Geostatistical analysis of 3C-3D seismic data for depth, isopachs, and sand/shale distribution.

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ABSTRACT

Three examples of applying geostatistical methods in the Blackfoot area, Alberta, are shown. The examples include time-to-depth conversion, isopach estimation, and sand/shale determination. Conventional time-to-depth conversion requires a correct velocity model, which is often difficult to obtain. Using well depths and two-way traveltimes to the Mannville horizon, a cokriging depth structure map is generated. The estimated Mannville depth in the area varies from 1480 m. to 1520 m. Cross-validation test is used to evaluate the result and shows a very small absolute error in the range of –3.30 m. to 2 m. In a similar fashion an isopach map for the Mannville – Mississippian is obtained showing an interval thickness from 160 m. to 200 m. The cross-validation absolute error is from –13 m. to –4.5 m. Gamma ray logs are used to deduce the shale content at the well locations. An average Vp/Vs map is used as a second variable in the cokriging estimation and a sand/shale distribution map is generated. The shale content varies from less than 35% in the producing area to over 50% in the dry wells area. For the three examples, fifty Gaussian simulations are performed. The average maps show very similar features with the cokriging results.

INTRODUCTION

Geostatistical methods are becoming widely used in exploration and reservoir geophysics (Journal, 1988). They have an important ability to integrate different types of information, including seismic data, well logs, VSP, and core analysis into a consistent subsurface model.

Geological models, based on sparse well logs, depend heavily on the well locations. Unlike well log data, seismic data often provide good coverage of the exploration area but have limitations associated with noise, phase error, resolution etc. The geostatistical approach allows us to develop a detailed geological model, combining both data sets.

Conventional methods for estimating rock and reservoir properties from seismic data rely on empirical or regression formulas. Such approaches treat the data as spatially independent observations and ignore the existence of spatial patterns. Geostatistical techniques offer improved geology description and add the ability to assess uncertainty in the process.

METHODOLOGY

Kriging is an interpolation technique based on best linear unbiased estimate (Journal, 1988; Deutch and Journal, 1992; Geostat workshop, 1995). Cokriging extends kriging by adding a second variable in the estimation process. It is of a particular interest in exploration and reservoir geophysics due to its ability to integrate sparse well log information and 3-D seismic data. Well logs are considered noise free and honored exactly at the well locations while the seismic data guide the interpolation process. The methods are based on the spatial variability of the data. The first step is to calculate the experimental variogram followed by its modeling. The most common variogram models are (Deutch and Journal, 1992):

- spherical, defined by:

$$\gamma(h) = c[1.5(h/a) - 0.5(h/a)^3],\ h \le a$$

$$= c,\ h > a$$

- Gaussian, defined by:

$$\gamma(h) = c[1 - \exp(-h^2/a^2)]$$

- exponential, defined by:

$$\gamma(h) = c[1 - \exp(-h/a)]$$

where:

h – offset

a – range

c - sill

To perform cokriging three variogram models are required: well-to-well, seismic-to-seismic, and well-to-seismic. The variogram modeling is the most important stage in geostatistical analysis and the quality of the generated maps depend heavily on it.

Often a small number of well samples are available, which leads to unreliable well-to-well and well-to-seismic variogram models. A solution to this problem is to use an assumed linear relationship between the two data sets. In this case we calculate one experimental variogram, seismic-to-seismic, and fit a model to it. The well-to-well and well-to-seismic variograms are derived from that model assuming a linear relationship.

The quality of the estimation result is evaluated by a cross-validation test, i.e. “hide” one well, estimate its value and compare it with the known one. The process is repeated for all well locations.

Kriging and cokriging are weighted moving averages of the original data and thus they have less spatial variability. The answer may be too smooth and lack extreme high and low values. Where estimation techniques provide a single smooth solution, simulation techniques provide many equally probable solutions. The most common simulation algorithm is Sequential Gaussian simulation (Journal, 1988; Deutch and Journal, 1992; Geostat workshop, 1995). By creating a large number of simulation maps, we hope to reproduce the probability distribution at each point of the grid.

From these probability distributions, we may derive probabilities associated with ranges of the measured parameter.

