

Estimating low frequency spatial trends for reservoir characterization using multiscale data and models

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Abstract

Much of the focus in reservoir characterization has been on capturing fine-scale high resolution features. Many of the fine scale features can play an important role in fluid flow. But in addition to the fine scale features, accurately estimating the low frequency trends can be equally important. Some examples include estimating low frequency trends for seismic impedance inversions and low frequency trends for geopressure estimation. The paper describes how different multi-scale data types and models can complement each other and fill in the gaps to estimate low frequency background trends. One example will be the use of controlled source electromagnetic data that can be used to fill in the gaps in seismic low frequency bandwidth. Another proposed example will be the use of basin modeling to constrain low frequency trends in reservoir properties.

Introduction

Over the decades there have been important advances in high resolution reservoir characterization, including advances in seismic data acquisition, instrumentation, processing, inversion, and integration of different data. The need for high resolution characterization has been driven by the need to capture realistically and with increasing accuracy the complexity of the subsurface. Seismic imaging and inversion combined with geostatistical simulations conditioned to log data have shown great promise for mapping out spatial trends of fine-scale reservoir properties that are critical for reservoir flow simulation.

Understanding and accurately estimating the low frequency background trends of spatial heterogeneity can be equally important. As an example, predicting overpressure from seismic observations before drilling, requires estimating the background trends of velocity, and understanding the links between trends of velocity, stress, and pore pressure. Sometimes a low-velocity anomalous deviation from the background trend might be indicative of overpressured zones (Figure 1). At other times, there may not be a clear anomaly, but the trend itself might be different from the trend in a normally pressured environment.

Another example involves seismic impedance inversion, which is one of the inputs in reservoir characterization. Inversion schemes typically involve a prior impedance model that is iteratively updated to minimize the misfit between observed and computed seismic traces. Reflection seismic data "see" earth structures through two spectral windows: the so-called velocity band (below ~ 2 Hz) and the reflectivity band (above ~ 10 Hz), and has an information gap in the ~2-10 Hz band (Claerbout, 1985; Jannane, 1989). Since conventional band-limited seismic reflection data do not contain information about the

impedance in the low frequency (~ 2-10Hz) band, it is important to constrain the low frequency seismic impedance trend in the prior model used for impedance inversions. The critical role of the low frequency impedance trend has been highlighted by many authors (e.g. Dragoset and Gabitzsch,

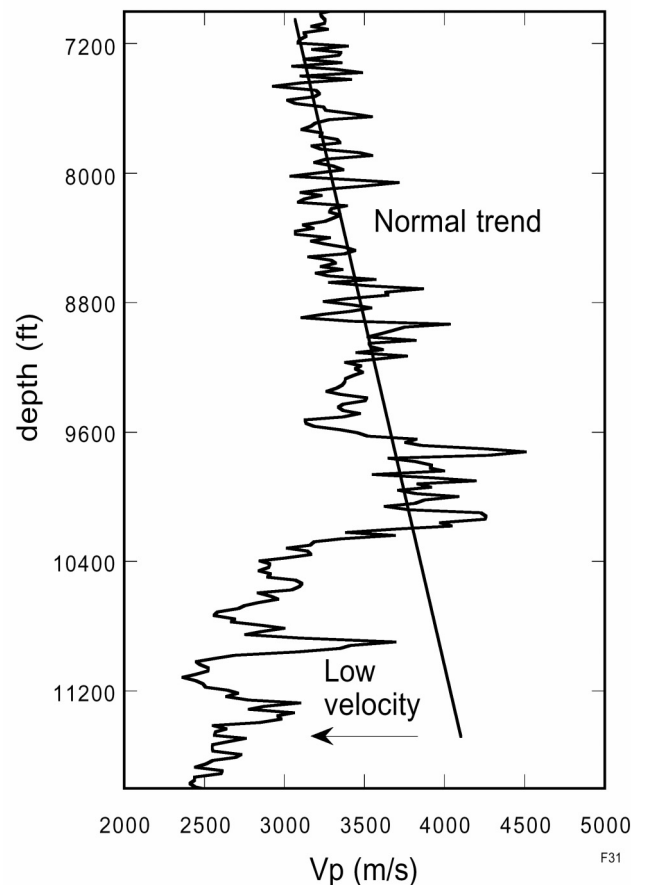


Fig.1 A low-velocity anomalous deviation from the background trend might be indicative of overpressured zones. Well log data from Gulf of Mexico.

2007). The paper describes how different multi-scale data types and models can complement each other and fill in the gaps to estimate low frequency background trends. One example will be the use of controlled source electromagnetic data that can be used to fill in the gaps in seismic low frequency bandwidth. Another proposed example will be the use of basin modeling to constrain low frequency trends in reservoir properties.

