Geophysical basin modeling: Methodology and application in deepwater Gulf of Mexico

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Abstract

A truly integrated velocity model building method has been developed and applied for seismic imaging. Geophysical basin modeling is designed to mitigate seismic data limitations and constrains the velocity model building by taking advantage of information provided by geologic and geophysical input. The information from geologic concepts and understanding is quantified using basin model simulations to model primary control fields for rock properties, temperature, and effective stress. Transformation of the basin model fields to velocity is made by universally calibrated rock models. Applications show that high-quality seismic images are produced in areas of geologic complexity, where it is challenging to define these properties from seismic data alone. This multidisciplinary operation is of high value in exploration because it offers a significant reduction in the time and effort required to build a velocity model, while also improving the resulting image quality.

Introduction

The high demand for oil and gas in the world today is a driver to explore for hydrocarbons in more extreme environments, deeper waters, and more geologically complex areas. Advancements in seismic data acquisition technology and subsurface imaging algorithms are crucial for identification and evaluation of hydrocarbon prospects under these conditions. However, despite advanced acquisition schemes and sophisticated computer algorithms, there are still fundamental limitations in our ability to accurately extract subsurface properties from the seismic data alone. A major challenge in imaging of the subsurface is to derive optimal velocity models for input to the imaging algorithms. The quality of imaging is strongly related to how successful we are in solving this challenge.

Conventionally, velocity and anisotropic models are derived from surface-seismic data in combination with well-log data. Initial velocity and anisotropy models for imaging are estimated at well locations, extrapolated/interpolated throughout the full volume, and iteratively updated using the seismic data until a good fit between data and models is achieved. The estimated models are, however, nonunique because several “earth models” may fit the measured data (Bakulin et al., 2010). Recently, rock-physics modeling has been proposed as an additional source of information in the derivation of the anisotropic subsurface response (Bachrach et al., 2010, 2011; Brevik et al., 2011). Li et al. (2011) and Helgesen et al. (2013) show further how rock-physics constraints could be used in combination with seismic data to better address the nonuniqueness problem.

The task of deriving adequate velocity models for imaging is especially challenging in geologically complex areas, such as in subsalt environments. Conventional model building methods relying solely on the information contained by the seismic data often struggle to provide good-quality velocity models due to poor seismic signal and very limited angular illumination subsalt. Sparse and limited depth interval well-log data cannot really aid the subsalt velocity model building in a substantive way. In complex environments such as the subsalt, where varying salt body movements influence sediment velocities, we also lack good constraints to interpolate between well locations. Therefore, well measurements are typically used only as quality control points of the derived velocity models. In this setting, the quality of an initial model becomes crucial for successful imaging, and because seismic data and well-log data have obvious limitations in establishing such a model, one needs to exploit new concepts and independent information to accomplish this.

The subsalt complexity is related to salt body movements, rapid sedimentation, and spatial and temporal variations in source terrains and associated lithologies. Variations in temperature and effective stress over time add even more complexity to this scenario. Present-day

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temperature and effective stress under such conditions are severely affected and deviate strongly from the traditional assumption of a steady-state, depth-dependent function. Because present-day seismic velocities are products of the basin evolution or "geohistory," quantification of geologic information, typically estimated using a basin model, has an obvious potential in assisting seismic velocity model building. Basin modeling in various forms has previously been used with reported success to build velocity models (Chengbing et al., 2007; Petmecky et al., 2008, 2009; Brevik et al., 2014).

Basin modeling is a standard subsurface tool to simulate the effect of the geohistory on petroleum systems through time. An existing basin model represents an investment already made, and it can be leveraged directly to establish a velocity model that reflects the geohistory. Rock-physics models form a link between the basin model (geohistory) and the seismic domain. Appropriately designed, the rock model honors the time dependency of the control factors for rock properties, allowing transformation of this information to elastic properties.

The concept of linking geologic information through rock-physics transformation to obtain elastic model properties for application in integrated exploration analysis has been described by Brevik et al. (2011, 2014) and is named *geophysical basin modeling* (GBM). In this paper, we further describe a multidisciplinary methodology and we show the application of GBM to seismic imaging in the deepwater Gulf of Mexico. The GBM provides a high-quality initial model that can be further refined using conventional methods.

Methodology

A multidisciplinary workflow (Figure 1) was designed to mitigate the seismic data limitations by taking advantage of information provided by geologic and geophysical input. Basin modeling and rock-physics transformation are essential components of the GBM method, in which elastic properties such as P- and S-wave velocities, anisotropy parameters, and density are predicted based on geologic input. The GBM-predicted model properties can be directly used in velocity modeling for depth imaging.

Basin modeling

Basin modeling is commonly used for petroleum system analysis to address critical exploration risk factors, such as maturation of source rocks, migration and capture of generated hydrocarbons, and seal integrity. Basin modeling is used here in a targeted way to provide an input to rock-physics predictions; specifically, time-dependent temperature and effective stress.

An example of a geohistory at one specific location is shown in Figure 2, and a magnified geohistory showing the impact of salt emplacement is shown in Figure 3. The influence of salt on the temperature history is evident (Figure 3). In the period 2.8–2.4 million years (Ma) ago, subsalt layers were cooled down, followed by cooling or warming dependent on the layer's distance from the base of salt.

