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Geophysical Inversion of 3D Seismic Data in Panax's Limestone Coast Geothermal Project to Determine Reservoir Porosity

Margarita A. Pavlova[1] and Ian Reid[2]

[1]Schlumberger Victory House, Churchill Court, Manor Royal, Crawley, RH10 9LU United Kingdom
[2]Panax Geothermal Ltd, Ground Floor, 20 Railway Terrace, Milton, Queensland 4064 Australia

[1]mpavlova@slb.com; [2]ireid@panaxgeothermal.com.au

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ABSTRACT

Panax Geothermal Limited is developing a geothermal resource in South Australia, the Limestone Coast Project, which is a conventional "hot aquifer" reservoir in a deep sedimentary basin. The initial development is the Pretty Hill Formation sandstones in the Penola Trough of the Otway Basin. The area is an exploited gas basin with modern 3D seismic and excellent existing petroleum well data coverage. Wireline logging in the petroleum wells has already identified a low to moderate temperature geothermal resource, and reservoir quality is well-understood based on numerous well cores and wireline log data. This resource is currently at the development stage, the first known such resource in Australia.

Salamander-1, the first production well on the project, is scheduled to be drilled in Panax's Geothermal Exploration License 223 (GEL223), in the second half of 2009. The Limestone Coast Geothermal Project is designed to deliver the first proof that conventional geothermal resources within Australia's sedimentary basins can be used to generate large amounts of competitively priced, zero-emission, base-load power.

Innovation is required to optimize productivity. Panax worked with Schlumberger to derive data on the Pretty Hill Formation reservoir properties. This 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. The method used is genetic inversion of the 3D seismic (a patented Schlumberger product integrated within the Petrel 2009.1 seismic to simulation software). It produces a nonlinear multitrace operator that is applied to the seismic cube, and converts it into the property described by the logs used during the training phase. Wireline log sonic-derived porosities from six petroleum wells were used to train the data and invert the seismic cube to the porosity volume. The modeling indicated that relatively attractive reservoir qualities comparable to those measured in nearby gas wells could be expected at the proposed Salamander 1 location. This paper summarizes the results of this study together with the status of the geothermal development.

1. INTRODUCTION

1.1 Geothermal Energy in Australia

Reducing CO2 emissions is a vital component of worldwide energy challenges. A cost-effective energy source, alternative to the fossil fuels, needs to be found to curb global warming caused by CO2 emissions.

Geothermal is a safe, alternative energy resource providing zero-emission base-load power. So far, geothermal energy is considered to be the most cost-effective of all the alternative energy sources.

The Australian geothermal industry is rapidly growing due to the abundance of hot and hydrothermal energy resources plus favorable market conditions. Nationally, over 43 companies have applied for 363 geothermal licenses. South Australia has the greatest number of geothermal exploration licenses of all the states in Australia.

Currently two different types of different geothermal systems are under investigation in Australia: hot dry rock and hot wet rock. Hot dry rock systems are found in deep (>3,000 m) and hot (>150^{o}C) granites. The heat is extracted from these granites by circulating water through them in an engineered, artificial reservoir or underground heat exchanger. This artificial reservoir needs to have an interconnected fracture system to allow the passage of water, so in most cases it requires induced seismic fracturing of the granites as well as a supply of water for circulation. The biggest hot dry rock company in Australia is Geodynamics, operating in the Cooper Basin. Hot wet rock systems are usually shallower, less hot (<150^{o}C), and located in sedimentary rock reservoirs. Unlike hot dry rock systems, their technical and commercial risks are not related to the development of deep underground reservoirs as it targets existing hot geothermal brines in buried sandstone reservoirs. The time frame from drill testing to development is reduced in comparison with the hot dry rock reservoirs. In addition, drilling costs are substantially lower in this geological environment.

1.2 Field and Available Data Description

The area of this study, the Penola Trough, is located in the onshore Otway basin, South Australia (Fig. 1). It is a proposed wet rock geothermal system. It is an area of historical and present-day gas production from five gas fields. Various data were recorded and interpreted during the petroleum exploration stage, such as 2D and 3D seismic surveys and 27 deep petroleum wells with well wireline logs and cores. It is a part of Panax Geothermal Limestone Coast Project, which is now approaching the drill test phase.

The Limestone Coast Project is a proposed geothermal energy development of a naturally occurring aquifer in porous rocks with no requirement to artificially fracture the rocks. Several indicators point to the high potential of this geothermal system — one is high temperatures recorded in Katnook 4 (146^{o}C). Another is >875 m of Pretty Hill Formation sandstone penetrated with high net sand, suitable as a reservoir. There is also developed infrastructure in place within proximity to the power grid, a gas-fired plant, and potential cogenerated heat applications.

Logging of the wells for gas exploration has provided measurements of the porosities, which were derived from sonic logs. By correlating these porosity values with drill core permeability measurements, a measure of permeability was obtained. Finally, the transmissivity was derived from integrating permeability over formation thickness.

In the past, Boult and Donley (2001) have created an inversion porosity cube using Hampson and Russell's Emerge software to aid the hydrocarbon volumetric calculation at the Pretty Hill Formation. However, this porosity cube included 50 ms (milliseconds two-way time TWT) of the seal and 100 ms of the reservoir formation (less if the base of the well was encountered first) and the deepest inverted data was at 2,100 ms. The study proposed in this article examines a window over 400 ms window and creates and inversion cube for the depths up to 2,400 ms which is more suited for the geothermal exploration purposes.

2. METHODOLOGY

2.1 Data Preparation

Panax Geothermal Limited has undertaken petrophysical evaluation on wireline logs from the wells Pyrus 1 (479 m of Pretty Hill Formation), Balnaves 1 (164 m), Haselgrove South 2 (128 m), Katnook 2 (603 m), Ladbroke Grove 1 (875 m) and Redman-1 (140 m). The petrophysical evaluation over these sections was calibrated to the porosity measurements in the available core data. Review of the logs and cores from the wells Ladbroke Grove 1 and Balnaves 1 indicate that the log derived porosity using the sonic log is more appropriate than the density log, due to the hole conditions having affected the latter's reliability. The gamma ray logs were used to estimate Vshale, which was used to correct the sonic log porosity to effective porosity.

