Constrained optimization method for seismic stratigraphic analysis – Implications for interpretation quality and machine learning applications

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Summary

Considerable time and money are expended on the acquisition, processing, and evaluation of seismic data for subsurface resource characterization. Maximizing the value of this investment requires data interpretation methods that generate high fidelity models of the subsurface. These models are essential to any exploration or production project because they provide the primary basis for risk and resource assessments, well site selection, and field development planning. Seismic stratigraphic analysis (in conjunction with structural analysis, where necessary) is fundamental to developing robust subsurface models. Using a constrained optimization approach for seismic stratigraphic analysis yields a more complete and accurate interpretation of the subsurface, especially in areas with lower seismic data quality.

Introduction

Seismic stratigraphic interpretation is a complex, high effort undertaking that requires extensive subject matter knowledge and interpretation experience. Seismic stratigraphic interpretation has long relied on observations of reflection terminations and geometry to identify and map key surfaces and stratigraphic intervals. Seismic attribute extractions and other plan view observations should also be integrated into the analysis. Together, these observations provide the basis for stratigraphic and environment of deposition (EOD) interpretations. More recently, the trend toward ‘data-driven’ or quantitative seismic interpretation has placed greater emphasis on mapping and characterizing individual seismic reflections, often to the exclusion of much of the available stratigraphic information. Without the larger depositional context, stratigraphic/EOD interpretations have higher uncertainty and are more prone to error, potentially impacting field development planning and project economics. While these methods can be adequate in settings with good data quality, they become difficult to apply where data quality is lower.

When working with lower-resolution and/or noisy seismic data, standard seismic stratigraphic observations like lapping relationships or diagnostic map patterns are poorly resolved, sparse, or ambiguous. The constrained optimization method described here enables the interpreter to extract meaningful stratigraphic information from the data and construct a high-quality model of the subsurface. The key components of this method are: 1) incorporation of a robust, process-based depositional model (constraints) *during* the interpretation for the purposes of 2) developing, testing, and integrating multiple interpretation hypotheses to converge on a high-confidence solution (optimization).

Constraints

The constraints used for the constrained optimization method come primarily from a geologic depositional model. The constraints must include the spatio-temporal relationships between major depositional elements and the basic recognition criteria for key features. This information is augmented by knowledge of the variability in size, shape, and properties of depositional features. The geological constraints must also be complemented by a thorough understanding of geophysics and the possible seismic expression of stratigraphic features.

Since the depositional model (the constraints) is an integral part of the seismic stratigraphic analysis, the model must be an accurate generalization of natural systems. The model should be based on a parsimonious set of known physical processes or principles that interact to plausibly reproduce the features and relationships observed in nature. The model should also be considered as a time series of sequential steps to ensure logical consistency and plausibility of the entire model. In contrast, the use of postulated processes or controls should be avoided, as these introduce significant uncertainty to the model and can severely compromise the optimization process.

To effectively communicate or evaluate a seismic stratigraphic analysis using constrained optimization, the depositional model must also be made explicit. If the constraints used to perform a stratigraphic analysis are not known, or if constraints from a *different* model are assumed, it is difficult (impossible?) to make or communicate the relevant observations and how they are assembled into the final interpretation. The examples presented here are from deep-water turbidite systems, and a corresponding landscape-scale general model will be presented. The model outlines the key spatial and temporal relationships between major depositional elements (*i.e.,* distributary lobes, levees, channel belts, etc.) and provides the constraints used to generate the optimized interpretations summarized in subsequent sections.

Optimization

Optimization is the process of iteratively generating, testing, and integrating multiple interpretation hypotheses to

