The Tempest Project—Addressing challenges in deepwater Gulf of Mexico depth imaging through geologic models and numerical simulation

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Performing depth imaging is an essential part of deepwater Gulf of Mexico (GOM) exploration. Over the years, depth-imaging technology has provided the most reliable seismic images below salt and has been implemented in the workflows of the prospect generation process. But how accurate are these images? Since model building for depth imaging is partially an interpretative process, and depth imaging involves resolving seismic propagation through complicated geologic features, it is easy for the resulting prestack depth-migrated images to include imaging and positioning errors.

Much deepwater GOM exploration focuses on targets beneath the regional allochthonous salt. Due to the complex structural geometries associated with salt tectonics and the geophysical characteristics of salt, the acquired seismic data sets universally include areas of very poor signal. Over the years, improvements in both seismic acquisition techniques and implementation of new imaging algorithms have improved subsalt imaging. However, there are still large areas where the image quality is not sufficient to generate confident interpretations, impacting prospect generation in ways ranging from the ability to estimate value for lease sale acquisition to maturing prospects to drill-ready status (Figure 1a). Key information gaps include: (a) Is this due to acquisition parameters, errors in velocity models, or a combination of both? (b) What effect do complex salt geometries, such as steep allochthonous salt flanks and rugose base of salt have on the ability to image the subsalt section (Figure 1b)? (c) Can subsalt fault planes be accurately imaged? And, (d) in a general sense, how do these challenges affect imaging and positioning of potential exploration targets?

In order to improve our ability to correctly interpret areas of low illumination and poor signal-to-noise ratio as illustrated in Figure 1, we needed to find a way to enhance our understanding of the limitations of subsalt seismic data as well as prestack depth-migration algorithms. In the past few years, we realized the need to develop a GOM 3D model-based synthetic data set in order to quantify deepwater subsalt interpretation concepts and how well current technology can image them. Several two-dimensional synthetic data sets were generated over the years and became available to the industry. These include the Marmousi data set, the various SMAART JV data sets (i.e., Pluto and Sigsbee), and the more recent BP data set. In three dimensions, only the SEG salt model synthetic data set was widely available. SEG is currently working on creating a more realistic model and data set through the SEAM project (Fehler and Larner, 2008), but these will only be available to the industry at a future date.

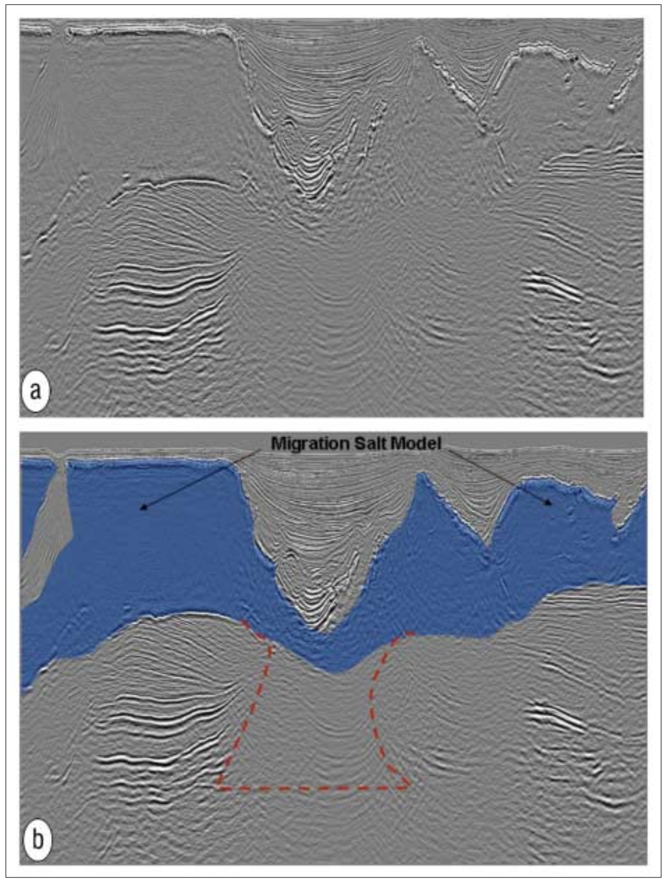

Figure 1. (a) Seismic example of imaging challenges in the subsalt Gulf of Mexico. (b) Seismic example with migration salt model and alternative salt model. Seismic data courtesy of CGGVeritas.

Leveraging the growth of compute power in conjunction with affordability, the industry has improved its ability to simulate field-acquired data phenomena such as optimal acquisition geometry, optimal processing flows, and selection of prestack depth-migration algorithms. This growth in compute power enabled us to move from ray-based numerical simulation to wave-based numerical simulation. As importantly, simulation projects can now be done using appropriate key parameters such as large apertures and high-frequency bandwidth and can be done in a timely manner so their results will be used as part of an exploration project.

