Developments in AVO and 4D Statistical Inversion

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ABSTRACT

Previous developments in statistical inversion have enabled the integration of petrophysical, stratagraphic and geophysical information. The result is an ensemble of N (usually about 50-200) equally probable models that honor the distributions of all three types of information. The ensemble can then be used to form averages and standard deviations of important reservoir properties such as net pay. The ensemble could also be used as input to multiple reservoir simulations and business analyses. The geophysical information that has been incorporated up to this point has been a single full or partial stack volume. The integration with the reservoir modelling tools such as DepSim has been cumbersome. There also has not been a natural way for the petrophysicists who work with Gulf of Mexico data to input their information.

Work will be presented that shows progress towards incorporation of AVO and 4D (time-lapse) into the statistical inversion algorithm of PROMISE. The inclusion of realistic Gulf of Mexico petrophysical trends into PROMISE and the seamless integration of PROMISE into the DepSim modelling environment will also be shown. Preliminary results of applying the AVO inversion to synthetic data based on the Gulf of Mexico prospect Ram/Powell will be presented.

INTRODUCTION

There has been substantial previous development of statistical methods of geophysical inversion (Tarantola, 1987; Lortzer, 1993). These methods are based on Baysian statistics and are constructed to estimate the distribution function (that is the probability density function) of a model given the geophysical and petrophysical data. Here a model is a set of parameters such as net-to-gross, porosity, density, seismic velocities and fluid saturations for each blocked layer of the subsurface. More precisely the distribution function is estimated by an ensemble of models which fairly sample the distribution function (each model is equally probable). The difficulty in forming this ensemble is that there is not a closed form for the distribution function given the seismic data. Given a model one can evaluate the value of the distribution function. Each one of these evaluations takes some effort so that one needs to minimise the number of the evaluations. Efficient methods of iteratively converging to an ensemble of N models which fairly sample this distribution function have been developed (Metropolis, 1953) and applied to geophysical inversion (Leguijt, 1995).

The previous application of these methods has been only for single stack inversion, the petrophysics has not been compatible with Gulf of Mexico deepwater geology, and the links with integrated subsurface modeling tools such as DepSim (Wattenbarger, 1994) have been cumbersome. It was the purpose of this research to streamline the links between DepSim and the RTS developed probabilistic inversion code PROMISE, to create a description of the petrophysics that naturally maps to the Gulf of Mexico rock properties, and to extend PROMISE to allow a multiple stack inversion that would allow AVO and 4D (time-lapse) inversion.

This paper will present this research in five parts. The first is a description how the Gulf of Mexico petrophysics is implemented in PROMISE. The second and third parts describe the implementation of the AVO and 4D inversion, respectively. The fourth part outlines the implementation of the DepSim/PROMISE links. The last part describes the application of this method to a synthetic dataset.

PETROPHYSICAL MODEL

The petrophysical model is based on the concept of end member trend curves for sand and shales (Wieseneck, 1994). For the sands, linear relationships are assumed for compressional velocity as a function of depth, the shear velocity as a function of compressional velocity and the porosity as a function of compressional velocity. These relationships are found for sands with a constant reference fluid, in most cases clean wet sands. A Gassman fluid substitution is then done to derive the seismic properties of the proposed saturation of the sand. For the shales, linear relationships are found for the compressional velocity as a function of depth, and the shear velocity as a function of compressional velocity. A power law relationship is assumed for the density as a function of compressional velocity. For laminated sands that can not be resolved by the seismic data the sand and shale properties are Backus averaged with a given net-to-gross ratio (Backus, 1962).

A few words about the practical aspects of these end member trend curves - they are derived by fitting well log data. This is done by examining both regional data (Chang, 1995) and well logs specific to a particular field. The later is obviously more relevant, but the information is less copious. It is also possible to not only determine the best fit relationship between the quantities but the scatter, that is standard deviation of the properties, about those regressions. It is important to note that the scatter is taken into account in the statistical inversion by having a prior distribution that has some gaussian width about the correlations specified by end member trends. There is also assumed to be a gaussian distribution to the net-to-gross ratios. The mean and standard deviations are determined by well information and concepts about the depositional environment of the laminated sand facies. There is also an issue of the pressure environment of the particular rocks being modelled. The higher pressures of a geopressured environment lead to distinctly different trends. This has been compensated in regional studies by adding a low frequency interval velocity term to the regressions. Since there is at least one well penetration before a statistical inversion is attempted, we have adopted the approach of a separate trend for each layer. The information from the well penetration is used to determine whether the layer is geopressured, then the trends capture the hydrostatic pressure differences within the layer.

