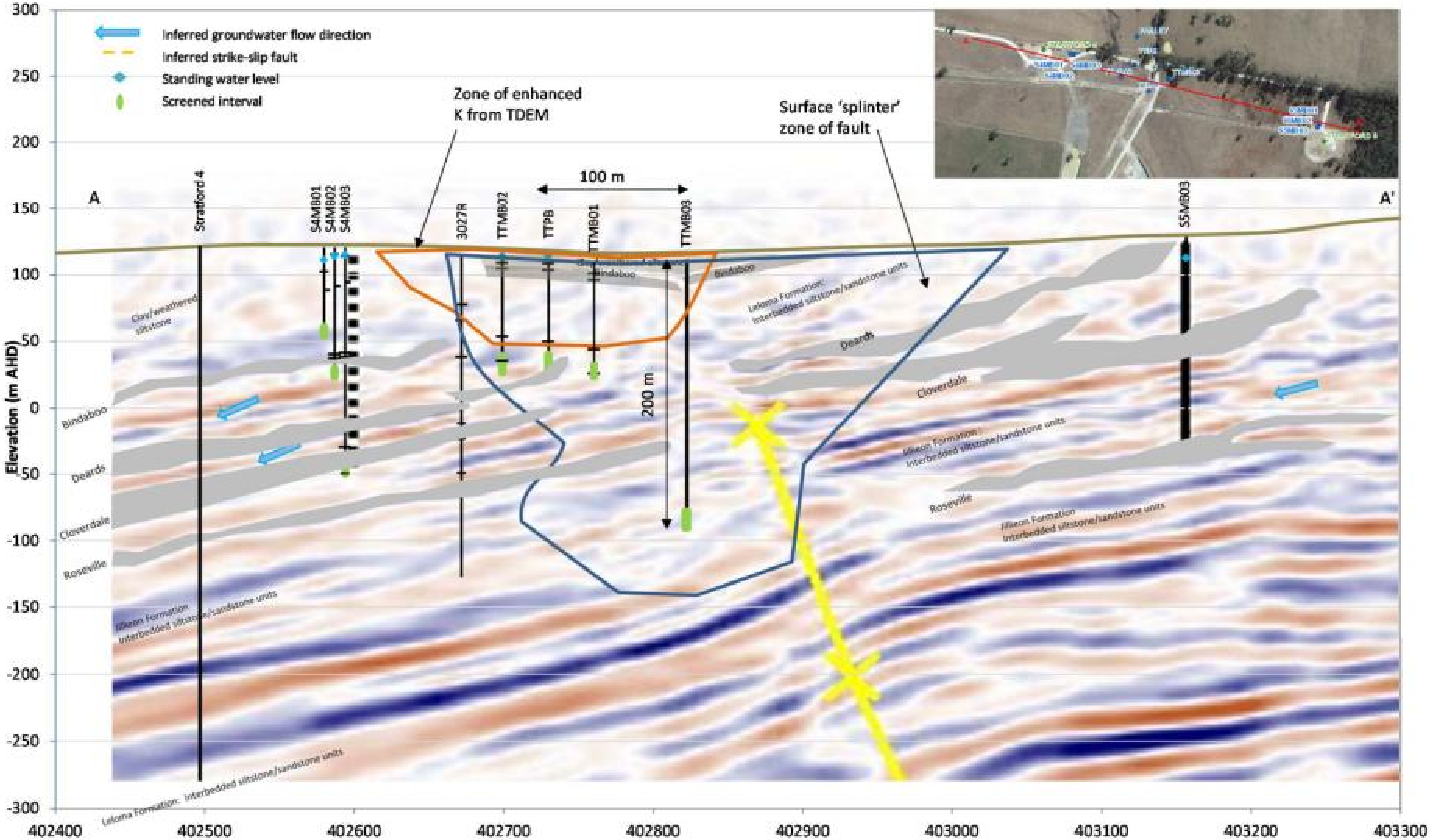
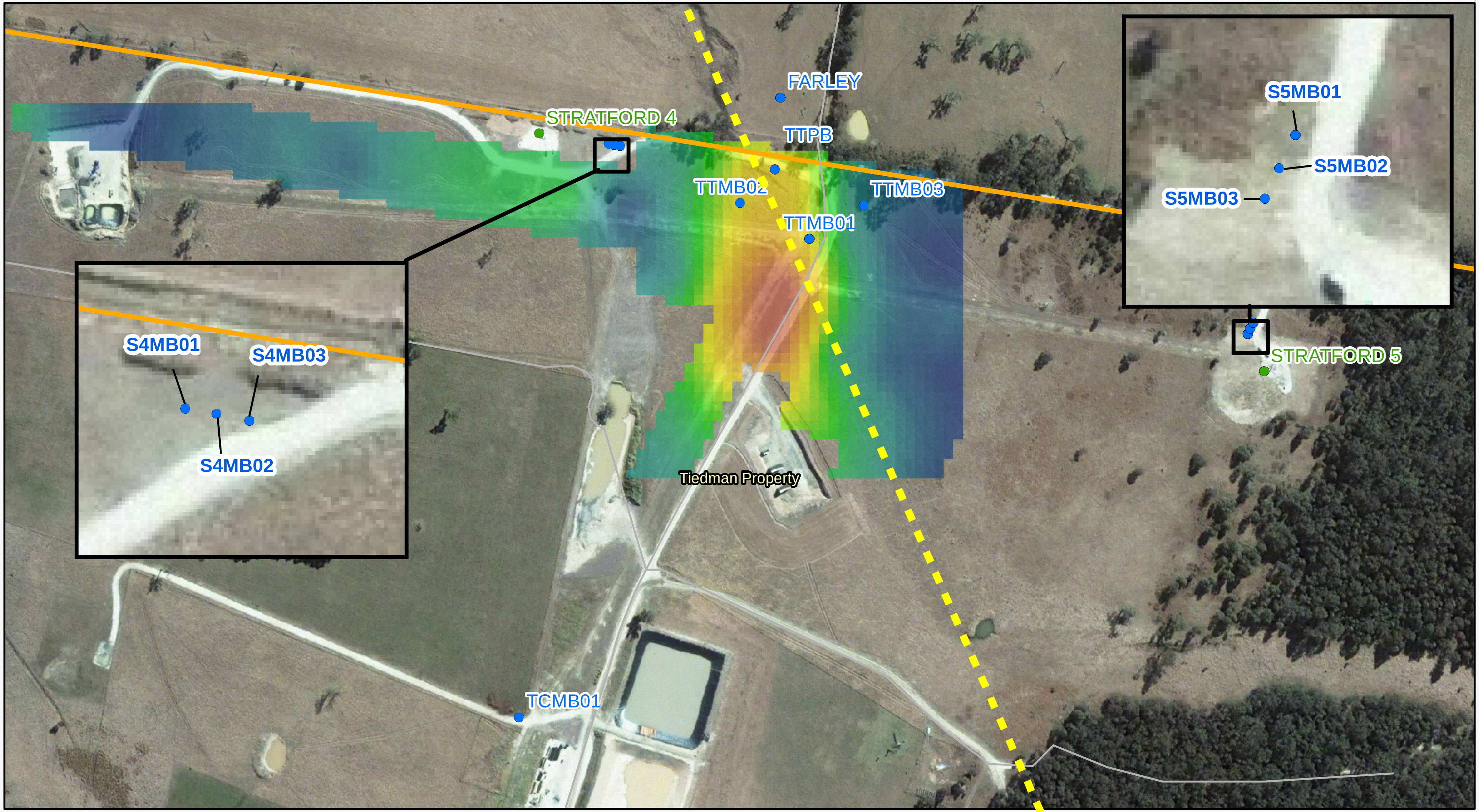


Figure 4.1 Cross-section (E–W), perpendicular to the fault zone, showing bore locations and geophysical interpretations



Groundwater monitoring bore
AGL Stratford pilot test gas well
Roads
Property boundary
Inferred fault
Channel 23 (approx 30m BGL) Amplitude (uV/Amp)
High : 1817.74
Low : 586.287

0 200
Metres

Figure 4.2
TEM amplitude Channel 23
(approximately 30m BGL)

4.2 Water-bearing horizons from drilling observations

Observations of water make during drilling give some indication of where water bearing fractures or shear zones occur at depth. The following observations were made during drilling of bores into and adjacent to the inferred fault zone:

- In all four bores (TTPB, TTMB01, TTMB02 and TTMB03), the first significant groundwater make occurred at approximately 60 m depth (~1 L/s) and the water make gradually increased to ~2 L/s between 60 and 90 mbgl.
- TTMB01 was an exception with slightly higher water makes of 2.5 L/s at 60 m depth increasing to 3.3 L/s at 90 mbgl.
- Bore logs include details of the water cuts at 6 m intervals (Appendix A). The test production bore and monitoring bores were designed to target the most productive water bearing zones, which are assumed to represent water-bearing fractures.

4.3 In situ permeability (slug tests)

Falling and rising head slug tests were conducted at monitoring bores TTMB01, TTMB02 and TTMB03 to estimate the horizontal hydraulic conductivity of each of the screened water bearing zones. Test results were analysed in AQTESOLV Version 4.5 using the Bouwer and Rice (Bouwer, 1989) or the Butler method (Butler, 1998). Results are presented as estimates of hydraulic conductivity (m/d)) in Table 4.1.

Table 4.1 Hydraulic conductivity results from slug tests

Monitoring bore	Screened section (mbgl)	Screened lithology	Estimated hydraulic conductivity (m/d)
TTMB01	76 – 88 (12 m)	Deards Coal Seam/Leloma Formation: siltstone/sandstone (inferred fault zone)	2.4×10^{-3}
TTMB02	76 – 88 (12 m)	Deards Coal Seam/Leloma Formation: siltstone/sandstone	2.5×10^{-3}
TTMB03	187 - 199 (12 m)	Leloma Formation: siltstone/sandstone (inferred fault zone)	3.5×10^{-3}
S4MB01*	58 – 64 (6m)	Leloma Formation: siltstone/sandstone	4×10^{-5}
S4MB02*	89 – 95 (6 m)	Leloma Formation: siltstone/sandstone	5×10^{-3}
S4MB03*	162 – 168 (6 m)	Jilleon formation: Cloverdale Coal Seam	0.01
S5MB01*	52 – 58 (6 m)	Jilleon formation: siltstone/sandstone	2×10^{-6}
S5MB02*	100 – 112 (12 m)	Jilleon formation: siltstone/sandstone	7.9×10^{-4}
S5MB03*	158 – 164 (6 m)	Jilleon formation: Roseville Coal Seam	0.01
TCMB01	87 – 93 (6 m)	Leloma Formation: siltstone/sandstone	2.8×10^{-3}
TCMB02	175 – 181 (6 m)	Leloma Formation: siltstone/sandstone	1.1×10^{-4}
TCMB03	260 – 266 (6 m)	Jilleon Formation: Cloverdale Coal Seam: coal and sandstone	1.6×10^{-3}

Monitoring bore	Screened section (mbgl)	Screened lithology	Estimated hydraulic conductivity (m/d)
TCMB04	327.3 – 333.3 (6 m)	Jilleon Formation: Roseville Coal Seam	2.3 x 10^{-3}

(1) * Results obtained from the Phase 2 Groundwater Investigation (Parsons Brinckerhoff, 2012).

Appendix C includes worksheets for each analysis, with details and a graphical fit for each of the measurements.

The slug test results indicate that shallow rock (comprising siltstone, sandstone and some coal) is heterogeneous with a hydraulic conductivity ranging over three orders of magnitude (2 x 10-6 to 5 x 10-3 m/d) (Table 4.1). The monitoring bores screened specifically across coal seams show higher hydraulic conductivity (10-2 m/d) (Table 4.1) suggesting these form water bearing zones within relatively less permeable interburden.

It is important to note that bores screened within the inferred fault zone (TTMB01, TTBM02 and TTMB03) yield values of hydraulic conductivity that are closely similar to one another (~10-3 m/d), but are within the range (albeit at the higher end) of values obtained from bores outside the inferred fault zone that are screened within the shallow interburden.

4.4 Pumping test results

Based on the results of the step-drawdown test, the 72-hour constant rate test was carried out at TTPB at a flow rate of 0.77 - 0.8 L/s. Water levels were monitored in the pumping bore and all monitoring bores using automated dataloggers for the duration of the test, and following the test to observe recovery of groundwater levels. Observations of groundwater drawdown are presented below using standard graphical methods to draw conclusions relating to the hydraulic characteristics of the shallow fault zone.

4.4.1 Drawdown and recovery in the pumping bore

Groundwater drawdown at the test production bore, TTPB, during the pumping test is shown in Figure 4.3 (drawdown versus linear time) and Figure 4.4 (log-linear plot). Despite small fluctuations in the pumping rate, it can be assumed to be more or less constant for the duration of the test. The total water level drawdown in TTPB at the end of the three-day test was 72.04 m. After pumping ceased the groundwater level in TTPB recovered quickly, with 97% recovery after 72 hours. This implies some additional recharge during recovery, most probably due to the rainfall towards the end of the test.

The log-linear drawdown-time plot (Figure 4.4) shows a sinuous, rapid drawdown phase to approximately 100 minutes during which bore storage effects are evident. After that time, drawdown stabilised at a steady drawdown rate of approximately 5.5 m per log cycle. Despite minor fluctuations, which may be due to an uneven pumping rate, there is no evidence that the cone of drawdown intersected a significant hydraulic barrier or recharge boundary within the test period. A hydraulic barrier (such as a fault boundary) would be evident from a steepening of the drawdown gradient whereas a recharge boundary (e.g. stream) or leakage from an adjacent aquifer would cause the drawdown to flatten or plateau.

