

# Exploration and assessment of Hot Sedimentary Aquifer (HSA) geothermal resources in the Otway Basin Victoria

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The Otway Basin contains a number of Hot Sedimentary Aquifer (HSA) geothermal resources with potential for commercial development. The methodology Hot Rock Limited has used to assess these resources is detailed in this paper. The resulting stored heat estimates for the HSA resources of the Otway Basin is large, even by world geothermal standards. A total of 550,000 PJ of HSA resources have been so far estimated and declared by three companies.

While there is confidence in the estimation of in-place heat in the Otway Basin HSA resources and the rate that heat in geothermal water recovered to surface can be converted to electricity, there is less certainty as yet on the amount of heat that can be recovered and the rate it can be recovered. Both of these variables are determined by permeability in the geothermal reservoir.

By comparison with both HSA and volcanic geothermal systems elsewhere, and a detailed assessment of the structural geology at the Otway Basin tenements, HRL considers that the HSA resources in the Otway Basin are dominated by secondary fracture permeability, with primary permeability being subordinate. HRL is proceeding to drill in early 2010 two proof of concept wells into its flagship HSA project at Koroit. These wells are specifically targeted on both primary and secondary permeability, with the firm expectation that secondary permeability will prove to be dominant and that commercial grade temperatures and well flow rates will be obtained.

## Keywords:

Geothermal, Otway Basin, Hot Sedimentary Aquifer, HSA, resource assessment, Monte Carlo, proof of concept, generation potential, well targeting.

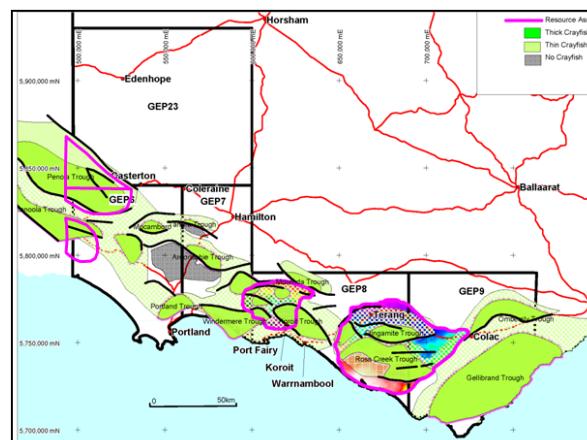
## Introduction

Hot Rock Limited (HRL) holds a large geothermal tenement position in Victoria of 27,500km<sup>2</sup> in five permits. Some 15,000km<sup>2</sup> of this holding contains rocks of the Crayfish Subgroup in the onshore portion of the Otway Basin within Victoria. These are predominantly sandstones of Cretaceous age and have known geothermal potential.

They occur in a series of individual depositional centres (shown coloured in both light and dark green in Figure 1), deposited onto the tops of

subsiding basement fault blocks developed along the northern margin of the rift zone which led to Australia separating from Antarctica during the breakup of Gondwanaland in late Cretaceous times.

The crustal thinning produced in this extensional tectonic environment allows for elevated heat flow through the Palaeozoic basement into the overlying sediments over most of the Otway Basin where geothermal gradients of 35 to 45°C/km are measured. This combination of regional shallow heat and large areal extent, thickness and hence volume of geothermal reservoir rock makes the Otway Basin a significant terrain for potential HSA geothermal development, even by world standards.



detailed data, of value for prospect scale studies, include seismic reflection data, geological logs and cores from existing petroleum and ground water wells, and measurements of temperatures and other data in these wells.

In addition to use of existing data, HRL has applied to its HSA exploration studies in the Otway Basin a number of exploration methods that are routinely used in the exploration and delineation of volcanic geothermal systems. The most significant of these has been the use of magneto-telluric (MT) resistivity surveying and the application of geothermal geochemistry interpretative methods to ground water and petroleum well fluids analyses.

Key deliverables from the HRL exploration studies include the following:

*Starting Point:* An initial review of geothermal gradients as a tool for prioritizing areas for detailed geothermal assessment.