The fluid that is substituted into the sand is one of several specific integer cases - brine, commercial oil, commercial gas, residual oil, and residual gas (Wieseneck, 1994). This corresponds to the phase cases that occur in exploration. Initially the sand is brine filled. It is then charged by oil or gas that displaces the brine. The amount of residual brine is determined by the surface tensions and grain structure. If the trap is breached the gas or oil will migrate out with the amount of residual charge determined again by the surface tensions and grain structure. Prior probabilities are provided for each fluid. These can be obtained from regional information or neural network estimates of fluid saturations.

AVO MODEL

The AVO model used in the inversion is consistent with the common approximations used in time migration. The relevant equations are expanded to leading order in the dimensionless offset, X/VT, and the dimensionless lateral gradient, V dT/dx; where, X is the offset, V is the migration velocity, T is the migrated time of the reflector, x is the migrated subsurface point, and v is the interval velocity. As you can see in Fig. 1, the angle of incidence θ is (v/V)(X/VT) and the dip angle of the reflector α is 0.5 (V dT/dx) plus third order terms that are neglected. The reflection coefficient as a function of offset

$$R(X) = A\ L + B\ M\ (v/V)^2\ (X/VT)^2 + 4^{th} \text{ order term,} \tag{1}$$

where L and M are the usual small contrast approximation terms used in AVO analysis (Castangna, 1993), and the two squared terms are the usual $\sin^2\theta$ term. The A and B terms are correction factors that are derived during the inversion and are related to the orientation of the background normal. The A term corrects for changes in the wavelet scaling from things such as a changing overburden. The B term corrects for a rotation of the background normal that is commonly found in data and could be attributed to a constant offset dependent scaling factor imposed by the processing (Wang, 1995). The expected value for B is determined during the wavelet derivation process. Not only is the wavelet shape varied during the wavelet derivation process, but the value of B is also varied to find an optimal value. This process is demonstrated in Fig. 2. The optimal value for B will be $(p_{eff} /p)^2$, where p_{eff} is the value of the ray parameter which minimises the deviation of the synthetic seismic at the well location from the actual seismic, and p is the ray parameter calculated by averaging over the offset range used in the stack.

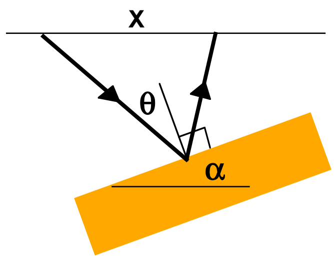

Figure 1. Ray geometry used in the AVO inversion.

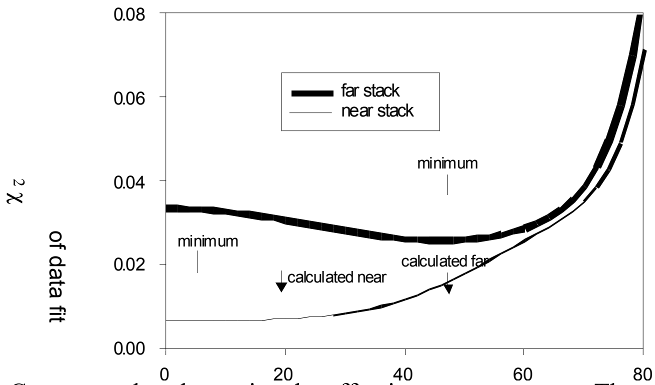

Figure 2. Curves used to determine the effective ray parameter. The curves are the mean squared deviation of the modeled trace from the data as a function of ray parameter used to model the amplitude response. The value is normalized by the mean squared amplitude of the data. Also shown is the ray parameter calculated by averaging over the offset range used in the stack.

Wavelet stretch is modelled as an expansion about the derived wavelet for the substack. The offset average reflected wavelet used to construct the synthetic can be shown to be $\langle RW\rangle_X = \langle R\rangle_X\langle W\rangle_X$ + 4th order correction, where the stretched wavelet $W(X,t) = W_0(t/S(X))$, and the stretch factor

$$S(X) = 1 + 0.5\,(X/VT)^2 + 0.125\,(V\,dT/dx)^2 + 4^{th} \text{ order.} \tag{2}$$

The second term is the well known NMO stretch and the third term is the dip stretch.