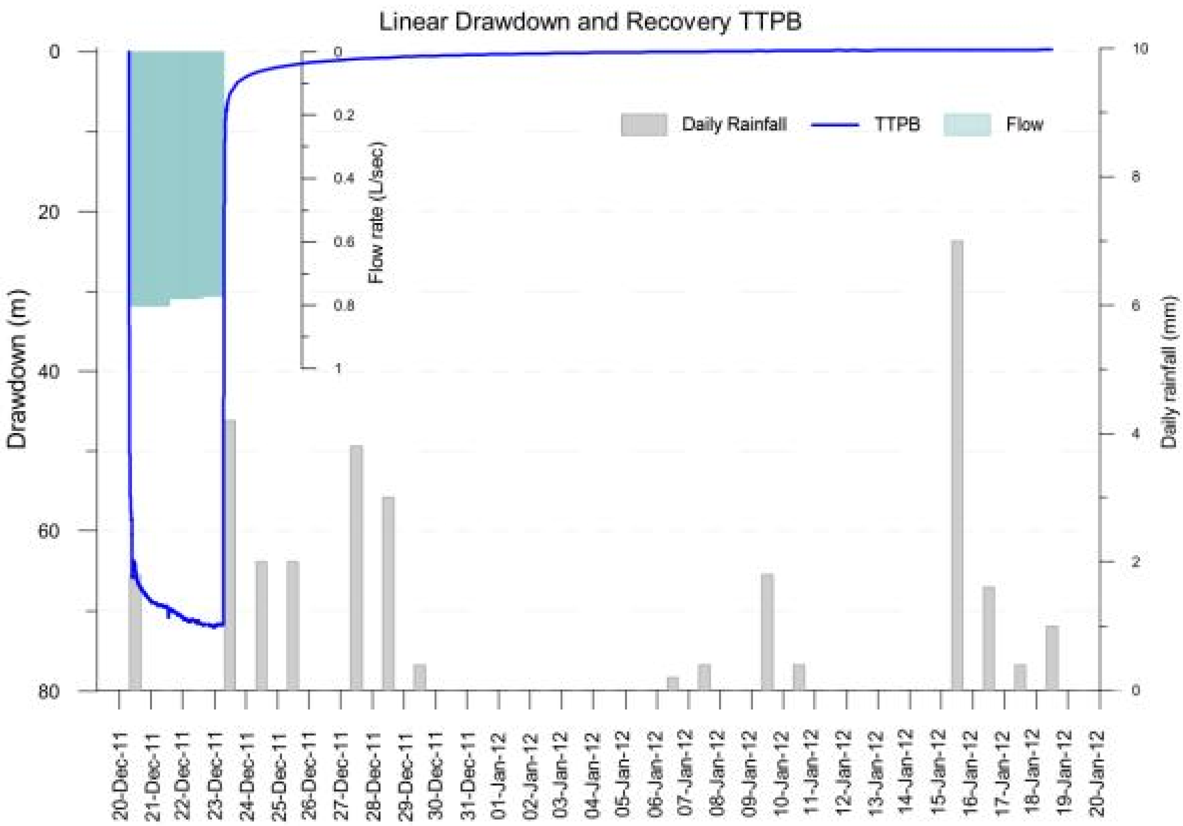


Figure 4.3 Linear plot of drawdown in TTPB versus time (minutes)

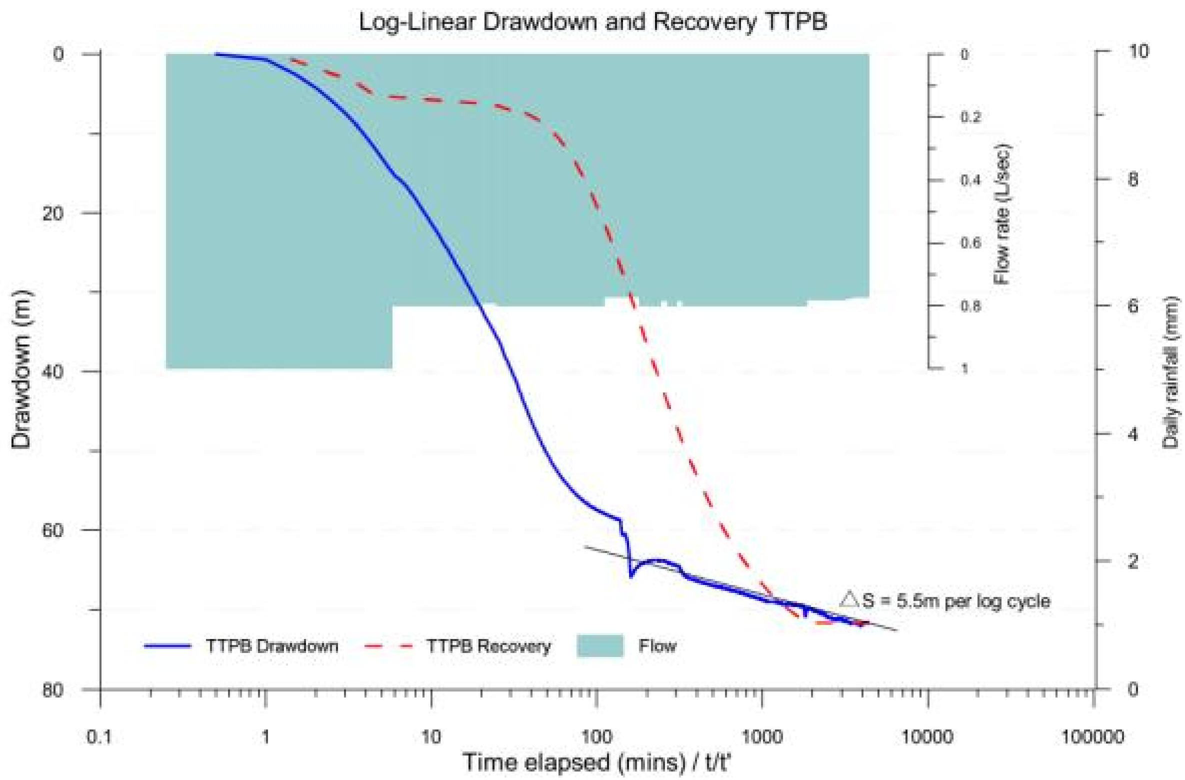


Figure 4.4 Log-linear plot of drawdown in TTPB versus time (minutes) and residual drawdown in TTPB versus t/t'

4.4.2 Drawdown in monitoring bores

Groundwater drawdown at monitoring bores during the pumping test is shown in Figure 4.5 (drawdown versus linear time) and Figure 4.6 (log-linear plot). Drawdown at all bores is also summarised in Table 4.2.

Significant drawdown due to pumping was observed at seven of the eleven monitoring bores monitored during the test with the largest drawdown observed at TTMB02 (7.4 m after 72 hours). No significant drawdown was observed at the S5 series monitoring bores located ~450 m to the east of the pumping bore, nor at S4MB01, the shallowest of the S4 series bores located ~150 m west of the pumping bore. This implies that the cone of drawdown did not extend to these locations beyond the fault zone due to the limited hydraulic connection (low permeability) of the respective formations.

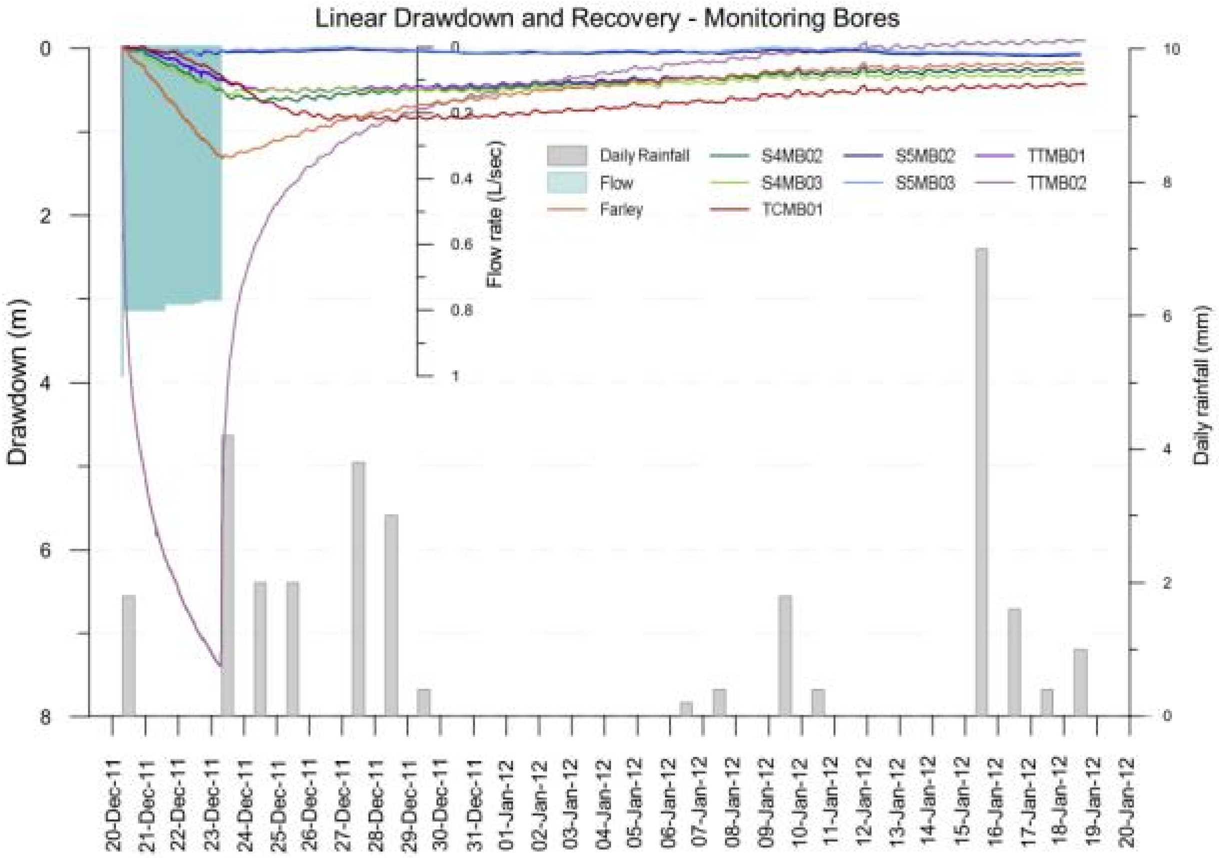


Figure 4.5 Linear plot of drawdown versus time at monitoring bores

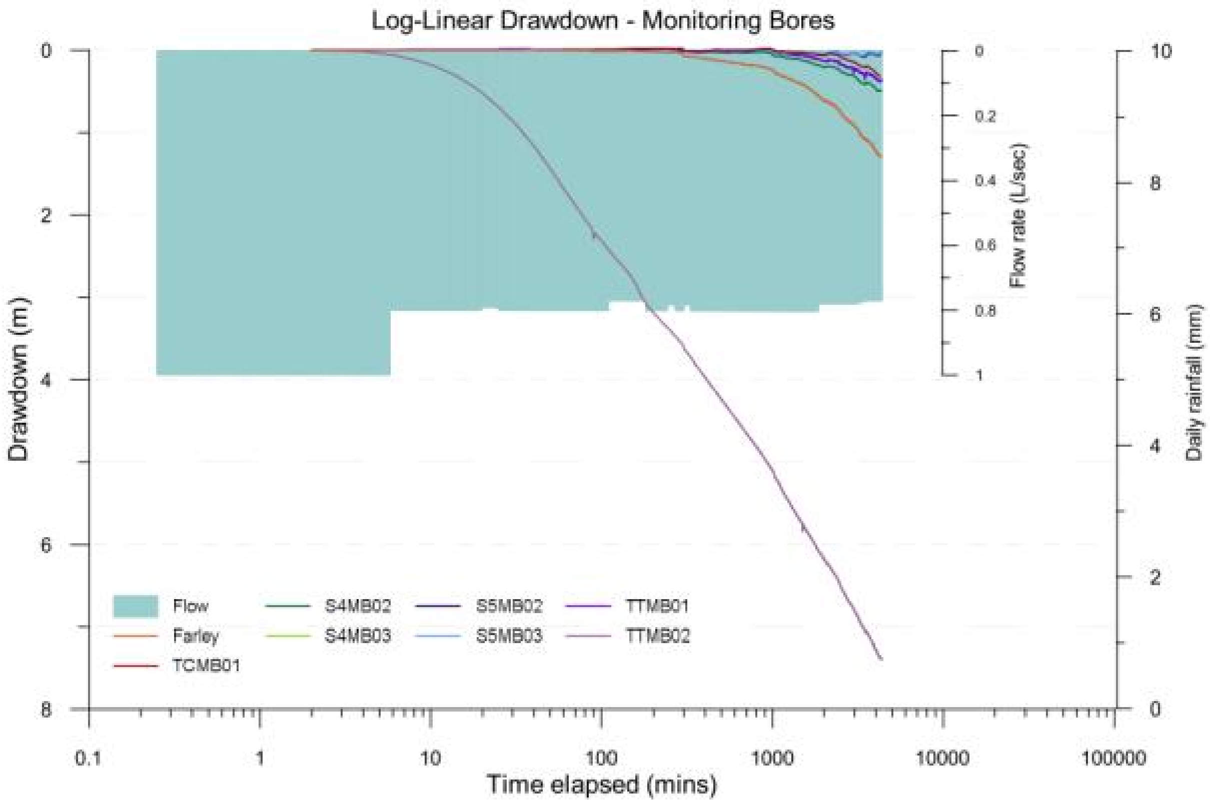


Figure 4.6 Log-linear plot of drawdown versus time at monitoring bores

Table 4.2 Summary of pumping test drawdown and recovery

Bore	Screened formation	Distance from TTPB (m)	SWL prior to test (mAHD)	Drawdown after 72 hours pumping (m)	Maximum drawdown (m)	Time to max drawdown since start of pumping (days)	Recovery after 72 hours
TTPB	Deards Coal Seam/ Leloma Formation	0	113.01	72.04	72.04	2.71	98.2%
TTMB01	Deards Coal Seam/ Leloma Formation	69.1	115.14	0.37	0.54	5.38	8%
TTMB02	Deards Coal Seam/ Leloma Formation	43.1	113.98	7.39	7.39	3.0	82%
TTMB03*	Leloma Formation	Not constructed for this test					
S4MB01	Leloma Formation	149.8	111.43	No response to pumping			
S4MB02	Leloma Formation	144.9	114.01	0.49	0.63	4.21	11%
S4MB03	Cloverdale Coal Seam	139.6	114.90	0.47	0.56	3.29	14%
S5MB01	Jilleon Formation	447.4	110.70	No response to pumping			

Bore	Screened formation	Distance from TTPB (m)	SWL prior to test (mAHD)	Drawdown after 72 hours pumping (m)	Maximum drawdown (m)	Time to max drawdown since start of pumping (days)	Recovery after 72 hours
S5MB02	Jilleon Formation	446.7	112.56	No response to pumping			
S5MB03	Roseville Coal Seam	446.1	112.70	No response to pumping			
TCMB01	Leloma Formation	539.1	113.95	0.32	0.87	4.67	0.8%
Farley bore	Unknown	63.8	114.28	1.29	1.31	3.05	29%

(1) * Not constructed at the time of the pumping tests.

In an ideal aquifer that is isotropic and of large extent, a cone of drawdown should expand symmetrically around the pumping bore such that monitoring bores will register drawdown in the closest bores first, followed by bores further out. Both the magnitude of the drawdown and the delay in the start of drawdown at each bore is related to the transmissivity and storage characteristics of the aquifer. If the aquifer is isotropic, then the magnitude of drawdown at each bore should be inversely proportional to the log of the distance from the pumping well at any point in time. That is, the drawdown in all bores at the end of the test should plot along a straight line against the log of radius from the pumping bore. Any deviation from this condition implies that the aquifer is heterogeneous or anisotropic with respect to transmissivity and/or storativity.

A plot of drawdown at the end of the pumping test versus the log of distance clearly shows such anisotropic conditions exist in the vicinity of the fault (Figure 4.7). This is further illustrated in Figure 4.8 in which the drawdown at each monitoring bore is shown on a map of the site and Figure 4.9 on a conceptual cross section.