CSEM and Background trends

The low frequency seismic impedance trend can be estimated in various ways such as interpolation based on filtered well log data (e.g. Whitcombe and Hodgson, 2007; Cerney and Bartel, 2007; Hansen et al., 2008), or geostatistical techniques such as factorial kriging combined with NMO velocities (Nivlet, 2004). Well log data are often missing in the overburden zone, while zones of poor illumination by seismic waves may not have reflection events that may be used for velocity estimation. In both these situations, conventional methods for estimating low frequency impedance trends may not work very well. As an alternative consider a different type of data. Controlled source electromagnetic (CSEM) data contain information about the earth resistivity in the low-frequency band where the seismic data has an information gap (Figure 2). Calibrated cross-property rock physics relations between elastic and electrical properties can be used to extract information from the CSEM data to provide constraints on the low frequency seismic impedance trend (Mukerji, et al., 2008, 2009).

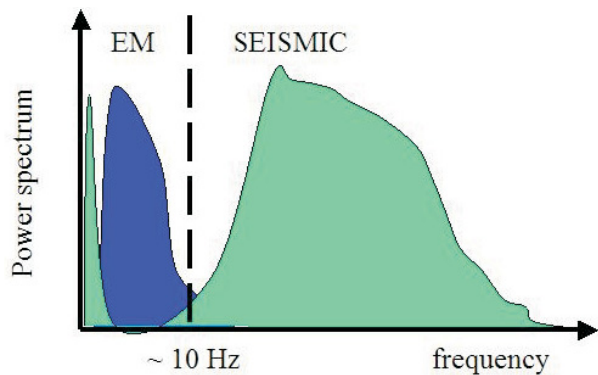


Fig.2 Schematic representation of the domains where seismic reflectivity data and CSEM data contain information about the subsurface. Seismic data lacks information about the low frequency (~2-10 Hz) impedance, while CSEM data contains information in this band about the earth resistivity.

Relations between different rock properties such as elastic and electrical properties have been studied both empirically and theoretically. Cross-property relations are useful to fill in missing data when, for example, one property is more easily available than the other. Some relevant theoretical work includes Berryman and Milton (1988), Gibiansky and Torquato (1995), and Kachanov et al. (2001). Dos Santos et al. (1988) used cross-property relations to estimate velocity logs from resistivity logs. More recently,

Carcione et al. (2007) have compiled and derived cross-property relations and bounds relating electrical conductivity to elastic moduli and velocities of rocks.

We first show an example with log data. A cross-property relation is derived based on two well-known relations (Faust's relation and Gardner's relation, see e.g. Mavko et al., 2009). We calibrate the coefficients using data from well A and validate it at well B. In this example with logs, we take the low-pass (~10 Hz) filtered resistivity log to represent "CSEM" resistivity that might be obtained from a perfect resistivity inversion. Figure 3 compares the actual low frequency impedance estimated from the sonic and density logs with the low frequency impedance estimated using the cross-property relation with the smoothed resistivity as input. The correlation coefficient between the two impedance curves is 0.92 in the calibration well. When the same relation is applied in the validation well we still have a high correlation coefficient of 0.89, and the low frequency impedance from smoothed resistivity captures the background trend of seismic impedance.

Next we show an application to field data and apply the methods to a resistivity section obtained by inverting CSEM data. The resistivity inversion was done by a commercial vendor using a 2.5 D inversion algorithm. The data set that we use is from the Nuggets-1 gas field. This

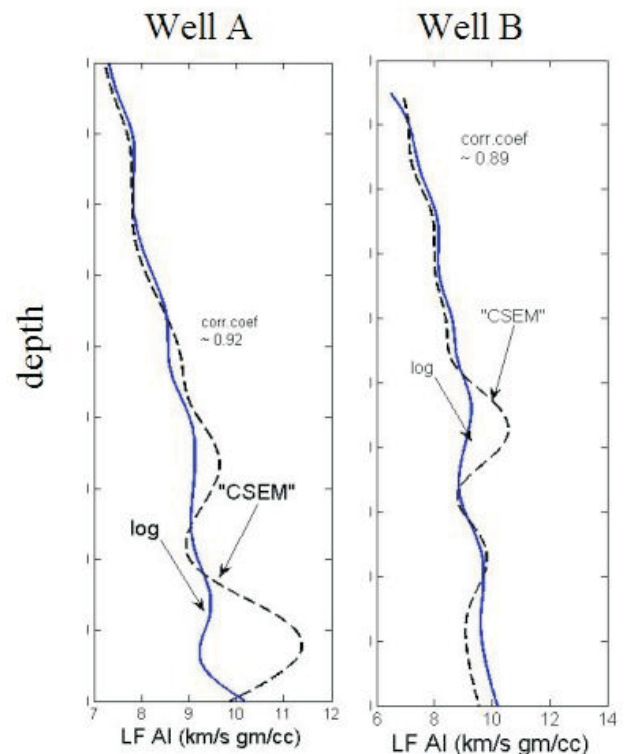


Fig.3 Low frequency impedance trend from log sonic and density data (solid blue curve) compared to the estimated trend (dashed black curve) from resistivity data using a cross-property relation. Well A (left) calibration well; Well B validation well. Each tick on depth axis represents 100m. The background impedance trend is reasonably well captured by the estimate from resistivity.