There was generally a good match between the sonic derived porosity logs and the core porosities used to calibrate them. Balnaves 3D filtered migrated seismic cube was used as input for the inversion.

2.2 Genetic Inversion Theory

Seismic data is widely used to aid hydrocarbon exploration by providing in-fill data on the rock properties between wells. Many inversion techniques are available that use seismic for property prediction based on the correlation between the property (e.g., acoustic impedance, porosity, Poisson's ratio) and the seismic.

Genetic inversion is a new algorithm incorporated into Petrel 2009.1 seismic to simulation software. Specifically it does not require an input wavelet or initial model like many other currently available poststack inversion methods. It also allows getting results quicker compared to the traditional methods. Genetic inversion is based on the neural network process but with the addition of the genetic algorithm which together generate a nonlinear multitrace operator. This multitrace operator is produced as a result of training a seismic subvolume against well data. And it is used to invert the seismic data into the desired well log response producing a best fit to the given well data (Figs. 2, 3). (Veeken et al., 2009). The nonlinear genetic inversion can be distantly compared to the "colored inversion", which uses a linear algorithm (Lancaster and Whitcombe 2000, Veeken 2007). The linear mode computes a series of weights derived by a curve fitting procedure that utilizes a least-squares minimization, while in the non-linear mode a neural network is trained, using the selected attributes as inputs (Figure 2, 3). The more complex genetic inversion scheme generates improved results, because it better honours subtle changes in the input dataset (Veeken et al, 2009). This phenomenon has been demonstrated already by Hampson et al. (2001), who pioneered the neural network application for seismic reservoir characterization purposes. Hampson et al 2001 shows how a combination of seismic attributes is used to create a function that links the seismic to the petrophysical property in order to match the given well data (e.g., Hampson et al., 2001, Boult and Donley, 2001). The complexity of this multi-attribute method is that it is difficult to define attributes that should be used and the combination varies from volume to volume. It is also difficult to control the prediction quality and there is a chance of neural net overtraining (Priezzhev et al., 2009) and especially overfitting when the training set is "memorized" in the network (Van der Baan and Jutten, 2000).

Genetic inversion requires a single seismic cube (e.g.,, post-stack migrated true amplitude or acoustic impedance) and a set of wells with a petrophysical property which has some relation to seismic (e.g., porosity, velocity, bulk modulus). During the learning phase of the neural net instead of the back propagating the error (standard neural net algorithm) the genetic algorithm is used. This algorithm updates the weights for the neural network using the Evolutionary approach (i.e., Selection, Cross-over and Mutation). The use of the genetic learning algorithm allows the Neural Net to find the global error minimum of the function and therefore an optimal solution, while standard Neural Net algorithms generally reach the local minimum error of the function (Veeken et al., 2009).

As mentioned earlier the unknown weights in the Neural network are updated by the genetic algorithm. Initially 50 weight combinations are chosen at random, which all pass through the first iteration of the Neural network. The output result is then compared with the observed datasets (i.e., well logs) by calculating an error function. As soon as an error value is computed for each of the 50 input weight combinations the process enters into the Genetic part of the algorithm: Selection, Crossover and Mutation (Klinger et al., 2008).

Selection – weight combinations with the smallest error are selected. In analogy to the natural selection hypothesis of Charles Darwin which favors only the best adapted individuals to survive; in this case the survival criteria is given by the individual with the smallest error.

Cross-over – weight combinations are exchanging single weights from one combination to another (the number of exchanged weights can be singular or multiple). This crossover phenomenon occurs with a given probability after and within each iteration. Mutation – as in evolution single weights are exchanged randomly from one weight combination to another. This ensures that the process does not converge to a local minimum. The mutation event occurs with a higher probability as soon as the error function starts to stabilize (i.e., reach a minimum).

It is important that a population has a constant number (e.g., 50) at each iteration of the inversion. Thus, even if selection reduces the size of the population by taking, for example, the 10 best weights, applying "cross-over" and "mutation" to those selected combinations of weights will recreate a full set of 50 "chromosomes" in the population.

The output of this workflow is a nonlinear multitrace operator which is applied to the whole seismic dataset, and transforms it into the property described by the logs used during the training phase (Klinger et al., 2008).

Seismic subcubes represent the operator structure (i.e., multitrace or 3D) and are utilized during the training and the modeling phase (Fig. 4). The middle trace passes through the well and the number of surrounding traces can be set from 0 to 21 in InLine and Xline directions. The vertical range can be 10–200 ms. Vertical as well as lateral components are taken into account to establish the operator. The program allows input of the top and bottom surfaces between which the inversion is run. Computation of the derived neural network operator is made step by step from top surface down to the bottom surface, each step being equal to the seismic sample interval (e.g., 1 to 4 ms) (Veeken et al., 2009).

2.2 Application of Genetic Inversion

The training wells were: Ladbroke Grove 1, Katnook 2, Haselgrove South 2, Pyrus 1 and Balnaves 1. Redman 1 was used for quality control (QC); it was not used in the training phase and was compared against the inverted porosity volume.

The porosity logs were smoothed to match the frequency of the seismic data. The "sm_PHIE_8" are the porosity logs smoothed using a box filter with the arithmetic method over an 8 m window length.

The Settings section of the genetic inversion controls the number of seismic samples that are included in the training.

The top Pretty Hill Formation seismic horizon was used to create a vertical window of interest. The inversion was run between two surfaces representing the Pretty Hill Formation from 50 ms above to 350 ms below. This vertical interval of 400 ms was chosen as an optimum. It would be mathematically impractical to try and establish the statistical relationship for the whole Pretty Hill Formation sequence where logged porosity exists. As the training logs were constrained by the two surfaces, the inversion results were also bounded by these surfaces.

Advanced options allow definition of the "maximum number of iterations" and the desired "correlation threshold." The inversion stops once either of the above mentioned parameters is reached.