BLACKFOOT CASE STUDY

Blackfoot 3C-3D data set

In October, 1995, Boyd Exploration Consultants Ltd. and the CREWES Project recorded a 3C-3D seismic survey to evaluate the effectiveness of integrated P-P and P-S surveys for improved hydrocarbon exploration (Lawton et al., 1996). The chosen area was over the Blackfoot field (township 23 Range 23 W4M) near Strathmore, Alberta.

The primary target of the survey was the Glauconitic member of the Mannville Group. The reservoir occurs at a depth of 1550 m., where Glauconitic sandstones and shales are incised into the regional Mannville stratigraphy valleys.

The main objectives of the survey are:

- to investigate whether 3C-3D seismic data could build on and improve conventional 3D P-wave data
- to provide stratigraphic and structural images of the subsurface
- to distinguish between sand-fill and shale-fill in the valley

Time-to-depth conversion

Seismic data are recorded in time. To obtain a depth image of the earth subsurface, a velocity model is required. It can be developed using well logs, calculated from velocity analysis, or by combining both sources. Well information is often too sparse. Developing a model from velocity analysis could be problematic due to the large number of variables that influence the velocities and/or structural complexity. So it is nearly impossible, except for some simple cases, to derive a correct velocity solution and thus the corresponding depth structure. The error may result in mispositioning of future wells or in miscalculation of potential reserves.

In the current case, we use P-P two-way traveitimes to a horizon and corresponding well depths, adjusted to the seismic processing datum, as input information to generate a depth structure map.

Figure 1 shows a P-P two-way traveltime map to the Mannville event in the Blackfoot area. Figure 2 is a cross-plot of the traveltimes verses adjusted depths at the well locations. The measured cross-correlation is 0.96.

We notice a general trend of decreasing traveltimes from the west to the east. The geostatistical estimation algorithms assume that our data are stationary over the area (Wackernagel, 1995). If there is a trend in our data, the basic assumption is violated. To solve the problem, we calculate and remove the trend from the seismic data. The trend also is removed from the well data assuming a linear relationship. We perform cokriging with the residual data and restore the trend in the final result

The trend in the seismic data is calculated as average over a 2200 m. square area (Figure 3). Figure 4 is the residual map after removing the trend. The experimental seismic-to-seismic variogram is calculated (Figure 5). The bars represent the number of points used in the calculation for every offset. The chosen model, shown as a red curve on Figure 5, has the following parameters:

- variogram type: spherical
- sill = 9.0
- range = 1900.0 m.

Cokriging is performed using a linear relationship, i.e. well-to-well and well-to-seismic variogram models are calculated from the seismic-to-seismic model. Figure 6 is the cokriging result – the Mannville depth structure. The estimated depth decreases from west to east and has a value of 1505-1510 meters in the channel area. The cross-validation test (Figure 7) shows an absolute error confined in the interval (-3.30 m. to 2.0 m.). Since a relatively small absolute error is achieved, we consider the generated Mannville depth structure as a reliable result. The method shows good performance and does not require an input velocity model. In addition, fifty Sequential Gaussian simulations are generated and Figure 8 is a map showing the average result.

Thickness estimation

The problem with the thickness estimation is similar to that of time-to-depth conversion. The usual approach requires the average velocity over the studied interval. In the current example, we integrate, in a geostatistical fashion, a seismic isochron map, derived from the 3-D survey, and the corresponding interval thickness at the well locations to generate an isopach map.

Figure 9 is an P-P isochron map from Mannville to Mississippian events. The thickness of the same interval was estimated from the well tops. Figure 10 is a cross-plot of the P-P isochrons versus the well thickness. The measured cross correlation is 0.86. Figure 11 is the calculated experimental seismic-to-seismic variogram and the red curve is the chosen model. The parameters of the model are:

- type: exponential
- sill = 55
- range = 1400 m.

Figure 12 shows the cokriging isopach map. The mapped Mannville – Mississippian interval has an estimated thickness from 160 m. to 200 m. in the area. Figure 13 is the cross validation test. The absolute ranges from –13 m. to

-4.5 m. The error is higher than the time-to-depth conversion example due to difficulties associated with the correct Mississippian picking. Fifty Sequential Gaussian simulations are generated and Figure 14 is a map showing the average result.