4D (TIME-LAPSE) MODEL

The formalism of AVO inversion described in the previous section requires that multiple stacks and wavelets be input to the inversion process. A simple extension of this multiple stack input is made to enable 4D or time-lapse inversion. A tag is added to each stack that identifies from which seismic survey it came. Compaction effects and effective stress effects are ignored so that the thickness of each layer and the rock matrix properties are assumed to be the same for both surveys. Both of these effects could be taken into account by future model extensions. The fluid within the rock matrix is allowed to change between the two surveys. The specification of this fluid is currently limited to the integer cases described in the section on the petrophysical model.

There are several possible justifications for the simultaneous inversion of both surveys. The first is preserving the full fidelity of the data. Since the data equalisation is done via the use of separate wavelets for each inversion, the quality of the higher fidelity data does not need to be degraded to match that of the lower fidelity data. The higher fidelity data is likely be the major factor in determining the structure, while the lower fidelity data would primarily determine the fluid saturations at that time. The second is the systematic propagation of errors from the seismic data to the quantities that are being estimated like fluid saturations and net pore volume. This will enable quantitative estimation of the uncertainties for use in the business analysis.

COMPUTER IMPLEMENTATION

There have been several philosophies that have governed the computer implementation of these concepts. The first is a view of DepSim as the IO engine for the probabilistic inversion. The second is the rapid prototyping and the familiar user interface given by putting a SPIRIT II wrapper around the C prototype probabilistic inversion code PROMISE developed at RTS. We also wanted to make sure that the implementation would be expandable and compatible with neural network fluid estimation, AVO modelling as it is done in SAVIOR, and Gulf of Mexico petrophysical specification.

RESULTS

These algorithms have been applied to a synthetic dataset characteristic of turbidite geology and petrophysics in the Gulf of Mexico. The structure and petrophysics is that of Ram/Powell and the sequence stratigraphy was a characteristic one prepared by Shell Deepwater Development Inc. Oil was assumed to be in all layers except one which had both a water-oil and oil-gas contact. There was a lateral gradient in the lower bounding shale. A REX, full elastic model, was generated including all mode conversions and interbed reflections. The inversion was done on this synthetic seismic.

The results of the inversion at the well location at bin 400 are shown in Fig. 3. Note the combination of the lower three sand layers caused by the inability of the seismic to resolve them. Also note that the estimates of both L and M were improved by the inversion but there was a greater sensitivity of the data to estimation of L. A plot of the REX generated seismic of the near stack and the initial and final estimates of the net-to-gross ratios of the sands are shown in Fig. 4. Note the channel centered at 7000 ft. found by the inversion in the upper sand packet. Quantitative comparisons of the net sand in the upper sand packet for the PROMISE inversion and FLINT inversion (Nieuwoudt, 1992) to the true value are shown in Fig. 5. The FLINT results match those of PROMISE within the expected error of the PROMISE result. There is a modest discrepancy between the PROMISE result and the true value near bin 780. The cause of this is currently being investigated.

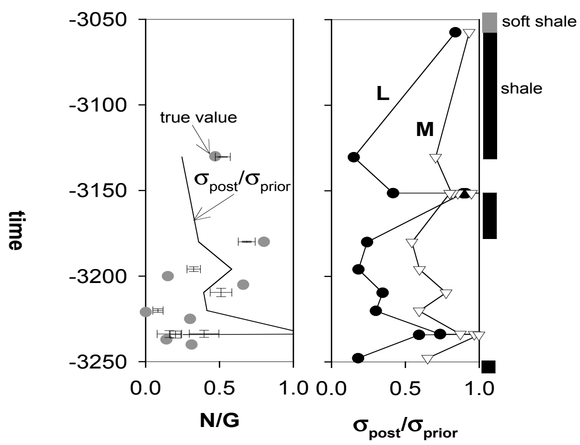

Figure 3. A detailed comparison of the well tie.