*End Point:* A range of 3-D models gridded at typically 100m centers over geothermal resource areas of typically 300 to 500 km<sup>2</sup> areal extent which include:

- Stratigraphic models defining formation tops, bottoms, vertical (cross sections) and horizontal sections (slices in plan)
- Structural geological models
- Thermal models showing distribution of isotherms in 3-D, isothermal sections in 2-D combined with geology, estimates of temperature in each grid block at any depth
- Multi discipline, integrated, conceptual hydro geological models which form the basis for subsequent resource assessment, and formulation of exploration drilling and development strategy.

## Assessment of HSA Resources

The Otway Basin HSA resources have been assessed in terms of in-place stored heat contained in the Crayfish subgroup reservoir rocks between assigned upper and lower depth limits. This involves initially considerations of resource thickness, lateral extent and hence volume, followed by considerations of porosity and temperature from which heat contained in both the rocks in the resource volume and hot water contained in pores and fractures in the reservoir rocks can be estimated.

The upper depth limit to the resource is referred to as the resource temperature cut off (or abandonment temperature) and the lower depth limit is an assumed depth limit to which geothermal fluids can be reasonably recovered

from the resource, and is taken to be a practical drilling depth limitation.

Estimates of temperature values throughout the resource volume have been obtained from 3D thermal modelling. Porosity has been assessed conservatively at 10% throughout and although this is an important parameter in considering the amount and rate at which hot water can be recovered from the geothermal resource, the amount of heat stored in the rock and the water is relatively insensitive to porosity.

The values used for the above parameters in HRL's assessment of HSA resources are given in Table 1 where they are compared with a range of values used by other developers working in the HSA environment. Relative to these other values, those used by HRL are conservative.

Table 1: Comparison of parameters used by HRL for estimating the thickness, volume and in-place heat of HSA geothermal resources.

Parameter	Values used by HRL	Values used by others in OB
Minimum resource temperature	130°C (GEP6 and 23) 140°C (GEP-8)	125°C
Power plant rejection temperature	70°C	70°C
Resource base: i.e. practical depth limit for recovery of geothermal fluids	4500m	5000m
Porosity	10%	5 % to 15%
Minimum reservoir thickness	500m	Nil to 250 m

The computation of in-place heat has been undertaken by HRL on a probabilistic basis using a purpose developed Monte Carlo simulation model in which probability distributions are used to characterise the key resource assessment parameters. The stored heat is summed over individual resource blocks for which formation tops, top and bottom resource limits and modelled temperature distribution have been gridded at 1000m intervals. The Monte Carlo model is run 2,000 times to obtain the frequency distributions and cumulative probability distributions for the stored heat contained in the geothermal resource volume.

The results of the resource assessments are reported in accordance with the Australia Geothermal Reserve Reporting Code (1st edition, 2008) in terms of in-place stored heat. At this stage in the exploration of HRL's Otway Basin HSA resources, two types of geothermal resources have been determined:

- "Inferred resource" – where temperatures are not directly measured, and

- “Indicated resource” where temperatures are measured in-situ within the geothermal resource. Typically the former is declared where temperatures are measured in petroleum and / or deep ground water wells that have not penetrated as deep as the geothermal reservoir in the Crayfish Subgroup and the latter is where existing wells have been drilled into the Crayfish thus allowing for temperatures to be measured directly within the geothermal resource. If and when wells drilled into the geothermal resource are successfully flow tested then the “Inferred resource” estimate can be upgraded to “Measured resource”.

## Results of Resource Assessments

HRL has completed resource assessments at the following Crayfish Subgroup depositional centres in the Victorian portion of the Otway Basin. These centres are shown outlined in pink in Figure 1 and include (from west to east):

- GEP-23: Penola Trough
- GEP-6: Penola Trough
- GEP-6: Tantanoola Trough
- GEP-8: Koroit Trough
- GEP-8: Ross Creek Trough
- GEP-8/9: Elingamite Trough

From these assessments a number of geothermal resources have been declared, as summarised in Table 2.

Table 2: Results of estimations of Inferred and Indicated HSA geothermal resources identified and declared by HRL within GEP-6, GEP-8 and GEP-23 in the Otway Basin.

