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The Limestone Coast Geothermal Project, South Australia: a Unique Hot Sedimentary Aquifer Development

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ABSTRACT

Panax Geothermal Ltd (“Panax”) holds the geothermal rights covering four Hot Sedimentary Aquifers (HSA) within troughs or sub-basins in the Otway Basin in southeast South Australia, covering an area of more than 3,000 km^2. The Limestone Coast Geothermal Project is designed to demonstrate that conventional geothermal resources within Australia's hot sedimentary basins can be used to generate large amounts of competitively priced, zero-emission, base-load power. Due to an existing comprehensive database acquired by the petroleum industry, the initial development of its Limestone Coast Geothermal Project is focused on the Penola Trough (GEL223).

The first well, Salamander-1, is the first in a series of wells in the development of a 50 MWe geothermal power plant, which could become the first grid connected geothermal power plant in Australia.

A Pre-Feasibility study has also been completed to assess the total cost per MWh of power produced after taking into account all plant and pump requirements. This study found that electricity can be sustainably generated at a total cost (capital and operating) of AUD$63 per MWh.

The Penola Trough has been subjected to intensive oil and gas exploration, including 27 deep petroleum wells with wireline logging and conventional core measurements of reservoir porosity and permeability. In addition, there are 271 km^2 of 3D seismic and a significant amount of 2D seismic data. These data are available as part of the Open File data base and studies have shown that the over 1,000m thick Cretaceous Pretty Hill Formation (sandstones) of the Penola Trough has the capacity to deliver geothermal waters of >140˚C at high volumes, sufficient for the operation of a commercial, medium temperature geothermal power plant. The generating potential is large, as is evidenced by a recent independent Geothermal Resource assessment, which has estimated a “Measured Geothermal Resource” of 11,000 PJ for the Penola Trough.

1. INTRODUCTION

Panax Geothermal Ltd (“Panax”) holds eight Geothermal Exploration Licences (GELs), over four Hot Sedimentary Aquifers (HSA) within troughs or sub-basins in the Otway Basin in southeast South Australia, covering an area of more than 3,000 km^2 (see figure 2). The Limestone Coast Geothermal Project is designed to demonstrate that conventional geothermal resources contained within Australia's sedimentary basins have the capacity to generate large amounts of competitively priced, zero-emission, base-load power. The initial development of its Limestone Coast Geothermal Project is focused on the Penola Trough

(GEL223, see figure 2), as this trough has a comprehensive exploration database acquired by the petroleum industry,.

The Penola Project is located in Geothermal Exploration Licence (GEL) 223, approximately 40 km north of Mount Gambier in South Australia.

The Penola Trough is a sub-basin or trough in the on-shore Otway Basin area of south-eastern South Australia. It is one of several sedimentary troughs and represents an area of thick sediment and relatively recent volcanic activity as indicated by the presence of extinct volcanoes such as those associated with the Mount Gambier region 40km to the south. It is an area of anomalously high heat flow (see figure 3).

The Penola Trough (GEL 223) has been selected for the first deep well because this trough has an extensive database of the target productive reservoir, based on more than 20 deep petroleum wells, many of which have intersected the target reservoir, as well as extensive seismic data, including 271 km^2 of 3D seismic.

2. GEOLOGICAL SETTING

The Penola Trough is a sub-basin within the Otway Basin, an intra-cratonic rift basin initiated during the Late Jurassic to Early Cretaceous on the now southern margin of the Australian mainland. The trough holds a thick accumulation of Late Jurassic to Cretaceous sediments and formed on top of Palaeozoic basement. Seismic evidence suggests that the sediment pile much of which is the Createaceous Pretty Hill Formation, is 6,000m thick or more in the deepest sections of the trough (figure 1). This interpretation is supported by data from 18 wells that have penetrated the Pretty Hill Formation—the thickest intersection equal to 882m of predominantly sandstone. Sandstone units are also documented throughout the underlying Sawpit Sequence and Casterton Formation. All units from the top of the Pretty Hill Formation to the Basement are therefore considered viable reservoir targets.