Sand/shale distribution mapping

Gamma ray logs are measure of the natural radioactivity of the formations in a borehole. In sediments, this value reflects mainly shale content because the radioactive elements tend to concentrate in clays and shales. We use the following expression to obtain a measure of shale content at the well locations, called fractional percentage shale (FPS):

$$\mathrm{FPS} = \frac{\mathrm{GRlog} - \mathrm{GRsand}}{\mathrm{GRshale} - \mathrm{GRsand}}$$

where:

GRlog – measured gama ray log

GRsand – sand line

GRshale – shale line

Using the above expression, FPS values are calculated for the channel interval and the results are shown in table 1.

well	FPS	well	FPS
01-08	0.35	05-16	0.44
08-08	0.31	04-16	0.46
2/09-08	0.27	12-16	0.48
16-08	0.35	01-17	0.45
14-09	0.52	09-17	0.50

Table 1: Calculated FPS in the Blackfoot field.

Figure 15 is a average Vp/Vs map from the Top Channel event to the Wabamun using P-P and P-S isochrons from the Blackfoot 3C-3D survey (Yang et al., 1996). Low Vp/Vs values tie producing oil wells in the area and follow the general trend of the sand channel.

Figure 16 is a cross-plot of the Vp/Vs values at the well locations vs calculated FPS. The measured cross-correlation is 0.95, i.e. low Vp/Vs values correlate very well with low shale content. The experimental seismic-to-seismic variogram is calculated and modeled (Figure 17). The model variogram parameters are:

- type: exponential
- sill = 0.018
- range = 550 m.

Cokriging assuming a linear relationship is performed (Figure 18). The generated map shows the distribution of fractional percentage shale, i.e. areas with low values on the map may be interpreted as sand bodies. The cross-validation test (Figure 19) shows an absolute error of shale content from 0.03 to 0.09. Figure 20 is an average result from 50 Sequential Gaussian simulations. One of the strength of the geostatistical methods is the ability to assess the uncertainty in the process. Figure 21 is a plot of the probability to find a FPS value less than 0.35, i.e. high percentage of sand. This outlines the favorable regions of reservoir sand development.

CONCLUSIONS

The cokriging method can be used to derive depth and interval thickness maps. The method performs well and does not require a velocity model. A good correlation between Vp/Vs values and shale content in the are is found, i.e. Vp/Vs can be used as a second variable in a cokriging interpolation of a shale content. A cross-correlation test may be used to evaluate the performance of the process. Generally the geostatistical integration of well log information with 3C-3D seismic data is very helpful in developing an accurate geological model of the earth subsurface. The uncertainty estimation can be helpful in quantifying the likelihood of various geologic factors.

ACKNOWLEDGEMENT

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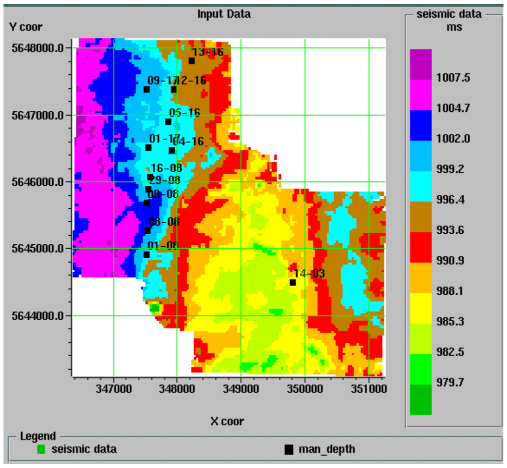

Figure 1: P-P two-way traveltime, Mannville event.

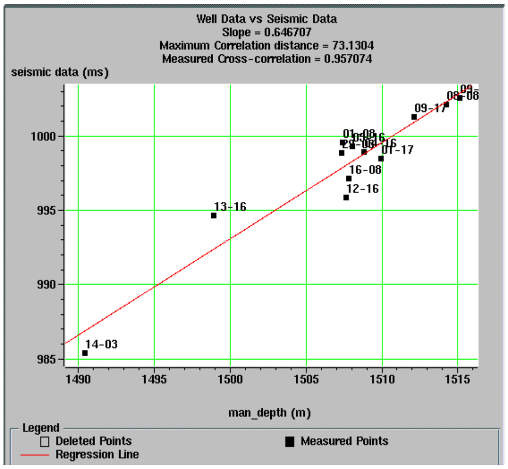

Figure 2: Cross-plot, Mannville two-way traveltime vs adjusted depths.