In order to analyze subsalt depth imaging accuracy and algorithm limitations, Devon Energy, in collaboration with SeismicCity, decided to create a model and a data set that represent true GOM geology. The model and data set were given the name "Tempest." The key component of the simulation part was to use wave-equation techniques for generating the seismic data. The Tempest project was executed in three

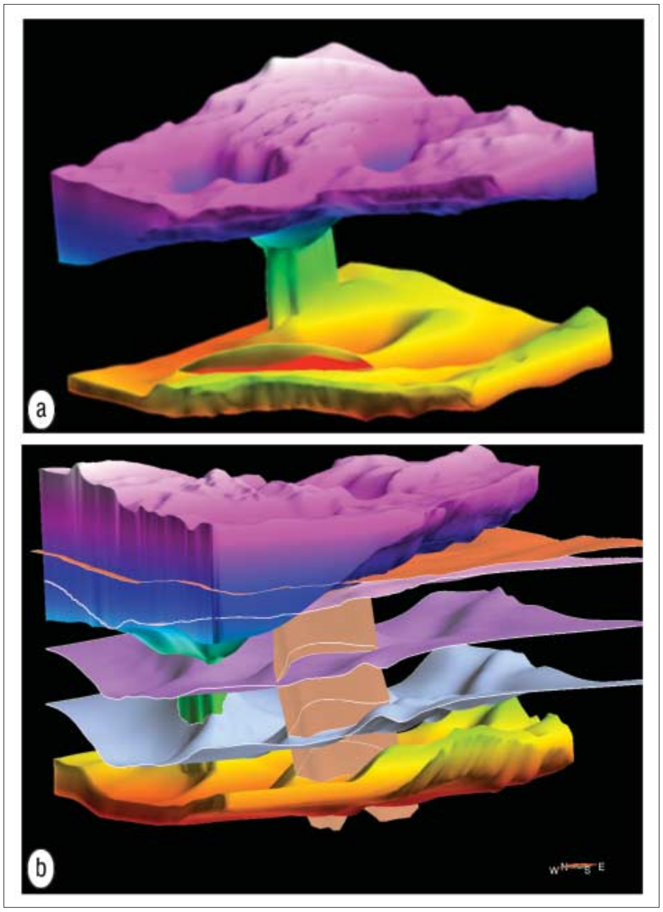

Figure 2. (a) 3D view of the Tempest model autochthonous and allochthonous salt. (b) 3D view of the Tempest model autochthonous and allochthonous salt, fault, and surfaces.

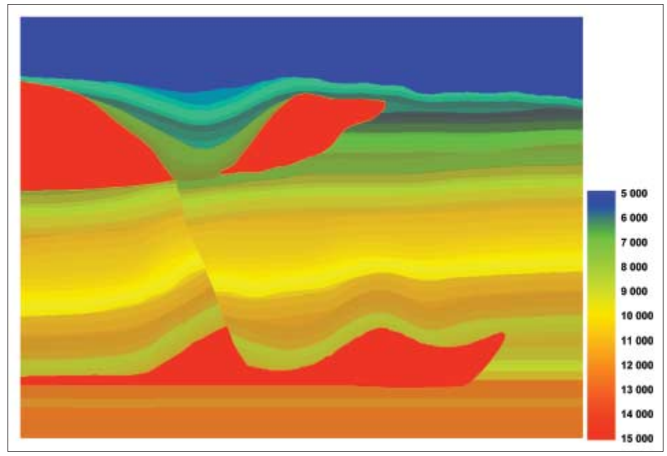

Figure 3. A profile from the Tempest 3D velocity model. Velocity scale is in ft/s.

phases. The first phase included design and construction of a realistic deepwater GOM geological model, and simulation and imaging of the data sets using the known velocity model. Phase two was to provide the simulated data to several processing companies who regularly process data for Devon and have them construct a model and apply prestack depth migration as if the data were real GOM field data. The third phase included interpretation and analysis of the results, comparing the developed models to the exact model, to compare derived prestack depth-migration results to results achieved using the exact Earth model, and to compare the synthetic-imaged data to field-acquired data sets.

Model design and building

From inception, we attempted to build an Earth model that was representative of deepwater GOM geology and would address 3D imaging challenges that geoscientists encounter exploring the salt province of the deepwater GOM. Input from geophysicists was utilized to the fullest extent to ensure that the final product represented documented GOM geology and ensured that it was not a model consisting of unrealistic structural and salt geometries aimed at testing algorithm limitations. Major features in the model include: realistic water-bottom geometry, allochthonous and autochthonous salt bodies including salt stalks, allochthonous minibasins, subsalt faulting, and deep target three-way and four-way structures.

