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Seismic Modeling of Experimental Stratigraphy

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Abstract

Seismic modeling of experimental stratigraphy provides a far more realistic framework for studying the seismic response of stratigraphy through synthetic modeling than has previously been available. The XS basin, a unique facility developed at the University of Minnesota, paves the way for a detailed study of the evolution of stratigraphy under controlled rates of sea-level changes, sediment supply and subsidence. The stratigraphy generated by this experimental basin approaches the appearance and complexity found in sedimentary bodies ranging in scale from bedforms to continental margins. We describe a preliminary methodology to map digital photographs of the resulting stratigraphy into acoustic models that are then used as input to seismic modeling algorithms.

INTRODUCTION

Experimental stratigraphy formed in a new laboratory basin offers a novel opportunity to explore several fundamental issues regarding the relationship between stratigraphy and its seismic response. The XS basin (Mullin *et al*., 1997) is a unique facility developed at St. Anthony Falls Laboratory (SAFL) of the University of Minnesota for studying the evolution of stratigraphy under specified rates of sea-level change, sediment supply and subsidence. The basin forms experimental stratigraphy that approaches the appearance and complexity of natural stratigraphy found in sedimentary bodies ranging in scale from bedforms to continental margins. At the end of each basin run, this experimental stratigraphy is dissected and digitally photographed, so it is fully imaged and quantified in three dimensions.

Given its natural appearance, the experimental stratigraphy provides a far more realistic framework for studying the seismic response of three-dimensional stratigraphy through synthetic modeling than has previously been available. Among a number of possible applications, such seismic response can be used to quantitatively assess the performance of seismic inversion algorithms under circumstances that are geologically realistic. Here, we outline a preliminary procedure to map the digital photographs of the experimental stratigraphy into acoustic models than can be used as input to seismic modeling algorithms.

EXPERIMENTAL STRATIGRAPHY

THE XS BASIN

The XS basin (Figure 1) is large by experimental standards -- 13 m by 6.5 m, with up to 1.3 m of accommodation space for deposition. Sediment and water can be fed from one or more points anywhere along its perimeter and base level can be precisely adjusted over time. Its subsiding floor consists of 432 hexagonal-shaped subsidence cells arranged in a honeycomb pattern. At the beginning of an experiment, these cells are buried with dry, well-sorted commercial gravel. The top of the gravel is then covered with a thin rubber membrane upon which the sediments introduced into the tank accumulate. The membrane subsides by withdrawing a small volume of gravel from the bottom of the underlying subsidence cells. The subsidence in each cell is controlled independently to a precision of ~0.1 mm. Therefore the subsidence is smooth and continuous in time and space, and can be varied between adjacent cells to produce slopes in the membrane of up to 60°. This flexibility to the basin floor allows the creation of a nearly unlimited range of spatial and temporal subsidence patterns. At the end of an experiment, cross-sections of stratigraphy are revealed by cutting the final deposit parallel to its average dip direction. Digital pictures of these cross-sections are then stacked in sequence to create a 3-D, CAT scan like image of the stratigraphy in its entirety.

AN EXAMPLE

An example of the experimental stratigraphy is shown in Figure 2. This example was in fact produced in a prototype of the XS basin, which is ~1.5 m in length on all three of its sides and floored by 10 subsidence cells. In the experiment, water mixed with a 50%:50% blend (by volume) of quartz and coal was fed from a single source point into one side of the basin while base level was adjusted from the other side. The crushed coal, which is more buoyant than quartz, was used as a proxy for mud. Subsidence was induced in a bowl-shaped pattern such that it was a maximum at the basin’s center.

This subsidence pattern and the sediment supply were held constant throughout the experiment. The only factor that was varied was base level, the history of which is shown at the bottom of the figure.

The experimental stratigraphy produced in the basin prototype is rich in three-dimensional structures and stratal patterns encountered in real basins. These include normal faults, reverse faults and growth faults, facies regressions and transgressions, sequence boundaries, truncations, and offlapping and onlapping strata. We know of no other modeling technique that simultaneously captures the complexity and appearance of natural stratigraphy so well.

SEISMIC MODELING

By replicating the same fundamental patterns found in sedimentary bodies over a broad spectrum of scales, the experimental stratigraphy is an excellent model for the architecture of real stratigraphies ranging from reservoir deposits to full basins. Interpretation of the seismic response of such features can provide valuable analogues for exploration plays in depositional environments similar to the ones being generated by the XS basin. Here, we generate the seismic response of the XS basin prototype by simulating the propagation of sound waves through acoustic models built from the digitized images of the experimental stratigraphy. Next, we describe the procedure to construct such acoustic models.