"Nodes in hidden layer" is the neural net concept of describing the number of cells in the hidden layer used to compute the inversion operator. The "weight decay" is the neural network smoother and overfitting prevention parameter. By increasing this parameter the correlation of the training wells usually decreases but the correlation of the QC wells might increase as a result of less overfitting of the training data.

When inversion stops, the inverted porosity 3D SEGY cube is produced and the message log gives information on the correlations. Correlation per well is computed by crossplotting the input and the inverted porosity that is extracted from the SEGY cube along the well. The linear regression coefficient is then calculated on the points cloud. For the global wells correlation, all the input porosity well logs are crossplotted with inverted porosities in all wells and one single linear regression coefficient is computed for all of them. This method is valid if log values of the same order of magnitude for all the wells exist. If this is not the case, it may end up in situations where there is a higher global correlation factor than the one taken for each well individually (Jimmy Klinger).

3. RESULTS AND DISCUSSION

As seen in Fig. 6 the smoothed porosity log closely follows the original wireline measured porosity, but due to the smoothing window length it does not capture porosity fluctuations of thin beds. High-frequency information such as thin beds is not likely to be preserved by the genetic inversion as the seismic does not contain equivalent high frequencies. In traditional inversion methods the initial model does contain a larger frequency bandwidth because it is built using well logs, but the seismic is usually not able to represent this part of the data.

The genetic inversion output correlation between the smoothed and inverted porosity was calculated at the wells as follows:

Global Correlation = 0.6607936

	Correlation	Samples
Training wells:		
Pyrus 1	0.7560384	87
Katnook 2	0.6573857	79
Balnaves 1	0.6216437	17
Ladbroke Grove 1	0.5560895	96
Haselgrove South 2	0.5303227	35
QC well:		
Redman 1	0.6622095	27

As seen in Fig. 7 the inverted porosity matches the smoothed porosity in Katnook 2, Pyrus 1, Balnaves 1, Redman 1, and in most of Ladbroke Grove 1. Some of the Ladbroke Grove 1 well (2,900–3,100 m SSTVD) has a discrepancy between the output and input porosities. A possible reason for this is that there could be subseismic resolution thin sand beds. Also, as can be seen in the extracted seismic (radial extraction with the azimuth of 60 degrees and with 50 traces displayed each side from the well), there are no high amplitudes in that depth range in comparison to the prominent amplitude peak observed at the Pretty Hill (~2500 m SSTVD) (Fig. 7).

In Haselgrove South 2, the inverted porosity matches the shape of the smoothed porosity log but does not match the scale. Not much variation is observed in both the smoothed log and the extracted seismic, and in such situations the genetic inversion algorithm is not likely to give a good match. Some diversity in the input data usually allows the genetic algorithm to utilize its optimization better (Veeken et al, 2009). The Haselgrove South 2 well is located ~6 km east from the main interest area containing Ladbroke Grove 1 and the Salamander 1 location.

Higher porosities can be seen predicted in the Salamander 1 location, and in Ladbroke Grove 1 and other wells close to the top of the Pretty Hill formation (Figs. 7, 8). Fig. 9 shows the extent of inverted porosity cube which was produced.

Inverted porosity and seismic amplitude in the vicinity of the Salamander 1 location are similar to the values in the area around Ladbroke Grove 1. The inverted seismic data porosity volume provides confidence that the reservoir quality at Salamander 1 well location will be comparable with that encountered in Ladbroke Grove 1. The seismic porosity cube also gives some indication as to the extent of the sandstone bodies both laterally and vertically, and thus provides some confidence as to the sustainability of production from Salamander 1 and allows avoidance of "short-cutting" between cooler reinjected water and production. Note the higher-porosity elongate zone between Ladbroke Grove 1 and the Salamander 1 location (Fig. 10a). This is interpreted to be a sandstone channel fill deposit. Extraction of the seismic amplitudes along the top Pretty Hill Formation also shows higher values in the area between Ladbroke Grove 1 and the Salamander 1 location (Fig. 10b). This suggests the presence of a single sandstone body over 4,000 m long and 600 m wide and tens of meters in width. Reservoir modeling is planned to assess the suitability of interpreted sandstone bodies such as these for reinjection and completion in future geothermal development. Preliminary modeling indicates that such sandstones stacked at Salamander 1 should sustain production for 30 years. There are future plans to recomplete one of the existing depleted gas wells as a water injection well for the production from Salamander 1.

At the time of submission of this paper, Salamander 1 was planned to be drilled in the second half of 2009. It is intended that wireline logs will be acquired to ensure a suitable well seismic correlation of the well, and it will be used to revise the porosity inversion and improve the prediction of the distribution of Pretty Hill Formation reservoirs in the subsurface.

CONCLUSION

Petrel genetic inversion produced an inverted porosity cube based on the correlation of smoothed porosity logs with the 3D poststack seismic amplitude volume. Comparison of the inverted and wireline porosities suggests that the genetic inversion produced a robust property prediction at the 6 input well locations over the 400 ms time window. The genetic inversion interface allows the user to fine-tune the algorithm parameters and optimize the inversion result for the given input dataset.

Based on the inverted porosity cube, a location for Salamander 1 geothermal well was determined. At the chosen location, Salamander 1 porosity is predicted to be comparable to the measured Ladbroke Grove 1 porosity. The inverted porosity cube has also provided insights into the distribution of Pretty Hill Formation sandstones for reservoir modeling of future geothermal production and injection. The Salamander 1 well results will be incorporated into a future porosity inversion and used for larger-scale geothermal development planning and the locations of further production and injection wells.