The Jurassic aged Casterton Formation locally underlying the Crayfish Group represents the earliest synrift fill in the Penola Trough. It is only penetrated by wells on the flanks of the trough but interpreted from seismic to extend into its axis. It is an interbedded carbonaceous shale and volcaniclastic sequence deposited in a low energy fluvial-lacustrine environment (Morton, 1990). The Pretty Hill Sandstone consists predominantly of braided fluvial sandstones (Morton, 1990) with thin interbedded siltstones and shales.

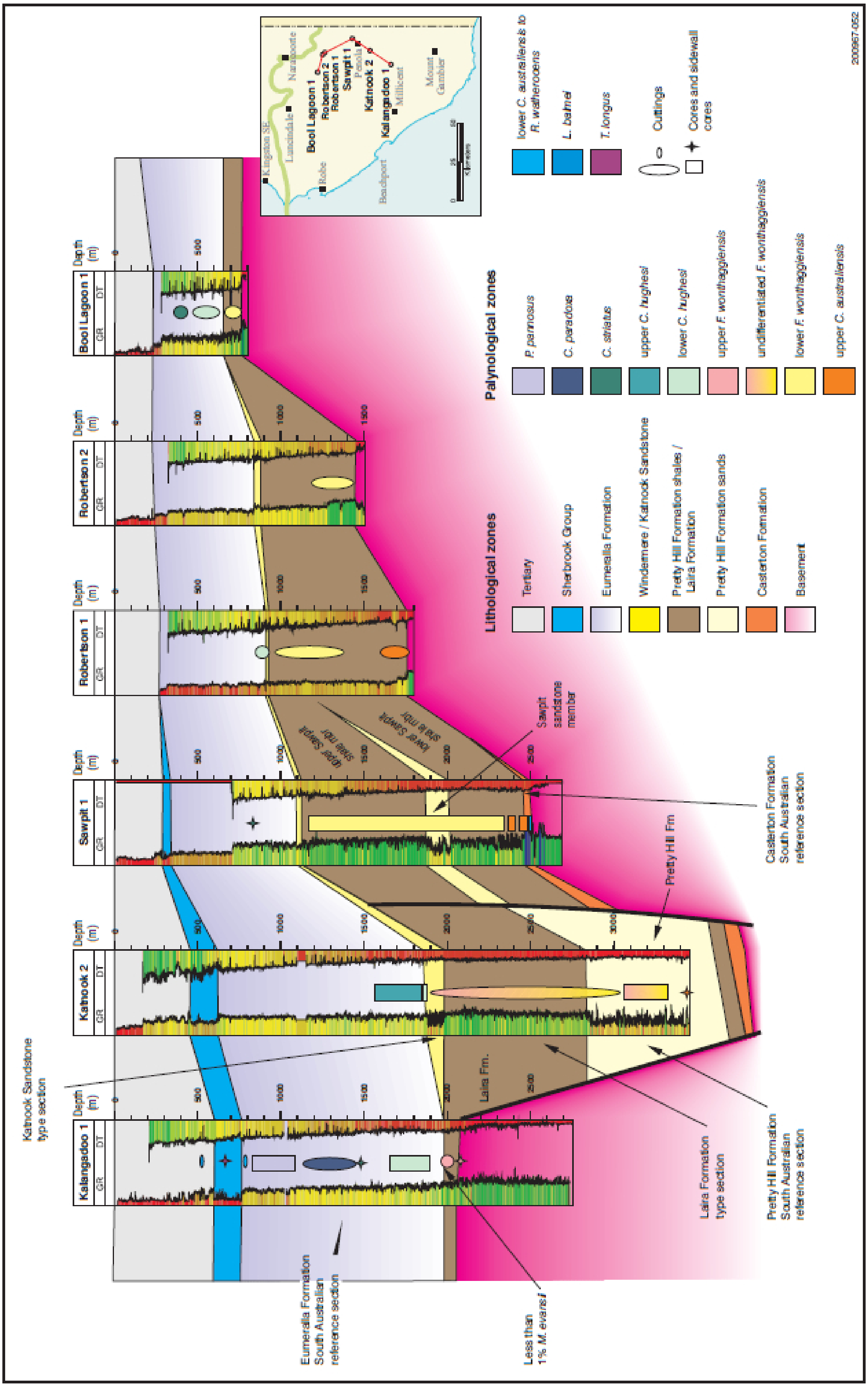

Figure 1. Schematic cross-section of the Penola Trough (from north to south, see inset). Correlated, wireline logs from several wells are also shown. The target reservoir formation, the Pretty Hill Formation, attains maximum thickness in the Katnook Graben (near the Katnook 2 well). After Boult et al. (2002).