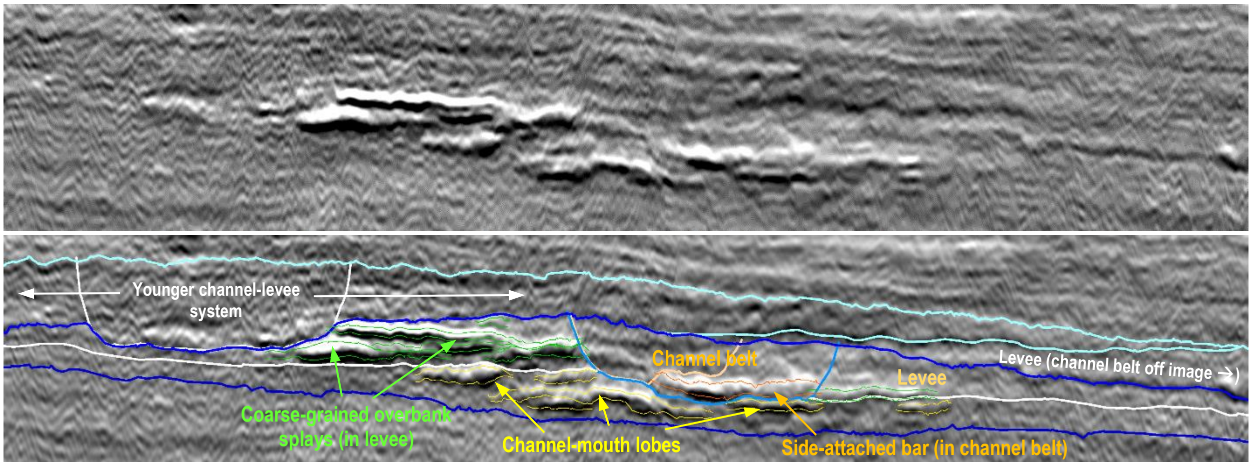

Figure 1 – Seismic line through the target depositional system without (top) and with (bottom) stratigraphic interpretation. Stratigraphic framework surfaces (top, base, channel belt boundaries) shown as thick lines; individual reservoir body tops/bases are shown as thin lines. The stratigraphic framework can not be defined on this line alone; it is the product of the identification, testing, and integration of multiple interpretation hypotheses.

progressively define a complete stratigraphic interpretation. An interpretation hypothesis is generated by convolving observations from seismic data with recognition criteria defined in the depositional model (*e.g.*, converging seismic reflections and the thinning wedge of a levee). After an interpretation hypothesis has been established, it must be tested with additional observations from the data. The hypothesized feature must remain plausible over a significant distance and must continue to satisfy relevant constraints (*e.g.*, a levee should thin consistently in the same general direction). A failed hypothesis must be rejected, and new or modified hypotheses must be generated for further testing. A hypothesis that remains plausible after testing can be retained and used for further optimization.

Multiple interpretation hypotheses must also be integrated to ensure they satisfy the spatial constraints defined in the depositional model (*e.g.*, an interpreted levee must be adjacent to a channel belt). If the integration of multiple interpretation hypothesis does not satisfy the constraints, then one or more of the hypotheses must be rejected, and new hypotheses must be generated and tested. An additional, and essential, constraint that must be satisfied in the optimization process is to account for the full rock volume of the stratigraphic region or interval of interest. Any volume that cannot be integrated into the interpretation significantly increases the uncertainty of the interpretation.

Application

There are two important aspects of the constrained optimization method that significantly improve interpretation quality and confidence. First, actively utilizing constraints from a depositional model means that more information (processes, analogues, spatio-temporal relationships, etc.) is incorporated into the interpretation. Second, the process of generating and testing multiple

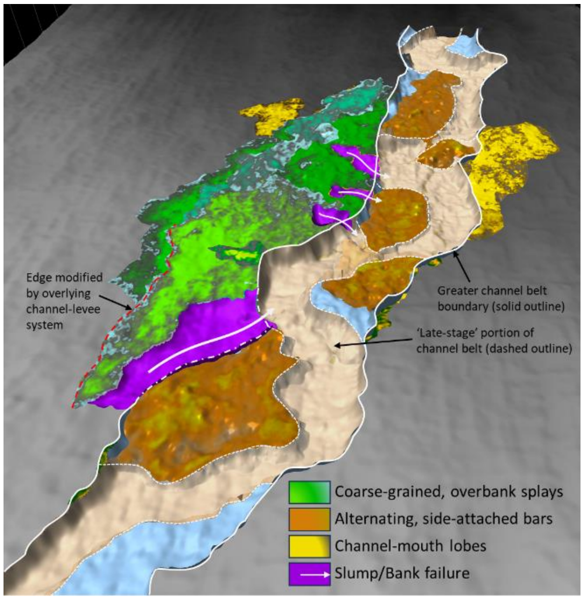

Figure 2 – Perspective view of the target depositional system showing channel belt boundaries and major reservoir bodies (for clarity, additional geobodies in the channel belt and right-hand levee are not shown). An optimized interpretation must plausibly and logically account for all significant features within the context of the stratigraphic framework. Environments of deposition (EOD) are interpreted primarily from their position within the stratigraphic framework, and less so from any particular pattern or property.