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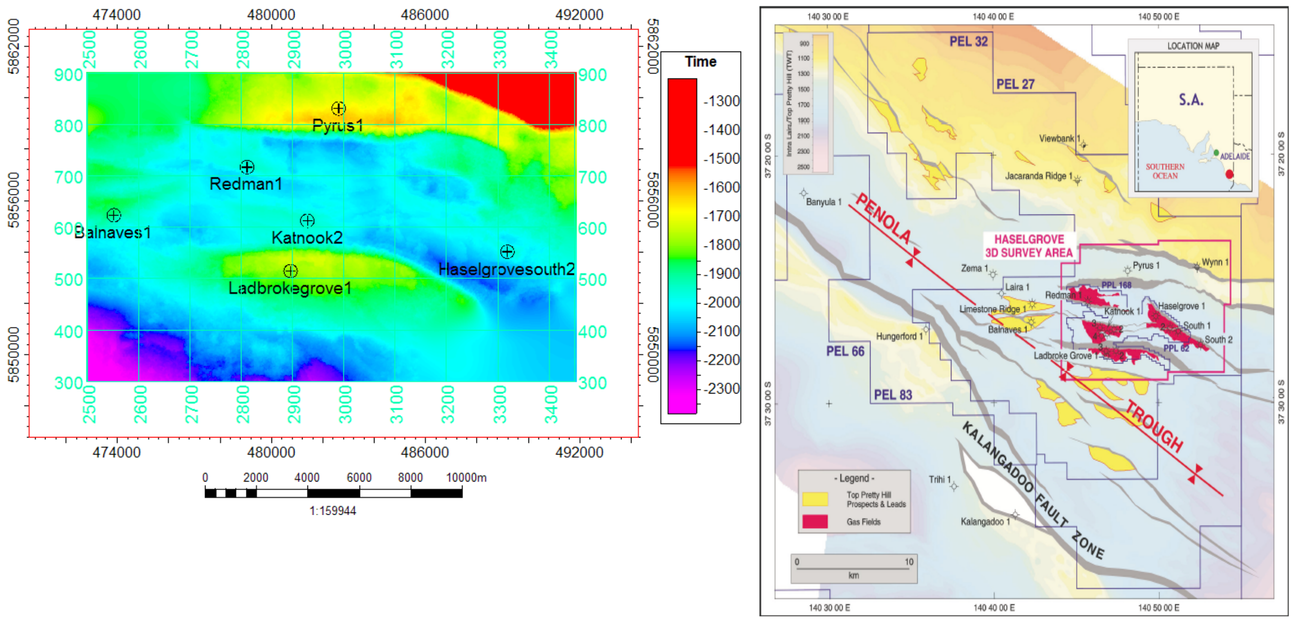

Figure 1: Study Location Map showing 3D survey extent, wells and interpreted Pretty Hill formation (left) and a general map (right)

(Boult and Donely, 2001)

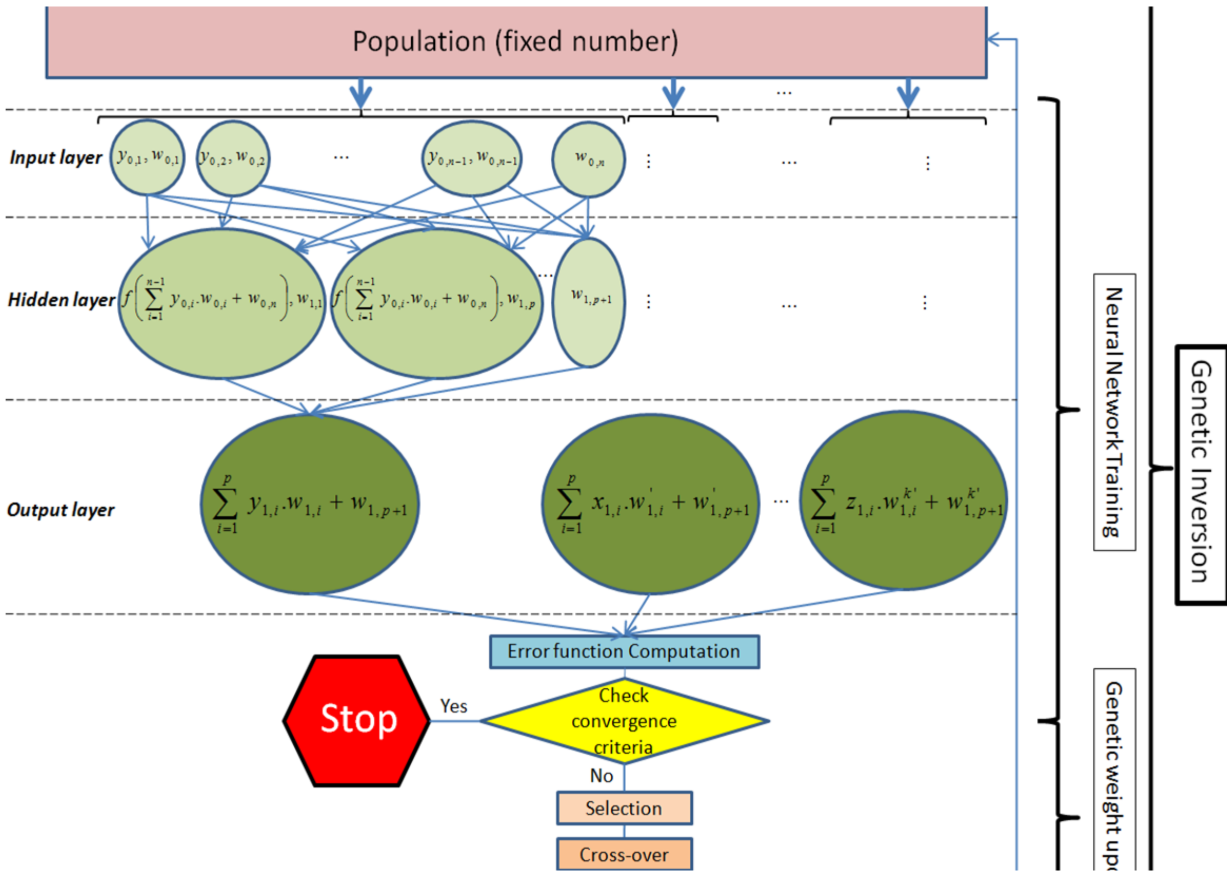

Figure 2: Genetic inversion workflow scheme

(Klinger et al., 2008)