As illustrated, salt geometry has a strong impact on temperature distribution in the subsurface, and it is therefore a key control on rock-physics predictions of velocity and density. For quality assurance of present-day salt body interpretation (as represented in the basin model), we use the density as predicted by the GBM workflow to model the gravity response and compare this with real gravity measurements (Figure 4). We thereby make use of independent geophysical data (gravity as opposed to seismic) to assist model building and validate salt body interpretation (Huston et al., 2004; O'Brien at al., 2005). We also compare the basin model salt body representation with the latest seismic imaging. If relevant, salt body reinterpretation and resimulation of the basin model are executed ensuring optimal and consistent temperature and stress fields for rock-physics modeling.

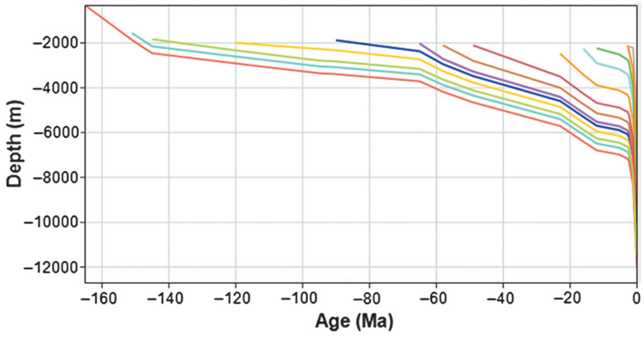

Figure 2. Subsea-surface depths of basin model layers (colored lines) at various times in geohistory at one location. The latest stage of allochthonous salt emplacement started approximately 2.8 Ma ago.

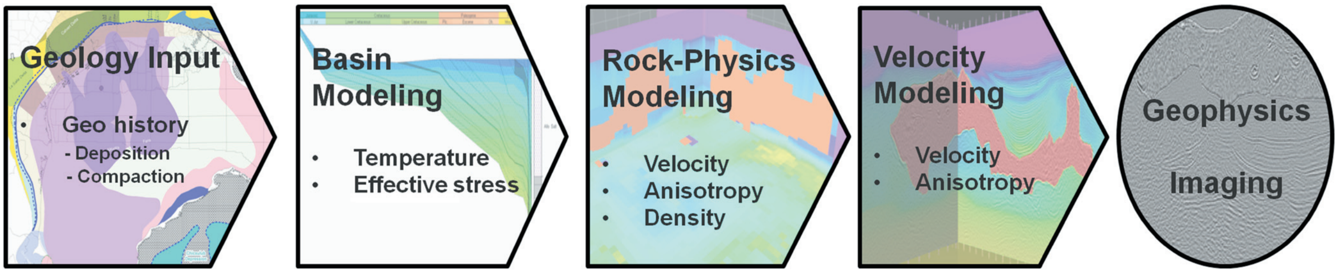

Figure 1. The GBM in the workflow linking geology and geophysics.

Generally, input to modeling is intrinsically uncertain; this is also true for basin modeling. The timing of tectonic events, salt movement, and sediment deposition has a direct impact on the model results. It is therefore important that this model uncertainty is quantified and propagated to the velocity and density predictions (De Prisco et al., 2014). Including uncertainty information in our workflow will be a focus for future work.

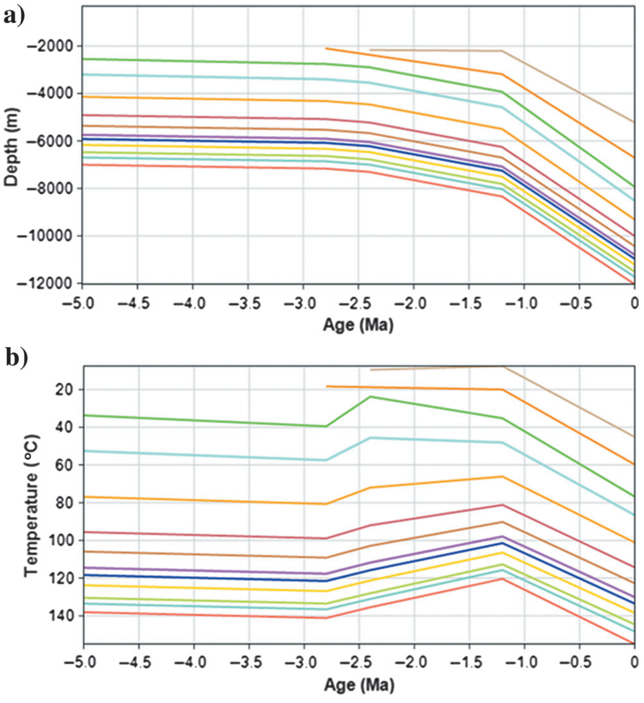

Figure 3. (a) Subsea-surface depths and (b) temperature of basin model layers (colored lines) for the recent five million years of its geohistory of the same location as shown in Figure 2. Salt emplacement started approximately 2.8 Ma ago. The two upper lines represent the top and base of the salt.

Rock-physics modeling

From a rock-physics perspective, primary control factors for rock properties (for a given lithology) are temperature and effective stress as functions over geologic time.