field is located in the North Sea, offshore from the UK in 115 m of water. The sand reservoir belongs to the Eocene Frigg formation and is about 25 m thick at a depth of 1690 m (Harris and MacGregor, 2006). In order to have a P-wave impedance - resistivity transform, we combined the soft-sand model (Dvorkin and Nur, 1996) with Archie's equation (Archie, 1942). We use this transform to generate an initial acoustic impedance section from the resistivity section inverted from CSEM data, and replace it by the log data where available (Figure 3). We performed the seismic inversion in Hampson and Russell commercial software using a multi-trace, model-based method. To analyze these results, we perform seismic inversion using the same parameters, but building the prior model in two different ways: first using only the well log acoustic impedance as initial input, and second using the CSEM resistivity transformed to background impedance along with the log impedance. Validation was done by leaving

out a portion of the log data, and comparing the inversions from the two prior models. The log data above and in most of our reservoir, hence any depths shallower than 1700 m is left out. Acoustic impedance sections are created using only the partial log data from 1700 m and deeper, and combining this limited log data with the background trend estimated from the CSEM data (Figure 4, top).

We compared the well log data and the resulting acoustic impedance from the inversions at the well location (Figure 5). In particular in the section we had excluded as input, we observe that we fit better the well data when we start with the model that includes the background trend derived from the CSEM data. The median residual are reduced by an order of magnitude when the background trend derived from CSEM is used to constrain the impedance inversion (Figure 6).

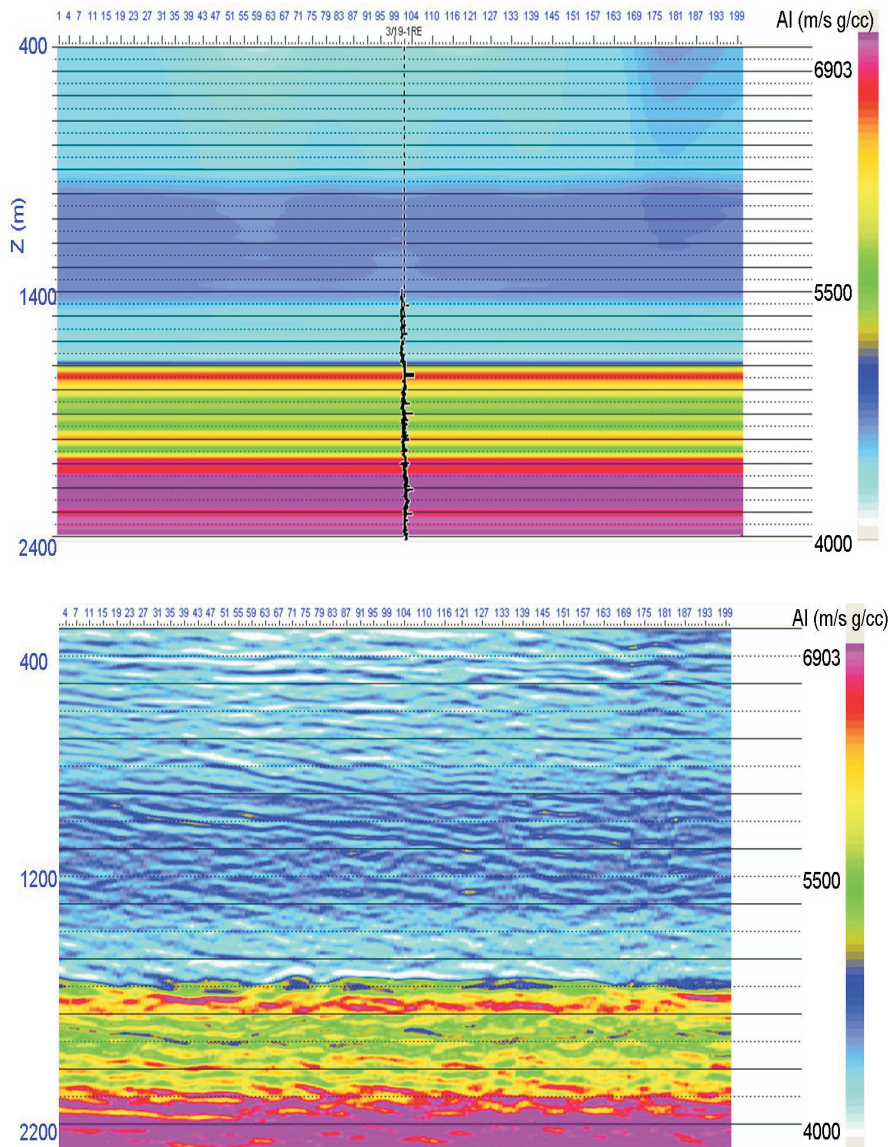


Fig.4 Top: Initial model of background trend of acoustic impedance in depth, generated from CSEM data and partial well information for depth greater than 1700 m. Bottom: Corresponding inverted acoustic impedance (m/s g/cc).