Resource	Tenement	Resource Area	Resource Volume	Indicated Resource	Inferred Resource	Report Date
		km2	km3	PJ	PJ	
Koroit	GEP-8	50	47	7,600		
Koroit	GEP-8	400	340		59,000	
<b>Koroit</b>	<b>GEP-8</b>	<b>450</b>	<b>387</b>	<b>7,600</b>	<b>59,000</b>	<b>1-Oct-09</b>
Penola	GEP-23	20	24	5,000		
Penola	GEP-23	120	150		29,000	
Penola	GEP-6	8	9	1,700		
Penola	GEP-6	290	306		55,000	
<b>Penola</b>	<b>GEP23 &amp; 6</b>	<b>440</b>	<b>490</b>	<b>6,700</b>	<b>84,000</b>	<b>27-Jul-10</b>
<b>Tantanoola</b>	<b>GEP-6</b>	<b>180</b>	<b>130</b>		<b>22,000</b>	<b>27-Jul-10</b>
<b>Totals</b>		1,070	1,010	14,300	165,000	<b>180,000</b>

## Power Generation Potential

The estimated geothermal resources declared to date by HRL in the Otway Basin total 15,000 PJ for Indicated resources and P165,000 PJ for Inferred resources, at the P50 level. These figures represent very large store of geothermal heat, however, not all of this heat is available for conversion to electricity. Only a small amount of the geothermal heat will be recoverable from the resource and only a small amount of the heat recovered to surface will be converted to electricity in a power plant due to thermal and mechanical energy losses.

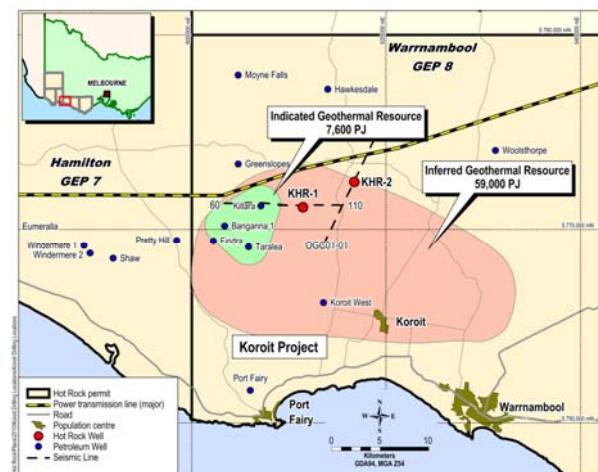


Figure 2: "Inferred" and "Indicated" geothermal resources declared in the Koroit area, GEP-8 (Source: HRL, 2009).

Representative values for HSA geothermal resource are 5% and 12%, respectively, which means that only about 1% of the in-place heat in the geothermal reservoir will be converted to electricity. On this basis, only some 1,000 PJ of the total value of 180,000 PJ of heat contained in the Koroit geothermal resource, would be able to be extracted and converted to electricity. Nonetheless, 1000 PJ of energy in electrical energy terms is still a large value, equivalent to about 300,000GWh. To achieve generation at this level a power plant with a generation capacity of about 1300MWe would be required to operate at a capacity factor of 90% for a period of 30 years.

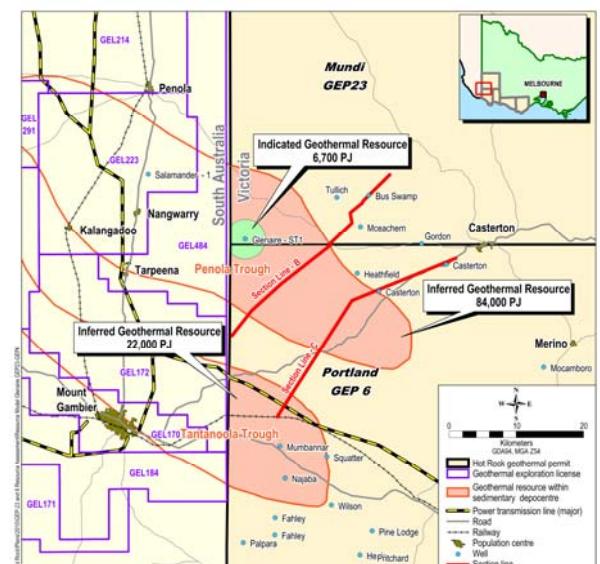


Figure 3: "Inferred" and "Indicated" geothermal resources declared in the Penola and Tantanoola Troughs in GEP-23 and GEP-6 (Source: HRL, 2010)