Velocity (and density) models for imaging are made in the depth domain. Standard rock-physics reference models using depth as the controlling factor for velocity and density are not recommended because their validity is restricted to the area/basin in which they are developed. Increased geologic complexity (e.g., subsalt settings) will limit the value of such models.

The GBM is designed to honor the time variability of the primary velocity and density control factors such as temperature and effective stress for various lithology types. The rock-physics model follows mechanical and chemical compaction laws when modeling the porosity and anisotropic or isotropic stiffness components from which properties such as P- and S-wave velocities, anisotropy, and density are calculated. The rock model is universally calibrated to various depositional and geohistory sets from hundreds of wells worldwide (Brevik et al., 2011), and the only parameterization needed is for lithology type and depositional attributes. Access to well-log data (also for better lithology and depositional attribute definition) helps to build confidence in the produced velocity and density fields.

For GBM, the functional form of P-wave velocity (V_P) is

$$V_\mathrm{P} = V_\mathrm{P}(t, T(t), \sigma(t), \mathrm{DA}(t)), \tag{1}$$

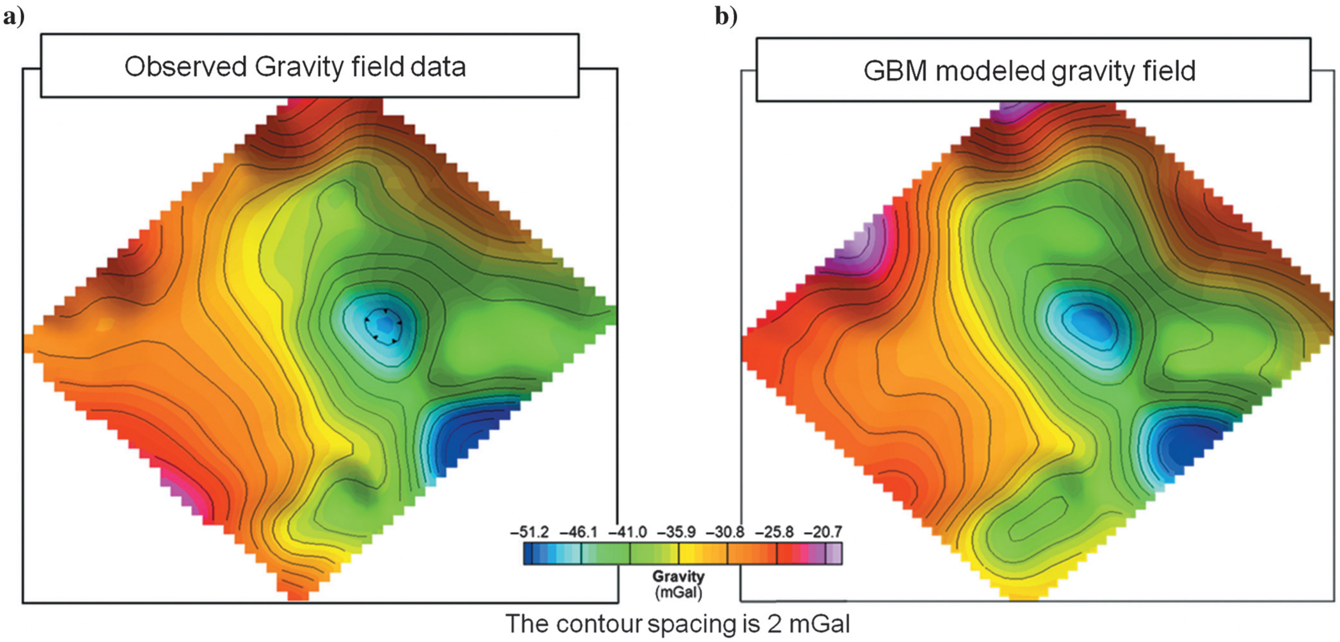

Figure 4. (a) Observed gravity field data and (b) the GBM-modeled gravity field. The contour spacing is 2 mGal.

where t is the time, T is the temperature, σ is the effective stress, and DA is the depositional attributes (one set for each lithology type). An example of depositional attributes for shale is the volumetric amount of the minerals/particles of smectite and quartz, specified at the time of deposition. The above volumes will change during burial, according to compaction laws.

Figure 5 shows an example of modeled transverse isotropy (TI) parameters, such as P- and S-wave velocities, epsilon, and delta for subsalt shale layers at the location shown in Figures 2 and 3. The sudden variation in the P- and S-wave velocity trend (Figure 5a) represents a very active chemical compaction condition.

Velocity modeling

In a geologically complex environment with salt structures, velocity model building techniques typically follow an iterative, top-down approach resolving first seismic properties in the suprasalt section, then the salt body definition, and finally tackling the subsalt part of the model. Depending on a priori information and seismic data quality, different methods are used to update velocity model properties in a given subsurface zone.

Modern seismic data acquisitions typically yield very good seismic data quality including high angular illumination in the suprasalt zone. Methods such as tomography and full-waveform inversion can be used to produce high-quality, high-resolution velocity models when provided with adequate initial models (Woodward et al., 2008; Virieux et al., 2009).