As a first step, vertical and horizontal length scales need to be assigned to the individual pixels comprising the digital image, such that the entire image has the dimensions of a sedimentary body of interest. Here, pixel scales of *dx* = 5m and *dz* = 1m were selected to yield dimensions for the image matching those of a segment of a continental slope having a seafloor dip of ~4°. We then relate the gray scale values $g_{i,j}$ of the stratigraphic image to bulk density ρ_{bulk} via the following linear relationship:

$$\rho_{bulk_{i,j}} = \frac{(g_{i,j} - g^{\min})}{(g^{\max} - g^{\min})}(\rho_{bulk}^{\max} - \rho_{bulk}^{\min}) + \rho_{bulk}^{\min},$$

where the bulk density of clay ($\rho_{bulk}^{\min} = 1800 kgm^{-3}, 2\mu m$) is associated with pixels in the image that have gray levels of $g^{\min} = 0$, and the bulk density of fine sand ($\rho_{bulk}^{\min} = 2055 kgm^{-3}, 100\mu m$) is associated with gray levels of $g^{\max} = 255$. All other pixels with gray levels between 0 and 255 were linearly scaled to result in bulk densities that lie within the clay-sand range. We then used porosity values computed from bulk densities via

$$\phi_{i,j} = \frac{\rho_s - \rho_{bulk_{i,j}}}{\rho_s - \rho_w},$$

where $\rho_s = 2650 kgm^{-3}$ and $\rho_w = 1030 kgm^{-3}$ in the determination of P-wave velocity data. Specifically, we applied the correlation published in Hamilton (1972) derived from near-surface marine sediments given by:

$$V_{p_{i,j}} = a_0 + a_1\phi_{i,j} + a_2\phi_{i,j}^2,$$

where $a_0 = 1{,}782$, $a_1 = -833$ and $a_2 = 522$. The P-wave velocity model is shown in Figure 3.

A stratigraphic acoustic model is now in place to simulate seismic reflection data of the experimental stratigraphy. It is worth emphasizing that the specific steps used in the example above represent just one possible model. Alternative models could have been obtained, for example, by using porosity-velocity relationships that account for clay content. Moreover, depth-dependent porosity due to compaction by the overlying sediments could also be considered, and bulk densities in certain regions of the image could have been adjusted to account for the presence of oil and gas. In short, a number of possible geologic scenarios can be constructed for any one image of the experimental stratigraphy by modifying some of the steps above and by accounting for additional physical processes. The impact of such change on the seismic response of the model can then be evaluated through seismic simulation. The result is a very powerful form of sensitivity analysis for quantifying the stratigraphic information contained in seismic reflection data.

NUMERICAL SIMULATIONS:

We have used the flux-corrected transform approach (Fei *et. al*, 1995) to numerically solve the 2-D acoustic wave equation for the subsurface model developed in the last section. Such approach theoretically reduces numerical dispersion; thus allowing larger time steps in the simulation. To maintain accuracy we opted for a 4th-order discretization in space and 2nd-order discretization in time. The acquisition layout consists of split-spread shot gathers with 201 channels. The receiver spacing was 5m and the source spacing was 10m. We have generated 300 shot gathers with maximum time of recording of 2.5s. The dominant frequency of the source wavelet was approximately 20Hz. The 300 shot gathers were then input to a standard processing flow built with the Seismic Unix (SU) software package developed at the Center for Wave Phenomena in the Colorado School of Mines. The processing flow steps are listed below with, for completeness, the name of the respective SU computer codes:

1. Geometry, common-mid-point (CMP) sorting and muting (suaddhead, sushw, susort, sumute).

2. Spiking deconvolution (supef).
3. Normal-moveout (NMO) correction, dip moveout and inverse NMO (sunmo, sudmotx).
4. Velocity analysis and stacking (suvelan, sustack).
5. Predictive deconvolution (supef).
6. Time migration (sumigtk).
7. Band-pass filtering, geometrical spreading correction and automatic gain control (sufilter, sugain).