Construction of the Tempest 3D model began with a base map of the input area, covering an area equivalent to 36 Outer Continental Shelf (OCS) blocks (6 × 6 blocks, 3 miles × 3 miles for each block). Four common salt features—(1) a salt stalk connecting the autochthonous to allochthonous salt, (2) a welded minibasin, (3) a salt-floored minibasin, and (4) a representation of the Sigsbee escarpment—were placed and used as the first guidance for the model. While additional structural geometries occur in the GOM salt province, including all such features in a limited area would create an unrealistic geologic model that could not be reproduced in the real world.

The 3D model was developed by transferring the concepts expressed in a paper-map format to the digital realm by digitizing the initially generated three hand-drawn cross-sections into three-dimensional space. These "seed" cross-sections were then used to guide further model development. For evaluation and final validation, the macrolayered geologic model was convolved with a wavelet to produce a theoretical seismic volume. The resulting product (Figure 2) is a three-dimensional model that emulates the geologic environment of interest.

Additional details were added to the 3D macromodel in order to create a realistic GOM velocity gradient by incrementing the velocity from one layer to another. From the first macromodel consisting of about 15 layers, a second detailed model consisting of about 60 layers was built (Figure 3). This would produce a model that when used for simulation will result in seismic data consisting of reflections in close proximity to one another, making the synthetic data more similar in character to field-acquired data. The final model that was built to a total depth of 42,000 ft includes several main features—a large allochthonous salt body that is fairly easy to image and interpret, a subsalt fault and a vertical salt stalk that are difficult to image, and a deeper autochthonous salt that is spread throughout the model. The subsalt section consists of a series of sedimentary layers with several key structures. The model reflects a deepwater GOM geological model of exploration interest and importance.

Marine acquisition survey design and numerical simulation

The acquisition simulation of the Tempest survey was designed to achieve two primary goals. The first was to create a narrow-azimuth (NAZ) data set that will be used to test the ability to image subsalt structures and be compared to field-acquired images generated over the years using NAZ seismic data collected in the GOM. The second was to create a wide-azimuth (WAZ) data set that will be used to test the advantages of WAZ imaging. In order to test both NAZ and WAZ acquisition, three independent data sets were recorded. The first was a NAZ data set. The second was a narrow WAZ data set where the streamer boat is located about 2 km from the source boat. And the third was a wider WAZ data set where the streamer boat is approximately 4 km from the source boat. These three data sets can be combined to a single, full-scale WAZ data set. Figure 4 shows the offset azimuth distribution of the three recorded Tempest data sets as well as the combined data set.