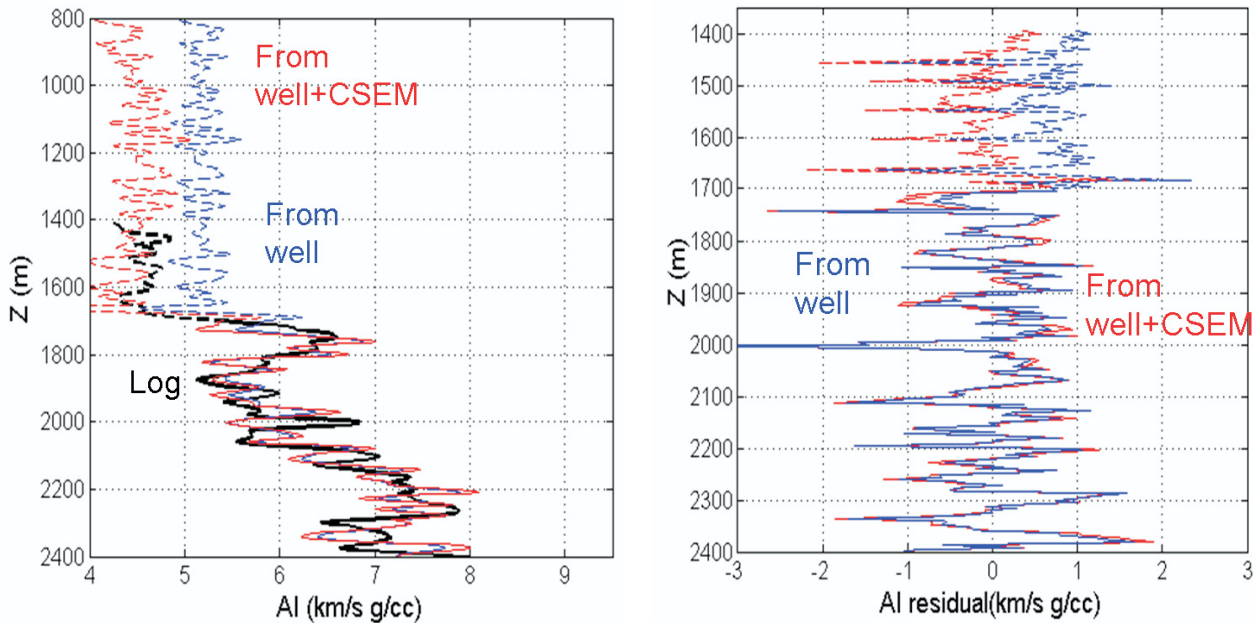


Fig.5 On the left, acoustic impedance at well location. On the right, difference between acoustic impedance well data and inversion. Well data is in black, inversion result starting only with well is in blue, and inversion result starting with CSEM and well is in red. Dashed interval is where no well data was included.

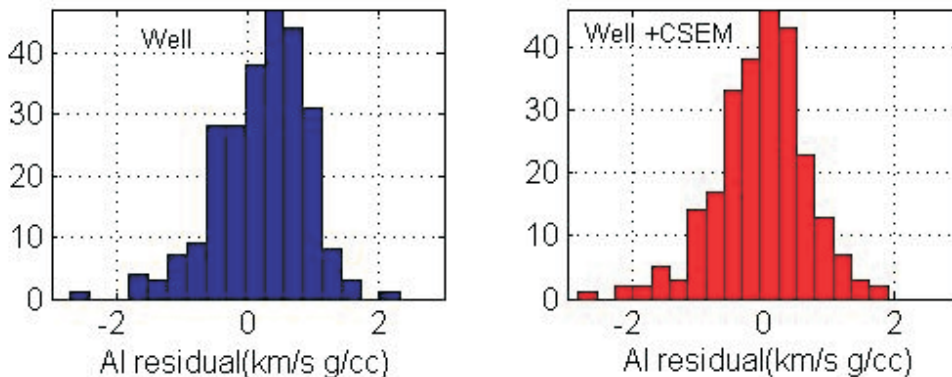


Fig.6 Histograms of the acoustic impedance residuals after inversion at the well location: (1) blue is using only the well as input, and its median and mean are 0.297 and 0.211 m/s g/cc, (2) red is using CSEM and well data as inputs, and its median and mean are 0.0080 and -0.047 m/s g/cc.

Basin Models and Background trends

In this section we discuss another example of models at different scales helping to estimate background trends. Basin and Petroleum System Modeling (BPSM) is a key technology in hydrocarbon exploration that reconstructs deposition and erosion history and forward simulates thermal history and the associated generation, migration and accumulation of petroleum (Peters, 2009). The modeling process can cover very large geological time and space scale. BPSM involves solving coupled nonlinear partial differential equations with moving boundaries. The equations govern deformation and fluid flow in porous media, coupled with chemical reactions and energy transport. The coupled system has to be solved numerically on discretized time and spatial grids with the integration of geological, geophysical, and geochemical input. PetroMod, a commercial software, uses the finite element method to solve these equations.