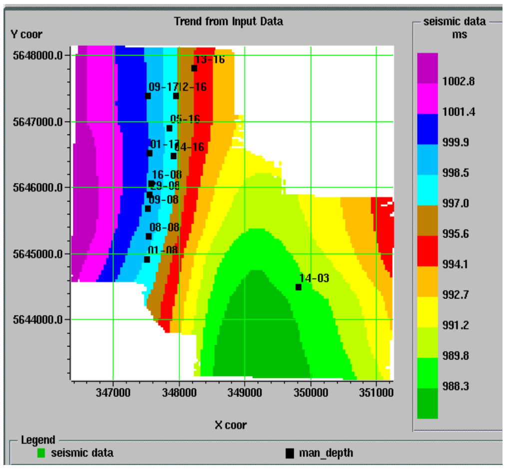

Figure 3: Calculated trend for the Mannville event.

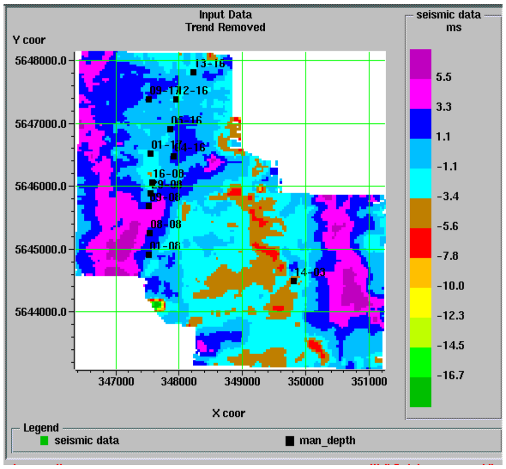

Figure 4: Residual after trend removing.

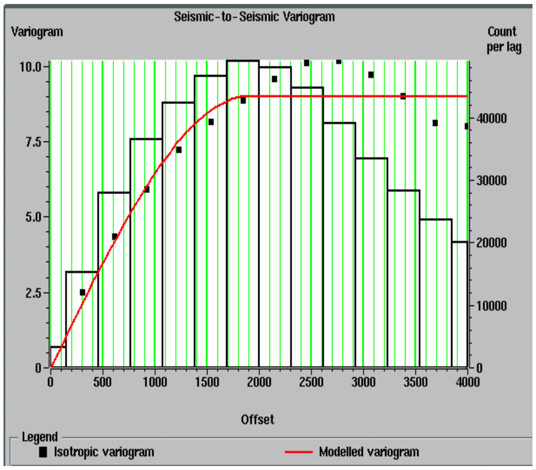

Figure 5: Seismic-to-seismic variogram.

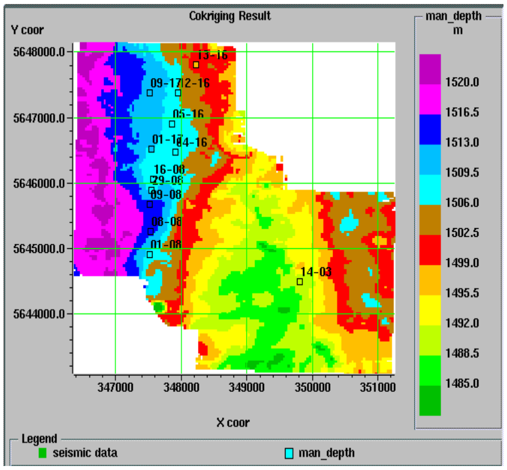

Figure 6: Mannville depth structure, cokriging result.

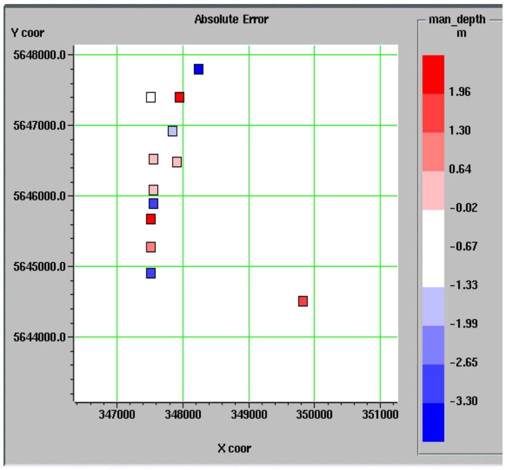

Figure 7: Cross-validation test, absolute error.