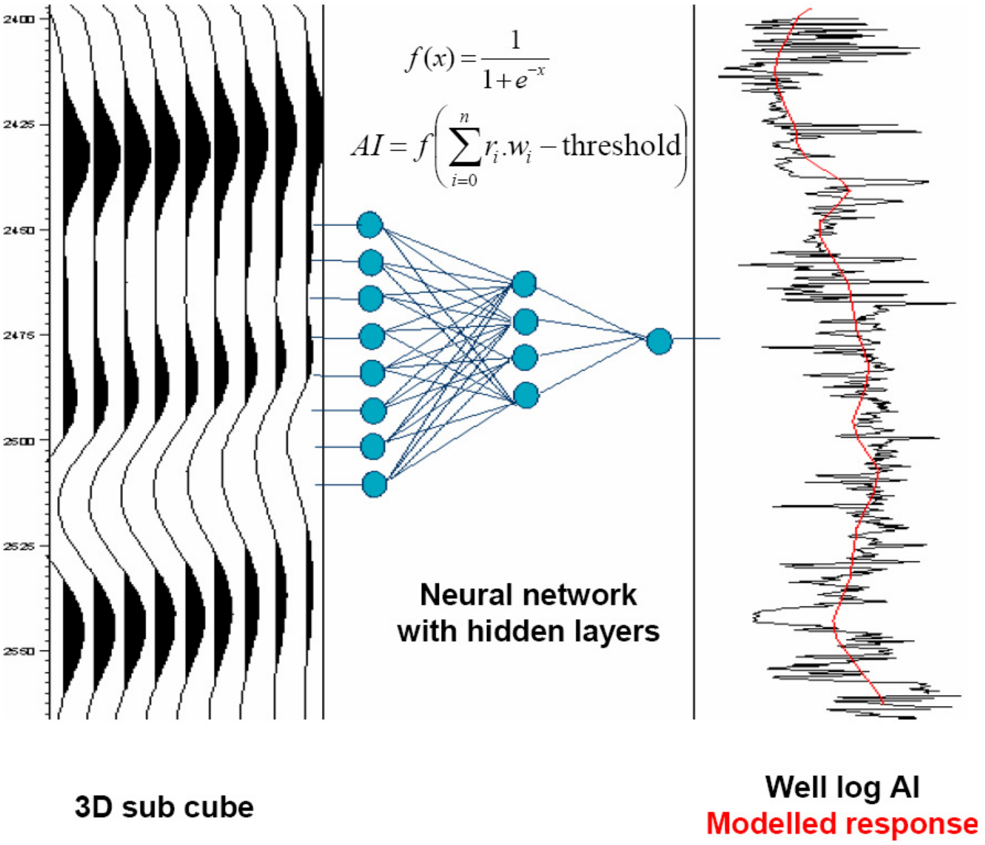

Figure 3: Schematic approach of the link between seismic traces and property logs, through Neural Nets

(Veeken et al., 2009)

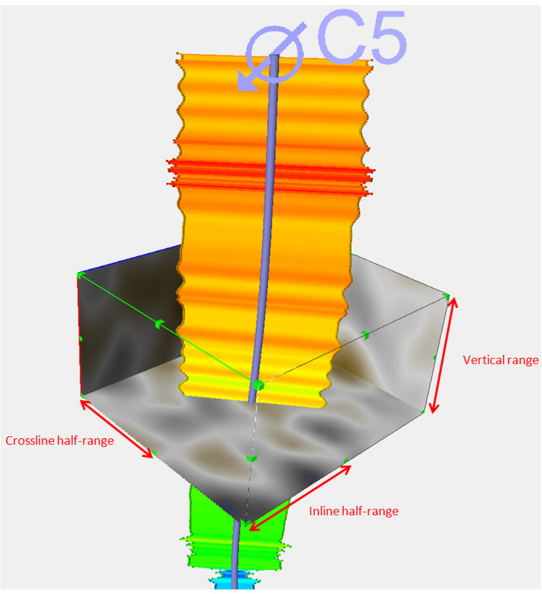

Figure 4: Illustration of the subcube used for the Neural network

(Klinger et al., 2008)