The typical outputs from numerical basin modeling include vitrinite reflectance (a measure of maturity of source rock) and temperature. The basin models are calibrated by comparing these outputs with data on vitrinite reflectance and temperature from wells and core analyses. In addition to these typical outputs related to the thermal history, we can also extract other outputs which can be very useful for defining background trends. As a simple example, we show a 2-dimension model (Figure 7) of reservoir sandstones underlain by salt body that pierces through the sand. From the basin modeling we can also get estimates of effective stress, porosity, and pore pressure, which when combined with the appropriate rock physics models can also give the trends of seismic velocity (Figures 8, 9). Basin modeling requires as inputs structural horizons that have to be positioned in depth using an initial velocity model. However in situations such as sub-salt or sub-basalt where ray

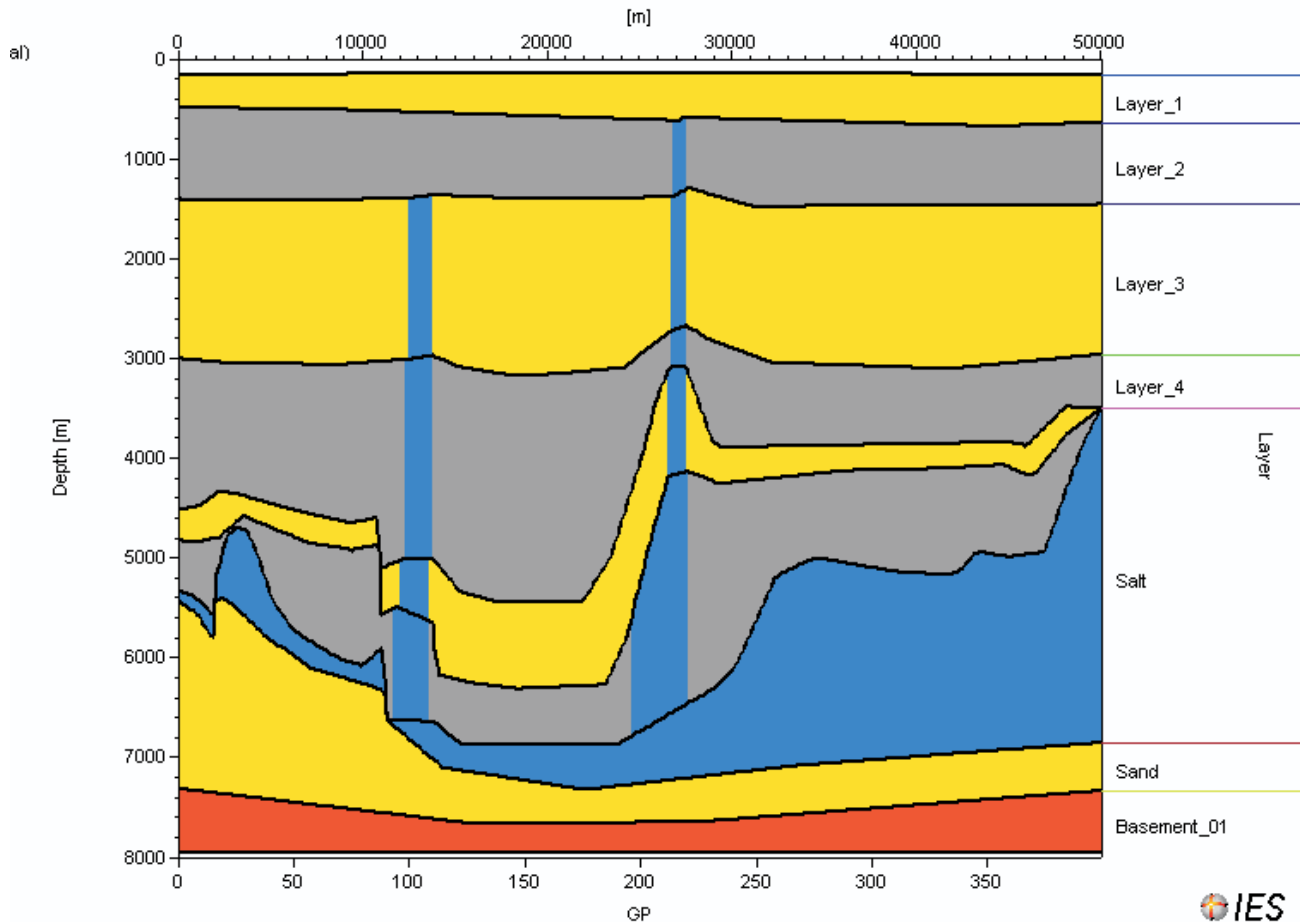


Fig.7 Model for the synthetic example. Blue is the salt body that has pierced through the sand layers (yellow).

illumination is poor and velocity estimation by conventional methods is problematic, the estimate of the smooth background velocity obtained from basin modeling and rock physics can guide seismic imaging to constrain and update the initial approximate velocity model. Thus basin modeling can provide a very useful input for seismic imaging. On the other side, seismic attributes such as velocity cubes and amplitudes can provide very useful constraints on the basin model that can be used to calibrate the models. Seismic calibration of basin models is not limited to only well locations (as in conventional basin model calibration), but is available over a much larger spatial extent. Currently though seismic velocities are used for positioning of structural horizons in basin models, there is much more information in the seismic velocities and amplitudes that could potentially be used to improve basin models. Estimates of pore pressure from basin modeling are complementary with seismic methods of pre pressure estimation, and together can yield superior results. While basin models provide the low frequency spatial trends, geostatistical methods can help to estimate the effects of spatial uncertainty in basin models..

