SEAM update:
Models for EM and gravity simulations

The primary objective of SEAM is to conduct geophysical modeling of relevance to the petroleum industry. Most of the discussion to date regarding the project and its Earth model has focused on its seismic aspects. Since the initial modeling objective of the SEAM Phase I project was variable-density acoustic simulation, P-wave velocity and density were the primary parameters defined for the model. However, the project is also simulating gravity, controlled-source electromagnetic (CSEM), and magnetotelluric (MT) data acquisition, which require the construction of a resistivity volume as well. These nonseismic simulations are funded under a research subcontract (#07121-2001) from the Research Partnership to Secure Energy for America (RPSEA).

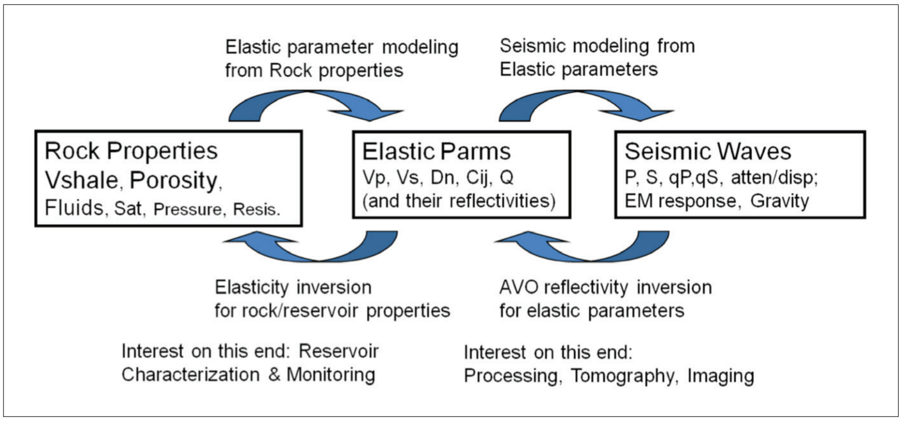

Figure 1. *Rooting the SEAM model in rock properties: from geology and petrophysics to geophysics.*

The main elements of the SEAM Phase I model have been described in an article in the August 2008 issue of *TLE*. The goal at the start of the SEAM project was to capture as much physics and realism as possible in a 3D model that was relevant to oil and gas exploration. Certain facets of the model were designed to go beyond the capabilities of current seismic modeling technology. The philosophy behind this was that, over the 10 or more years of the expected lifetime of the model, such capabilities would evolve and become available.

An important design goal for the SEAM Earth model is internal consistency across the domains of rock properties (e.g., fundamental parameters like Vshale, porosity, and pore fluid type), the intermediate level elastic and electromagnetic parameters, and the output simulations for seismic, electromagnetic and gravity fields. (Vshale varies from 0 to 1 and in-