The migrated image is shown in Figure 4. Figure 5 shows a convolutional model simulation for the same acoustic model. Both images illustrate the expected resolution loss of the underlying stratigraphy due to the limited frequency bandwidth of the seismic source. Fine details of the stratigraphy and structures defining the growth faults are lost as individual beds are lumped together into single seismic events, which amplitudes can be regarded as an average of the reflectivity of those beds. In addition, comparison of the two seismic images reveals some of the limitations associated with the processing sequence to attenuate wave-propagation effects that distort the final stratigraphic image. For example, sand-to-shale transitions along the beds that truncate against the growth faults are less resolvable by the processed data than they are by the convolutional data. In addition, reflections from the base of the growth faults are less continuous in the processed data. Those issues are mostly associated with imperfections of the migration velocities.

CONCLUSIONS

We have presented a preliminary methodology to generate synthetic seismic data for the experimental stratigraphic models produced by the XS basin. The methodology consists of the construction of an acoustic model from gray scale images of the experimental stratigraphy, which is input to seismic modeling and processing algorithms. We illustrated the loss of stratigraphic resolution due to the finite frequency bandwidth of the seismic source and due to inherent limitations of processing algorithms to account for wave-propagation related effects that compromise the final seismic image.

The preliminary work discussed here is one out of a number of possible geophysical applications of the experimental stratigraphy generated by the XS basin. Near-future research plans include the construction of more realistic elastic models for the stratigraphic model accounting for confining pressure effects on velocities, and the use of fluid-substitution techniques to modify fluid saturations on pre-specified regions of the model. Seismic data generated for such models will offer the opportunity to improve our understanding of the seismic response of models under a geologically sound framework. Finally, the seismic simulations also provide a unique opportunity to assess and improve the performance of seismic inversion algorithms on models that incorporate the complexities present in the subsurface.

ACKNOWLEDGEMENTS

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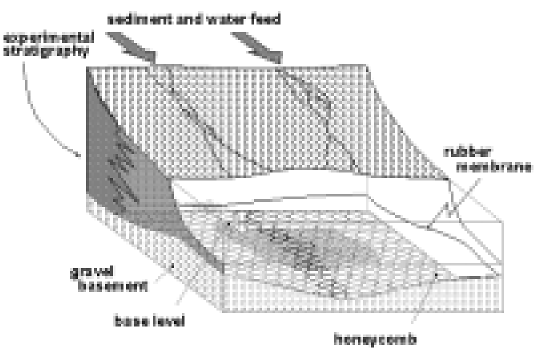

Figure 1. Sketch of the XS basin.

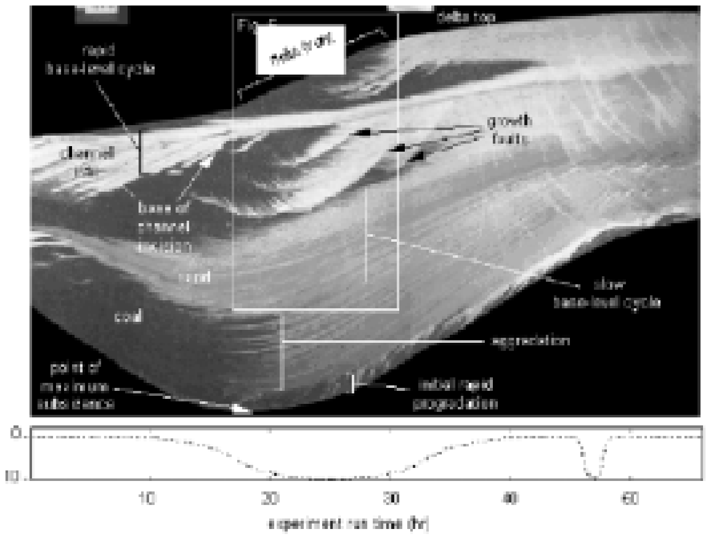

Figure 2. Crosssection of experimental stratigraphy.