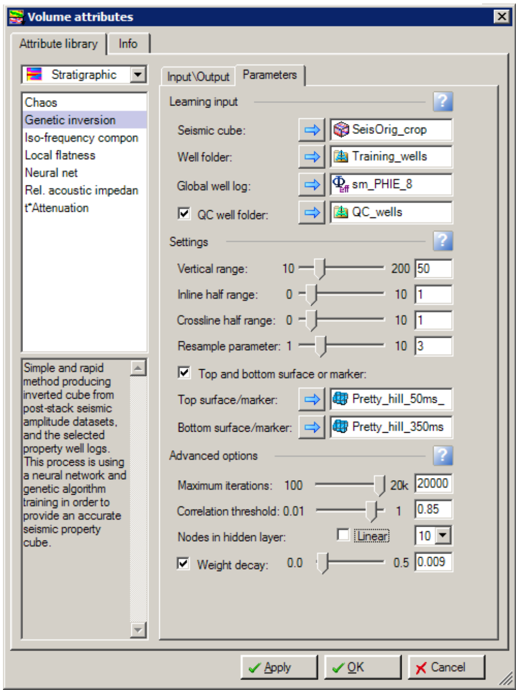

Figure 5: The genetic inversion was run with the following settings

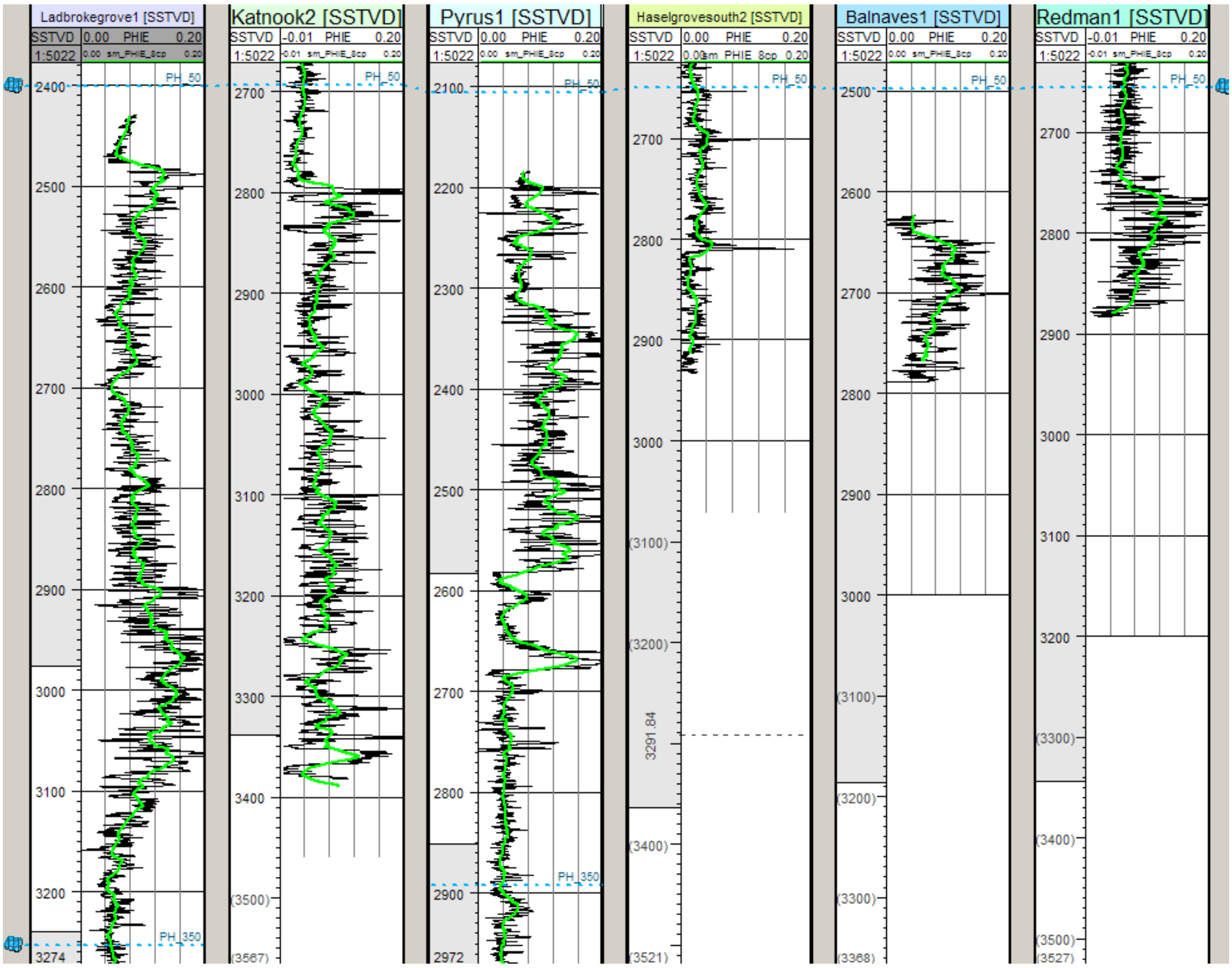

Figure 6: Well section display: Porosity derived from sonic (black) and smoothed porosity (green)