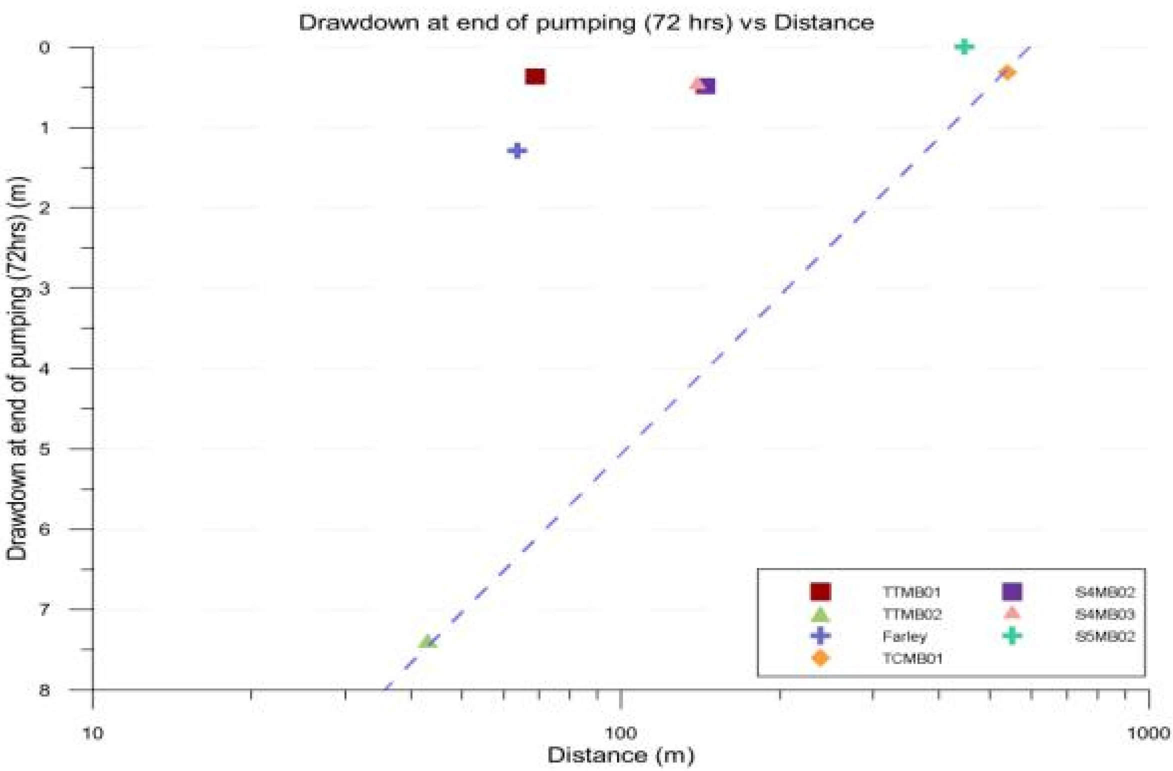
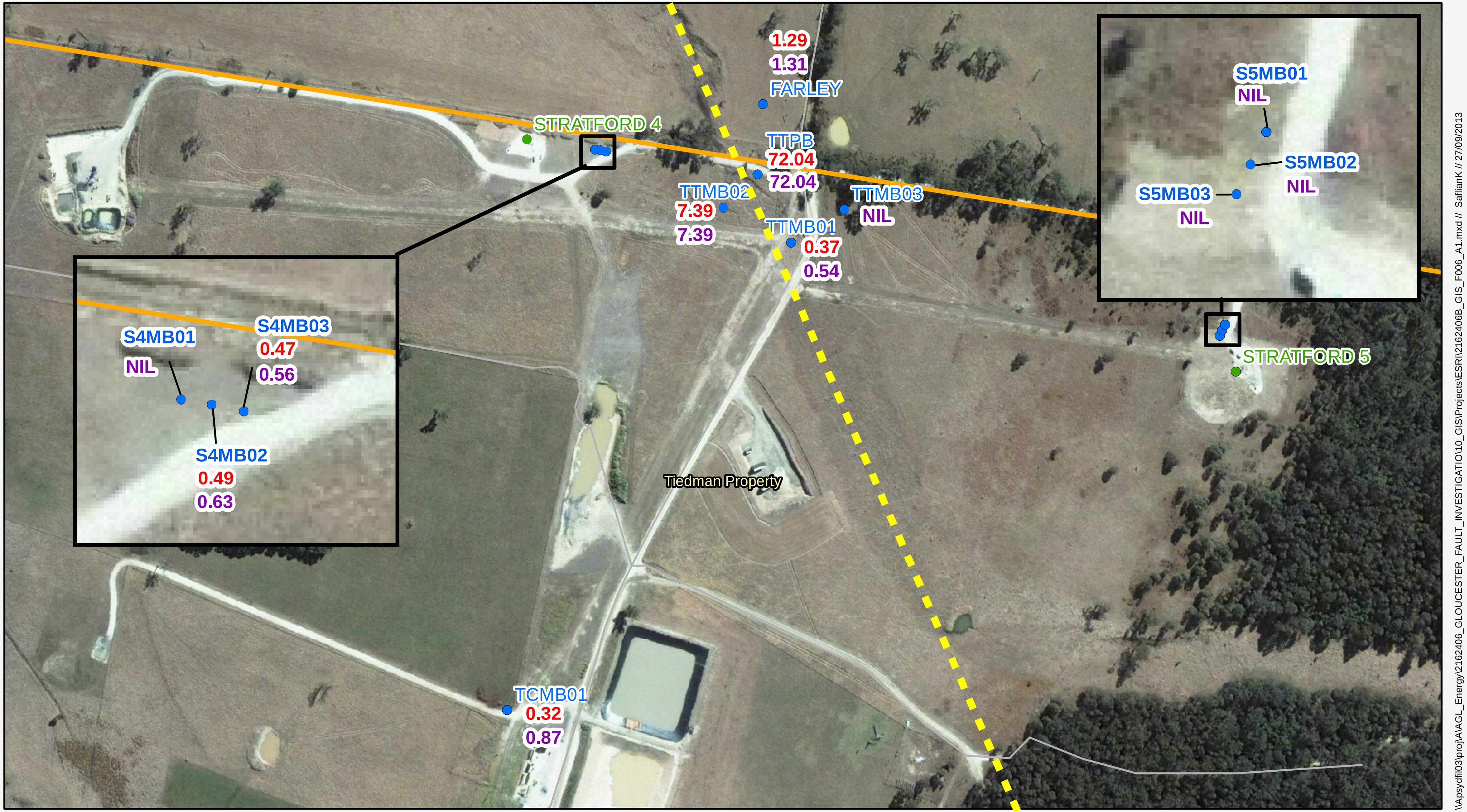


Figure 4.7 Plot of drawdown versus log distance from the pumping bore (TTPB). The dotted line represents the expected log-linear distance-drawdown relationship.



Groundwater monitoring bore
AGL Stratford pilot test gas well
Roads
Property boundary
Inferred fault
0.32 Drawdown at end of pumping (72 hrs) (m)
0.32 Maximum drawdown (m)

0 200
Metres

Figure 4.8
Drawdown after 72 hours and maximum drawdown at each monitoring bore

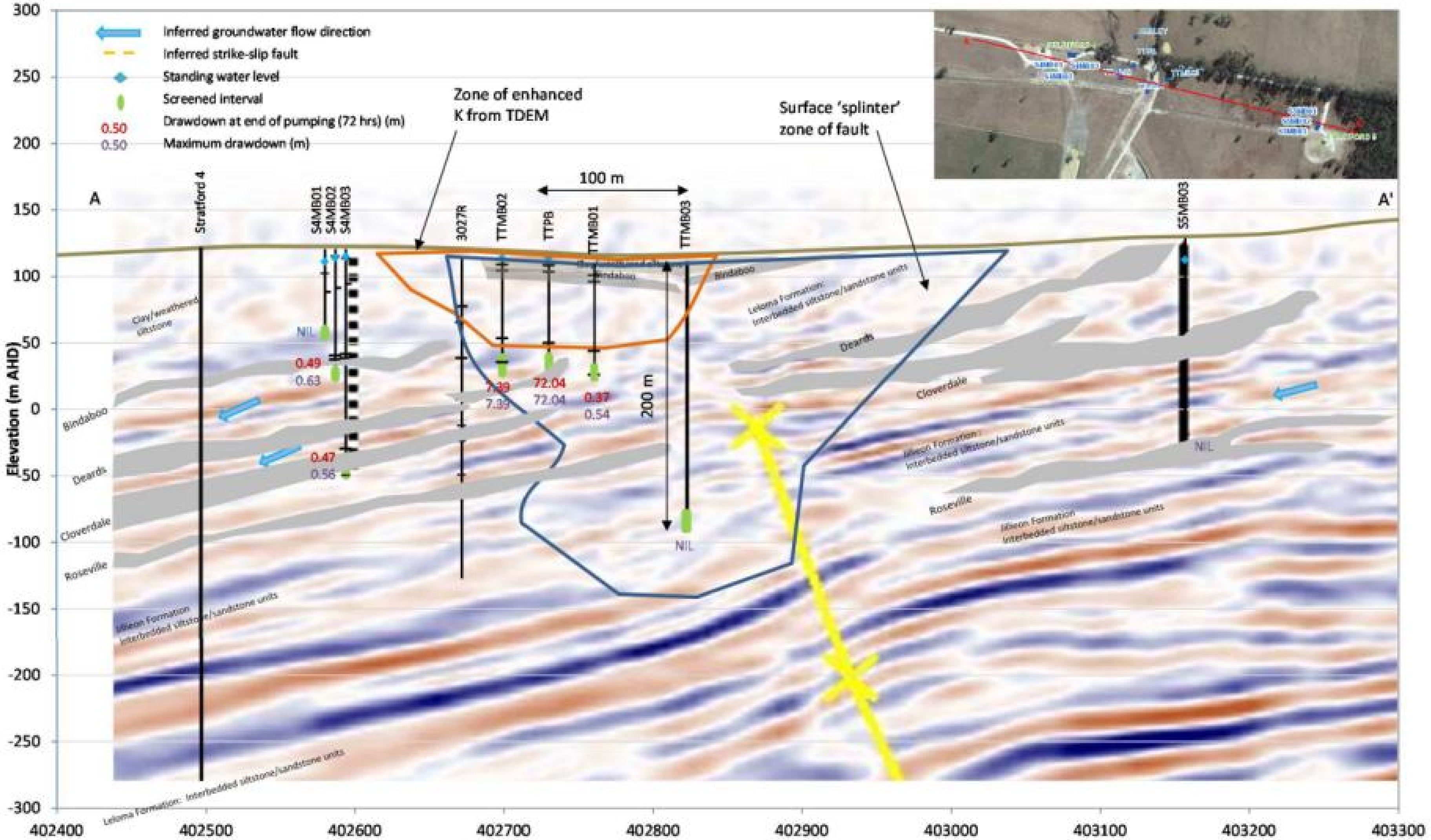


Figure 4.9 Cross-section showing the drawdown after 72 hours and maximum drawdown at each monitoring bore

The following are concluded from these Figures:

- Compared with other bores, anomalously high drawdown is seen in TTMB02 (7.4 m drawdown at 43 m from TTPB) and in TCMB01 (0.32 m drawdown at ~540 m from TTPB). This implies that there is enhanced hydraulic connection (higher permeability) towards the SSW of the pumping bore and fault surface trace.
- In contrast, other monitoring bores, S4MB02, S4MB03, TTMB01 and the Farley bore all show drawdown due to pumping, but less than would be expected in an isotropic aquifer (assuming that TTBM02 and TCMB01 fall on a straight line). These responses imply a poorer hydraulic connection (lower permeability) between the pumping bore and the screened intervals of these monitoring bores.
- There may be a weak relationship between drawdown and the stratigraphic interval screened by the bores. Monitoring bores that register no drawdown (S4MB01 and the S5-series) have screened intervals that are stratigraphically higher and lower (respectively) than the pumping bore suggesting that the poor connection with these bores is partly due to low vertical permeability in the stratigraphic sense.
- However it is noted also that the S5-series bores are located well outside of the inferred fault zone in an area shown by slug testing to have generally lower permeability (by about an order of magnitude).
- Although the fault zone appears to be slightly more permeable than other (non-fractured) parts of the shallow rock aquifer, there is no evidence for preferred groundwater flow (i.e. anisotropy in hydraulic conductivity) in the direction of the fault trace. Rather, the drawdown data are consistent with preferred flow in multiple anastomosing shear splays within a broad zone of faulting.
- It is noted that many of the monitoring bores did not fully recover to pre-test groundwater levels by 72 hours after the test finished. This implies that parts of the fracture network are of limited extent and/or have limited storage capacity, taking longer to recharge than an ideal porous aquifer.

The overall conclusion of the test pumping is that, in the natural system, the faults do not form barriers to flow in the near surface, nor cause strong preferred longitudinal flow, but may form weakly transmissive zones, relative to unfractured shallow-rock domains.

4.4.3 Aquifer parameters

Pumping test data can be used to determine key aquifer parameters such as transmissivity (T, m2/day), hydraulic conductivity (K, m/day) and storativity (S, dimensionless). The Cooper-Jacob method is a common approach that applies a number of assumptions to allow these parameters to be derived using straight-line relationships on log-normal plots to drawdown versus time.

In the case of this fault investigation it is clear that a number of the key assumptions are not met and therefore derivation of these parameters is not entirely valid for all bores. This is not due to a fault in the design of the investigation, but is a function of the groundwater system itself (i.e. it is a heterogeneous fractured rock aquifer). Also it should be noted that derivation of aquifer parameters is not a central objective of this study and therefore this limitation does not affect the conclusions derived from the drawdown observations discussed above.

The Cooper-Jacob method has been used to calculate key parameters for the pumping well (TTPB) and two of the monitoring bores (TTMB01 and TTMB02), for which certain (but not all) conditions of the method are met. The assumption related to the linear plot of drawdown with log time is accurate and valid when the parameter u is less than 0.05 (or at most 0.1). This condition is met for monitoring bores that are relatively close to the pumping bore (e.g. TTMB01 and TTBM02) and for data gathered late in the pumping test (in this case, after one or two days of pumping). For this reason, parameters are calculated only for the pumping bore and those monitoring bores (Table 4.3).

Table 4.3 Summary of pumping test aquifer parameters

Bore	Screened formation	Screen length (m)	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)*	Storativity
TTPB	Deards Coal Seam/ Leloma Formation	12	2.3	0.01	N/A
TTMB01	Deards Coal Seam/ Leloma Formation	12	14.9	0.1	7.3×10^{-3}
TTMB02	Deards Coal Seam/ Leloma Formation	12	3.3	0.02	9.7×10^{-5}

(1) * Assumes that the shallow rock aquifer extends to 150 m depth.

Drawdown due to the pumping test implies that the transmissivity within the fault zone is in the range of 2 to 15 m2/d, which is consistent with the low yield of the pumping bore (<1 L/s). The range also implies some heterogeneity or anisotropy in the fault zone. If the thickness of the shallow rock aquifer, in which the permeability is enhanced due to near-surface fracturing, is assumed to be approximately 150 m, then this implies a hydraulic conductivity in the order of ~0.01 to ~0.1 m/d. This is somewhat higher than results of the slug testing, which is not uncommon for pumping tests in fractured rock environments (Cook, 2003). The implied aquifer storativity ranges between 7 x 10-3 and ~10-4 which is low, but consistent with the limited groundwater storage in fracture systems.

4.4.4 Groundwater quality results

Water chemistry and isotope samples were collected from TTPB prior to (2 hours into the step test on 19 December 2011) and at the end of the 72-hour constant rate pumping test (0.5 hours prior to pump shut off on 23 December 2011).

Samples for water quality and isotope analysis were not collected from surrounding monitoring bores.

The complete set of water chemistry and isotope results are presented in Summary Table 1 in Appendix E. The relative percentage difference between analytes at the start and end of pumping test were calculated to assess changes in chemistry as a result of pumping (see Summary Table 5, Appendix E). Results for key analytes and isotopes are presented in Table 4.4 and Table 4.5 and the major findings are discussed below.