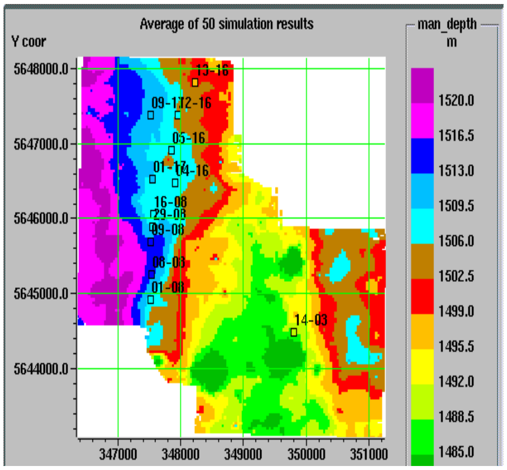

Figure 8: Manville depth structure, average of 50 simulations.

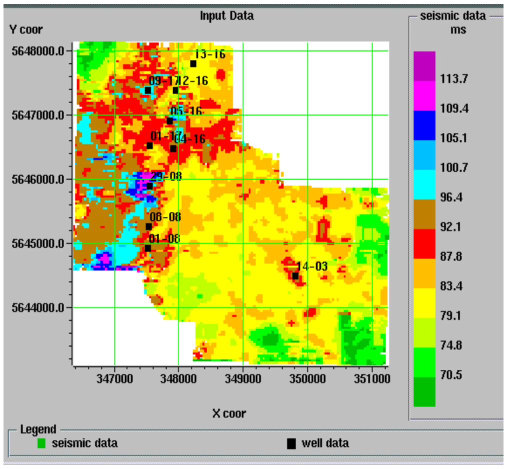

Figure 9: P-P isochron map from Mannville to Mississippian.

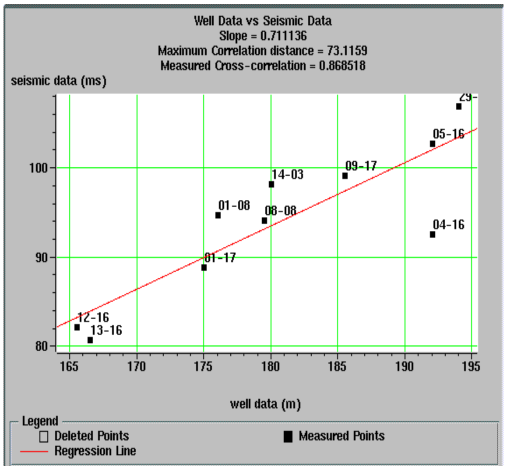

Figure 10: Cross-plot, isochrons vs interval thickness.

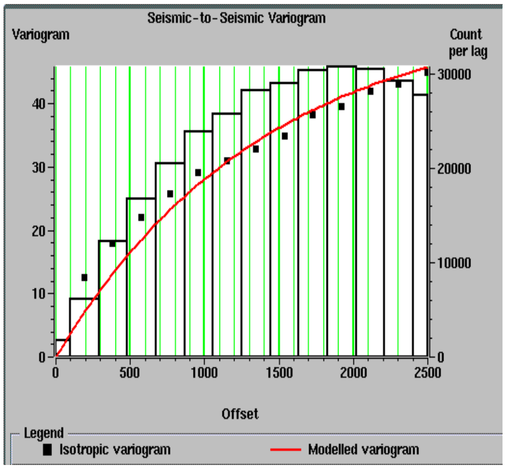

Figure 11: Seismic-to-seismic variogram.