Conclusions

Accurately estimating low frequency trends of spatial heterogeneity can be important for reservoir exploration and characterization. Some examples include estimating low frequency trends for seismic impedance inversions and low frequency trends for geopressure estimation. The paper described how different multi-scale data types and models can complement each other and fill in the gaps to estimate low frequency background trends. One example is the use of controlled source electromagnetic data that can be used to fill in the gaps in seismic low frequency bandwidth. Results show that appropriate cross-property rock physics relations can capture the background low-frequency impedance trend, particularly at shallow depths where no well information is available, and can provide useful constraints on prior models for inversion. Validation test showed that residuals are lower, and the fit is better with the background model constrained by the impedance trend obtained from CSEM data. Current methods exist for estimating the background impedance trend that do not require using

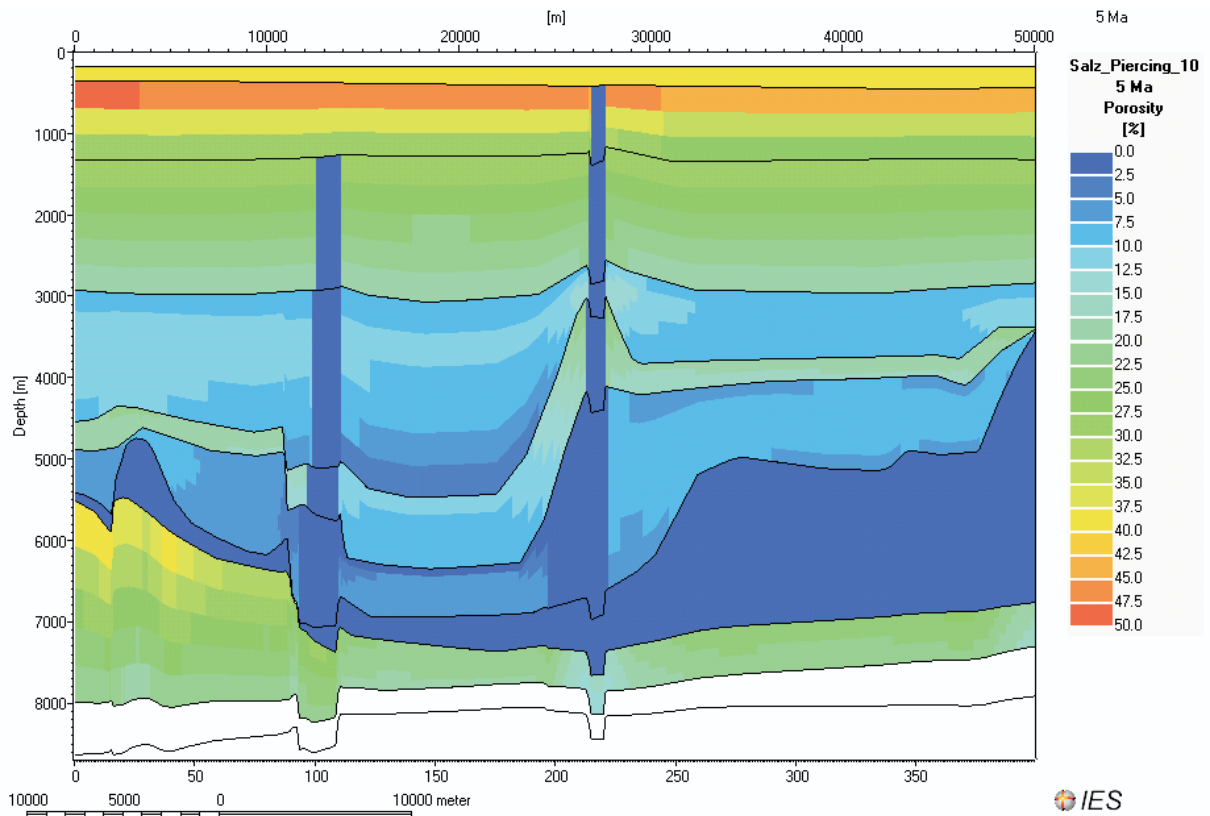
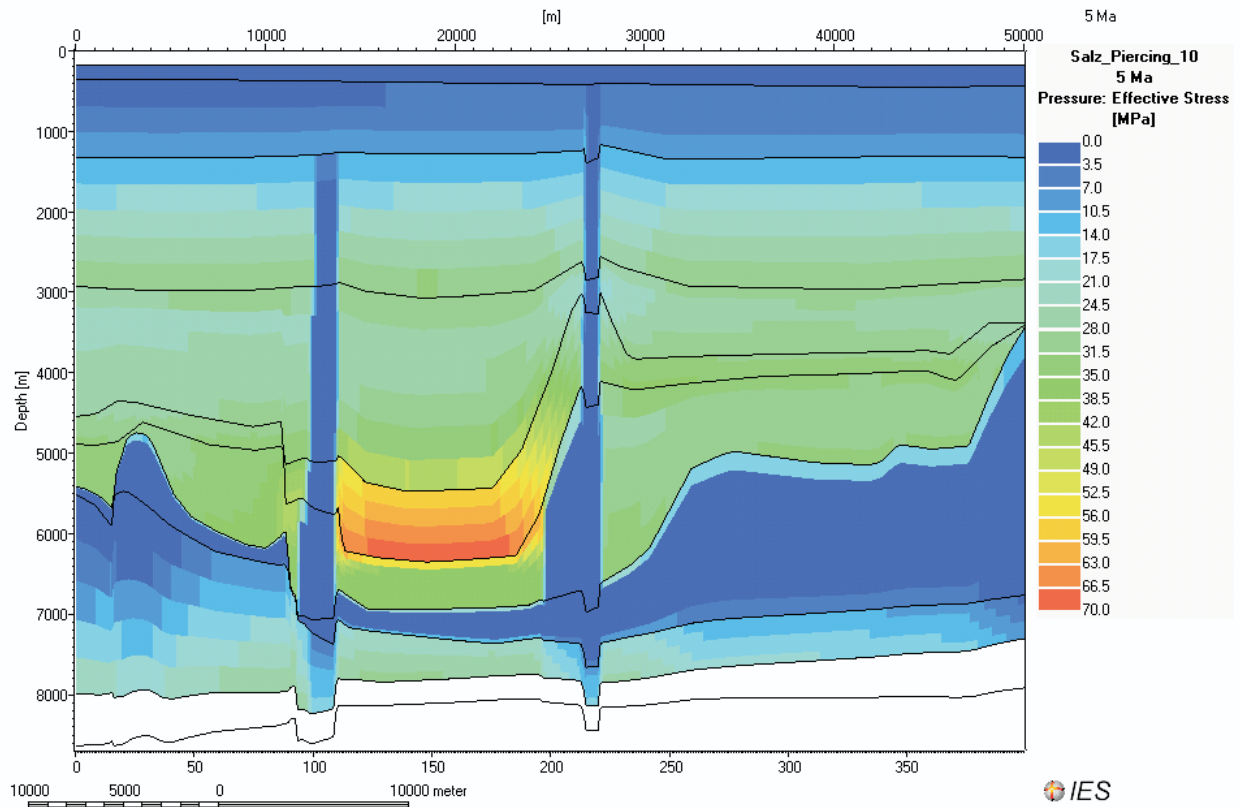