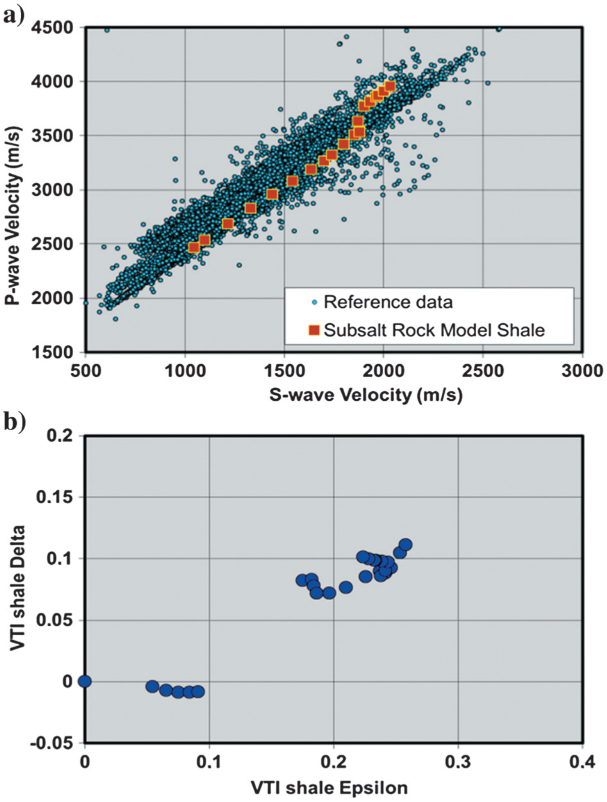

Figure 5. (a) The GBM-modeled subsalt section P- and S-wave velocities and (b) coefficients epsilon and delta in the supra- and subsalt sections at the location for which its geohistory is shown in Figures 2 and 3. A reference velocity data set is shown for comparison (blue circles) in panel (a).

For the subsalt zone, the situation is often different. The salt bodies can cause seismic energy scattering and severe wavefront distortions leading to subsalt illumination problems (Muerdter et al., 2001a, 2001b, 2001c). In addition, the range of reflected angles at the subsalt reflectors is very limited due to the large salt-sediment velocity contrast. Consequently, data-driven velocity model update methods often fail to provide any significant improvement to subsalt initial models. Establishing a high-quality initial velocity, in this case based on GBM, is therefore essential for successful imaging of the subsalt section.

Generally, we may consider velocity modeling as a refinement/update of the initial model, where the strategy for updating is dependent on the quality of the geophysical and geologic inputs. The uncertainty of these inputs may, in a quantified form, be used as constraints in the model update, where the objective is to find models that honor geophysical and geologic inputs (Li et al., 2011; Helgesen et al., 2013).

Application to seismic imaging

We apply GBM to seismic imaging in a geologically complex area of the deepwater Gulf of Mexico. A Gulf of Mexico regional basin model that uses our current database and regional geologic understanding is used. From the regional model, we extract a local basin model covering the study area. The local basin model was updated to honor a new, more detailed interpretation of the salt geometry. From the basin-model simulations, we obtain 4D (3D over time) data for subsequent rock-physics transformations. Each layer extracted from the basin model has the geohistory of relevant properties, in our case, temperature and effective stress. The 4D data can be quality controlled prior to the rock-physics transformation.

Figure 6 shows a single horizon's burial history obtained from the local basin model. The vertical axis is

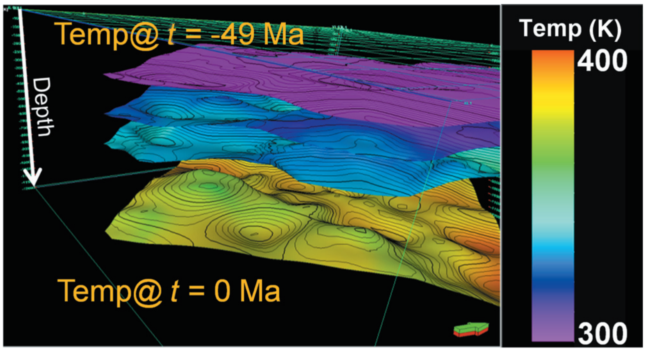

Figure 6. The 4D data showing a single horizon's burial history with temperature history overlain. As the geological time progresses, burial depth increases (vertical axis) and the layer temperature changes.

the burial depth; the surfaces represent one specific horizon (layer boundary) at selected time periods between deposition at 49 Ma ago and the present day (0 Ma). The surface is colored with temperature values.

The elastic model properties resulting from the rock-physics transformation are consistent with the geologic 4D data. Figure 7 shows a comparison of the GBM-predicted shale P-wave velocity at the present time and the P-wave velocity derived by conventional model-building methods. The velocity variation on the GBM depth slice reflects the geohistory in this area.