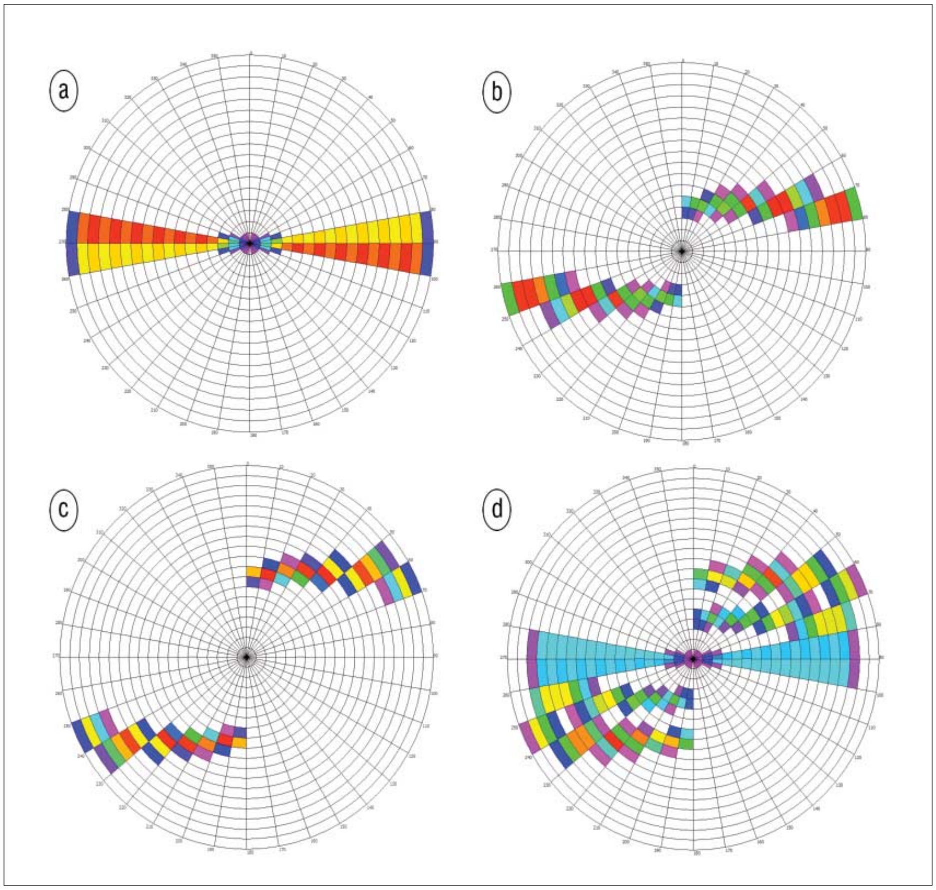

Figure 4. *Azimuth distribution of the Tempest data sets: (a) Azimuth distribution of the narrow-azimuth data set. (b) Azimuth distribution of the midrange azimuth data set. (c) Azimuth distribution of the wide-azimuth data set. (d) Azimuth distribution of the three combined data sets.*

The streamer configuration for the Tempest acquisition is 13 streamers for each boat, each streamer with 200 channels. This resulted in 2600 channels for each recorded shot. The distance between receivers is 40 m, and the distance between streamers is 40 m. The complete acquisition consists of a total of 111 sail-line passes where each pass generates 181 shots. The shot-point interval along any given sail line is 160 m, and the distance between two sail lines is 260 m. These acquisition parameters resulted in a constant surface fold of 25 for the NAZ data set and 75 for the WAZ data set. The total number of simulated shots was 20,091 with recording time of 12 s. The number of shots per block is lower than that usually acquired in a typical NAZ field acquisition. This was done in order to produce a 3D data set which is reasonable in size, so different industry and academia groups will be able to process it in the future.

A key decision in the simulation of the Tempest project was to use a wave-equation algorithm for the modeling of the shot gathers. Wave-equation simulation is much more appropriate than ray-based simulation methods for generation of synthetic seismic data that can then be used for testing processing and imaging. Full offset, multishot 3D wave-equation simulation is a computer-intensive process. In order to complete the generation of the 20,091 shots in a timely manner, a series of multinode computer clusters were dedicated for the simulation of the data. The wave-equation solution that was used for the simulation is a finite-difference-based algorithm. Since the main objective is to investigate subsalt imaging quality, we used the acoustic wave equation with constant density scheme for the simulation. As well, the simulation used an absorbing surface condition. The resulting data set includes interbed multiples, but surface multiples are not present. This way the simulated data can be directly used as input for prestack depth migration with little or no preprocessing.

The resulting simulated data set was written in SEG Y format and stored as a regular 3D field data set. The Tempest data sets were then used for depth imaging using the exact model. In parallel, the recorded NAZ data set was distributed to the participating depth-imaging companies to assess their model building and depth-imaging capabilities and results.

Depth imaging using the exact model

Depth imaging the exact Tempest model achieved three goals. The first tested differences between two major depth-imaging technologies—Kirchhoff summation prestack depth migration and downward extrapolation wave-equation prestack depth migration. The second compared depth imaging resulting from NAZ acquisition to depth imaging result-