Fig.8 Effective stress (top) and porosity (bottom) from basin modeling.

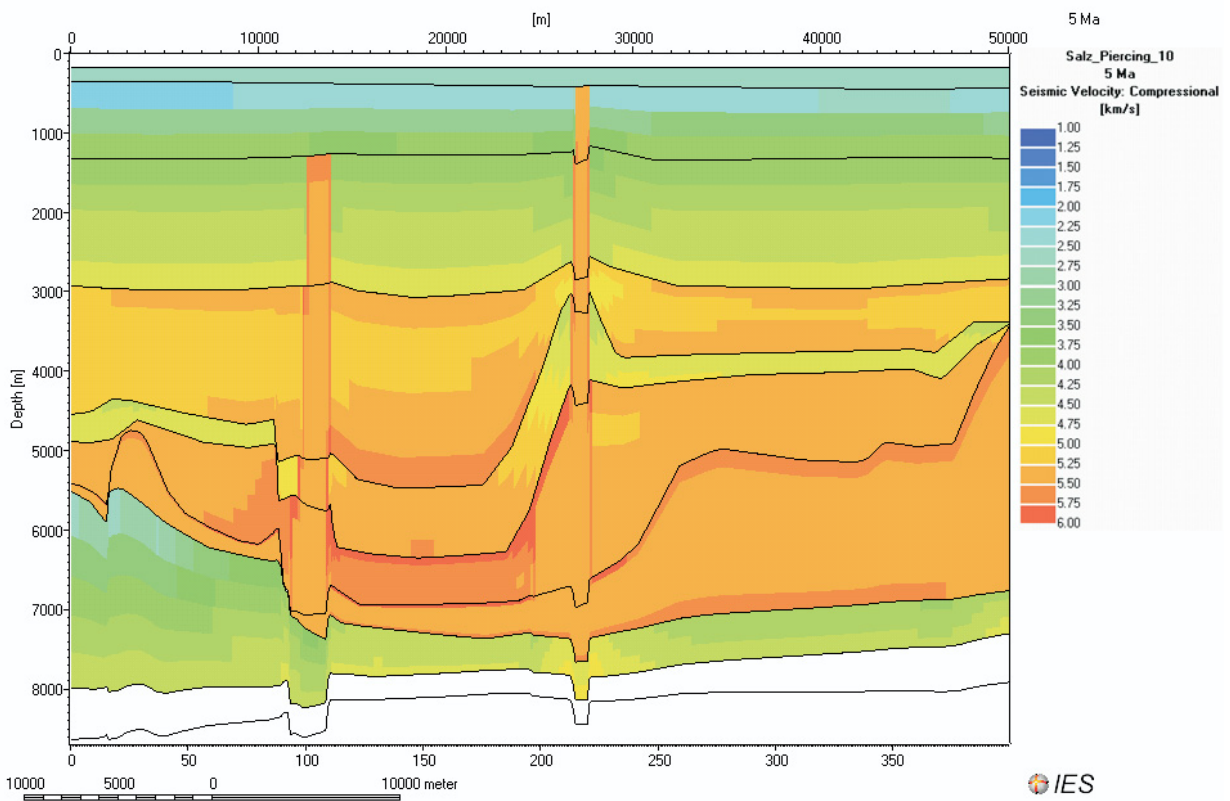
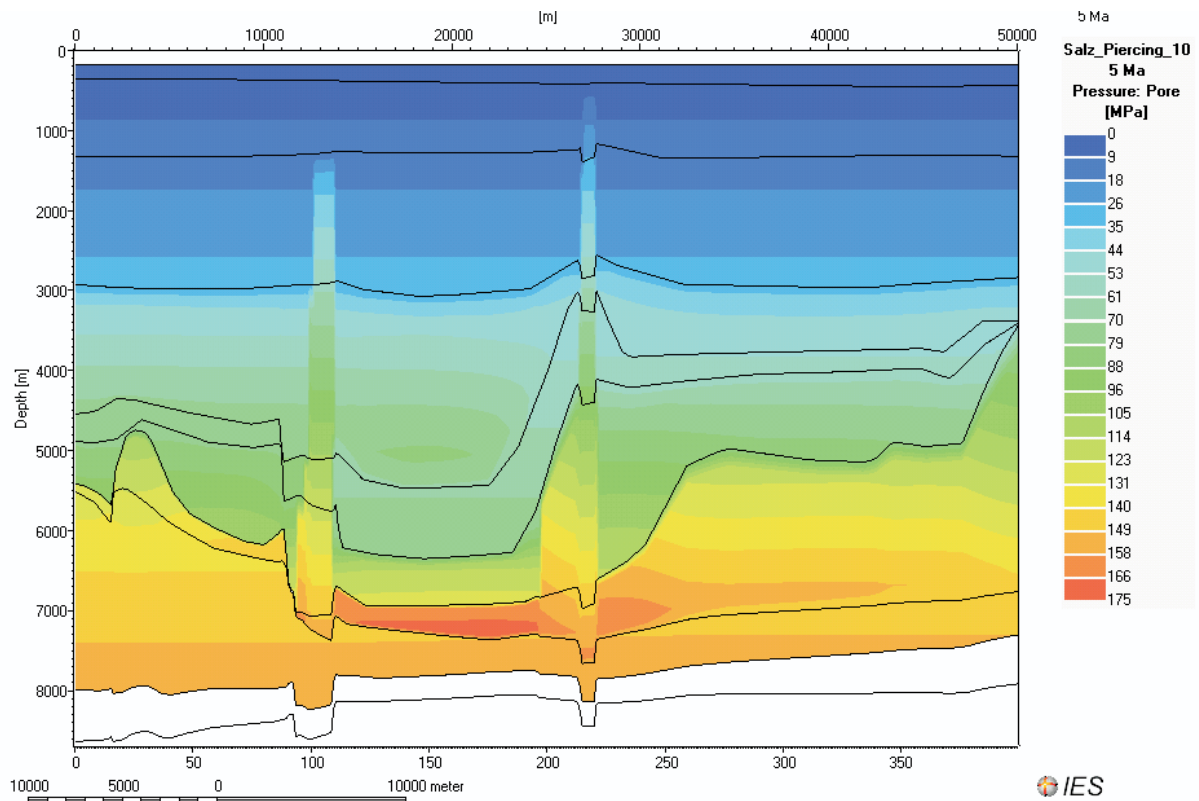


Fig.9 Pore pressure (top) and P-wave velocity (bottom) outputs from basin modeling.

any cross-property relations. Such methods, based on moveouts of reflector events, and geostatistical calibration to well logs can be quite successful. Using cross-property relations and low-frequency electromagnetic data for estimating the background impedance trend offers a complementary approach that might be useful when e.g. reflector events are not well defined and moveouts cannot be estimated reliably, or when well logs are missing in the overburden. Another example of models at different scales helping to estimate background trends, and complementing each other involved discussion of basin models and their links to seismic imaging and geostatistical methods. Outputs from basin models can help to estimate the low frequency seismic velocity trend, thus guiding seismic imaging where velocity estimation is problematic. Geostatistical methods can help to incorporate spatial uncertainty in basin modeling, while seismic attributes such as velocities and amplitudes can provide useful calibration of basin models.

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