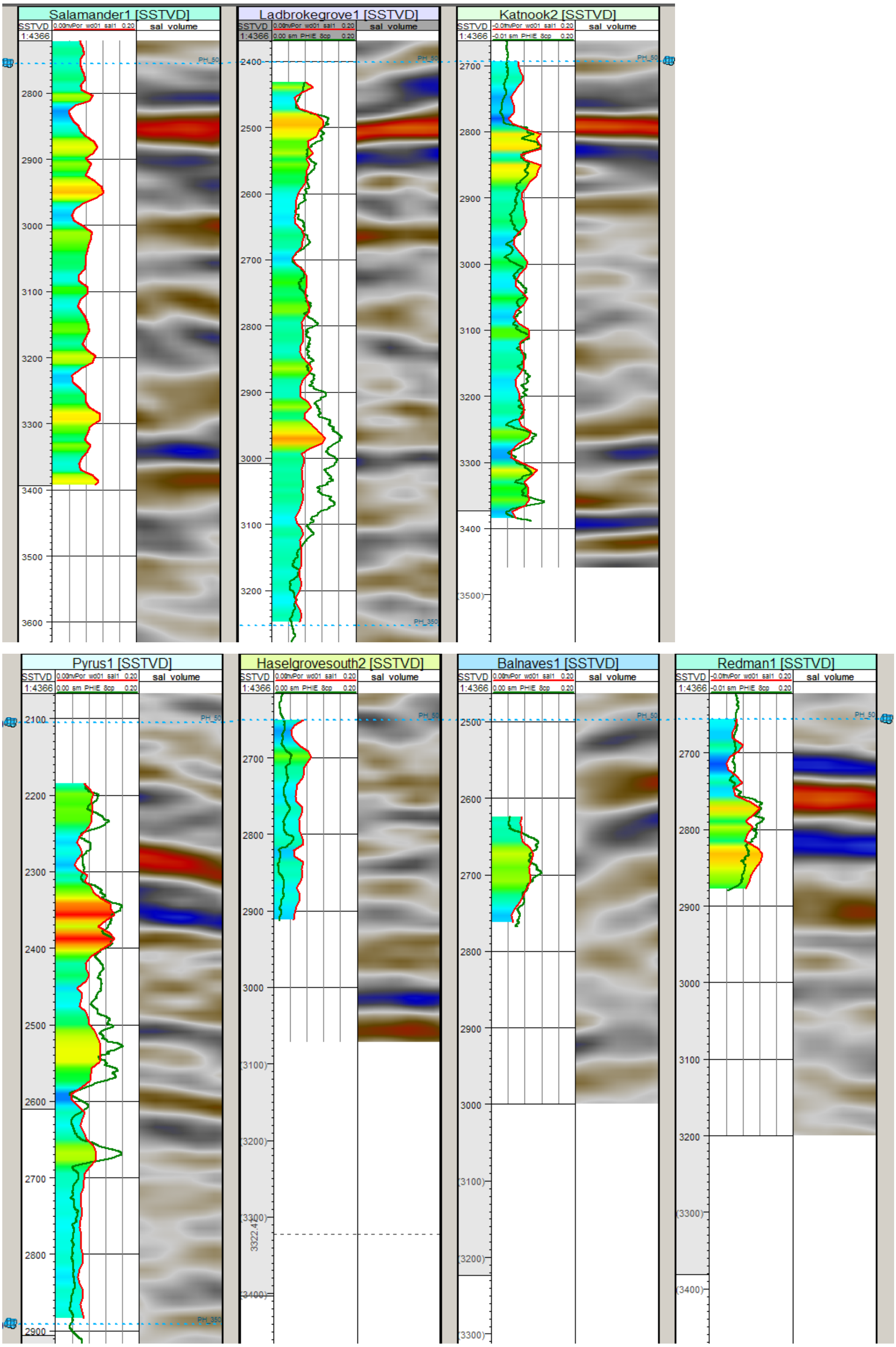

Figure 7: Well section display: smoothed porosity and inversion output. Green – smoothed porosity, red and color-filled – inverted porosity. Top Blue line – Pretty Hill-50 ms. Note: Ladbroke Grove 1 TDR was applied to the proposed Salamander 1 well

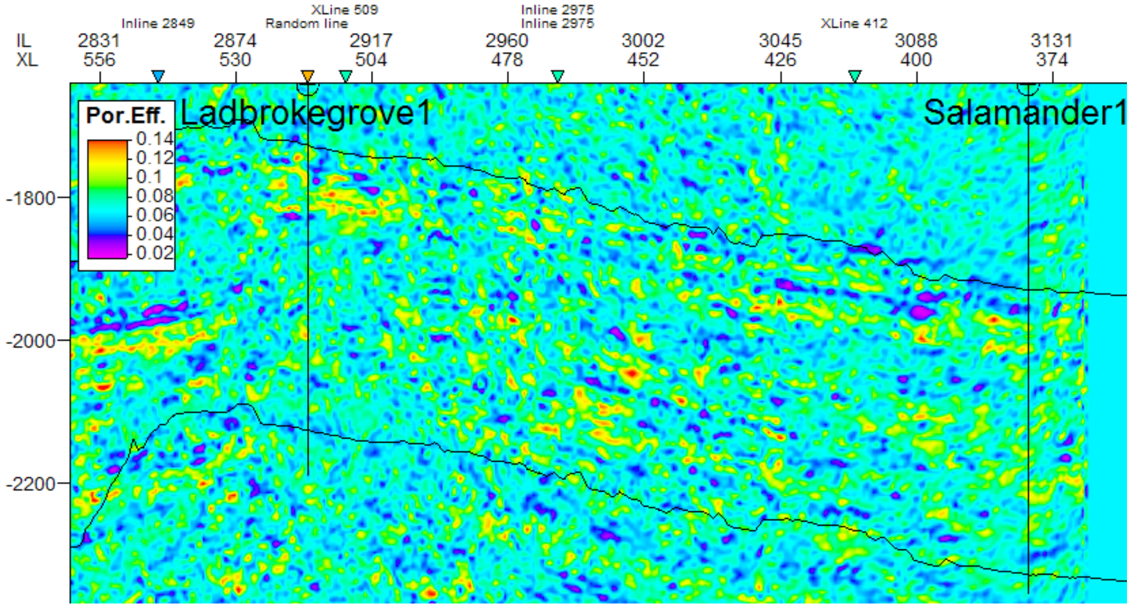

Figure 8: Section window: Traverse seismic line showing inverted porosity intersected by Ladbroke Grove 1 and the proposed Salamander 1 well. Black – Pretty Hill-50 ms and Pretty Hill+350 ms

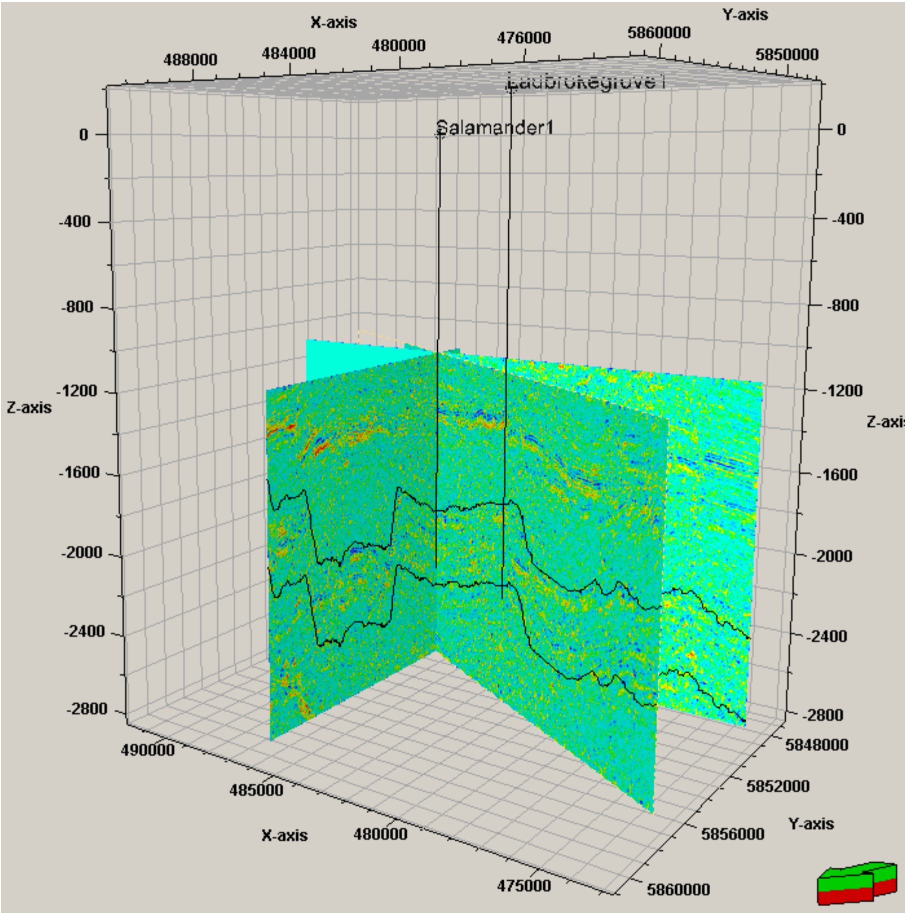

Figure 9: 3D display: Proposed Salamander 1 and Ladbroke Grove 1 wells along the seismic section. Black – Pretty Hill-50 ms and Pretty Hill+350 ms