Additional 3D cubes of S-wave velocity, density, as well as the TI coefficients delta, epsilon, and gamma, were generated. As with the velocity field, the predicted

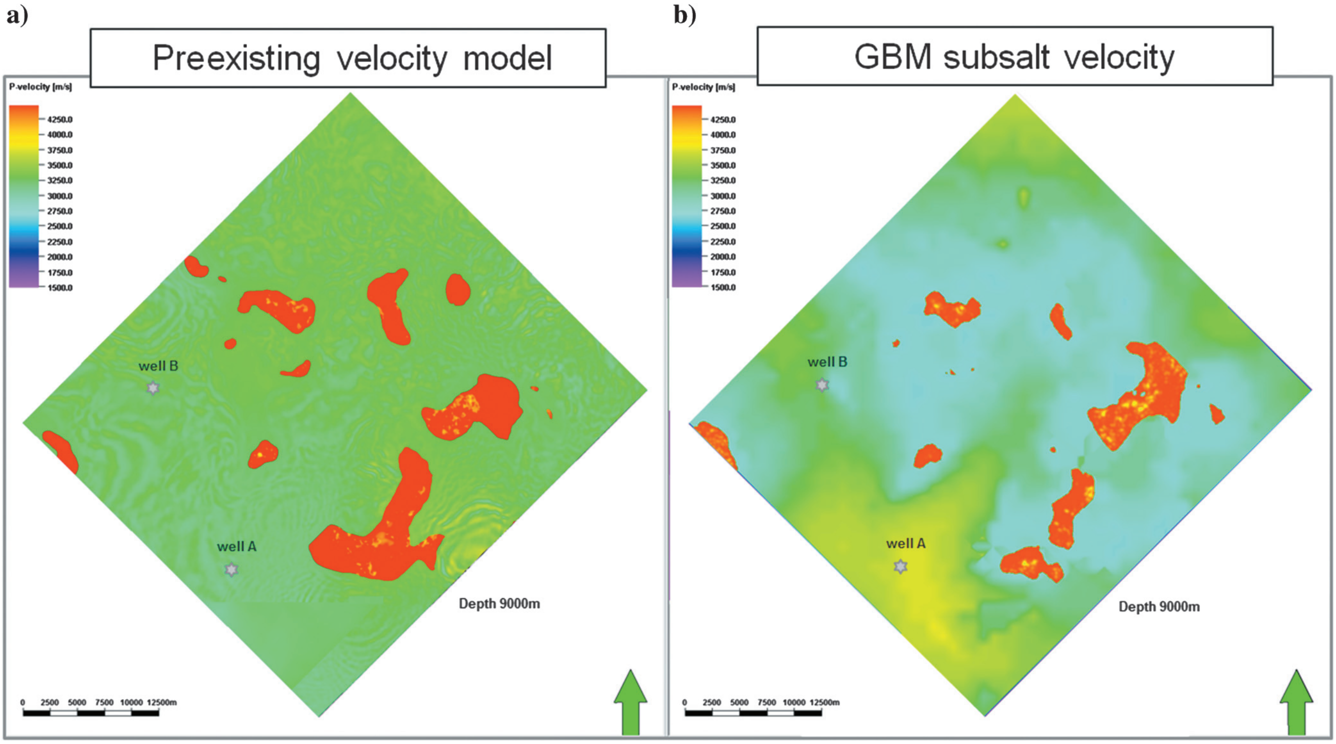

Figure 7. (a) Conventional velocity model and (b) the 3D GBM-predicted shale P-wave subsalt velocity. Salt is in red, with the yellow color representing dirty salt. The subsalt seismic well tie shown in Figure 10 was performed at wells A and B. The subsalt velocity on the GBM depth slice varies between approximately 2500 (light blue) and 3800 m/s (yellow). The velocity change demonstrates how the geologic history impacts elastic model properties.

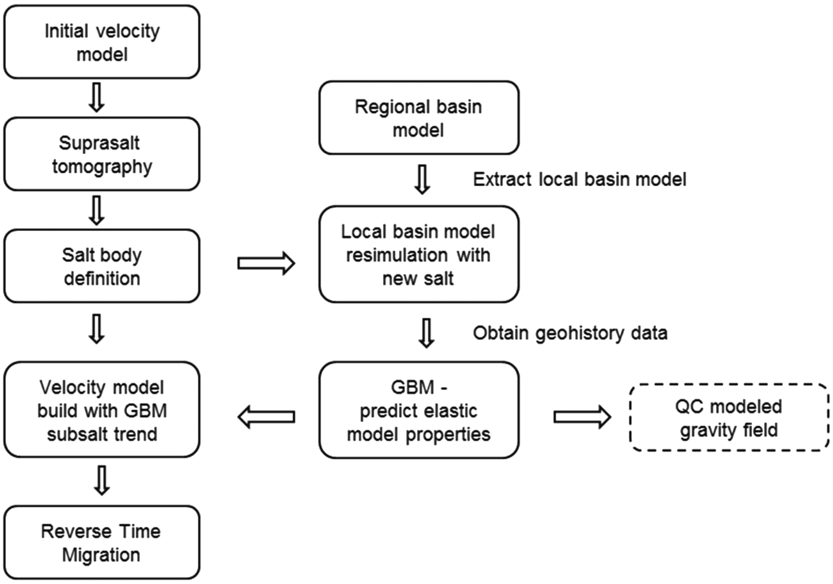

Figure 8. Workflow using GBM in seismic imaging.

spatial variation of delta and epsilon reflects the geohistory. However, due to the limited-angular-resolution subsalt and lack of anisotropy estimates from well measurements, it is very difficult to fully validate the magnitude of the GBM-predicted anisotropy values.

Figure 8 shows how GBM was integrated in a seismic imaging workflow. Initial velocities were updated in the suprasalt section using conventional tomography constrained with well information to ensure a good seismic well tie above the salt. Salt body structures were defined through several iterations of interpretation and reimaging using reverse time migration (RTM). The GBM velocity predictions were applied in the subsalt section. The resulting velocity model was then used to image the seismic data with RTM.