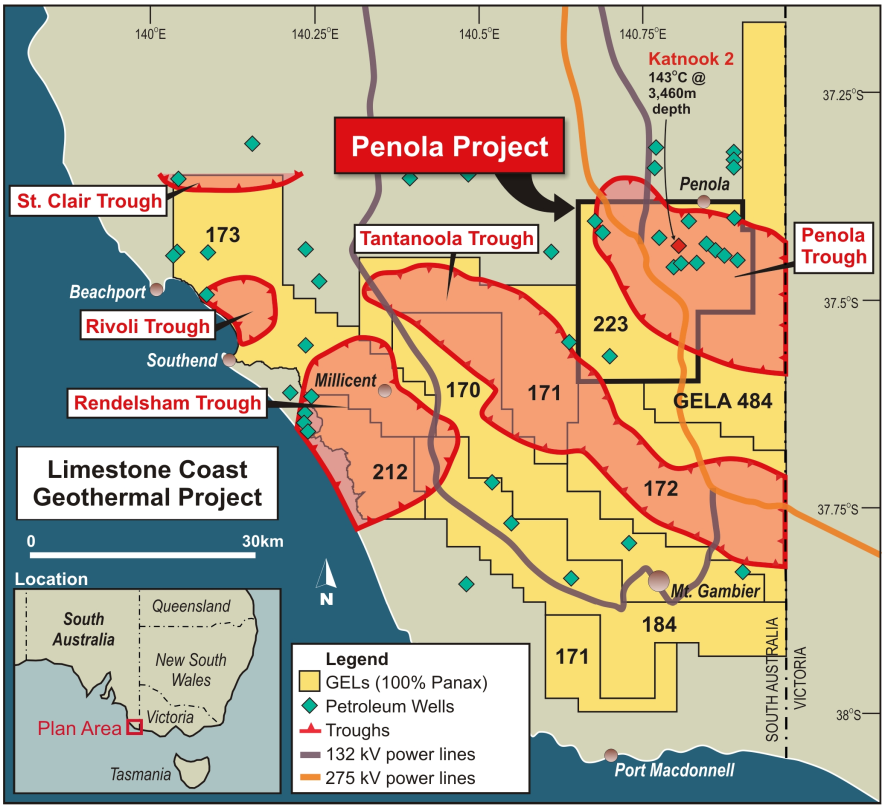

Figure 2. Outline of Sub-basins or troughs of the Limestone Coast Geothermal Project.

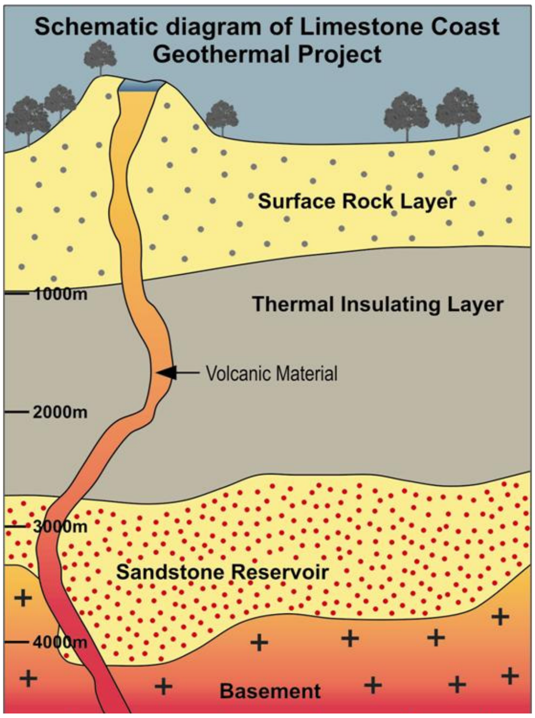

Figure 3. Schematic diagram of the Limestone Coast Geothermla Project.