Table 4.4 Water quality analysis of groundwater from the test pumping bore

Bore	Hydrostratigraphic unit	Event	EC (µS/cm)[a]	pH (pH units)	Water type	Dissolved metals (mg/L)						CH_4 (µg/L)[b]
						Ba	Fe	Mn	Ni	Sr	Zn	
TTPB	Fault zone/shallow rock	Start of pumping	2,459	6.62	Na-Ca-Cl-HCO_3	2.29	**9.42**	0.191	0.002	3.10	0.056	1,210
TTPB	Fault zone/shallow rock	End of pumping	2,465	6.40	Na-Ca-Cl-HCO_3	2.25	**3.40**	0.137	<0.001	2.98	0.041	972

(1) a - Specific conductivity @ 25°C.

(2) b - Dissolved methane.

(3) **BOLD** - RPDs show significant change in parameters between events (see Table 5 Appendix E).

Table 4.5 Summary of isotope analysis of groundwater from the test pumping bore

Bore	Hydrostratigraphic unit	Event	$\delta^{18}O$ (‰)	δ^2H (‰)	$\delta^{13}C$ (‰)	a^{14}C pMC[a]	$^{14}C_{lab}$ age (Yrs BP)[b]	$^{14}C_{corr}$ age (Yrs BP)[c]
TTPB	Fault zone/shallow rock	Start of pumping	-4.89	-26.95	-19.0	1.16±0.05	35,750±370	>30,000
TTPB	Fault zone/shallow rock	End of pumping	-4.93	-26.39	-18.3	2.30±0.05	30,230±190	>30,000

(1) a - Carbon-14 activity @ 25°C.

(2) b - Uncorrected radiocarbon age provided by laboratory.

(3) C - Corrected radiocarbon age.

Salinity and water chemistry

The main findings of water quality sampling and analysis are summarised below:

- Groundwater salinity at TTPB is classified as brackish and EC values were lower than in bores screened at similar depths located outside of the inferred fault zone.
- Major ion chemistry indicates groundwater at TTPB is chemically classified as Na-Ca-Cl-HCO3 and is chemically different to other bores screened at similar depths outside the inferred fault zone (see Piper diagram in Figure 4.10).
- Dissolved metals present in concentrations elevated above laboratory limits of reporting (LORs) include barium, strontium, iron, manganese and zinc. These metals are ubiquitous in groundwater in the Gloucester Basin.
- Dissolved methane was present at low concentrations; this is consistent with results for other shallow monitoring bores screened within fractured rock and interburden.
- Groundwater salinity and chemistry showed no significant change during the 3-day pumping test (with the exception of iron) suggesting leakage from other aquifers was minimal during the length of the test. These results support the drawdown data which showed no evidence of intersecting a hydraulic barrier (such as the fault) or leakage from adjacent aquifers.

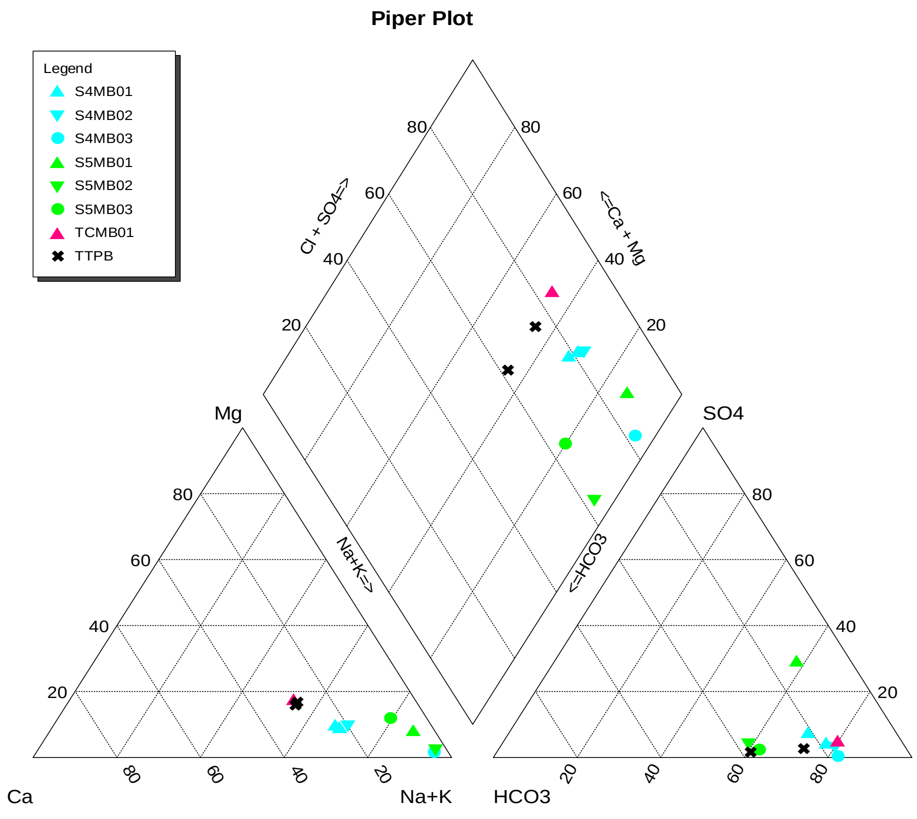


Figure 4.10 Piper diagram showing major ion composition from TTPB (TTPB is compared to monitoring bores located outside the inferred fault zone)

Stable isotopes of water (oxygen-18 and deuterium)

Stable isotope results for TTPB are compared to the Global Meteoric Water Line (GMWL) (δ2H = 8.13 δ18O + 10.8) (Rozanski et al., 1993) and Local Meteoric Water Line for Brisbane (δ2H = 7.7 δ18O + 12.6) on the plot of δ2H vs. δ18O in Figure 4.11. Samples from the pumping TTPB are also compared to nearby monitoring bores at TCMB01, S4 and S5 monitoring sites.

The main findings are as follows:

- The groundwater samples collected during the pumping test plot between the GMWL and LMWL, indicating samples are of meteoric (rainfall) origin.
- The stable isotopic composition of TTPB is within the range of values observed in monitoring bores adjacent to the fault zone.
- Stable isotope values showed no significant change during the period of pumping.

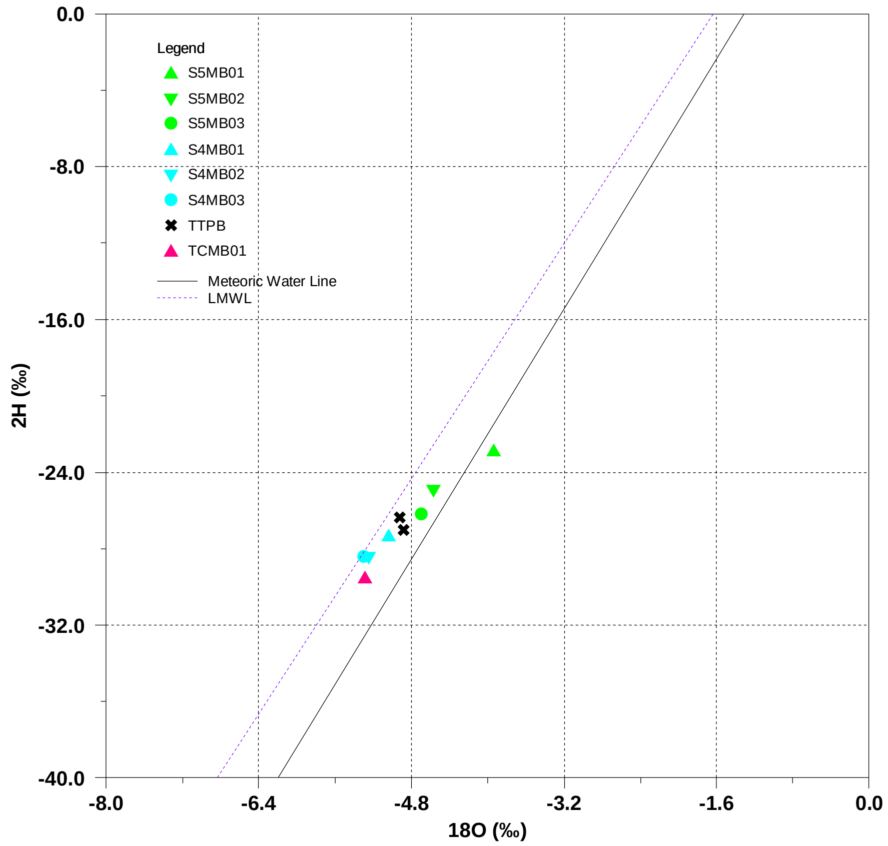


Figure 4.11 Bivariate plot of δ2H vs. δ18O showing stable isotope composition of TTPB, TCMB01 and nearby monitoring bores

Groundwater age (radiocarbon)

Radiocarbon ages have been corrected to account for potential dilution by processes such as carbonate dissolution, sulphate reduction and methanogenesis. However, it is important to note that the results for TTPB are at the limit of the radiocarbon dating and the results are only an estimate of age at best.

The main findings are as follows:

- Groundwater at TTPB is in the order of >30,000 yrs BP and is significantly older than at monitoring bores at similar or greater depths located outside the inferred fault zone.
- Radiocarbon ages did not change significantly during the period of pump testing.

Radiocarbon age of TTPB is significantly older than in nearby monitoring bores screened at equivalent depths/formations, suggesting there may be some contribution of deeper, older waters flowing upwards through the strike-slip fault.

4.5 Stratford 4 flow test

4.5.1 Groundwater drawdown

A 29 day flow test was conducted at gas production well Stratford 4 from 11 September to 9 October 2012. Stratford 4 gas production well is located approximately 300 m west of TTPB and therefore to the west of the inferred fault zone in low permeability rock. The well has a total depth of 846.3 m and has 10 sections that are open (perforated) against coal seams; the shallowest being the Bowens Road seam (515 mbgl) which is stratigraphically below the intervals screened by the monitoring bores.

During the flow test, the gas well was pumped at rates between 40 and 15 m^3/day. Pumping rates declined during the 29 day flow test period. A total of 0.292 ML was pumped during this period.

During the flow test it is assumed that the hydraulic pressure was lowered to just above the top perforated section and that all 10 coal seams were simultaneously depressurised. Monitoring was carried out at all monitoring bores in and around the inferred fault zone using automated dataloggers as part of the ongoing groundwater program. Groundwater hydrographs were assessed to determine whether depressurisation of the coal seams at depth resulted in measurable drawdown of groundwater levels in the shallow groundwater system in the vicinity of the fault. Table 4.6contains a summary of hydrograph observations. Figure 4.12 shows the total decline in groundwater levels over the Stratford 4 flow test period.

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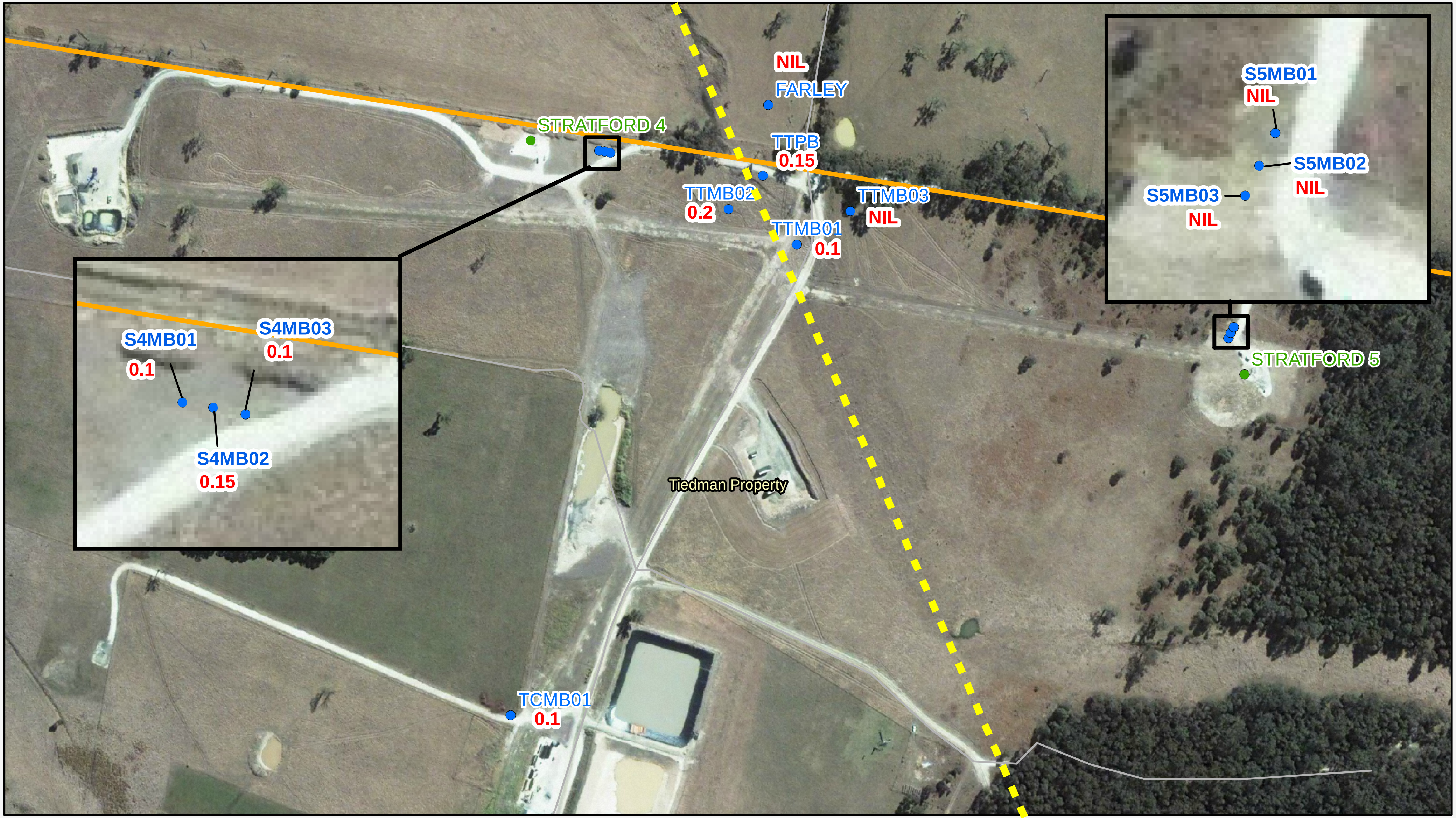
HYDROGEOLOGICAL INVESTIGATION OF A STRIKE SLIP FAULT IN THE NORTHERN GLOUCESTER BASIN
AGL UPSTREAM INVESTMENTS PTY LTD



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Groundwater monitoring bore
AGL Stratford pilot test gas well
Roads
Property boundary
Inferred fault
0.32 Drawdown over flow test period (m)

0 200
Metres

Figure 4.12
Total groundwater level decline over the Stratford 4 flow test period

Table 4.6 Stratford 4 flow test groundwater level observations

Monitoring bore	Distance from Stratford 4	Screen depth	Hydrogeological unit screened	Groundwater level observations
TTPB	212	76–88	Shallow rock	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.15 m)
TTMB01	258	76–88	Shallow rock	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.1 m)
TTMB02	189	76–88	Shallow rock	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.2 m)
TTMB03	296	186–199	Interburden	Stable water level prior to and following flow test; No apparent trend
S4MB01	62	58–64	Shallow rock	Stable but fluctuating water level prior to flow test; very slight declining trend from early October to mid-December <0.1 m)
S4MB02	67	89–95	Shallow rock	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.15 m)
S4MB03	73	162–168	Coal (Cloverdale Seam)	Stable water level prior to flow test; declining trend from early November to early January 2013 (~0.5 m)
S5MB01	658	52–58	Shallow rock	Continued slow recovery after sampling events; No apparent trend
S5MB02	657	110–102	Shallow rock	Stable water level prior to and following flow test; No apparent trend
S5MB03	656	158–164	Coal (Roseville Seam)	Stable water level prior to and following flow test; No apparent trend
TCMB01	520	87–93	Shallow rock	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.1 m)
TCMB02	515	175–181	Interburden	Slow recovery evident after sampling event in October; No apparent trend
TCMB03	510	260–266	Coal (Cloverdale Seam)	Stable but fluctuating water level prior to and following flow test; No apparent trend
TCMB04	505	327–333	Coal (Roseville Seam)	Stable water level prior to and following flow test; No apparent trend
Farley bore	217	unknown	unknown	Continuing declining trend from before the flow test (early September); No apparent change in trend.

