Z-99 Bayesian seismic inversion delivers integrated sub-surface models

JAMES GUNNING[1] AND MICHAEL GLINSKY[2]
[1]*CSIRO Petroleum, PO Box 3000, Glen Waverley, Victoria, Australia*
[2]*BHP Billiton Petroleum, Houston, Texas, USA*

Abstract

We introduce a new open-source toolkit for model-based Bayesian seismic inversion called *Delivery*. This inversion code uses a layer-based prior model with rock physics information taken from log analysis as the basic structure that generates reflection seismic data. The model allows for uncertainty in both the fluid type and saturation in reservoir layers: variation in seismic responses due to fluid effects are taken into account via Gassman's equation. Multiple stacks are supported, so the software implicitly performs a full AVO inversion using the Zoeppritz equations. Uncertainties and irresolvabilities in the inverted models are captured by the generation of multiple stochastic models from the Bayesian posterior, all of which acceptably match the seismic data, log data, and rough initial picks of the horizons. Post-inversion analysis of the inverted stochastic models then facilitates the answering of commercially useful questions, *e.g.* the probability of hydrocarbons, the expected reservoir volume and its uncertainty, and the distribution of net sand.

The *Delivery* software is java-based and thus platform independent. Input and output is driven via XML, Seismic Unix[1] (SU) and BHP_SU[2] data formats, and the output interfaces naturally with the free INT viewer[3]. The assumption of independent traces means that the inversion can be massively parallelized, and distributed across cluster computing systems.

Introduction

Development decisions in the oil industry are normally always driven from quantitative criteria about the asset in question, even if the quantities in question are poorly known. The particular questions of interest in such decisions will always relate to precise aspects of a reservoir, such as the fluid type, the permeability of the rock, the size of the oil column, and the amount of hydrocarbon in place. These questions can only be asked if an explicit model of the reservoir has been formulated, and thereafter the remaining task is to constrain this model (or a set of models) using the available data as much as is both possible and justifiable.

From this point of view, use of seismic inversion is now a fundamental process, since it confronts directly the problem of integrating reservoir models with seismic data. The integration is further enhanced if log information from salient wells is incorporated, since this will capture both regional trends in acoustic property variations and point constraints at the well locations.

Any inversion from seismic and log data will necessarily suffer problems of nonuniqueness and irresolvability of some model features. Hence it is vital that the inversion scheme produce not only "most-likely" estimates of model properties, but also measures of error attached to these. For this purpose, the most natural conceptual framework for seismic inversion is a Bayesian one, where a prior distribution of the model is constructed from regional knowledge of the relevant rock physics and approximate time picks of the model horizons, and a *likelihood* function is used to update this distribution to form a posterior model. The likelihood enforces a suitable match between the observed seismic data and the predicted seismic (generated using a convolutional forward model), based on estimates of the noise produced by the wavelet extraction. Related Bayesian approaches are described in Eide [4], Leguijt [5] and Eidsvik [6].

Delivery is designed to be used in an environment where global control of the inversion is exerted by an XML file, and local variations in the prior model are controlled by a special SU file matching the geometry of the actual seismic data set. The software produces a suite of "stochastic inverse" models (realisations) in SU format, which can be analysed using tools in the *Delivery* toolkit.

Details

The model used in the *Delivery* software is layer-based and local to each trace, each layer corresponding to a major facies unit (see figure 1). Each layer is modelled as a mixture of two end-member rock types; a permeable (reservoir) rock, and an impermeable rock. These are assumed to be finely mixed in laminar fashion with a net-to-gross parameter NG. Permeable rocks can be filled with brine, oil, gas, or low-saturation ("fizz") gas with prior probabilities specified by the user. Various density-ordering criterion for fluids can be specified by the user to guarantee lighter fluids above heavier ones in adjacent permeable layers if desired. The model properties and seismic data are assumed to be uncorrelated with adjacent traces, which can be guaranteed by reducing the seismic trace density down to a suitable spacing.

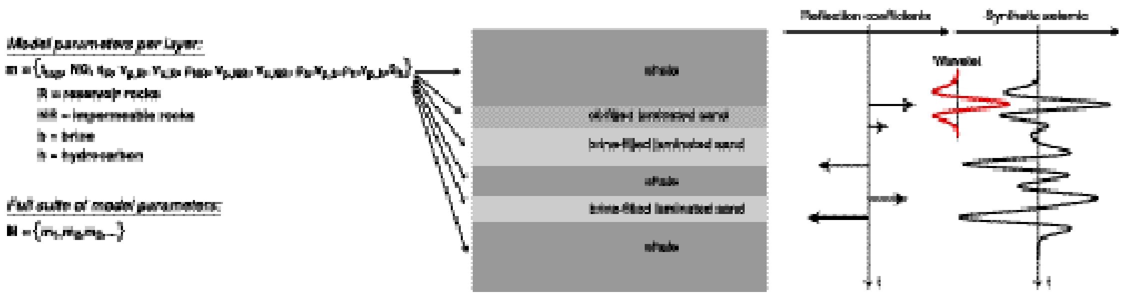

Fig.1 Layer based model with parameters for each layer, sequence of reflectivities, and synthetic seismic.

The parameters in the model are the layer times and relevant rock and fluid properties for each layer. The layer times are picked approximately and fed to the inverter in a set of "prior" traces. Their uncertainty is specified by picking errors, which are taken to be Gaussian. If the prior time uncertainties are sufficiently great, this allows the possibility of modelling pinchouts, wherein layers may disappear if their time-thickness is less than zero, yielding an acoustic contrast between the layer above and the layer below.