The Otway Basin rifting, was associated with volcanic activity in the Mount Gambier area in recent geological time. The Mount Gambier Blue Lake crater complex at Mount Gambier is only one of the better preserved examples of its type in Australia, and is a well-known scenic attraction. There are at least 20 eruptive sites in this part of South Australia. Mount Gambier and Mount Schank (10km south of Mount Gambier) represent the final phase of this activity and are the youngest volcanoes in Australia.

3. THE GEOTHERMAL RESERVOIR

The target reservoir is the Cretaceous Pretty Hill Formation, a member of the Crayfish Group. The good reservoir quality of the Pretty Hill Formation sandstones has been known from petroleum activities for some time. Gas was first discovered in the trough in 1987 in Katnook-1. These gas discoveries are mainly restricted to the top 25m of the formation, trapped beneath Laira Formation shale. This is relevant and significant because the Laira Formation shale has a low thermal conductivity and is assumed to be a thermally insulating unit, overlying the Pretty Hill Formation target reservoir.

The Early Cretaceous Pretty Hill Formation is typically a sandstone (quartz-feldspar litharenite) with varying proportions of siltstone to shale interbeds and is best known from the Penola Trough with a thickness of over 1,000m. The Pretty Hill Sandstone was deposited by a low sinuosity, high energy, sand-rich river system (Scholefield et al; 1996). The Pretty Hill Formation sandstones of the sedimentary basin have been relatively prolific producers of gas. High net to gross sandstones occur throughout the 875m so far penetrated. Katnook-2 flowed a maximum 16.4MMscf/d from a 23m zone at the top of the formation.

As part of the drilling of the petroleum wells, a significant amount of wireline logging, core sampling and resulting petrophysical evaluation were undertaken in the Pretty Hill Formation. The porosity of the target Pretty Hill Formation section was determined by Panax based on wireline logs calibrated to porosity samples from conventional cores and sidewall cores. The core porosities were calibrated to measured permeabilities using all the cores from a larger database of wells in the Penola Trough through the Pretty Hill Formation. Several studies such as Alexander (1992) and Scholefield (1996) provide insights into the petrophysical evaluation of the Pretty Hill Formation and its calibration of porosity to permeability. Using the calibration of porosity to permeability, and the calibrated porosity derived from wireline logging and cores, it is thus possible to determine the permeability of the Pretty Hill sandstone section and integrate this across the borehole to get the transmissivity or permeability metres.

Applying the outcomes and algorithm from these publications, we have estimated a total transmissivity (permeability thickness product) of 10-50 Darcy.metres (D.m) depending on well and thickness of Pretty Hill Formation penetrated. These results indicate a conventional sedimentary geothermal reservoir with normal hydrostatic pressures (no over pressures) should flow at economic rates from geothermal production wells. In addition, a significant volume of reservoir has been determined using the well and seismic data. For the purpose of reservoir volume estimates, the Pretty Hill Formation, Sawpit Sandstone and Casterton Formation are all included. Beardsmore (2009) determined that from the top of the Pretty Hill Formation (or a cut-off isotherm of 125^{o}C) to the base of the reservoir the estimated reservoir volume is 520km^3.

The known porosities at target depths are not common, but are likely to be related to the known presence of chlorite cementation along grain boundaries. Chlorite cementation is known to inhibit quartz cementation, thereby preserving porosity (Anna Berger, et al, 2009)

The availability of well data, combined with the available 3D seismic data gives the Penola Geothermal Project a significant degree of credibility and reduced technical uncertainty in regards to the existence of suitable geothermal reservoirs.

4. RESOURCE CLASSIFICATION AND TEMPERATURE DETERMINATION

Hot Dry Rocks Pty Ltd (HDRPL) undertook a geothermal resource assessment across all the Limestone Coast geothermal tenements owned by Panax, adhering to the Australian Code for Reporting of Exploration Results, Geothermal Resources and Geothermal Reserves, 2008 edition (the Code). This assessment established Inferred, Indicated and Measured geothermal resources, summarized in table 2 (Beardsmore, 2009).

The geothermal resource summary in table 2 shows the relatively large overall potential of the Limestone Coast Geothermal Project. The Penola Trough stands out as being the only trough with indicated and measured resources, courtesy of reservoir information derived from previous petroleum wells and 3D and 2D seismic data. The outline of the measured resource in the Penola Trough is shown in figure 5.