Hydrographs for the monitoring bores of interest for the period of the flow test until mid-December 2012 are shown in Appendix D. In interpreting the groundwater hydrographs it should be noted that the flow test was conducted during a period of very low rainfall during which time groundwater levels in many regional monitoring bores were declining. This regional decline can be seen in several of the hydrographs showing data since the start of the monitoring program, also shown in Appendix D.

Hydrographs for the bores located in and around the fault trace show to types of trends:

1. Eight out of the fifteen monitored bores show relatively stable groundwater levels with no consistent trend during or after the flow test.
2. Seven bores show relatively stable groundwater levels prior to the flow test, with a gradual decline in groundwater levels from early October.

The bores showing no apparent trend or no change in trend during and after the test are the S5-series bores, TCMB02-TCMB04, and TTMB03. These bores tend to be distant from the Stratford 4 well and have screened intervals that are relatively deep compared with other monitoring bores. The bores that show a slight declining trend from early October are TTPB, TTMB01, TTMB02, the S4MB-series and TCMB01. It is noted that these bores are identified as being within, or hydraulically connected to the fault zone, or in the case of the S4-series, located close to the Stratford 4 gas well.

4.5.2 Groundwater quality results

Water chemistry and isotope samples were collected from monitoring bores located both within and adjacent to the inferred fault zone prior to pumping and during the recovery period (one week after cessation of flow testing).

Samples were collected from the Stratford 4 gas well on days 6, 15 and 28 of flow testing. Specific conductivity was measured continuously by dataloggers placed in line before and after the gas well separator.

The complete set of water chemistry and isotope results are presented in Summary Tables 2 to 4 in Appendix E. The relative percentage difference between analytes at the start and end of pumping test were calculated to assess changes in chemistry as a result of pumping (see Summary Table 5, Appendix E). Results for key analytes and isotopes for monitoring bores and the Stratford 4 gas well are presented in Tables 4.7 to 4.10 and the major findings are discussed below.

Table 4.7 Summary of groundwater quality analyses for monitoring bores – Stratford 4 flow test

Bore	Hydrostratigraphic unit	Event	EC (µS/cm)[a]	pH	Water type	Dissolved metals (mg/L)						CH_4 (µg/L)[b]
						Ba	Fe	Mn	Ni	Sr	Zn	
TTPB	Fault zone/shallow rock	Pre-pumping	2,028	7.55	Na-Ca-Cl-HCO3	**6.420**	**7.64**	**0.14**	<0.001	**6.38**	**<0.005**	**3,790**
TTPB	Fault zone/shallow rock	Recovery	2,232	8.00	Na-Cl	**0.856**	**<0.05**	**0.026**	<0.001	**1.84**	**0.202**	**758**
TTMB01	Fault zone/shallow rock	Pre-pumping	1,878	6.82	Na-Cl-HCO_3	3.920	0.87	0.057	**0.005**	3.17	**0.035**	**7,570**
TTMB01	Fault zone/shallow rock	Recovery	2,052	6.99	Na-Cl-HCO_3	3.100	0.45	0.043	**0.002**	2.38	**0.138**	**4,430**
TTMB02	Shallow rock	Pre-pumping	2,374	6.74	Na-Ca-Cl-HCO_3	**0.861**	**2.14**	0.120	0.006	3.16	0.216	**50**
TTMB02	Shallow rock	Recovery	2,475	6.87	Na-Ca-Cl-HCO_3	**0.617**	**1.49**	0.124	0.008	2.88	0.187	**13**
TTMB03	Fault zone/interburden	Pre-pumping	2,725	10.51	Na-Cl-HCO_3	0.438	<0.05	**0.004**	<0.001	**0.413**	0.037	54,800
TTMB03	Fault zone/interburden	Recovery	3,023	10.92	Na-Cl-HCO_3	0.358	<0.05	**<0.001**	0.001	**0.292**	0.095	51,200
S4MB01	Shallow rock	Pre-pumping	4,337	6.95	Na-Ca-Cl	0.541	**0.57**	0.223	0.002	21.2	**0.021**	4,230
S4MB01	Shallow rock	Recovery	4,847	7.23	Na-Ca-Cl	0.599	**0.20**	0.231	0.003	20.6	**0.010**	4,460
S4MB02	Interburden	Pre-pumping	1,623	7.73	Na-Cl	4.260	**0.39**	0.058	0.003	9.15	0.011	8,900
S4MB02	Interburden	Recovery	2,274	7.67	Na-Cl	4.060	**0.07**	0.042	<0.001	8.81	0.011	6,960
S4MB03	Coal Seam	Pre-pumping	2,329	8.41	Na-Cl	1.650	0.09	0.023	<0.001	1.79	**<0.005**	39,600
S4MB03	Coal Seam	Recovery	3,183	8.08	Na-Cl	1.740	<0.05	0.016	<0.001	1.71	**0.008**	43,500
S5MB01	Shallow rock	Pre-pumping	5,219	7.40	Na-Cl-HCO_3-SO_4	0.109	**0.12**	0.096	0.022	16.5	**<0.005**	4,440
S5MB01	Shallow rock	Recovery	7,809	7.61	Na-Cl-HCO_3-SO_4	0.133	**0.07**	0.113	0.025	17.9	**0.017**	4,690
S5MB02	Interburden	Pre-pumping	4,123	8.21	Na-Cl-HCO_3	1.380	0.25	**0.037**	0.003	1.16	**0.032**	24,400
S5MB02	Interbruden	Recovery	4,517	9.23	Na-Cl-HCO_3	2.000	<0.05	**0.018**	0.002	1.4	**0.005**	26,800
S5MB03	Coal Seam	Pre-pumping	4,159	7.07	Na-Cl-HCO_3	**0.335**	0.35	0.143	**0.062**	6.24	**0.014**	**5,710**
S5MB03	Coal Seam	Recovery	5,597	6.89	Na-Cl-HCO_3	**0.159**	0.28	0.151	**0.005**	5.36	**0.029**	**291**
TCMB01	Shallow Rock	Pre-pumping	2,278	7.17	Na-Ca-Cl-HCO_3	**6.900**	1.58	**0.075**	**0.014**	**16**	**0.013**	**502**
TCMB01	Shallow rock	Recovery	3,309	7.45	Na-Ca-Cl-HCO_3	**3.230**	1.3	**0.127**	**0.002**	**11.6**	**0.026**	**162**
TCMB02	Interburden	Pre-pumping	2,699	9.40	Na-Cl	1.170	<0.05	**0.004**	**0.002**	2.78	**0.033**	10,800
TCMB02	Interburden	Recovery	2,994	9.55	Na-Ca-Cl	0.984	<0.05	**0.001**	**<0.001**	2.67	**0.062**	10,600
TCMB04	Coal Seam	Pre-pumping	4,358	11.54	Na-Cl-HCO_3	0.162	<0.05	<0.001	0.004	0.444	1.100	12,000
TCMB04	Coal Seam	Recovery	4,985	11.92	Na-Cl-HCO_3	0.182	<0.05	<0.001	0.003	0.605	0.832	10,900

(1) a - Specific conductivity @ 25°C.
(2) b - Dissolved methane.
(3) **BOLD** - RPDs show significant change in parameters between events (see Table 5 Appendix E.

Table 4.8 Isotope analyses of groundwater from monitoring bores – Stratford 4 flow test

Bore	Hydrostratigraphic unit	Event	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{13}C_{DIC}$ (‰)	$a^{14}C$ pMC[a]	$^{14}C_{lab}$ age (Yrs BP)[b]	$^{14}C_{corr}$ age (YrsBP)[c]	Tritium (TU)	$\delta^{2H}{}_{CH4}$ (‰)	$\delta^{13C}{}_{CH4}$ (‰)
TTPB	Fault zone/shallow rock	Pre-pumping	-4.68	-26.3	-18.9	0.82±0.03	38,523±341	**>30,000[e]**	0.25±0.03	-140.6	-49.0
TTPB	Fault zone/shallow rock	Recovery	-4.80	-26.1	-19.2	13.59±0.08	15,971±47	**15,000**	0.03±0.03[d]	-118.3	-38.81
TTMB01	Fault zone/shallow rock	Pre-pumping	-5.02	-27.9	-22.7	0.97±0.02	37,157±158	>30,000[e]	0.03±0.02[d]	-153.5	-45.2
TTMB01	Fault zone/shallow rock	Recovery	-5.06	-27.5	-20.0	1.863±0.05	31,933±212	>30,000[e]	0.06±0.03	nr	-39.39
TTMB02	Shallow rock	Pre-pumping	-4.78	-26.1	-18.2	2.27±0.02	30,354±78	29,400	0.08±0.03[d]	-129.4	-38.6
TTMB02	Shallow rock	Recovery	-4.78	-24.9	-17.2	3.795±0.08	26,219±172	27,000	0.07±0.03	nr	-40.78
TTMB03	Fault zone/interburden	Pre-pumping	-4.91	-29.8	-11.9	4.68±0.03	24,531±54	24,500	ns	*nr*	-41.3
TTMB03	Fault zone/interburden	Recovery	-4.96	-29.1	-14.6	7.053±0.06	21,240±68	21,200	0.13±0.03[d]	-245.3	-33.55
S4MB01	Shallow rock	Pre-pumping	-5.18	-28.2	-19.8	33.17±0.11	8,803±26	7,200	ns	-139.8	-48.4
S4MB01	Shallow rock	Recovery	-5.14	-29.5	-18.7	68.92±0.15	6,456±21	5,000	0.08±0.03	-160.6	-43.11
S4MB02	Interburden	Pre-pumping	-5.37	-30.6	-19.2	12.78±0.07	16,466±43	13,400	0.05±0.03[d]	-133.7	-46.8
S4MB02	Interburden	Recovery	-5.31	-29.6	-18.1	13.83±0.08	15,834±46	13,100	0.10±0.03[d]	-172.9	-36.81
S4MB03	Coal Seam	Pre-pumping	-5.32	-29.0	-13.8	50.68±0.13	5,399±21	**5,000**	0.12±0.03	-141.3	-44.5
S4MB03	Coal Seam	Recovery	-5.39	-28.8	-15.0	3.368±0.06	27,178±140	**22,100**	0.09±0.03[d]	-126.7	nr
S5MB01	Shallow rock	Pre-pumping	-4.42	-25.0	-19.9	56.96±0.14	4,461±19	4,500	0.29±0.03	-184.9	-39.6
S5MB01	Shallow rock	Recovery	-4.47	-24.4	-18.2	68.92±0.15	2,929±17	2,900	0.48±0.04	-218.1	nr
S5MB02	Interburden	Pre-pumping	-4.62	-25.3	-12.9	31.20±0.10	9,295±27	8,000	0.09±0.02[d]	-55.0	-36.0
S5MB02	Interbruden	Recovery	-4.51	-24.5	-15.3	31.82±0.12	9,136±29	8,000	0.22±0.03	-69.0	-39.48
S5MB03	Coal Seam	Pre-pumping	ns	ns	ns	ns	ns	ns	ns	ns	ns

Bore	Hydrostratigraphic unit	Event	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{13}C_{DIC}$ (‰)	$a^{14}C$ pMC[a]	$^{14}C_{lab}$ age (Yrs BP)[b]	$^{14}C_{corr}$ age (YrsBP)[c]	Tritium (TU)	δ^{2H}_{CH4} (‰)	δ^{13C}_{CH4} (‰)
S5MB03	Coal Seam	Recovery	-4.46	-23.1	-12.7	53.60±0.14	5,030±21	5,100	0.22±0.03	-147.5	-36.60
TCMB01	Shallow Rock	Pre-pumping	-5.36	-29.8	-19.2	4.68±0.03	24,531±54	23,300	ns	-121.9	-46.0
TCMB01	Shallow rock	Recovery	-5.16	-28.3	-17.9	10.37±0.09	18,145±67	18,700	0.09±0.03[d]	nr	-36.09
TCMB02	Interburden	Pre-pumping	-5.09	-27.8	-12.9	4.93±0.03	24,113±53	16,100	0.06±0.02[d]	-272.8	-50.3
TCMB02	Interburden	Recovery	-4.95	-27.2	-19.4	12.95±0.07	16,357±46	12,800	0.08±0.03[d]	-278.9	-47.10
TCMB04	Coal Seam	Pre-pumping	-4.84	-27.7	-1.8	9.13±0.06	19,166±49	15,000	0.09±0.02	na	na
TCMB04	Coal Seam	Recovery	-4.71	-24.9	-16.4	17.98±0.10	13,722±43	10,900	0.14±0.03[d]	-223.7	-50.07

(1) a - Carbon-14 activity.
(2) b - Uncorrected radiocarbon age.
(3) c - Corrected radiocarbon age.
(4) d - Below practical quantification limit.
(5) ns - not sampled; na - not analysed; nr - not reported; problem with laboratory analysis.
(6) **BOLD** - RPDs show significant change in parameters (Appendix X).

Table 4.9 Water quality analyses for Stratford 4 gas well – Stratford 4 flow test

Bore	Hydrostratigraphic unit	Event	EC (µS/cm)[a]	pH (pH units)	Water type	Dissolved metals (mg/L)						CH_4 (µg/L)[b]
						Ba	Fe	Mn	Ni	Sr	Zn	
S4	Coal seams	Day 6	8,397	6.97	Na-HCO_3	11.2	0.64	0.063	0.001	5.29	0.041	4,110
S4	Coal seams	Day 15	9,017	7.45	Na-HCO_3	12.3	0.96	0.113	0.002	8.07	0.056	12,100
S4	Coal seams	Day 28	8,323	7.40	Na-HCO_3	**6.62**	0.51	0.071	<0.010	4.30	<0.05	**90**

(1) a - Specific conductivity @ 25°.
(2) b - Dissolved methane
(3) **BOLD** - RPDs show significant change in parameters between first and last sampling events (see Table xx Appendix X).