In addition to the 180,000 PJ geothermal resources estimated by HRL, two other geothermal developers have also delineated,

assessed and declared HSA geothermal resources in the western and eastern ends of the Otway Basin, on either side of HRL's tenements. The total declaration of geothermal resources to date from the three companies for the onshore Otway Basin in both Victoria and South Australia totals some 550,000 PJ (Table 3). On the same basis as the calculations above for Koroit, this amount of thermal energy has the potential to generate some 900,000 GWh of electricity and this would require a power plant generating capacity of some 3,500 MWe for 30 years.

Table 3: Summary of all declared HSA geothermal resource assessments over the greater Otway Basin

Trough in Otway Basin	Tenement	Developer	HSA Inferred Resource PJ	HSA Indicated Resource PJ	HSA Measured Resource PJ	HSA Estimated Total PJ
Tantanoola	GEP-6	HRL	77,000	1,700		78,700
Koroit	GEP-8	HRL	59,000	7,600		66,600
Penola	GEP-23	HRL	29,000	5,000		34,000
Anglesea	GEP10	Green Earth	40,000			40,000
Tantanoola	GEL-170, 171, 172	Panax	130,000			130,000
Rendelsham	GEL-170, 184, 212	Panax	17,000			17,000
Rivoli St Clair	GEL-173	Panax	53,000			53,000
Penola	GEL-223	Panax	89,000	32,000	11,000	132,000
<b>Totals</b>			<b>494,000</b>	<b>46,300</b>	<b>11,000</b>	<b>551,300</b>

The in-place heat stored in the HSA resources in the Otway Basin and the potential generating capacity of these are large, even by world geothermal standards considering that the geothermal industry has a global installed capacity of 11,000 MWe.

The confidence in the estimation of heat in-place in the Otway Basin HSA resources is relatively high, as is the rate at which the heat in geothermal water recovered to surface can be converted to electricity. Of lesser certainty is the amount of heat that can be recovered from the HSA resource and the rate at which it can be recovered - both of these are determined by permeability in the geothermal reservoir.

## Permeability

Permeability in Otway Basin HSA reservoirs can be of two types (1) primary permeability, associated with natural porosity in the Crayfish Subgroup sandstone reservoir rocks, and/or (2) secondary permeability associated with faults and fractures in the reservoir rocks.

### Primary permeability

The petroleum industry has generated considerable data on porosity and permeability throughout the Otway Basin from geological and electrical logging and analysis of cores and cuttings from petroleum wells. Poro-perm data for the Pretty Hill sandstone from petroleum wells in both Victoria and South Australia (but predominantly from the latter) are shown in Figure

4. The pink line is a regression fit for channel sands in the Pretty Hill and the red line is the same for bar sands in the Pretty Hill. Clean channel sands are the prime target for geothermal development being more coarse grained and with both higher porosity and permeability at any depth.

As well as variation in primary permeability in the Otway Basin with depth there is also significant variation in the character and quality of the Crayfish Subgroup reservoir facies, depending on provenance of source material and environment of deposition.