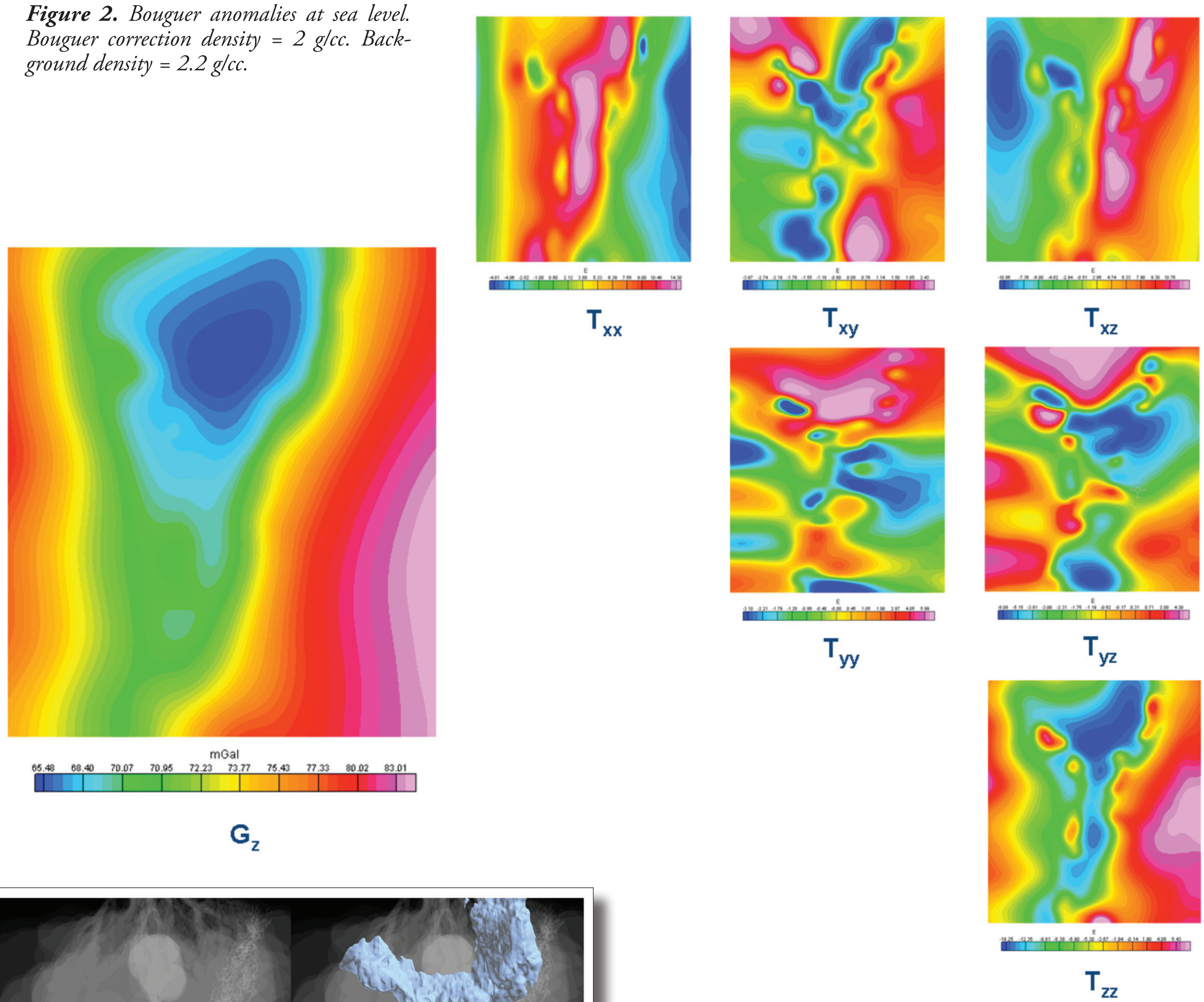

Figure 2. *Bouguer anomalies at sea level. Bouguer correction density = 2 g/cc. Background density = 2.2 g/cc.*

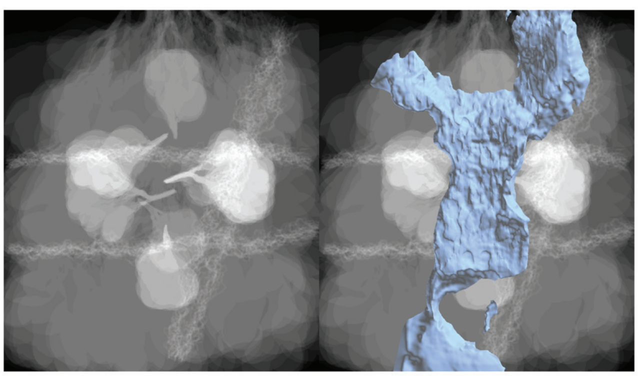

Figure 3. *Cumulative vertical sum of reservoir thickness. Black = 0 m. White = 800 m. Note how either salt or the northern model edge truncates the turbidite stems. The WE CSEM line at 20,750 is located slightly above the center of the figure.*

dicates the relative volume of sand and shale lithologies, where the shales are taken to be interbedded with sands. Within a cell of specified Vshale, the sand and shale end members follow different porosity and modulus trends.) By rooting the ultimate simulation back to the rock properties, any changes in the latter are guaranteed to change all the elastic and other parameters automatically, consistently, and with the appropriate correlations.

A model founded on rock properties provides a test bed not just for the inversion of seismic data for reflectivity, but also for the inversion of one or a combination of seismic, gravity, EM, or reflectivity data for reservoir properties. Thus it challenges not just processors, tomographers, and imagers, but also the reservoir characterization and monitoring interests. For this purpose, it was crucial to choose a set of geological property "basis functions" that are largely independent of each other, and in combination, span all pertinent elastic properties. Figure 1 illustrates the relationship between rock properties, geophysical parameters, and simulation output along with the inversion from simulated data back to rock properties.

The bulk density model used for the acoustic simulation formed the basis of the density model used for gravity, and it is a function of Vshale, mineral density, sand, and shale porosities, and fluid type. To facilitate the simulation of gravity responses over the model, the original density model (dX = dY = dZ = 10 m) was resampled to a grid size of 40 m in each horizontal direction and 20 m in depth. Gravity responses of the model include vertical component of gravity (Gz) and six gravity tensor components (gradients) Txx, Txy, Txz, Tyy, Tyz, and Tzz. Two sets of gravity anomalies were calculated, free-air and Bouguer (Figure 2). All calculations were performed on two levels: zero elevation to mimic marine data and 150-m elevation that roughly corresponds to typical airborne acquisition flying altitude in the Gulf of Mexico.