Table 4.10 Key isotope analyses for water from Stratford 4 gas well – Stratford 4 flow test

Bore	Hydrostratigraphic unit	Event	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{13}C$ (‰)	$a^{14}C$ pMC[a]	$^{14}C_{lab}$ age (Yrs BP)[b]	$^{14}C_{corr}$ age (Yrs BP)[c]	Tritium (TU)	$\delta^{2H}{}_{CH4}$ (‰)	$\delta^{13C}{}_{CH4}$ (‰)
S4	Coal seams	Day 6	-6.59	-42.4	29.1	0.012±0.005	35,287±304	>30,000[e]	0.037±0.03	-161.3	-40.6
S4	Coal seams	Day 15	-6.92	-46.6	29.3	0.897±0.08	37,805±707	>30,000[e]	0.30±0.03	nr	nr
S4	Coal seams	Day 28	-7.64	-50.1	28.7	0.492±0.08	42,622±1,283	>30,000[e]	0.24±0.03	nr	nr

(1) a - Carbon-14 activity.

(2) b - Uncorrected radiocarbon age.

(3) c - Corrected radiocarbon age.

(4) d - Below practical quantification limit.

(5) e - Limit of dating method.

(6) ns - not sampled; na - not analysed; nr - not reported; problem with laboratory analysis.

(7) **BOLD** - RPDs show significant change in parameter between first and last sampling events (Appendix X).

Salinity and water chemistry

Salinity (specific conductivity) measured by in line dataloggers for the Stratford 4 gas well during flow testing is shown on the graph in Figure 4.13. EC variability is not representative of coal seam conditions and is most likely related to:

- variable flow rates during the testing period, with periods of no flow, where water was stagnant in the discharge pipe housing the dataloggers located pre and post separator
- the dataloggers not being fully submerged by water in periods of low flow
- diurnal EC fluctuations with temperature when stagnant water remained in the pipe.

Despite the variability resulting from the above factors, it is evident that salinity increases over the period of flow testing. Stratford 4 is screened across ten coal seams and during flow testing it is expected the ratio of water from each seam in the final outflow will vary due to differences in permeability of each seam. Salinity is also likely to vary between each seam, hence the final EC will change over time as the ratios of each coal seam contributing to final outflow change.

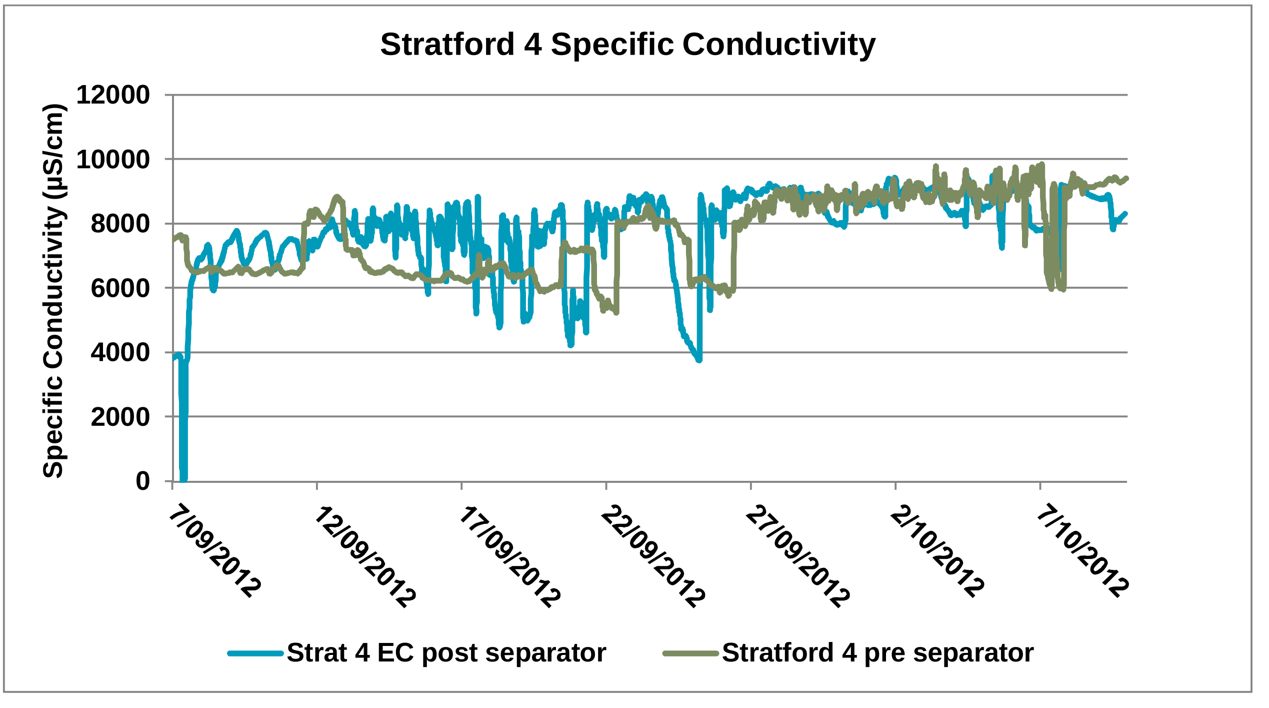

Figure 4.13 Stratford 4 specific conductivity during flow testing

The main findings of water quality sampling and analysis of Stratford gas well and monitoring bores are summarised below:

- The salinity of Stratford 4 is higher than the overlying shallow coal seams, interburden and fractured rock.
- The groundwater salinity is lower in monitoring bores located in the inferred higher permeability zone associated with the fault than in monitoring bores outside this zone.
- The water type of Stratford 4 is Na-HCO3 (Figure 4.14) and is distinctly different from the overlying formations. The chemical composition is typical of water associated with methane producing coal seams, where bicarbonate enrichment arising from sulphate reduction and methanogenesis drives the inorganic precipitation of calcite and dolomite.

- TTPB, TCMB01 and TTMB02 have a similar chemical composition; all three are chemically classified as Na-Ca-Cl-HCO3. TCMB01 and TTMB02 showed the greatest response to pumping during the 3 day pumping test of TTPB, suggesting a degree of hydraulic connection between the three bores.
- Dissolved metals present in concentrations elevated above laboratory limits of reporting (LORs) include barium, strontium, iron, manganese and zinc. These metals are ubiquitous in groundwater in the Gloucester Basin.
- Dissolved methane concentrations are highly variable in all formations monitored, and range from just above the laboratory LOR (10 µg/L) to concentrations above saturation (54,800 µg/L). The lowest dissolved methane concentrations occur in TCMB01, TTMB02 and TTPB, which showed the strongest hydraulic connection during the 3 day pumping test. The highest concentrations occurred at depth within the inferred fault zone at TTMB03.
- Groundwater chemistry at Stratford 4 gas well showed no significant change during the 29 day flow testing with the exception of dissolved methane. Variability in dissolved methane is expected and related to variability in methane present in the gas phase and flow volumes.
- Salinity and major ion chemistry of the shallow monitoring bores did not vary between pre and post flowing testing. Changes in trace metal concentrations occurred at some monitoring bores; however, these are not likely to be associated with flow testing as water levels remained constant throughout the flow testing period. Dissolved methane concentrations showed a significant reduction in monitoring bores within the inferred fault zone.

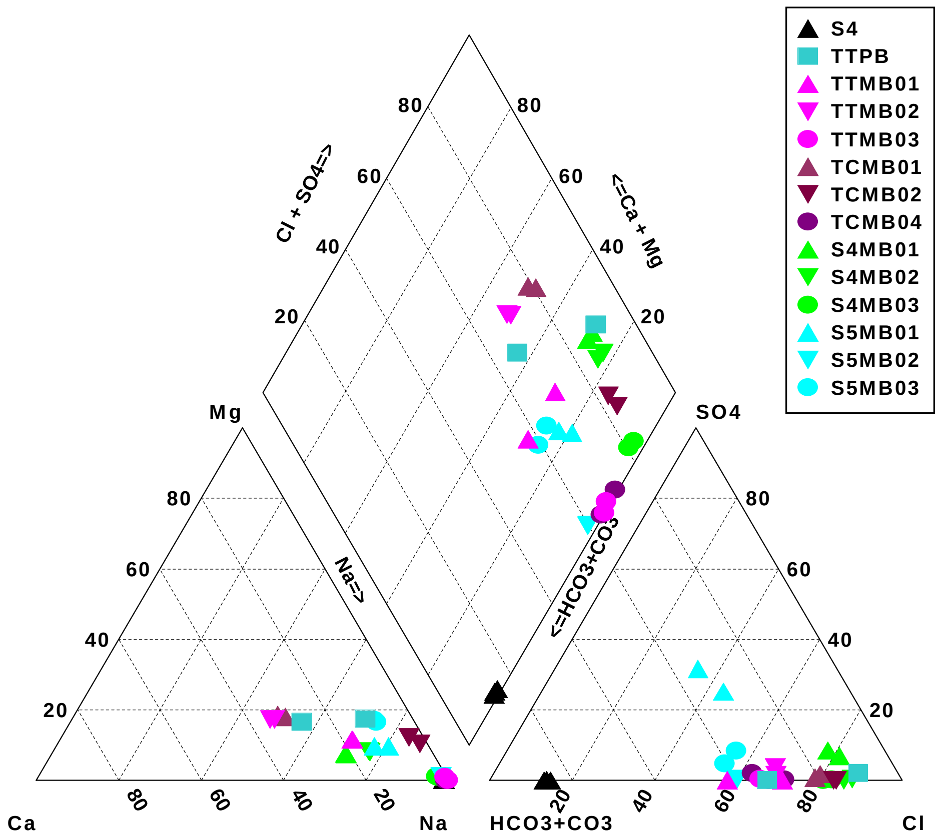

Figure 4.14 Piper diagram showing major ion chemistry for Stratford 4 gas well and monitoring bores

Stable isotopes of water (oxygen-18 and deuterium)

Stable isotope results for Stratford 4 gas well and shallow monitoring bores are compared to the Global Meteoric Water Line (GMWL) (δ2H = 8.13 δ18O + 10.8) (Rozanski et al., 1993) and Local Meteoric Water Line for Brisbane (δ2H = 7.7 δ18O + 12.6) on the plot of δ2H vs. δ18O in Figure 4.15.

The main findings are as follows:

- The groundwater samples collected during the flow test plot between the GMWL and LMWL, indicating samples are of meteoric (rainfall) origin.
- Stable isotope values in the shallow monitoring bores are similar on either side of the fault and this would suggest water communication occurs across the fault boundary.
- The stable isotope composition of the Stratford 4 gas well lies on the GMWL indicating a meteoric rather than connate source of water in the coal.
- The stable isotope composition of the Stratford 4 gas well is significantly more depleted than the shallow coal seams and interburden, and is a reflection of paleoclimatic conditions at the time of recharge.

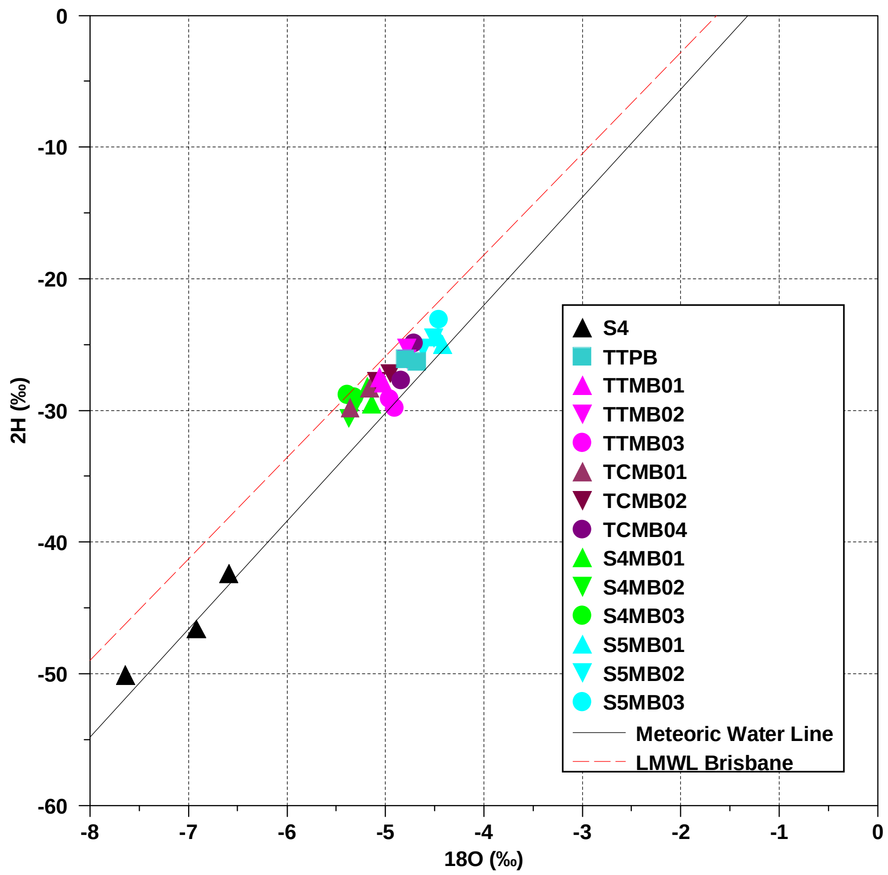

Figure 4.15 Bivariate plot of δ2H vs. δ18O showing stable isotope composition of Stratford 4 gas well and nearby monitoring bores

Groundwater age (radiocarbon and tritium)

Radiocarbon ages have been corrected to account for potential dilution by processes such as carbonate dissolution, sulphate reduction and methanogenesis. However, it is important to note that the results for the Stratford 4 gas well and some shallow monitoring bores are at the limit of the radiocarbon dating and the results are only an estimate of age at best.

The main findings are as follows (Figure 4.16):

- Groundwater at TTPB, TTMB01 and TTMB02 is in the order of ≥30,000 yrs BP and is significantly older than at monitoring bores at similar or greater depths located outside the inferred fault zone.
- Water associated with coals seams screened by Stratford 4 is >30,000 yrs BP.
- Groundwater at TCMB01 is older than anticipated based on the ages of bores at equivalent depths located outside the fault zone.
- An age inversion is present at the TCMB monitoring site, with the oldest water occurring in the shallowest formation monitored (TCMB01).
- Groundwater ages are younger at the S5 monitoring site than S4 which is expected as S5 is located closer to the recharge zone. Groundwater ages increase with depth at both monitoring locations.
- Tritium was negligible in all bores indicating no direct infiltration of modern water (<50 yrs).
- Groundwater ages in shallow monitoring bores did not vary between pre and post flowing testing, with the exception of TTPB where age decreased from >30,000 yrs BP to ~15,000 yrs BP.

Radiocarbon ages within the fault zone are significantly older than in monitoring bores screened at equivalent depths/formations outside of the high permeability zone, suggesting there may be some contribution of deeper, older waters flowing upwards through the fault.