The rock properties of the end-member rocks are constrained by a prior regression model developed from log analysis (see figure 2), with a reference fluid in place. The p-wave velocity is regressed against depth and a low-frequency interval velocity (taken from the migration), the latter absorbing any non-normal loading effects. Shear velocities, porosities and densities are then regressed against the p velocity to complete the prior model for the rock physics.

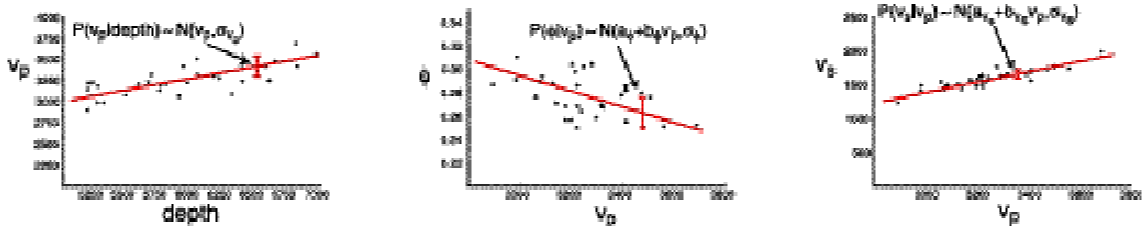

Fig.2 Construction of prior probabilistic model for rock trends from log data. The three regressions jointly form an approximately Gaussian prior.

The forward seismic model is the usual convolution model, with possibly distinct wavelets for each stack. This requires calculation of the reflection coefficients at each interface, and thus the effective properties of each layer. For any particular set of rock and fluid properties in a layer, the layer is homogenised using the following steps: (1) effective fluid calculation using the Reuss average for mixed phases in the permeable rock, (2) fluid substitution of the effective fluid to replace brine using Gassman's rule, (3) mixing of the permeable and impermeable rocks using Backus averaging. Reflection coefficients at the layer boundaries are computed using linearized Zoeppritz equations for all the stacks.

The likelihood function is based on the assumption of Gaussian noise, with the noise computed as the difference between the true seismic and the synthetic seismic summed over all stacks, and the noise level for each stack established from the wavelet extraction at the well tie.

The Bayesian posterior distribution resulting from this formalism is a mixture, with continuous components corresponding to the rock properties and layer times, and discrete elements of the mixture arising from different fluid combinations and possibly pinchout configurations. This posterior distribution summarises the full state of our knowledge after inversion, allowing for explanation of the observed data in terms of all reasonable structural, fluid, and rock physics effects built into the prior. Stochastic samples from the posterior distribution are drawn using Markov Chain Monte Carlo algorithms, which allow the formation of all posterior quantities of design interest, e.g. probability of oil, distribution of net-sand etc.

Example

Hydrocarbon detection and reservoir thickness

Figure 3 shows a single trace inversion problem, where oil in a lower layer generates a large reflection event due to the soft sands. The inversion puts the oil probability at over 80% at this location, includes all the possible effects from rock property variations and horizon uncertainty.

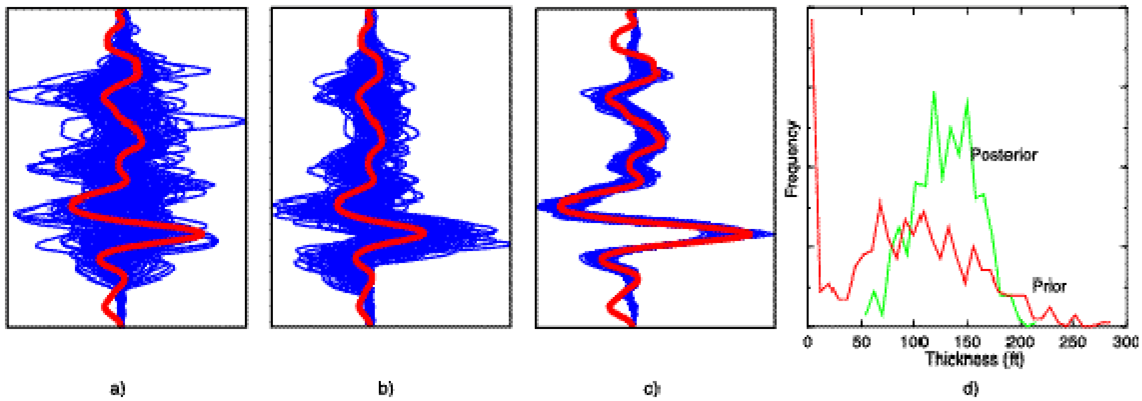

Fig. 3. Synthetic seismic traces overlaid by the observed seismic trace at a particular location in the survey. (a) Sample models drawn from the prior with brine filling a reservoir layer lower down in the model (b) The same, but with oil in the reservoir layer. (c) Traces computed from models drawn from the posterior distribution, conditional on oil present in the reservoir layer. (d) Histogram of reservoir thickness drawn from prior model and after seismic inversion (posterior). Pinchouts and very thin reserves are obviously precluded. The uncertainty in the reservoir thickness is considerably reduced.

Conclusion

Delivery is a free open source toolkit for Bayesian model-based seismic inversion that incorporates rock-property variations and regional trends, bed thickness and composition variability, pinchout effects, uncertainties in fluid kind and properties, and will operate with multiple stacks to exploit AVO effects. It is designed to work with SU data sets and interface cleanly with both SU and the SU extensions from BHP. Multiple-realisation style outputs are drawn from a Bayesian posterior distribution to facilitate risk assessment and decision making.

References

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