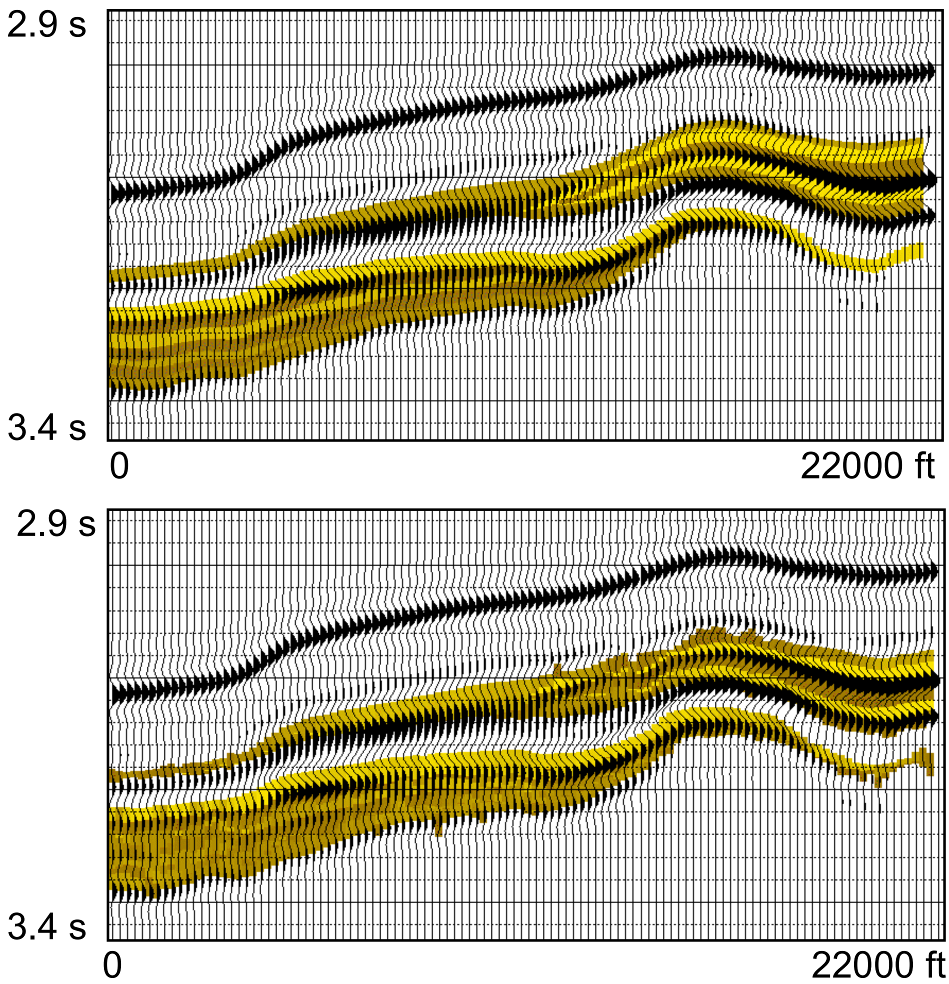

Figure 4. Net-to-gross ratio shown behind the REX generated seismic data of the near stack. Net-to gross varies from 0 to 1 (dark brown to yellow).

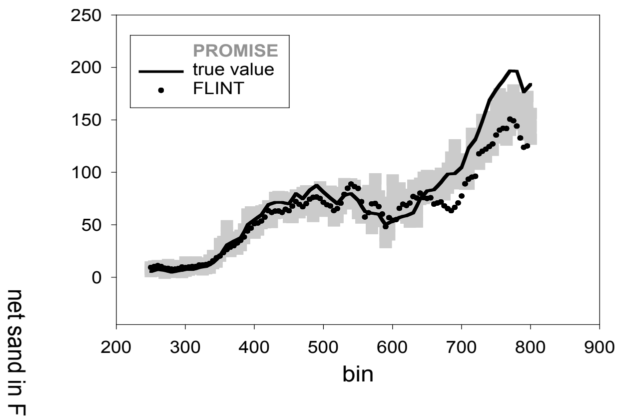

Figure 5. PROMISE results compared to the true value and FLINT results. The gray band is the range from P12 to P87.

CONCLUSIONS

PROMISE has been integrated into DepSim. The probabilistic inversion algorithm has been extended to do multi-stack inversion. This enables both AVO and 4D inversion. AVO inversion has worked with some success on synthetic data. For the most part, it matches the model used to generate the synthetic data within the expected error of the PROMISE result.

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