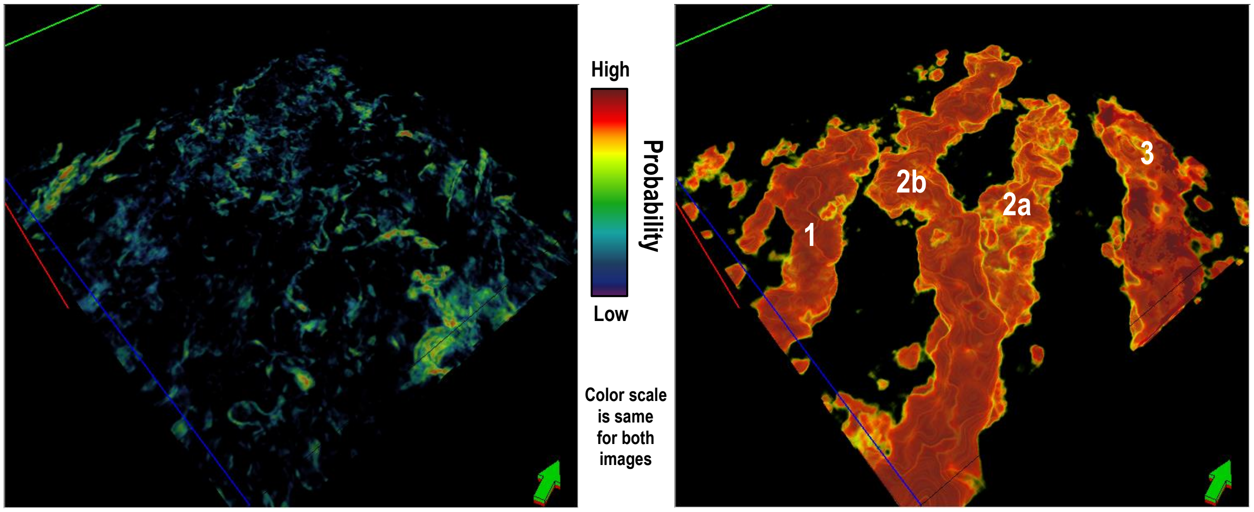

Figure 3 – Results of machine learning-based channel belt detection analysis with training labels generated from a two different interpretations. Images are 3D opacity views showing channel belt detection probability from a seismic volume approximately 30x30 km and 600 meters thick. Training labels are from both inline and crossline directions and are spaced ~5-6 km apart; same lines used for both detections. Analysis using poorly constrained, non-optimized interpretation (left) results in discontinuous, low-probability detections. Analysis based on properly-constrained, optimized interpretation (right) results in continuous, high-probability channel belt detections [note the clear delineation of the channel belt bifurcation (resulting from a channel avulsion) near image center].

interpretation hypotheses means that many different interpretation ideas are evaluated. These features are especially important where data quality is lower and making consistent, high-confidence observations is not possible.

Seismic stratigraphic analysis – Constrained optimization was used to develop the seismic stratigraphic interpretation for the case study included here. Seismic data used for the interpretation are relatively low-resolution with considerable noise (fig. 1). Although there are abundant reflection terminations and stacked amplitudes, there are no obvious reflection geometries or amplitude patterns that directly indicate stratigraphic architecture or depositional elements. The seismic stratigraphic analysis required combining sparse, often ambiguous, observations with recognition criteria from the depositional model to generate interpretation hypotheses. Initial interpretations were then extended see if the hypotheses remained plausible over a significant distance. Successful hypotheses were further integrated and tested against the spatial constraints from the model to develop the optimized stratigraphic framework and depositional feature interpretation (fig. 1 and 2).

Machine learning (ML) application – The use of optimized interpretations is considered essential for ML-based workflows for depositional feature detection. This is especially true with lower quality data where features are difficult to identify and ML detection can add the most value. ML typically requires training labels to delineate a sample of the feature(s) of interest to train the algorithms. Thus, these labels must be accurate and consistent for the detection algorithm to produce meaningful results. Labels generated from constrained and optimized interpretation are more consistent, accurate, and complete, with correspondingly superior detection results (fig. 3).

Conclusions

Constrained optimization is a powerful method for generating integrated, high-confidence seismic stratigraphic interpretations, especially with lower resolution and/or noisy seismic data. Resulting subsurface models contain significantly more and higher-quality information and provide an improved platform for defining and evaluating multiple geologic scenarios. Training labels derived from constrained optimization interpretations provide a better basis for emerging tools like ML-based feature detection. The method requires extensive knowledge and experience to apply independently but can be performed by less experienced interpreters with proper training/mentoring. Finally, interpretations done using constrained optimization are high effort and often require considerable time to complete. It is important for all stakeholders to understand the material advantages and requirements of using this method and plan accordingly.