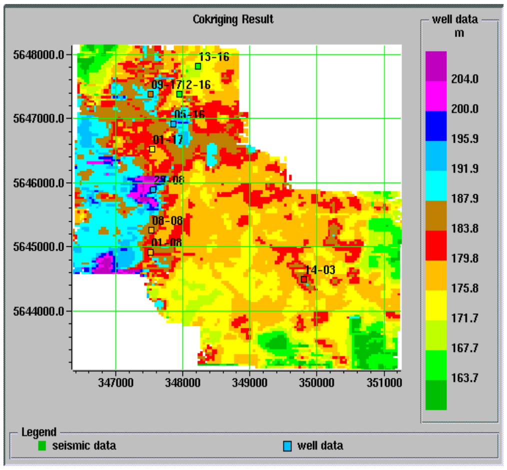

Figure 12: Mannville-Mississippian isopach map, cokriging result.

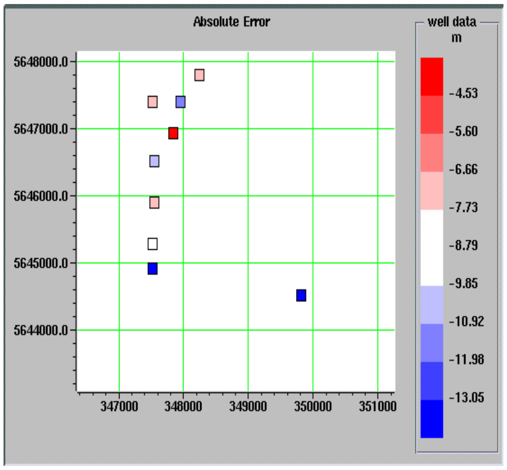

Figure 13: Cross-validation test, absolute error.

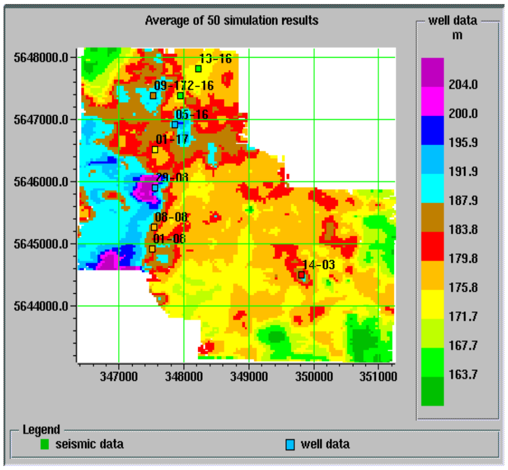

Figure 14: Isopach map, average of 50 simulations.

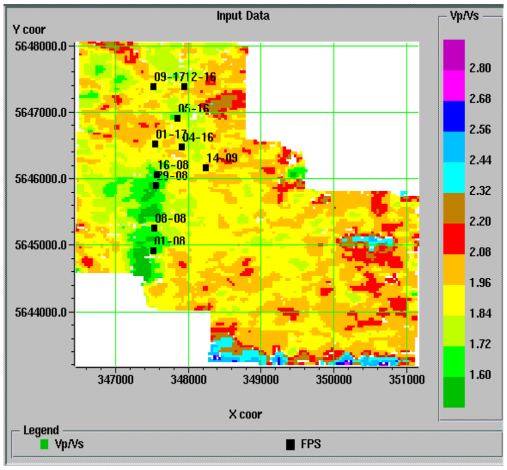

Figure 15: Vp/Vs map, Wabamun to Top Channel events.

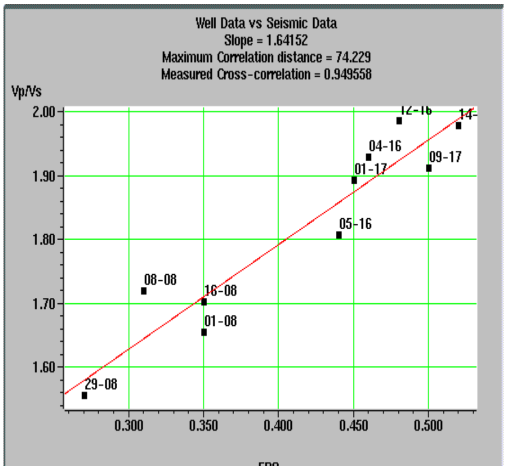

Figure 16: Cross-plot, Vp/Vs vs shale content.