Discussion

We show results of the GBM application to seismic imaging in the deepwater Gulf of Mexico with an objective to provide a high-quality initial model. We make comparisons of results using the seismic-data-driven methods to results obtained using the GBM scheme.

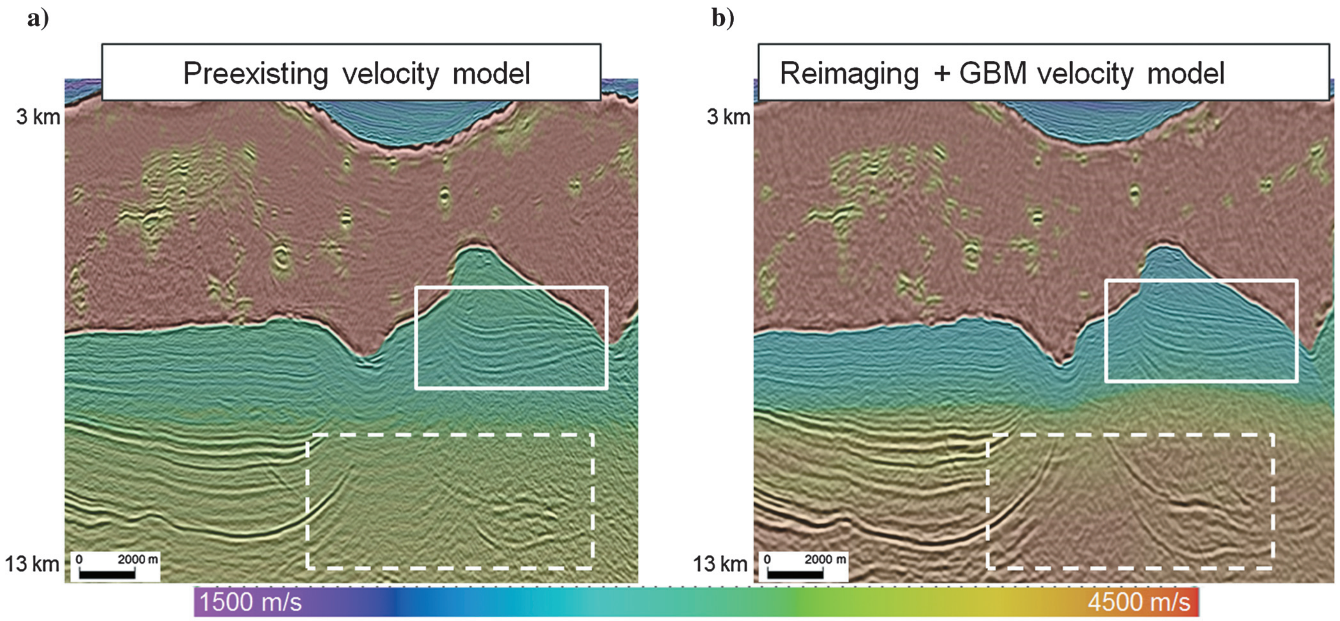

Figure 9. Comparison of images (a) using a state of the art conventional model-building methods and (b) using the GBM scheme.