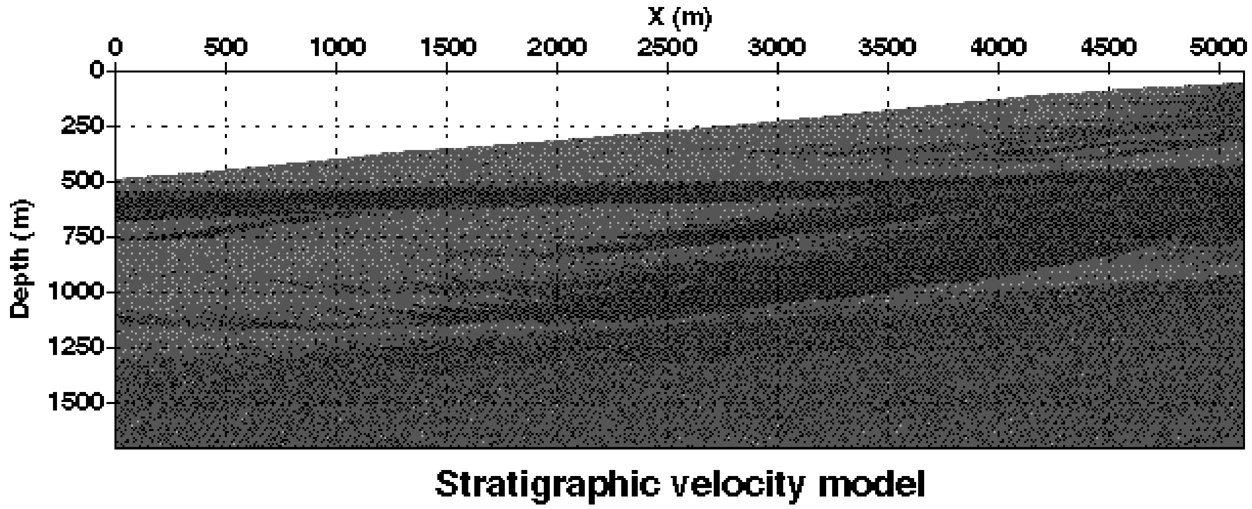

Figure 3. Stratigraphic velocity model.

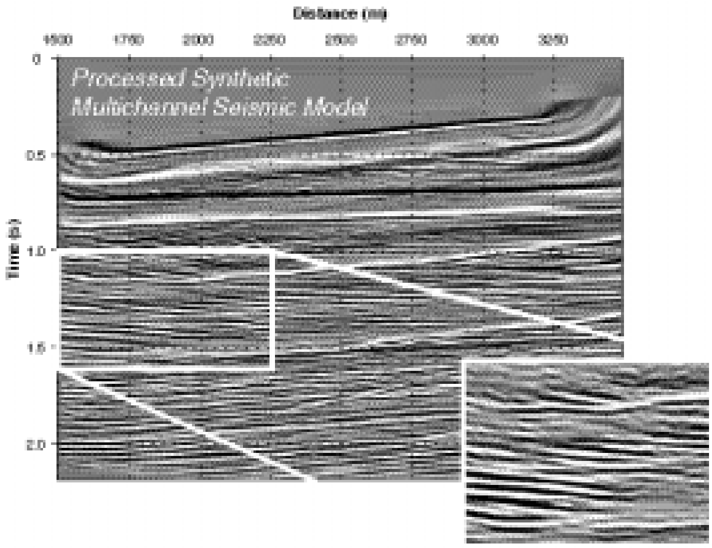

Figure 4. Processed seismic data.

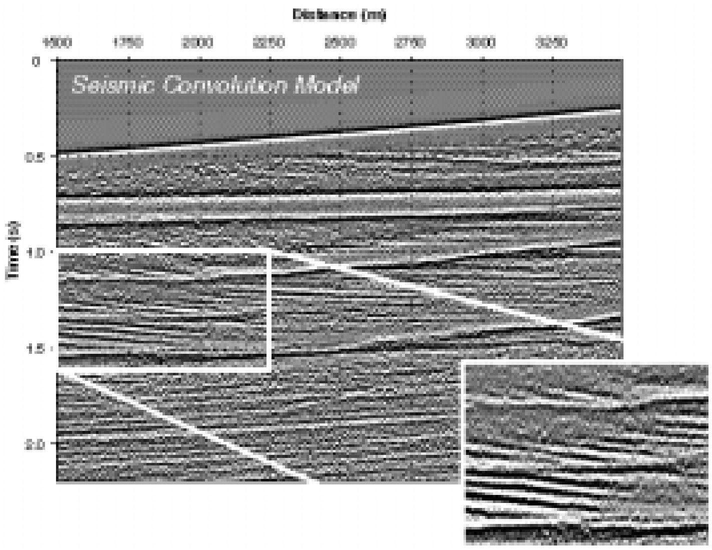

Figure 5. Convolutionmodel seismic data.