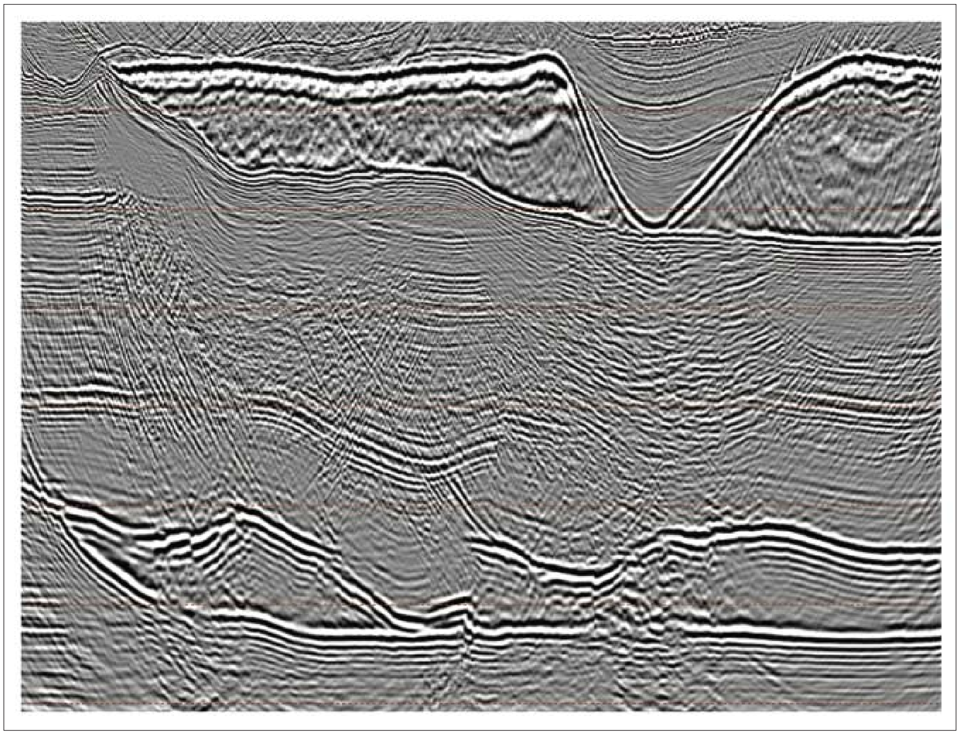

Figure 5. An inline section from the Kirchhoff summation WAZ prestack depth-migrated volume.

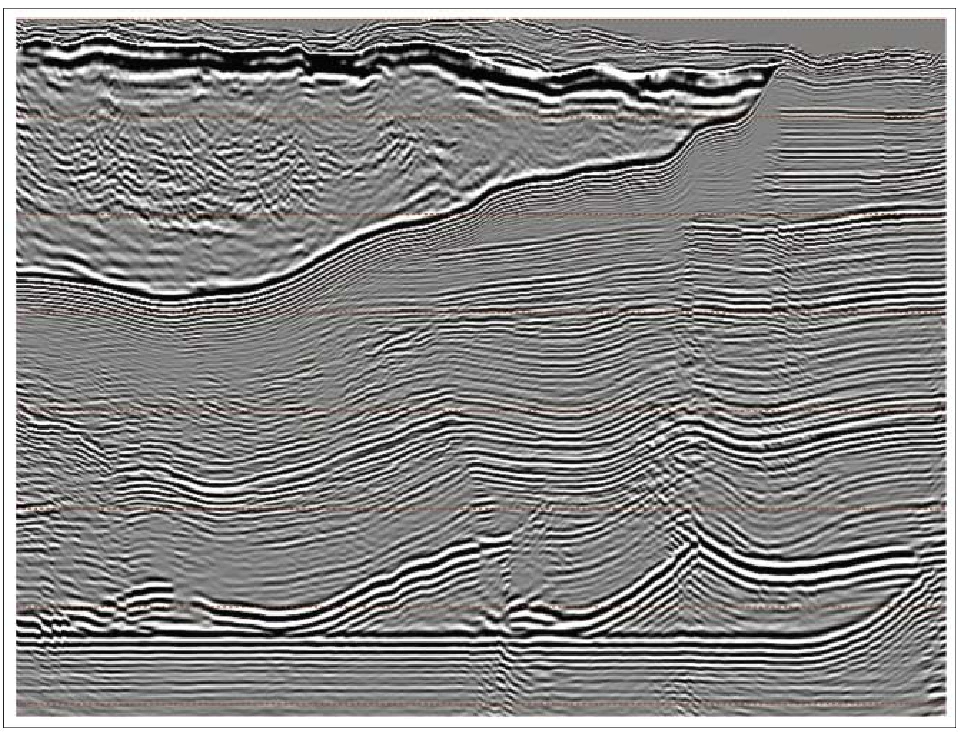

Figure 6. A crossline section from the wave-equation WAZ prestack depth-migrated volume.

ing from WAZ acquisition. The last and most important objective compared the synthetic data results to field-acquired results and with that to build guidelines for interpretation of real subsalt data.

As a first step, the NAZ data set was used for depth imaging. The Kirchhoff prestack depth migration produced a very clear allochthonous salt image, and the wave-equation prestack depth migration produced a superior quality subsalt image. None of the algorithms imaged the vertical salt stalk, probably due to the fact that reflections from the salt stalk were not recorded using the implemented acquisition scheme. The subsalt fault included in the model can be identified only on the wave equation image.

Next, WAZ data sets were migrated using both a Kirchhoff summation algorithm and a downward propagation algorithm. For depth imaging, the narrower WAZ data set was merged with the NAZ data set to obtain a typical "exploration" wide-azimuth prestack depth migrated volume (i.e., with 2 km boat separation) and then the wider WAZ data set was merged with the NAZ data set and narrower WAZ data sets to obtain a typical "production" WAZ prestack depth-migrated volume (i.e., with 4 km boat separation). Figures 5 and 6 show example sections from the WAZ prestack depth-migrated volumes.