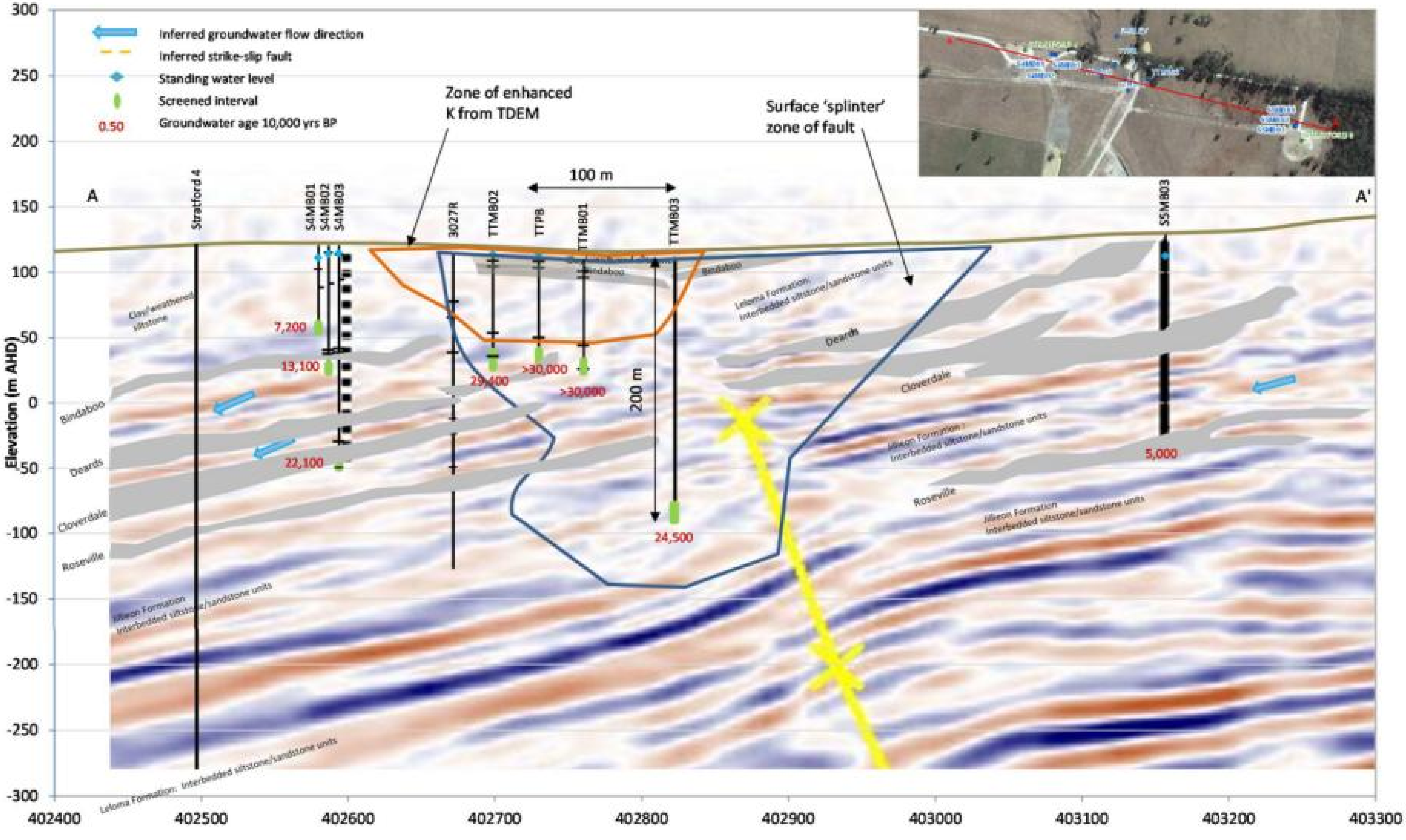

Figure 4.16 Groundwater age

Methane concentrations and carbon-13 (δ13C-CH4) and deuterium (δ2H-CH4) isotopes of methane

Dissolved methane concentrations were analysed in monitoring bores prior to Stratford 4 flow testing and during the recovery period (post flow testing).

- Dissolved methane concentrations were highly variable in all formations monitored, and ranged from just above the laboratory LOR (10 µg/L) to concentrations above saturation (54,800 µg/L).
- The lowest dissolved methane concentrations occurred in TCMB01, TTMB02 and TTPB, which showed the strongest hydraulic connection during the 72 hour pumping test, and are inferred to occur in a higher permeability zone associated with the fault.
- The highest methane concentrations occurred at depth within the inferred fault zone at TTMB03, where dissolved methane was present at concentrations above saturation. Methane concentrations were also saturated at locations either side of the fault (S4MB03 and S5MB02).

Compound specific isotope analysis of dissolved methane (carbon-13 (δ13C-CH4) and deuterium (δ2H-CH4)) was undertaken to 'fingerprint' the naturally occurring methane in shallow strata and the fault zone during baseline conditions and to assess the potential for methane migration during coal seam depressurisation.

The results from monitoring bores during the baseline and recovery monitoring rounds have been compared to isotopic results for the Stratford 4 gas well and for samples collected by AGL from coal seams during exploration.

The main results are as follows:

- Isotopic values for methane samples collected from monitoring bores varied from -50.3‰ to -33.5‰ for δ 13C-CH4 and -278.9‰ to -100.3‰ for δ2H-CH4, indicating methane is primarily thermogenic. At only a few locations methane isotopic signatures indicate methane had a mixed biogenic/thermogenic origin (Figure 4.17).
- The isotopic values of δ 13C-CH4 in the monitoring bores (depth <350 m) fall within the range of those measured in samples collected by AGL from deep strata (>300 m to 775 m) (-81.4‰ to -27.15‰ δ 13C-CH4), indicating there is no apparent trend with depth, and thermogenic methane is predominant throughout the entire strata sequence (Figure 4.18).
- Only a few AGL samples from deep strata have been analysed for δ2H-CH4 but these values (ranging from -251‰ to -195‰) are consistent with those of methane sampled from monitoring bores. Combined with the δ 13C-CH4 values, these values indicate the presence of thermogenic methane throughout the entire strata sequence.
- There is no correlation between dissolved methane content and isotopic signature (δ 13C-CH4) (Figure 4.19). Dissolved methane concentrations in monitoring bores ranged from just above the laboratory LOR (10 µg/L) to concentrations above saturation (54,800 µg/L), but all had a thermogenic or mixed thermogenic/biogenic signature.
- There were no significant changes in the isotopic signatures of methane (δ 13C-CH4 and δ2H-CH4) in shallow monitoring bores between pre and post flowing testing.
- The Stratford 4 gas well spans multiple coal seams (including the Bowens Road, Glenview, Avon and Tripple Coal Seams) between 515 and 739 mbgl. The combined isotopic signature of methane from the start of the flow test indicates thermogenic methane (-40.6‰ for δ 13C-CH4 and -161.3‰ for δ2H-CH4). Unfortunately there were issues with sample contamination for samples collected during the flow test, so no further conclusions can be drawn about the origin or migration of methane in these deep coal seams under depressurisation.

It is concluded that methane, which is ubiquitous across all strata in the Gloucester Basin, is of thermogenic origin. The distribution of methane in solution and gas phase is non-homogenous, and this variability is related to multiple factors including coal distribution, rank, permeability, hydrogeology, depositional structure and structural setting including faults. Lila and Webber (2000) state that changes in gas content in the coal seams of the Gloucester Basin coincide with the presence of fault blocks.

At a number of locations both within and outside of the fault zone, shallow coal seams and interburden are saturated with methane. At shallow depths (<100 m) within the higher permeability zone of the inferred fault, dissolved methane concentrations are lower than in strata at equivalent depths outside this zone, and it is concluded that methane escapes to the atmosphere under natural conditions (open boundary).

The decrease in dissolved methane concentrations in monitoring bores within the fault zone, and the lack of change in the isotopic signatures of methane pre and post flow testing, indicate that the depressurisation of deep coal seams at Stratford 4, did not result in any discernible vertical methane migration upwards along the fault during a 29-day flow testing period.

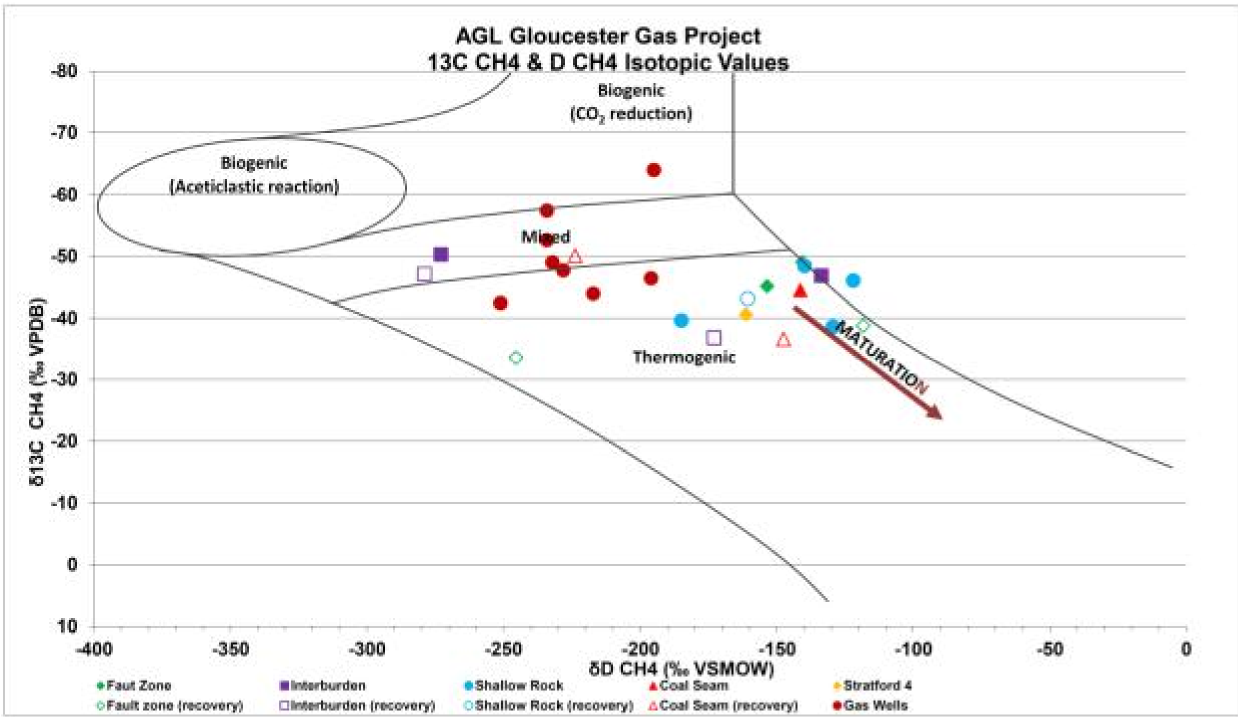

Figure 4.17 Plot of carbon-13 (δ 13C-CH4) and deuterium (δ2H-CH4) in methane gas from monitoring wells and Stratford 4

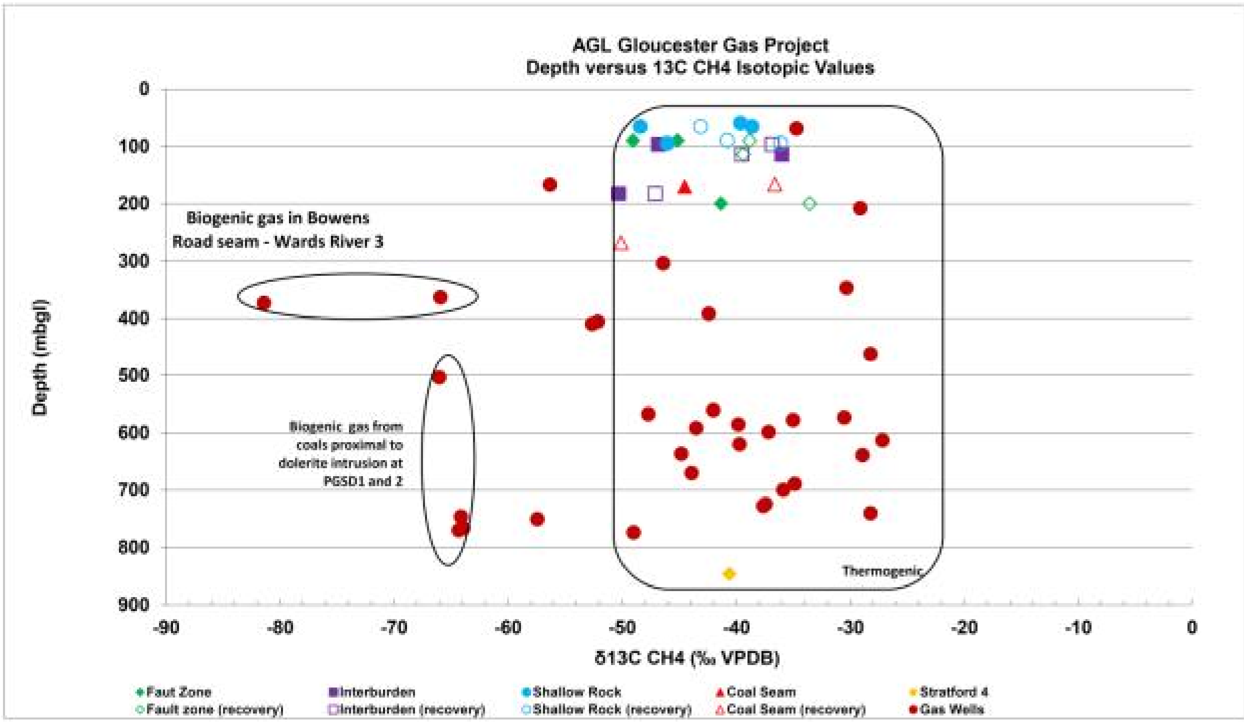

Figure 4.18 Plot of depth versus carbon-13 (δ 13C-CH4) in methane gas from monitoring and gas wells

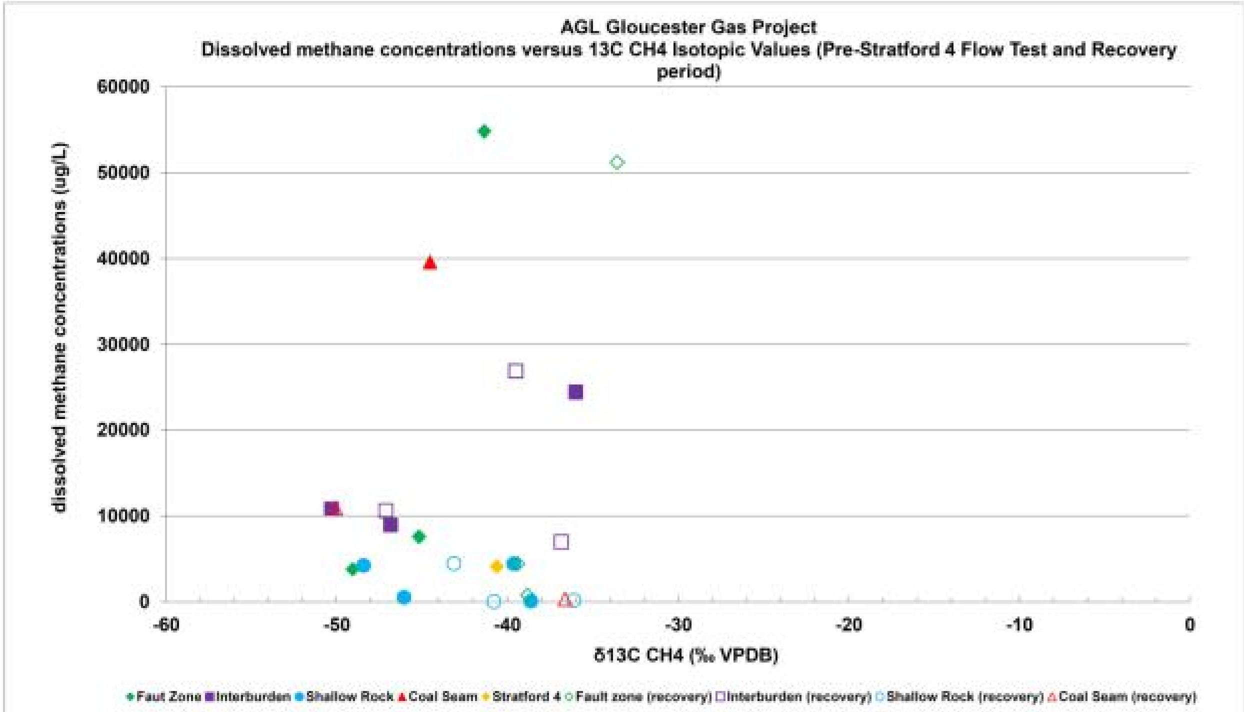

Figure 4.19 Plot of dissolved methane concentration versus carbon-13 (δ 13C-CH4) in methane gas from monitoring wells and Stratford 4

5. Discussion

5.1 Definition of the fault

The Gloucester Basin is a structurally complex geological basin formed during the Permian period. The basin is pervasively folded and faulted as a result of several syn- and post-depositional phases of deformation. Faulting therefore plays a key role in both the prospectively of the basin for coal and gas resources and in groundwater flow and gas migration under both natural and developed conditions. In this sense, the Gloucester Basin contrasts with the Sydney Basin which is, for the most part, less faulted and less structurally complex.