HDRPL used the principle of 'inversion' to estimate reservoir temperature. Known information about surface temperature (15°C) and surface heat flow was entered into a software module. A numerical process computed in three dimensions the distribution of temperature that best matched the observed surface heat flow distribution, while respecting the laws of conductive heat transfer and the thermal properties of the geological strata. Within most of the Penola Trough, consistent with observations in well Katnook 2, the model predicts that the temperature is relatively constant around 160°C at 4,000m (see table 1 and figure 6).

Table 1. Heat flow constraints on the 3D temperature inversion.

Well Name	Depth (m)	Heat flow (mW/m^2)
Balnaves 1	2832	72.0 ± 3.0
Haselgrove 1	3290	74.0 ± 3.0
Haselgrove 2	3053	71.0 ± 3.0
Hungerford 1	2196	68.0 ± 2.6
Jacaranda Ridge 1	2951	71.0 ± 2.7
Katnook 1	2520	73.0 ± 3.3
Katnook 2	3478	75.0 ± 3.0
Ladbroke Grove 1	3415	76.0 ± 2.8
Ladbroke Grove 2	2725	73.0 ± 3.0
Laira 1	3003	73.0 ± 2.9
Pyrus 1	3150	70.0 ± 2.3
Sawpit 1	2699	81.0 ± 3.0
Tilbooroo 1	2492	82.0 ± 3.6
Viewbank 1	2504	76.0 ± 2.7
Wynn 1	3066	75.0 ± 2.9

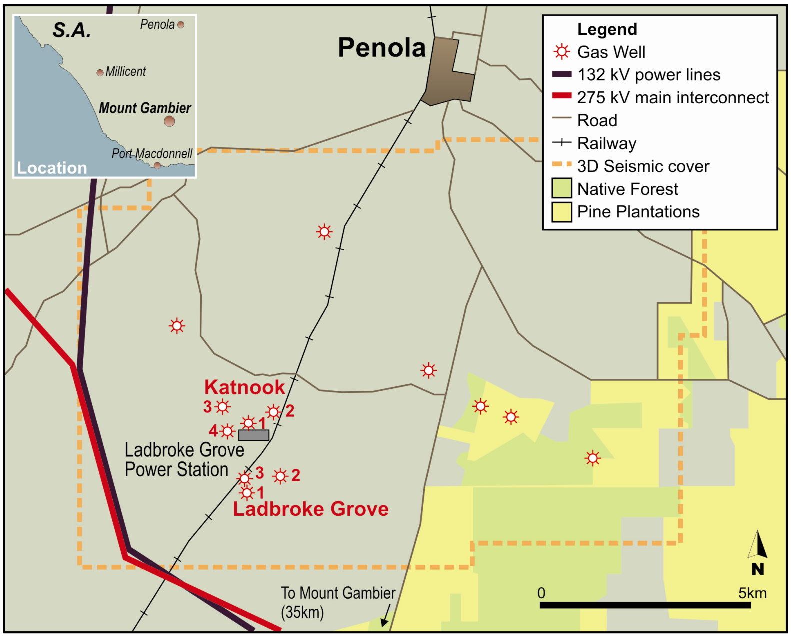

Figure 4. Penola Project – Location & Infrastructure.

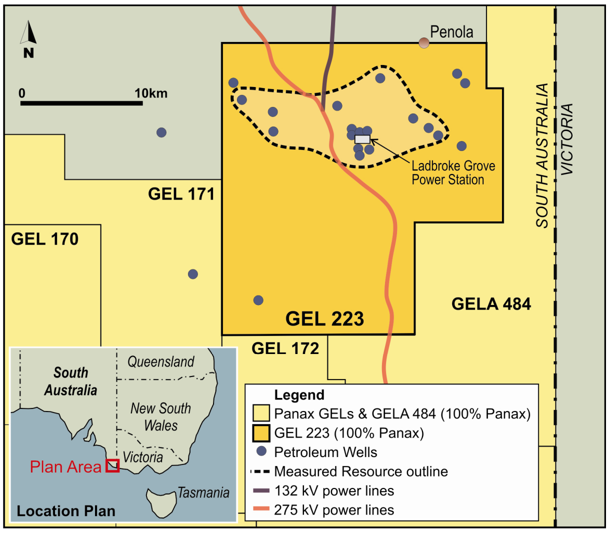

Figure 5. Surface outline of the Measured Geothermal Resources of the Penola Project.