The last step of depth imaging with the exact model part of the project compared the imaging results of the synthetic Tempest data set to prestack depth-migration imaging of field-acquired data. The focus was the Tempest subsalt section and its four main exploration objectives: mapping a four-way closure at about 26,000 ft; the ability to image a vertical salt stalk connecting the allochthonous salt to the autochthonous salt; the ability to image a major subsalt fault; and the ability to image a three-way closure against the subsalt fault. The conclusions of these comparisons are that we can image and interpret the subsalt structures, but at the same time it is almost impossible to identify subsalt steep-dip features such as the vertical salt stalk and the subsalt fault. Another feature that was analyzed and studied was the various noise artifacts produced in the low-illumination subsalt section. These noise artifacts are very important to identify and understand as they are commonly seen on field-acquired subsalt prestack depth-migrated volumes.

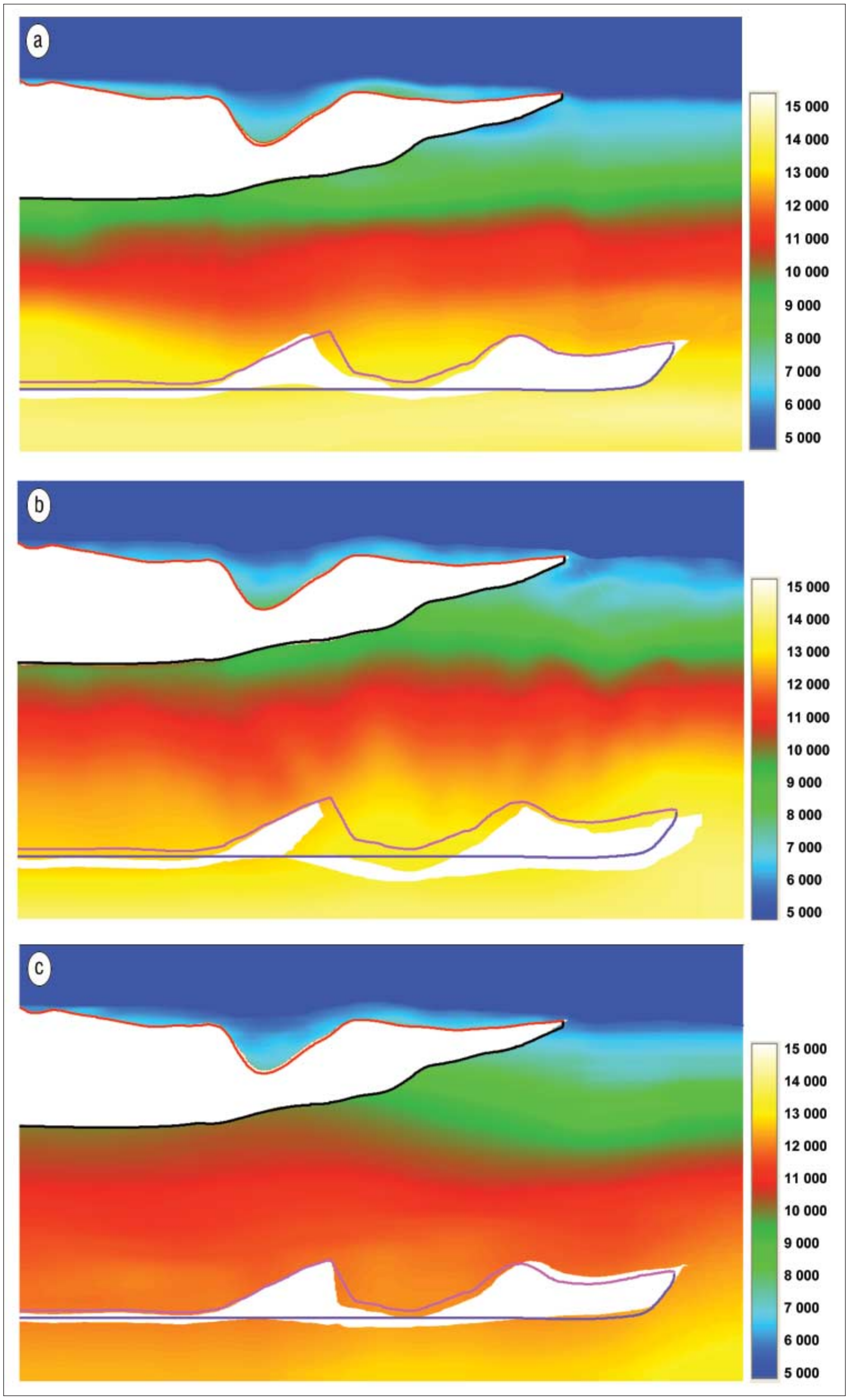

Figure 7. *An inline display from the velocity model developed by groups 1, 2, and 3 (a, b, and c, respectively). The salt surfaces show the exact velocity model. Color scale is velocity in ft/s.*

Both wave-equation and Kirchhoff algorithms did place basement reflectors in the proper position below the salt stalk. This result can be used as an analog to support interpretation models of salt stalks where imaging is not resolved in the depth-migrated field data. Other results show that fault planes are still difficult to resolve. Finalizing the imaging results using the exact velocity model, we were able to document specific migration noise types and multiples that are not a result of the free-surface multiple energy, but still present in the subsalt section. As well, by comparing the depth-migrated volumes generated using both the NAZ data and the WAZ data, we were able to document the areas where the WAZ data are superior to the NAZ data.