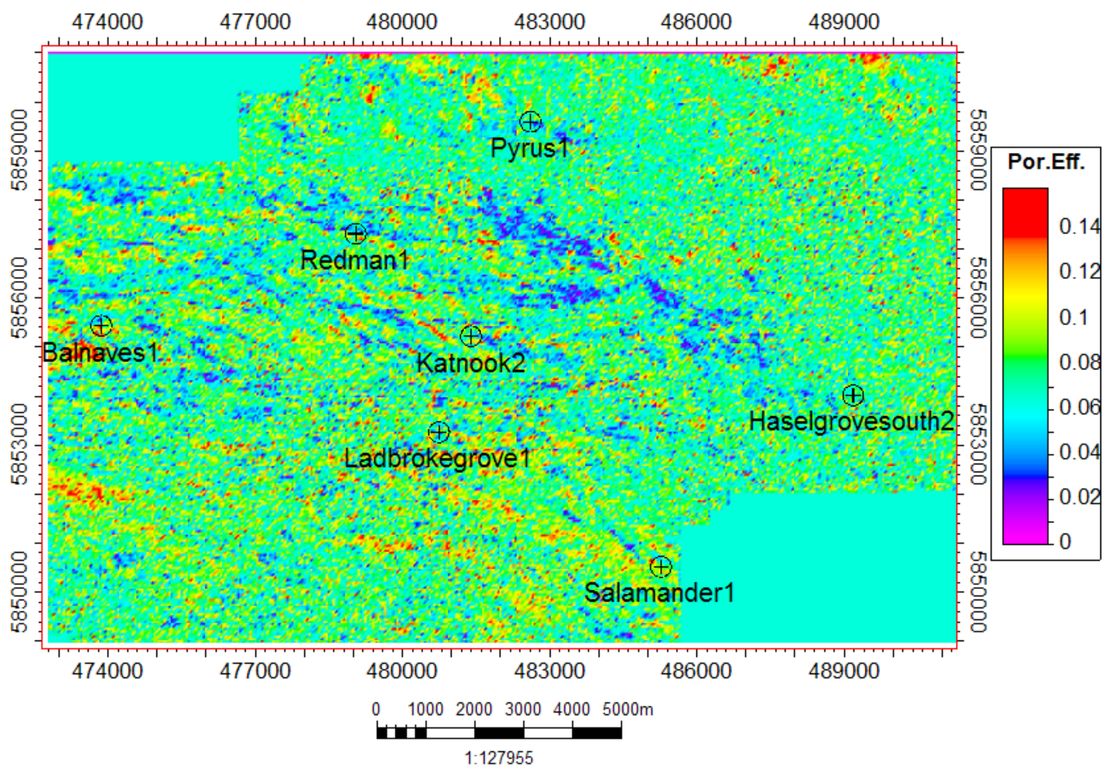

Figure 10a: Map window: inverted porosity extracted at the gridded Pretty hill surface

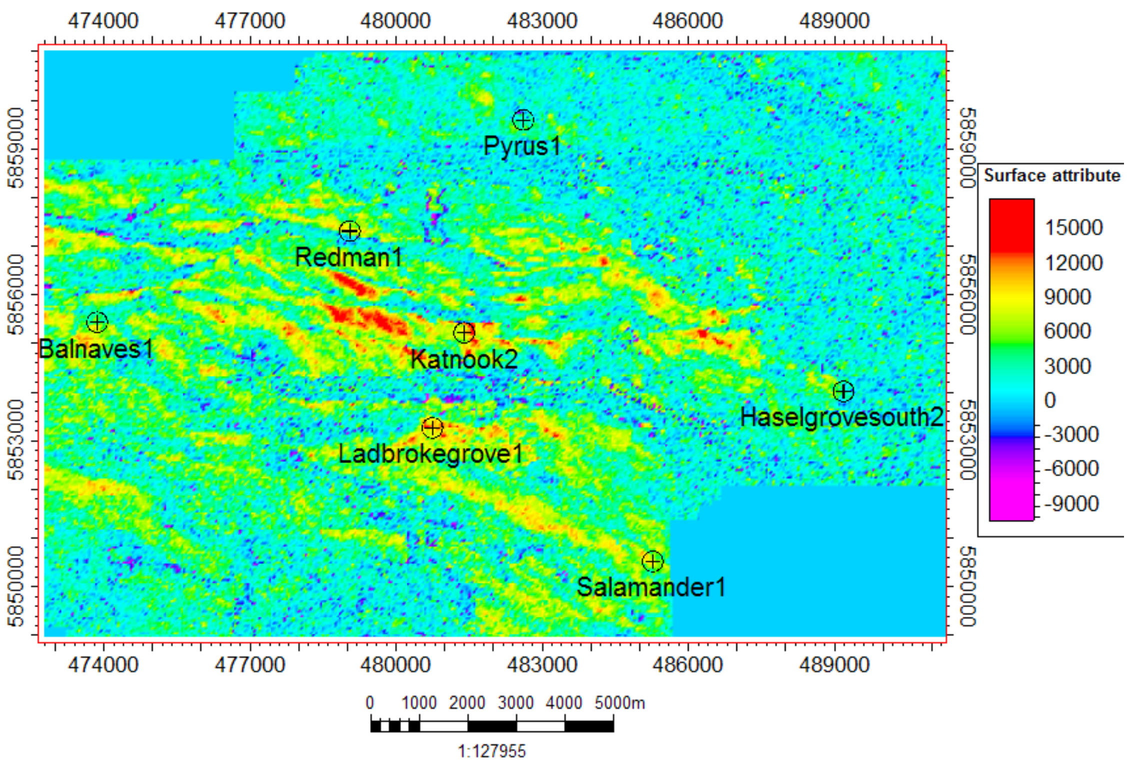

Figure 10b: Map window: Seismic amplitude extracted at the gridded Pretty hill surface