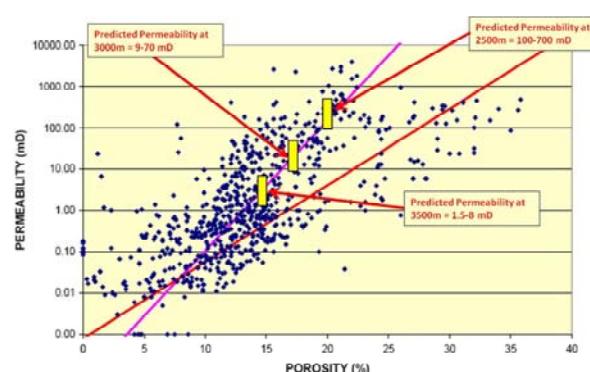


Figure 4: Summary of declared geothermal resource assessments in the greater Otway Basin with HSA geothermal development potential *Source: 3DGeo (2009)*

From a detailed analysis of seismic data and petroleum well data, the Koroit geothermal resource is assessed to have particularly good reservoir facies characteristics having thick accumulations of clean coarse grained sands, with minimal lithic material, especially in the Lower Pretty Hill Formation (3DGeo 2009). Based on statistical analysis of the poro-perm data in Figure 3, estimates have been of porosity and permeability potential with depth in the Koroit geothermal resource (3D Geo, 2009). These estimates are for better than average poro perm values than occur for the Otway Basin.

The variation in poro perm with depth in Figure 4 is instructive as it confirms:

- porosity in the Pretty Hill Formation to be reducing with depth, from 20% at 2500m to 14% at 3500m, and
- permeability decreasing by two orders of magnitude between 2500 and 3500m.

In spite of these reductions in poro-perm with depth, the evidence is that permeability within the Pretty Hill at Koroit will still be sufficient to give commercial geothermal well flows from primary reservoir permeability alone. For example, assuming, as a conservative case, that the lower value in the range of the permeabilities predicted at each the 3 depth ranges in Figure 4 apply, and a net to gross ratio of 50%, then a transmissivity

of 13 Dm would be expected over the depth range of 2500 to 3500m, with an expected temperature range of 130 to 170°C. For this transmissivity value, a standard size geothermal well completion (with a 9-5/8 inch diameter open production hole) can be expected to yield a flow rate of 90 kg/sec, and for a large diameter well completion (with 12-1/2 inch diameter production hole) to yield a flow rate of 160 kg/sec (SKM, 2009).

### Secondary permeability

The importance of secondary permeability in HSA geothermal systems seems not to be well appreciated in the Australian geothermal community. Few if any geothermal systems in the world, of any type, produce from only primary permeability. For example, for the following two key overseas analogues for HSA geothermal resources in Australia:

- Heber and East Mesa fields in Southern California: secondary permeability controls an upflow of hot geothermal fluids from basement into overlying fluvial sediments where primary permeability is high. Geothermal wells produce from both fractures around the upflow and primary permeability in the sediments
- Southern Germany: high flow rates (up to 140 kg/sec) are obtained from deep intersections (at depths of up to 4500m) of well bores with fractures in Malm limestone with little if any evidence of primary permeability

In conventional volcanic geothermal systems developed in sedimentary reservoir rocks, fracture permeability is also the major control on geothermal fluid hydrology and well productivity. For example:

- The large and very well documented Geysers geothermal field in California produces steam from fractured greywacke basement rocks which have low primary porosities and permeabilities.
- The Ohaaki geothermal field in New Zealand has good production well flows from fractured greywacke basement rocks which underlie lavas and volcani clastics.

In the Otway Basin there are well developed faults and structures at both large and small scale which affect both the Palaeozoic basement rocks and the overlying sedimentary successions, particularly the Crayfish Sub group. The present-day stress regime in the Otway Basin is on the boundary between oblique-slip and reverse faulting. The NW-SE maximum horizontal stress orientation is calculated at ~140 degrees N. Analysis of structural geologic data has been interpreted to show that faults and fractures orientated approximately WNW-ESE to NE-SW are consistent with the present day stress regime and structures on these orientations are considered to be mechanically open, with good

potential for providing secondary permeability channels for geothermal fluid flow (3D-Geo, 2009). The potential for secondary fracture permeability is therefore considered to be good in the HSA resources of the Otway Basin.

HRL is proceeding in early 2010 to drill two proof of concept wells at its flagship Koroit geothermal project. These two wells are specifically targeting major faults at depth as primary well targets. A subordinate target is porosity in the upper levels in the open production hole where porosity and permeability prospects are best. Having the highest geothermal gradient in the Otway Basin (of up to 46°C/km) at the Koroit resource, a minimum production temperature of 130°C can be targeted at the top of the geothermal reservoir within the Crayfish Formation at depths of only 2500m. At this comparatively shallow depth, poro-perm prospects are much better than at greater depth, particularly below 3500m as evident from Figure 4.