Model building and depth imaging using the simulated data set

Several companies were invited to participate in the second phase of the project and three accepted. All were given the same data set, as well as velocity information guidance. Our key request to the participating companies was to use their regular production workflow tools to develop the model and then apply Kirchhoff summation prestack depth migration. At the end of the work, each group provided a 3D velocity model and 3D prestack depth migrated volume. Model building and depth imaging were done using the NAZ data set.

Most deepwater GOM prestack depth-migration projects follow a generic workflow: (1) imaging of the water-bottom surface, (2) sedimentary section velocity analysis, (3) imaging of the top salt surface, (4) "salt flood" and imaging of base salt surface, (5) subsalt velocity analysis, and (6) final prestack depth migration. Most of the Tempest model can be constructed using these common model-building and depth-imaging workflow procedures.

Data-driven construction of the velocity model was done in a similar way by the three participants in the model-building phase of the project. It included several full-volume Kirchhoff summation runs for model-building, use of reflection tomography for construction of the sedimentary velocity field, and application of final Kirchhoff summation prestack depth migration. The interpretation of the salt bodies was done by the individual groups as part of the model-building process with some minor guidance from Devon personnel. Each group delivered their final velocity model at the end of the project (Figure 7).

Inspection of the three velocity models revealed the following observations: (1) all models are very similar in their definition of the allochthonous salt. (2) All models included a salt stalk connecting the allochthonous salt to the autoch-