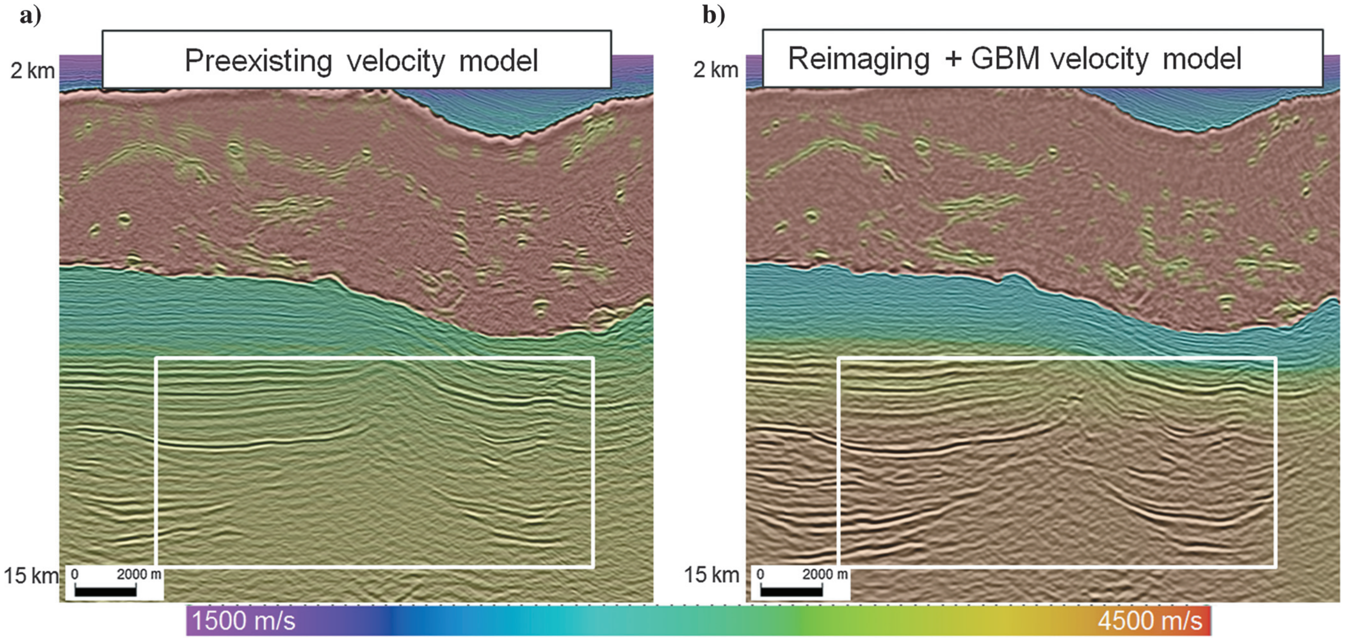

Figure 10. Comparison of images (a) using a state of the art conventional model-building methods and (b) using the GBM scheme.

Figures 9 and 10 show comparisons of previous images from (a) state-of-the-art depth imaging using conventional velocity model-building techniques and (b) images obtained using the GBM method. To better evaluate the effect of our workflow, the subsalt velocity models used in these comparisons are the "raw" GBM velocities, which have not been further refined with tomographic velocity updates.

The conventional model was built using the seismic information only and despite the efforts to obtain the best model possible, it suffers limitations in the subsalt section. In Figure 9, note the structure simplification (marked by the white rectangular) and improvement in the event continuity of the deeper reflections (dotted rectangular) on the image migrated with the GBM-modeled velocity subsalt. In Figure 10, the GBM result exhibits improved stacking response and event continuity. On the image migrated with the GBM subsalt trend, we see more data; hence, we have a better chance to succeed in further model updates using seismic-data-driven methods.

Figure 11 shows the seismic to well tie analysis performed at two well locations within the study area to assess the image and model quality. The blue traces are synthetic seismograms generated from the well logs, the red traces are seismic traces extracted along the well path from 3D seismic cubes, from the previous cube (left panel) and from the GBM (right panel). The black arrows point to the corresponding reflections at the Top Wilcox level.

There is a clear misalignment between the well depths and the preexisting seismic image observed at the two well locations. The depth misfit at well B corresponds to a 15% velocity error in the subsalt velocities at the target level. The GBM image shows excellent character and depth tie to the wells. This quality check (QC) gives us confidence in the predicted GBM velocities and the ability to predict accurate depths.

Figures 12 and 13 show comparisons of sonic measurements and imaging velocities extracted along the well paths: the previous velocities obtained from the seismic data (green) and the GBM predictions (blue). In general, the green curve (the previous velocity model) is too fast above the Wilcox interval and too slow within and below it. The GBM predictions follow the low-frequency trend of the well measurements much closer. Wells A and B (Figure 12) were used at an early QC stage of the GBM parameterization; however, to check the robustness of the method, we performed blind tests at several well locations outside the study area. Wells C and D (Figure 13) are examples of the blind well test results. In general, we observe a good correlation of the predicted velocities (blue) to the well measurements. The blind well test results are important, helping us to build confidence in the modeled subsalt velocities.

For gravity modeling, normally, input density volumes are obtained from converting interval velocities to density using velocity-density relations. This creates uncertainty due to the number of transformation choices such as Gardner's or Nafe-Drake relations (Nafe and Drake, 1957; Gardner et al., 1974). The GBM predicts elastic model properties together with density volumes. The GBM-produced density cube can be used directly as input for gravity assessment. As shown in Figure 4, the GBM-based modeled gravity field compares very favorably with real gravity measurements and indicates that the modeled density distribution fits well to gravity observations. This sort of analysis can be used as a QC of our models with respect to the long-wavelength variations due to the salt presence.