Table 2. Estimated Geothermal Resource within the Pretty Hill Formation and deeper reservoir units for the Penola Geothermal Play. Resource estimates rounded to two significant figures.

Limestone Coast Geothermal Resources					
Trough	**Measured (PJ)**	**Indicated (PJ)**	**Inferred (PJ)**	**Total (PJ)**	**Report Date**
Penola	11,000	32,000	89,000	132,000	18/02/2009
Rivoli & St. Clair			53,000	53,000	28/01/2009
Rendelsham			17,000	17,000	28/01/2009
Tantanoola			130,000	130,000	31/03/2009
Total	**11,000**	**32,000**	**289,000**	**332,000**	

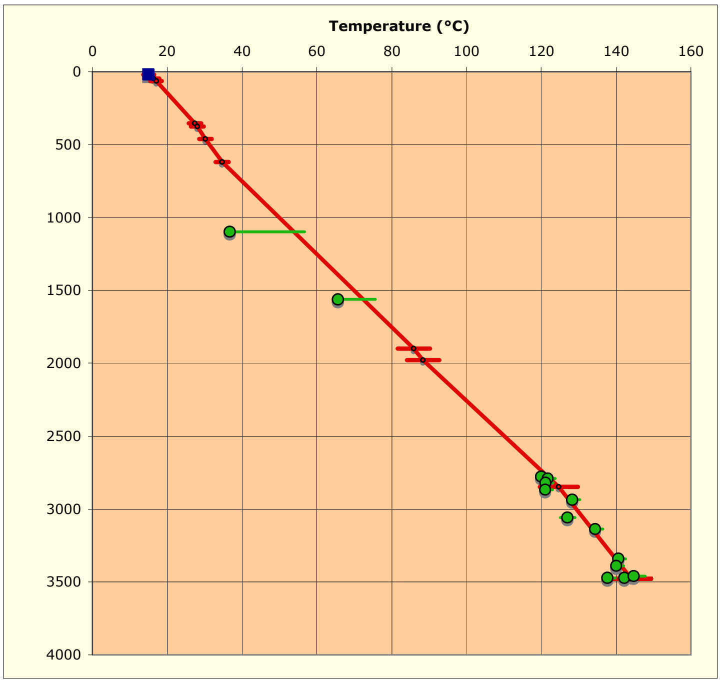

Figure 6. 1D heat flow model of combined temperature data from the Katnook wells. The temperature data have been obtained during logging runs and DST's.

5. LOCATION AND INFRASTRUCTURE

GEL 223 is located within 50km of Mt Gambier, which has an airport with twice daily services to Melbourne and Adelaide. The township of Penola (population 1,800) is located on the northern boundary of the exploration licence and is a centre for local services, communication, accommodation and basic supplies.

Most importantly, GEL 223 is transected by a transmission network of 275kV and 132kV power grid lines. The 275kV system is part of the Victoria-South Australia connection, while the 132kV system connects the 86 MW Ladbroke Grove gas fired power station to the broader South Australian transmission grid. Accordingly, the Penola Project may be connected to the transmission system either at the 275kV or 132kV voltage levels. Indications are there is sufficient capacity at two local substations to facilitate a low cost option (AUD$1-$2 million) for connecting the Demonstration Plant of the Penola Project.

6. SEISMIC INTERPRETATION

Seismic interpretation of the 3D seismic datasets has allowed a confident delineation of the top of the Pretty Hill Formation and the base of the rift. This has been used to estimate both the temperature and the volume of the target reservoir unit, the Pretty Hill Formation, with confidence. The 3D seismic surveys in GEL223 were interpreted. It was firstly reprocessed by interpolating a higher sample density and also converted to a depth dataset. The existing petroleum seismic data were then loaded to a workstation. The well data were loaded including well tracks, formation tops, well logs and time depth relationships. Synthetic seismograms were generated to correlate the well data. Well ties were checked for validity with the objective reservoir sequence. Five seismic horizons were interpreted over the 3D dataset including the key objective Pretty Hill Formation reservoir event. Faults were interpreted on every 25th inline and correlated spatially.