Geological mapping of the Basin shows that, in the vicinity of the Stage 1 GFDA, the geological structure is dominated by moderately to steeply west-dipping strata intersected by several westerly-dipping thrust faults and near-vertical to easterly-dipping oblique strike-slip faults. Recent seismic data acquired by AGL confirm the existence of such faulting within the Permian coal measures and identify numerous fault-bounded domains comprising relatively coherent strata. The interpreted seismic sections imply that there is potential for some of these faults to provide pathways for groundwater flow between the deeper and shallower groundwater systems. It is noted that faults can form either conduits to flow or barriers to flow, depending on the nature of the fault, infill materials, and the regional stress conditions. Field-based investigations, such as this study, are therefore required to determine the role of faulting in groundwater flow and gas migration.

An important phase of this investigation was to identify and characterise the target fault, so that groundwater monitoring equipment could be installed in the most appropriate configuration. Most fault traces tend to be obscured by regolith and alluvial deposits and therefore a combination of field and geophysical techniques was used to delineate the fault in the study area. The steeply east-dipping strike-slip fault was clearly identified in the seismic sections as a zone of offset and flexure of reflectors within the coal measures. In the upper 200 m, main fault zone appears to splinter into a number of related structures over a zone up to 300 m to 400 m wide although the exact location and nature of those structures is unclear. The surface projection of the dipping fault zone corresponds to a linear NW trending drainage feature which is thought to represent the surface trace for this fault zone. An electromagnetic survey carried out across this surface feature identified a corresponding zone of enhanced conductivity, consistent with weathering and/or groundwater movement in a fault zone.

Observations of water make during drilling give some indication of where water bearing fractures or shear zones occur at depth. In general groundwater was encountered within the fault zone at a depth of approximately 60 m, below which the water make increased gradually to between 2 L/s and 3.3 L/s. This implies that water bearing zones within the inferred fault zone comprise both discrete fractures and also broad zones of more pervasive fracturing.

5.2 Hydraulic characteristics of the fault

From the test pumping results, it can be concluded that in the natural system (pre-development), the strike-slip fault on the Tiedman property does not form a barrier to flow, nor does it form a preferential pathway for groundwater flow (i.e. anisotropy in hydraulic conductivity) in the direction of the fault trace. The fault zone appears to be slightly more permeable than other non-fractured parts of the shallow rock aquifer, forming a weakly transmissive zone near surface.

Anomalous high drawdown in some monitoring bores implies there is enhanced hydraulic connection (higher permeability) towards the SSW of the pumping bore and fault surface trace and the drawdown data are consistent with preferred flow in multiple anastomosing shear splays within a broad faulting zone. There may also be a weak relationship between drawdown and the stratigraphic interval, with monitoring bores screened above and below the pumping bore showing no drawdown during the pumping test. These results suggest that the poor connection with these bores may be partly due to low vertical permeability in the stratigraphic sense.

Distinct hydrochemistry and radiocarbon ages (>30,000 yrs BP) in monitoring bores within the fault zone suggest that the fault forms a weak conduit that enhances the discharge of deeper groundwater. However, the stable isotopic composition of the Stratford 4 gas well is significantly more depleted than the targeted shallow formations, suggesting that the connection is not strong and/or does not penetrate to the deeper coal seams.

Methane is ubiquitous across all strata in the Gloucester Basin, and is present in both the dissolved phase in groundwater and gaseous phase in the deep coal seams and interburden. The isotopic signatures of methane (δ 13C-CH4 and δ2H-CH4) indicate that the majority of methane, at depths ranging from surface to >850 m, is thermogenic. Methane concentrations are highly variable, both spatially and with depth, and can occur at concentrations greater than saturation in shallow coal seams and interburden. The distribution of methane in solution is non-homogenous, and this variability is related to multiple factors including coal distribution, rank, permeability, hydrogeology, depositional structure and structural setting including faults. Faults can form open boundaries for gas reservoirs, and can act as pathways for methane migration, which will naturally migrate from areas of high pressure to areas of low pressure. They can also act as sealing boundaries, when diagenetic cementation and cataclasis create pressure within the fault greater than the surrounding gas reservoir.

5.3 Response to depressurisation of deeper coal seams

The flow test carried out at the Stratford 4 gas well, located close to the monitored fault trace, provided an opportunity to assess impacts on the shallow groundwater system as a result of depressurising the target coal seams at depth. During the test, the deeper coal seams (515 m – 739 m depth) were depressurised for 29 days while groundwater levels and quality were monitored. Continuing regional groundwater monitoring provided a baseline and reference with which to compare observations from near the gas well and fault.

Monitoring bores in the vicinity of the gas well and fault showed two main types of responses: either no significant trend, or a declining trend that appears to start in early October. Bores that showed no apparent trend are distant from the Stratford 4 gas well and have relatively deep screened intervals. Approximately half of the bores show a slight declining trend (~0.1 m to 0.2 m over two months) that starts during the Stratford 4 flow test and continues to at least mid-December. Those bores tend to be nearer the gas well and/or have screened intervals that are within, or near the inferred fault zone.

While these observations appear to indicate drawdown in some proximal bores corresponding to the flow test, there is considerable ambiguity in the cause of that drawdown, based on three general observations:

1. As stated above, similar declining trends are apparent in several monitoring bores that are many kilometres distant from the test site (e.g. TMB01-03; AMB01-02; RMB01-02; WMB04) and those trends cannot be related to the flow test. The trends in those bores are clearly part of a regional declining groundwater trend in response to the very dry conditions that prevailed prior to and during the flow test. It is noted that the groundwater trends in those distant bores match closely the trend of the cumulative departure from the mean monthly rainfall (albeit lagging by up to a month).
2. Most of the bores that show no trends have relatively deep screen intervals. It would be expected that depressurisation of the deeper coal seams would impact on the deeper screened monitoring bores before the shallower bores. On the other hand, responses to monthly trends in rainfall recharge are

usually more apparent in shallower bores relative to deeper bores which often show no effects or much more subdued and delayed trends.

3. The gradual and linear decline continuing for at least two months contrasts with the theoretical pressure drawdown response that might be expected from this type of test.

Therefore it is concluded that the observed groundwater level trends are more consistent with regional rainfall and recharge effects. However it is not possible from the existing data to determine unequivocally the cause of the observed groundwater decline.

The groundwater salinity in the Stratford 4 well increased gradually throughout the test which is common in flow tests and reflects a gradual depletion in the residual fresh water used in drilling and workovers, and trend towards the mean salinity for groundwater in the screened coal seams. In general, groundwater quality did not change significantly in the monitoring bores between the start and end of the test. One notable change was in dissolved methane. Three monitoring bores located within or near the fault showed a significant *decline* in dissolved methane (e.g. decrease from 3,790 µg/L to 758 µg/L in TTPB), and showed no significant change in methane isotopic signatures. These results showed that depressurisation of deep coal seams during the 29 day flow test did not result in any discernible vertical migration of methane along the fault.

The shallow, higher permeability zone of the inferred fault on the Tiedmans property is interpreted to be an open boundary, where dissolved methane concentrations are lower than in strata at equivalent depths outside this zone, suggesting degassing of methane (from shallow reservoirs) has occured. There was no indication from the 29-day flow test of Stratford 4 that depressurisation of coal seams during this period resulted in any discernible vertical migration of methane along the fault.

6. Conclusions

A field based hydrogeological investigation was carried out to assess the hydraulic characteristics of a strike-slip fault within the Stage 1 GFDA. The investigation used field based studies and geophysical methods to identify and characterise the fault in the near-surface environment.

The hydraulic characteristics of the fault zone were investigated by inducing drawdown in both the fault zone (using a pumping test) and the deeper coal seam water bearing zones (gas well flow test) and monitoring the effects on the shallow groundwater system.

Water level trends were used as the primary proof of any enhanced connectivity within the fault zone. Water samples were collected and analysed for groundwater quality, dissolved methane content, isotopic composition and age to place further constraints on groundwater processes.

The following conclusions are drawn from the results of the investigation:

1. The Gloucester Basin is a structurally complex geological basin formed during the Permian period. The northern Gloucester Basin and the Stage 1 GFDA is dominated by moderately to steeply west-dipping strata intersected by several westerly-dipping thrust faults and near-vertical to easterly-dipping oblique strike-slip faults.
2. The target strike-slip fault is clearly identified in the seismic sections. In the upper 200 m, main fault zone appears to splinter into a number of related structures over a zone up to 300 m to 400 m wide. The surface projection of the fault zone corresponds to a visible surface trace and a zone of anomalous conductivity.
3. During the 3-day pumping test of a shallow test production bore in the fault zone, six out of 10 monitored bores registered some drawdown response, ranging from 0.5 m to 7.4 m. The magnitude and timing of the drawdown at each monitoring location reflected variation in aquifer characteristics across the site.
4. Results of the test pumping indicates that the fault zone is a broad zone of enhanced hydraulic conductivity within the shallow rock aquifer. The fault zone does not form a barrier to flow, nor cause strong preferred longitudinal flow in the direction of the surface trace, but may form heterogeneous, weakly transmissive zones in the near surface, relative to unfractured shallow-rock domains.
5. Distinct hydrochemistry and (older) radiocarbon ages within the fault zone suggest that the fault forms a weak conduit that enhances discharge of deeper groundwater under natural conditions. However, stable isotopes suggest that this connection is not strong and/or does not penetrate to the deeper coal seams.
6. Depressurisation of deeper coal seams was carried out during the 29-day flow test on Stratford 4 (Stratford 4 is located 200m west of the edge of the fault zone on the Tiedman property). Observations of groundwater levels indicated no apparent groundwater drawdown in most monitoring bores, while a few bores show a slight declining trend that appears to start in early October and early November 2012, after completion of the flow test. It is not possible from the existing data to determine unequivocally the cause of the observed groundwater decline. However it appears to be more consistent with the regional decline in groundwater levels due to the very low rainfall conditions in late 2012, than due to a possible depressurisation effect.
7. Methane is ubiquitous across all strata in the Gloucester Basin, and is present in both the dissolved phase in groundwater and gaseous phase in the deep coal seams and interburden. The isotopic signatures of methane (δ 13C-CH4 and δ2H-CH4) indicate that the majority of methane, at depths ranging from surface to >850 m, is thermogenic.
8. Methane concentrations are highly variable, spatially and with depth, and can occur at concentrations greater than saturation in shallow coal seams and interburden. The distribution of methane in solution is

non-homogenous, and this variability is related to multiple factors including coal distribution, rank, permeability, hydrogeology, and structural setting.

9. The shallow, higher permeability zone of the inferred fault on the Tiedmans property is interpreted to be an open boundary in the near surface environment, where dissolved methane concentrations are lower than in strata at equivalent depths outside this zone, suggesting some natural degassing of methane. There was no indication from the 29-day flow test of Stratford 4 that depressurisation of coal seams during this period resulted in any discernible vertical migration of methane along the fault.

In conclusion, a comprehensive field based investigation was carried out to determine the hydraulic characteristics of one of several strike-slip faults in the Gloucester Basin and its control on groundwater flow and impacts under CSG development. Test pumping and isotopic analysis indicate that the fault zone is a broad and heterogeneous zone of increased hydraulic conductivity within the shallow rock aquifer and, under natural conditions, may form a weak conduit for discharge of older groundwater. However monitoring of groundwater levels and dissolved methane during the Stratford 4 gas flow test provided no clear evidence of enhanced connections between the deeper coal seams and shallow groundwater system.

6.1 Recommendations

To better define the hydraulic processes operating in fault zones and their potential for gas migration during development of the site, the following recommendations are made:

- Undertake local scale numerical modelling to simulate the responses and distinguish between the potential causes of observed trends.
- Refine conceptual models and re-calibrate any local fault-scale numerical model of depressurisation using the results from any longer term flow tests.
- Because depressurisation effects may take some time to become apparent in the shallow rock environment, longer duration flow tests are required (6 months to a year). Such testing should be carried out during future (long term) pilot testing programs, and the first stage of gas field development within an adaptive management framework.
- Depressurisation effects from flow testing should be monitored with at least one array of vibrating wire piezometers installed to the full depth of the gas production zones, ideally at a distance of 200 to 500 m from the gas well (we understand that this is to occur by late-2013 at the nearby Pontilands 3 corehole site).
- Undertake methane isotope sampling and analysis during flow tests. The aim would be to obtain site specific data on methane abundance and provenance, and the role of faults in methane migration, during extended gas flow testing.

7. Statement of limitations

7.1 Scope of services

This report has been prepared in accordance with the scope of services set out in the contract, or as otherwise agreed, between the client and Parsons Brinckerhoff (scope of services). In some circumstances the scope of services may have been limited by a range of factors such as time, budget, access and/or site disturbance constraints.

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On all sites, varying degrees of non-uniformity of the vertical and horizontal soil or groundwater conditions are encountered. Hence no monitoring, common testing or sampling technique can eliminate the possibility that monitoring or testing results/samples are not totally representative of soil and/or groundwater conditions encountered. The conclusions are based upon the data and the environmental field monitoring and/or testing and are therefore merely indicative of the environmental condition of the site at the time of preparing the report, including the presence or otherwise of contaminants or emissions.

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The report has been prepared for the benefit of the client (and no other party). Parsons Brinckerhoff assumes no responsibility and will not be liable to any other person or organisation for or in relation to any matter dealt with or conclusions expressed in the report, or for any loss or damage suffered by any other person or organisation arising from matters dealt with or conclusions expressed in the report (including without limitation matters arising from any negligent act or omission of Parsons Brinckerhoff or for any loss or damage suffered by any other party relying upon the matters dealt with or conclusions expressed in the report). Parties other than the client should not rely upon the report or the accuracy or completeness of any conclusions and should make their own enquiries and obtain independent advice in relation to such matters.

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