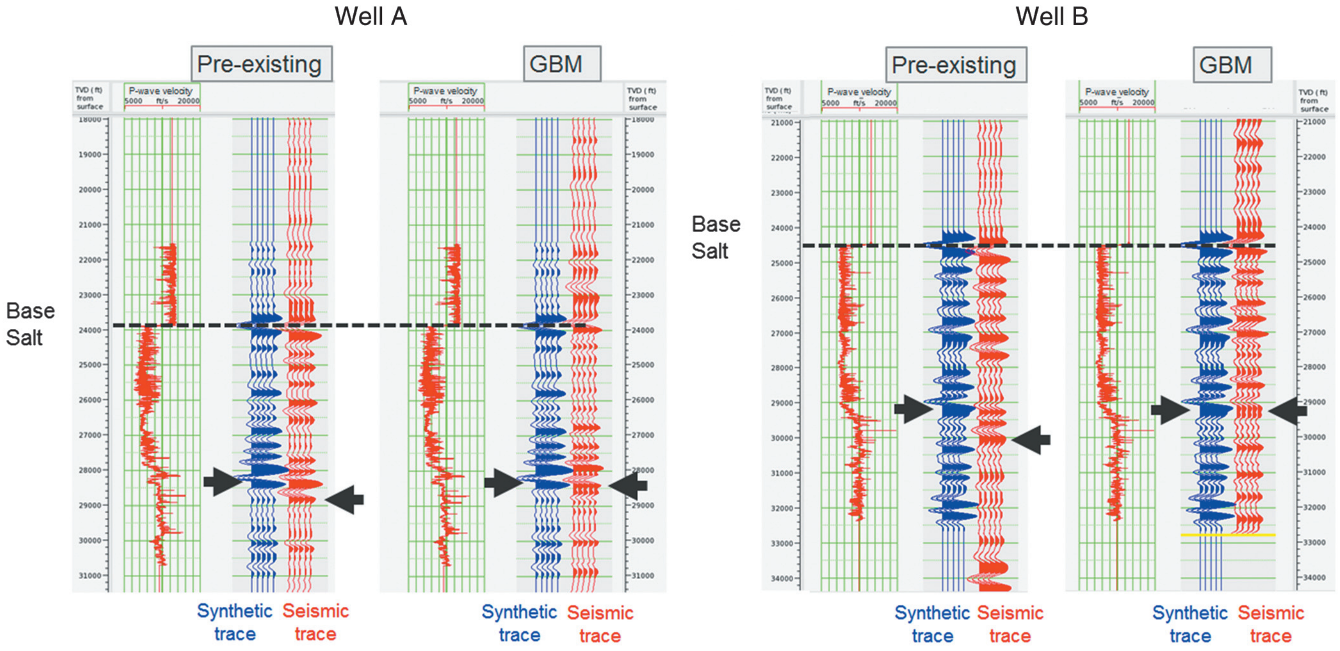

Figure 11. Seismic to well tie analysis performed for two subsalt wells within the study area.

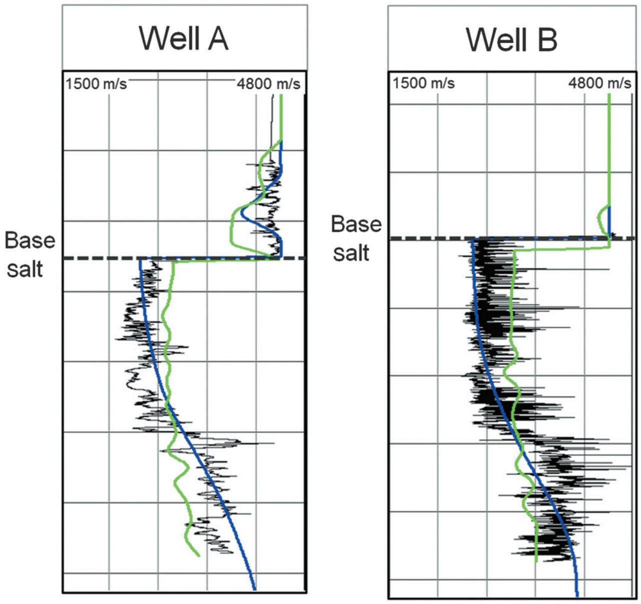

Figure 12. Comparison of the sonic measurements (black), the previous velocity model obtained from the seismic data in green, and the GBM predictions in blue. The vertical axis grid line spacing is 2000 ft.

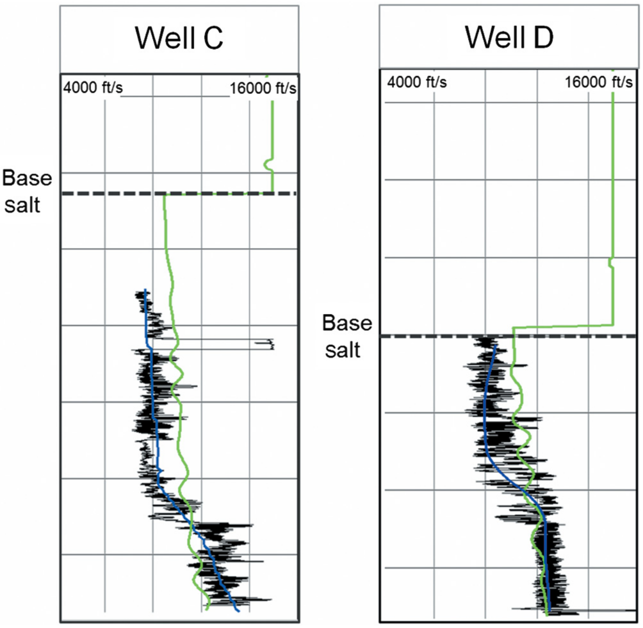

Figure 13. Blind well test result: The green is the velocity extracted from the existing velocity model, and the blue is the GBM-predicted subsalt velocity trend. The vertical axis grid line spacing is 2000 ft.

Conclusion

GBM has demonstrated its value for seismic imaging in geologically complex areas. In this study, the subsalt velocity trend is obtained using "nonseismic" data and is clearly different than the one obtained from the seismic data. The model is validated by seismic data migration and seismic image analysis. When a basin model is already available, the GBM turnaround time is very short; on this project, it took about a week, including resimulation of the local basin model with the latest salt geometry. Remigration with the new model comprising the GBM-derived velocity subsalt resulted in improved image quality, more geologically plausible subsalt structures, and excellent seismic well ties. Blind tests at selected well locations outside the study area confirm the method's ability to predict correct velocities and hence reliable depths. GBM was used to predict a low-frequency initial (subsalt) velocity model. This model can be further updated and refined using tomography or other conventional methods.

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