The seismic events were converted to depth and gridded. The depth interpretation of the top Pretty Hill Formation reservoir objective was used to define areas of known gas and potential gas accumulations, so that the location of the first geothermal well, Salamander-1 and future geothermal production wells, could be located to minimise the risk of encountering gas. The depth ranges for the target reservoir were also used with earlier modeling of temperature data of wells to determine the temperature range for aquifer water in the Salamander-1 well.

The seismic data was also processed to provide more information on the reservoir quality than from the well data alone. An 'acoustic impedance' inversion of the 3D seismic was undertaken to better identify the prospective reservoir section. This latter study aimed to generate a 'porosity cube' based on the 3D seismic and nearby well data, to assist in planning the Salamander-1 location and predict the likely well productivity. These seismic processing products were then used in the location selection to ensure the greatest probability that the Salamander-1 well location will achieve the production flow rates determined in the pre-feasibility study.

7. PRE-FEASIBILITY STUDY

Panax compiled a Pre-Feasibility Study of the Penola Project to determine the total costs per MWh of power generated from brine produced from the Pretty Hill Formation reservoir to provide an assessment of the economic viability of this project. The total cost per MWh is considered to be the cost per MWh of power generated after taking into account all plant and pump requirements. Total costs are defined to include both operating and capital costs (including drilling costs) on a whole of life basis (undiscounted and zero cost for funds). The result of this study provides an assessment of the economic viability of developing the Penola Trough "Measured Geothermal Resource". The Pre-feasibility Study is available from Panax's website, www.panaxgeothermal.com.au.

The Penola Project power generation is based on the production of 175kg/sec of brine (=166.4k gallons/hr (US)), at a temperature of 145˚C (293˚F) from each production well, and an injection temperature of 70˚C (158˚F)This Base Case using a standard binary organic rankine cycle binary geothermal power plant, has a Gross output of 6.7 MWe and Net output of 5.9 MWe and a net/net output of 4.5 MWe. Gross output is the output at generation terminals and Net output is Gross output minus all internal plant power demand, excluding facilities such as production and injection pumps. Net/net output equal net output minus well pump power demands (production and injection).The development of the Penola Project is based on a Gross output of 6.7 MW per production well. The development is divided up in three stages:

- a **Demonstration Plant** based on one production well
- the **Phase 1 Plant** based on a total of three production wells; and
- the **Phase 2 Plant** based on a total of ten production wells.

Costs assumptions have been bench marked from other geothermal operations around the world and from other published literature and are considered to be conservative. The base case plant inputs and plant outputs of the Pre-Feasibility Study have been subject to detailed review and assessment by Panax in association with expert external advice and review.

A summary of the output and total cost per MWh for the three stages and a summary of the total capital and operating costs per MWh is listed in tables 3 and 4 below:

The cost per MWh produced after plant and pump power demands (i.e. net plant, net pumps) is estimated at AUD$63 per MWh. This projected cost is highly competitive with other renewable forms of power generation, such as wind or solar thermal. The cost of connecting the Penola Project power generation to the grid (based on independent expert advice) adds approximately AUD$2 to the total cost per MWh generated, a direct reflection of the excellent infrastructure location of this project.

CONCLUSION

It can be concluded that the Penola Project represents a commercially attractive geothermal development proposition targeting a hot sedimentary aquifer which is well known from previous petroleum exploration. A pre-feasibility study indicates that a competitive total cost per MWh of AUD$63 can be achieved. Further, the plans for drilling the first well in the project, Salamander 1, are well advanced. Overall, the Penola Project has the scope to be of national significance in the quest to reduce carbon emissions through providing competitively priced, zero emission, base-load power, and to be the first grid connected geothermal electricity generator.

Table 3. Penola Project Summary of Base Case Output Gross, Net Plant and Net Plant/Net Pumps, Total Costs per MWh (AUD$)

	Output MW	$ MWh
Gross	67.0	42
Net Plant	59.0	48
Net Plant/Net Pumps	45.0	63

Table 4. Penola Project Capital and Operating Costs per MWh Phase 2 Plant (67 MW).

Capital & Operating Costs perMWh (Phase 2 Plant, AUD$'s)	
Capital Costs	$51
Operating Costs	$12
Total Costs	$63
Grid Connection	$2
Total	**$65**

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