HRL's "Proof of Concept wells" are therefore designed to intersect an optimum combination of primary and secondary permeability and HRL is optimistic of successful outcomes in terms of good permeability and transmissivity results and commercial grade temperatures and well flow rates.

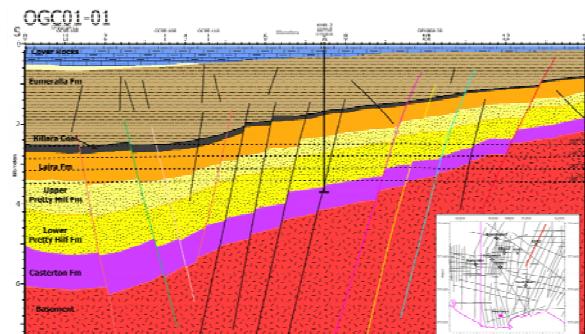


Figure 5: Geological section, Koroit HSA resource, showing proof of concept well targeted on (1) deep intercept with major fault target and (2) primary porosity target (upper and lower Pretty Hill Formations from 2500m) *Source: 3DGeo (2009)*

## Summary and Conclusions

The Otway Basin contains a number of HSA geothermal resources with good potential for commercial development.

These resources exist as a result of the favourable combination of:

- elevated geothermal gradients of typically around 40°C/km, but as high as 46°C/km in prime resource areas such as Koroit in GEP-8.
- Thermal gradients in this range are sufficient to obtain commercial grade geothermal temperatures within practical drilling depths

- The fortuitous occurrence of thick stratigraphic sequences of quartz rich sandstones in the Crayfish Subgroup reservoir rock within the same depths that commercial temperatures occur and within practical drilling reach

The stored heat contained in the HSA resources of the Otway Basin are large, even by world geothermal standards. A total of 550,000 PJ of HSA resources have been so far estimated and declared by three companies. Although current expectations are that only some 0.5% of this in-place heat can be recovered from the geothermal resources and converted to electricity, the generation potential on even this basis is large, requiring some 3,500MWe of generation capacity for 30 years.

There is confidence in the estimation of heat in-place in the Otway Basin HSA resources and the rate that heat in geothermal water recovered to surface can be converted to electricity. However, there is less certainty yet on the amount of heat that can be recovered from the HSA resources and the rate at which this can be recovered - both of these variables are determined by permeability in the geothermal reservoir.

HSA resources seem to be viewed by the Australian geothermal community as having only primary permeability. By comparison with both HSA and volcanic geothermal systems elsewhere, and a detailed assessment of the structural geology of its Otway Basin tenements, HRL views the Otway Basin resources to be dominated by secondary fracture permeability, with primary permeability being subordinate to this.

HRL is proceeding in early 2010 to drill two proof of concept wells at the Koroit HSA resource, specifically targeting both primary and secondary permeability with the firm expectation that secondary permeability will prove to be dominant and that commercial grade temperatures and well flow rates will be obtained.

### Statement of Competent Person

The information in this paper that relates to Exploration Results, Geothermal Resources or Geothermal Reserves is based on information compiled by Peter Barnett who is a full time employee of Hot Rock Limited. He has sufficient experience which is relevant to the style and type of geothermal play under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the Code. In this work he has drawn freely from reports on HSA geothermal resources in the Otway Basin prepared under his supervision, by both staff of Hot Rock Limited and by external consultants, notably 3D-Geo of Melbourne. The assessment of stored heat and levels of Indicated and Inferred Resources and the reporting of these have been

undertaken solely by Peter Barnett. Peter Barnett consents in writing to the inclusion in the report of the matters based on his information in the form and context in which it appears.

### Acknowledgments

This paper draws freely on graphical material prepared by 3D Geo of Melbourne under contract to HRL, particularly the power point presentation for this paper to be given at the conference.

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