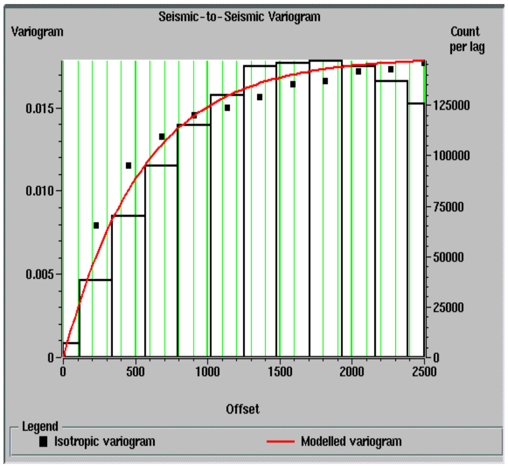

Figure 17: Seismic-to-seismic variogram.

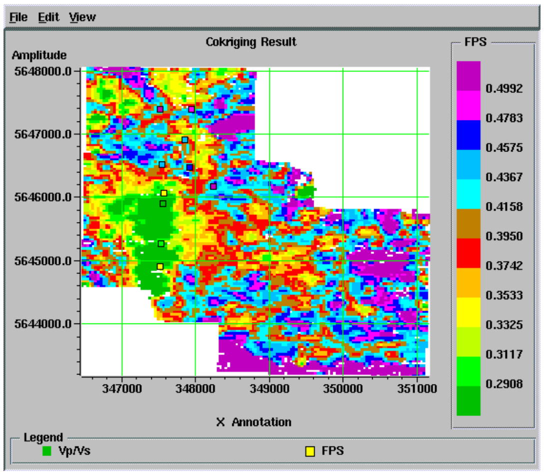

Figure 18: Shale content distribution, cokriging result.

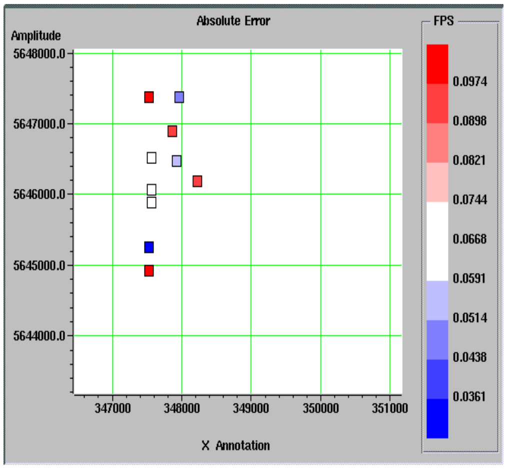

Figure 19: Cross-validation test, absolute error.

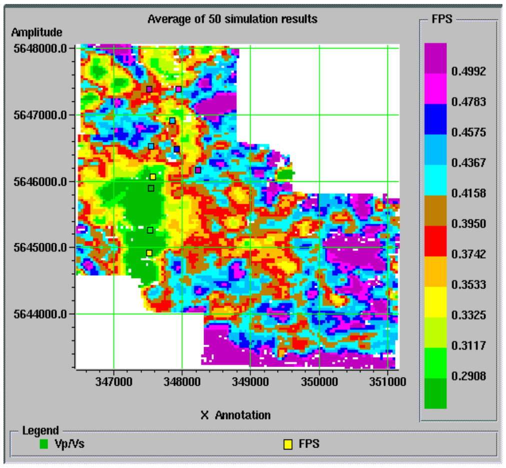

Figure 20: Shale content distribution, average of 50 simulations.

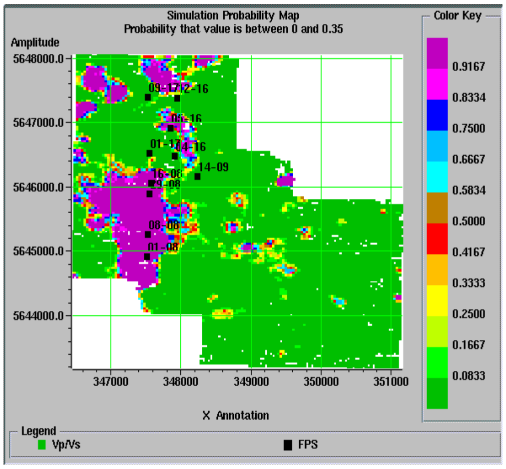

Figure 21: Sand probability map.