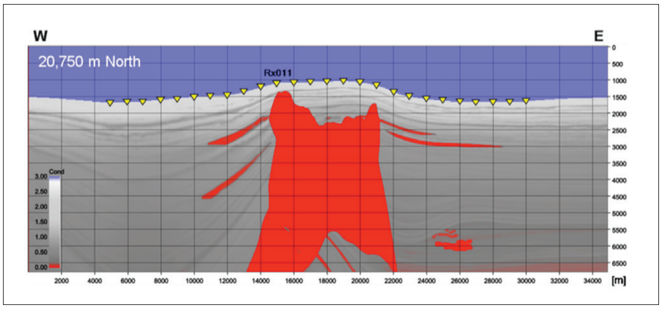

Figure 4. *Vertical cross section of σv along the modeled survey line.*

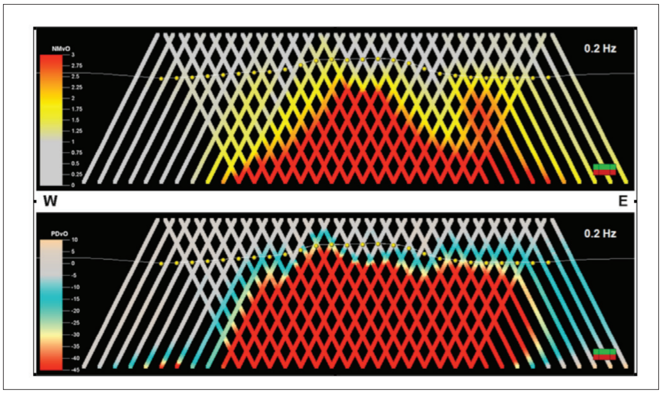

Figure 5. *Pseudo-sections for the inline electric field (E_x) at 0.2 Hz for the survey line at 20,750 m north. (top) Normalized magnitude. (bottom) Phase difference. The yellow spheres indicate the positions of the receivers on the seabed. Note that the vertical scale used to indicate the variations in bathymetry is exaggerated.*

In keeping with the basic model of interbedded sands and shales (as opposed to dispersed clays within the sand pore space), the resistivity model used for sand is appropriate for a granular medium containing ionic fluids (i.e., Archie's law with constant exponents) involving sand porosity, brine saturation, and brine resistivity. The native shale resistivity was modeled using an empirical relation involving shale porosity that is faintly similar to Archie's law and is intrinsically anisotropic, its anisotropy increasing with depth. The sand and shale resistivities in each cell were then combined into bed-normal and bed-parallel bulk resistivities using series and parallel averages, respectively, over Vshale. Hydrocarbon resistivity was taken as effectively infinite.

The rotation of the bed-normal and bed-parallel resistivity tensor into the geographic vertical and horizontal frame after structuring is a straightforward tensor rotation. However, discussions within SEAM revealed that little if any EM simulation is currently done using the full nine-component conductivity tensor, but is accomplished using at most three elements. One approach is simply to ignore the off-diagonal elements, but because this still requires the use of azimuth, which most EM simulation codes do not use, we decided to average the tensor about the vertical axis, thereby integrating out the azimuthal variation of resistivity. Then we masked seawater and salt resistivities into the model with constant isotropic values of 0.3 and 100 ohm-m, respectively.

Various reservoirs were included throughout the SEAM model to add more realism and to provide interesting targets for acquisition/VSP design, noise suppression, seismic imaging, EM discrimination, inversion, and interpretation. The imaging challenge presented by these reservoirs ranges from mild to severe. A reservoir might be difficult to image because it is in a seismic shadow or because its impedance contrast is small, but away from salt the seismic imaging or EM detection of shallow oil reservoirs should not present a problem. The three reservoir types employed represent localized turbidite fans, widespread and superposed turbidite sheets, and highly channelized complexes. They variously contain oil, gas, and brine.

To get a sense of the total areal distribution of the 15 reservoirs that are included in the model, Figure 3 shows a cumulative vertical sum of all reservoir thicknesses, without and with the salt body, which truncates all the exposed turbidite stems. The thickest cumulative areas are immediately east and west of salt where the channel systems cross the thickest turbidite concentrations. Visible in dark gray are the deepest sheet turbidites, superposed by the three channel complexes, and capped in light gray by the localized turbidites. Large areas of the deepest reservoirs are truncated by the salt.

Two CSEM line surveys over the anisotropic SEAM 3D resistivity model have been simulated using the fast 3D finite-difference time-domain (FDTD) modeling code of EMGS. Figure 4 shows a vertical cross section through the vertical conductivity model (σv) along one WE line at 20,750 m north.

The main objectives of this initial study were to become familiar with the SEAM model and to generate first synthetic data sets for benchmarking purposes. The results will also be useful for choosing the survey configuration and simulation parameters for modeling of a 3D CSEM survey, which is a much more resource-demanding computational task. The modeling resulted in electric and magnetic field data for frequencies between 0.05 and 4 Hz sorted in common-receiver gathers, as is typically the case for frequency-domain marine CSEM surveys. This allows easy extraction of magnitude versus offset (MvO) and phase versus offset (PvO) information for any field component and frequency.

A fast way to get a first impression of the spatial data variation and sensitivity of the CSEM measurements prior to running inversion-based subsurface resistivity imaging methods is to compute attributes such as normalized magnitude and phase difference using the synthetic in-towing response of the westernmost receiver as a reference and subsequently sorting these attributes into the midpoint-offset domain to create pseudo-sections. These pseudo-sections, shown in Figure 5, clearly show the presence of the salt and the thin resistors at the eastern flank of the salt body.

More details of both the gravity and CSEM simulations will be given in an upcoming report in *TLE*. TLE

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