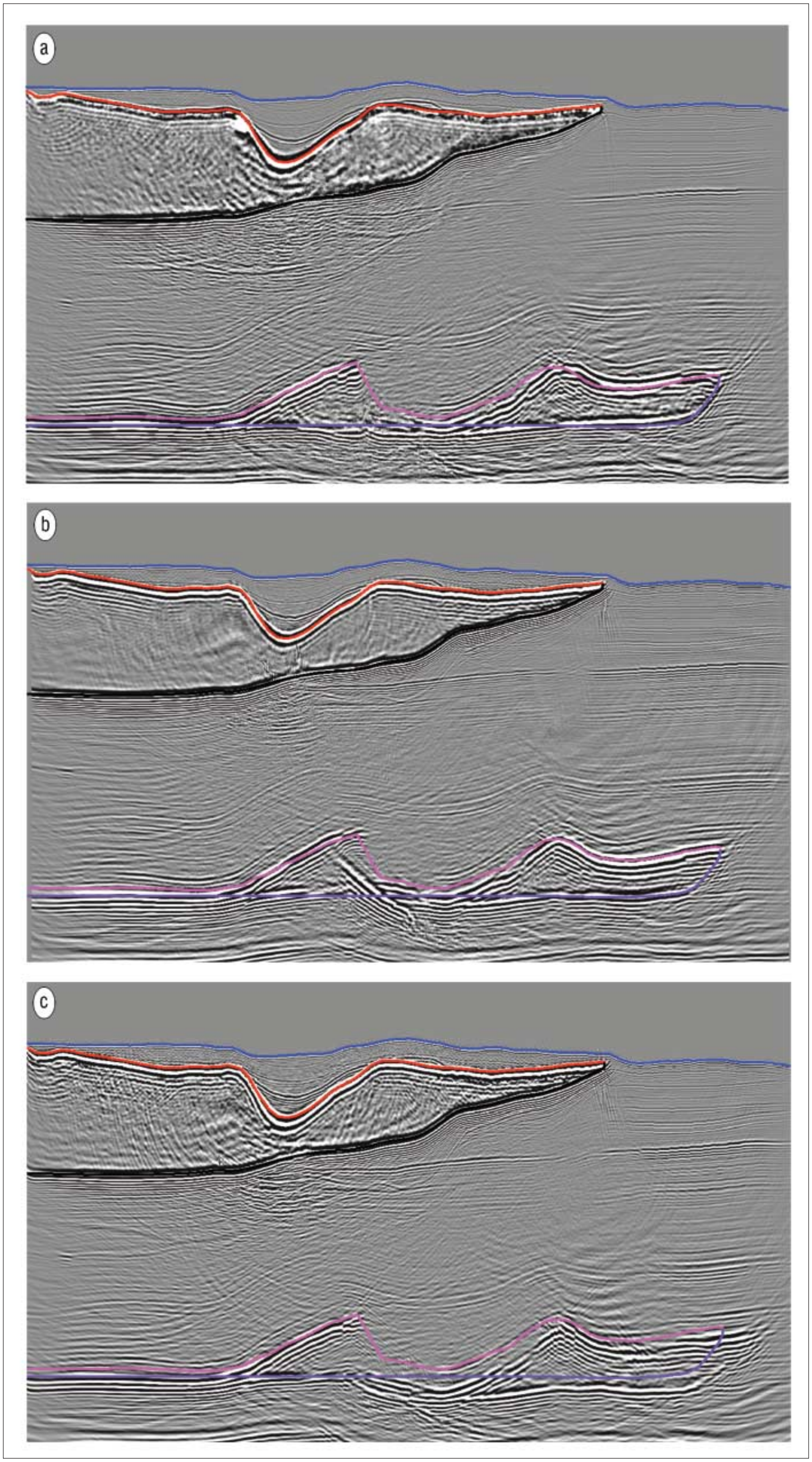

Figure 8. *An inline display from the Kirchhoff summation prestack depth-migration volumes produced by groups 1, 2, and 3 (a, b, and c, respectively). The water bottom and salt surfaces show the exact velocity model.*

thonous salt. However, only one of the three models included the correct shape of the salt stalk. (3) The models differ one from another in the subsalt section, and all differ from the true subsalt velocity field. (4) The definition of the autochthonous salt on all the models was less accurate than the definition of the allochthonous salt.

Using each of the final developed models, Kirchhoff summation prestack depth migration was executed by each participating group (Figure 8). Similar to the derived velocity models, the prestack depth-migrated volumes were similar to one another in the shallow section and in the imaging of the allochthonous salt. However, the results were measurably different from each other in the subsalt section as well as in the imaging of the autochthonous salt. Inspection of the depth-migration volumes resulted in the following observations: (1) some prestack depth-migrated volumes correctly imaged the main subsalt dips; (2) some prestack depth-migrated volumes included continuous subsalt events, but were imaged with an incorrect dip; (3) as a possible consequence of the recording time and the acquisition parameters that were used for generation of the data set, no depth-migrated volumes included an image of the salt stalk; (4) no prestack depth-migrated volumes included a clear image of the subsalt fault plane; and (5) some subsalt structure was laterally mispositioned which leads to structural positioning error within interpreted subsalt structure mapping.

Quantitative evaluation of the developed velocity models and prestack depth migrated volumes was done as well. This part of the project included two steps. The first compared each developed velocity model to the exact velocity model. The second compared the depth-migrated volumes produced using the developed model to the depth-migrated volume produced using the exact model. A series of analyses was performed on carefully interpreted horizons, which generated error maps. The error maps were constructed by interpretation of the main events in the various velocity models, including the derived and exact, as well as interpretation of the main events of the various prestack depth-migrated volumes.

Important knowledge was gained as to the accuracy of each volume at the different exploration targets that were included in the Tempest model and data set. As a general statement on the use of NAZ data and ray- and wave-based depth-imaging algorithms, we concluded the following: (1) The Kirchhoff summation algorithm is still a valid tool for velocity model building. (2) We can trust the Kirchhoff summation algorithm for imaging of complex salt bodies. (3) A wave-equation algorithm should be used when interpreting subsalt structures. (4) The accuracy of the model is more important than the depth-migration algorithm, and construction of the model should be the focus in execution of a depth imaging project.

Conclusions

The objective of the Tempest project was to evaluate the industry's ability to correctly image deepwater GOM subsalt structures, using both the exact and a developed velocity model. This was achieved by creating a realistic GOM Earth model and using it as a basis for generating synthetic seismic data. Depth-imaging results enabled the comparison of different depth-migration algorithms as well as various acquisition setups, highlighting their positive and negative attributes and, importantly, how they complement each other. This work has helped us understand seismic expressions of complex subsalt structures and salt geometries. The importance of this work is that by having a synthetic data set and model, we can quantitatively measure the accuracy of models and depth migrated volumes that are routinely produced using real field data and state-of-the-art imaging workflows that are used for subsalt exploration.

Suggested reading. "Three dimensional SEG/EAGE models—an update" by Aminzadeh et al. (*TLE*, 1997), "The 2004 BP velocity benchmark" by Billette and Brandsberg-Dahl (*EAGE*, 2005), "The Marmousi experience: Velocity model determination on a synthetic complex data set" by Versteeg (*TLE*, 1994), "SEG Advanced Modeling (SEAM): Phase 1 first year update" by Fehler and Larner (*TLE*, 2008).

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