De-risking Foothills Imaging with Realistic 3D Geological and Geophysical Modeling - SEAM Foothills Model

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Abstract

Exploration in foothills areas face many challenges. Areas of difficult access with rough terrain, elevation changes in the order of 1000 meters turn all operations costly. Heterogeneities in the near surface are responsible for most of the data quality problems, signal seismic recovery is poor and subsurface image quality is not helping interpreters with the reconstruction of complex structures.

The improvement of subsurface image will not be achieved by accessing to technologies developed without considering topographic variations or just tested on simplified models. Reduction of uncertainties will be achieved when developed technologies get stressed with simulated data obtained from realistic a priori known complex earth model.

To date, for foothills environment, there is no three dimensional synthetic model released publically with the structural and stratigraphic complexity alike 2D Marmousi Model.

This paper review the challenges and approaches applied when building a complex land model that should generate synthetic seismograms comparable with field recorded seismograms to de-risk foothills imaging.

One of main challenge in this process is the proper selection of geo-elements and rock properties to reproduce the presence of scattering noise commonly seen in foothills surveys. Second challenge is their distribution and positioning in a tridimensional space at real scale. Another challenge is the verification of the numerical modeling for seismic simulation. Critical steps are the calculation of adequate acquisition design followed by synthetic seismogram verification against field data and finally the verification of migrated seismic image.

The model to be considered is the newest 3D SEAM Foothills Model.

Introduction

Full wave-equation modeling has no dip limitations, produces all the events associated with the wave equation and offers the advantage of getting recorded on real scale Earth models compared to physical models.

Marmousi model (Versteeg and Grau, 1991 and Versteeg, 1994), it is still the model presenting the most complex structure and it is used for testing on most recent technologies, like FWI. This model alone is an example of the large benefit provided by seismic simulation of realistic or quasi-realistic models.

The advantage of synthetic seismograms computed with finite-difference approach to support interpreters in areas with complex subsurface geometries was presented by Kelly et al. (1976), this paper also presents the vision of using modeling approach in an interactive computer environment.

Imaging of complex thrust structures in the presence of scattering of surface waves remains one of the major challenges of land seismic exploration in foothills. The Foothills model represent different challenges of seismic exploration on land. This model was designed to include the types of geological features that are found in mountainous regions—such as rough topography and alluvial deposits at the surface, and, at depth, complex geologic structures that result from the compressive fold and thrust tectonics of mountain building. The geologic type area chosen for the model is the Llanos Foothills of the Andes mountains in Colombia, one of the most challenging regions of active land exploration. The article by Cooper et al. (1996) describes the tectonics and petroleum geology of the region, which contains the giant Cusiana field discovered in 1992 (Warren et al., 2003). Gibraltar field, also located is Llanos Foothills is reviewed by Villamal et al. (2004) (Figure 1). The Foothills model is generic and was derived from the main characteristics of two real fields. The surveys simulated is a realistic orthogonal design, with shot and receiver lines running in perpendicular directions, along the dip and strike, respectively, of the underlying structure (Figure 2). For this model, the interesting new feature of these simulations is the inclusion of topography, which was modeled with a conforming finite-element grid. The range of the topography, from the lowest to the highest points of the surface, is 1600 m.

The elastic model is isotropic with compressional wave velocity (V_p), shear wave velocity (V_s) and density (ρ) specified on a grid with cubic cells 10 m on a side, which cover a region approximately 14.5 by 12.5 km in horizontal extent and 11 km in depth extent. The grid specifying the model includes part of the air region above the topography; the average thickness of the sedimentary column is about 10.5 km. The model incorporates anelastic attenuation (“Q”) in the near surface.

Geomodeling

The structural geology that provided a framework for the digital Foothills model is characteristic of Subandean zone. This zone is an active and complex fold and thrust belt system that constitutes part of the Andean foreland basin and resulted from the eastward propagation of the eastern Andean orogenic front. The paper by Macellari, et al. (2009) reviews the different tectonic styles present in the front, the different trapping configurations and their relation to petroleum exploration.

The design of the Foothills model combines a near surface model with distinct characteristics of foothills areas with exploration programs, review presented by Oristaglio (2013, 2016). The near surface is a shallow 3D velocity model created to understand the extreme scattering of surface waves that occurs when rough topography interacts with strong contrasts in elastic properties just below the Earth's surface. This velocity model, which extended to a depth of about 1 km, was topped with a digital elevation map from a foothills region (Figure 2).

The deeper structures of the Foothills model derive from a set of horizons that were extracted from the second exploration survey of Andes region. The geometry of these surfaces results from compressive tectonics, in which layers are folded, faulted, and displaced large distances along multiple low- to high-angle thrust faults (Figure 2). Structural geology experts merged the two separate model components. After trimming and scaling deeper structural horizons, to match the dimensions of shallow velocity cube, a palinspastic restoration leading back to the undeformed layers and showing the sequence of folding and faulting that created the fault network and the displacements observed in the interpreted surfaces (Figure 3). Several deformation scenarios then were re-imposed on the layers. These scenarios respected the fault timing and displacements recorded in the restoration step, but varied the geologic boundary conditions to produce a suite of self-consistent structural models. One model in this suite had horizons consistent with trends in the velocity cube, highest amounts of fault displacement below areas of high topographic relief and it became the framework for the Foothills model.

In a last step of surface modeling, the shallow horizons of this framework were digitally eroded to produce two new surfaces: an upper surface following the topography above the shallow velocity cube, and a lower surface representing the base of alluvial fans spreading from the highlands into the

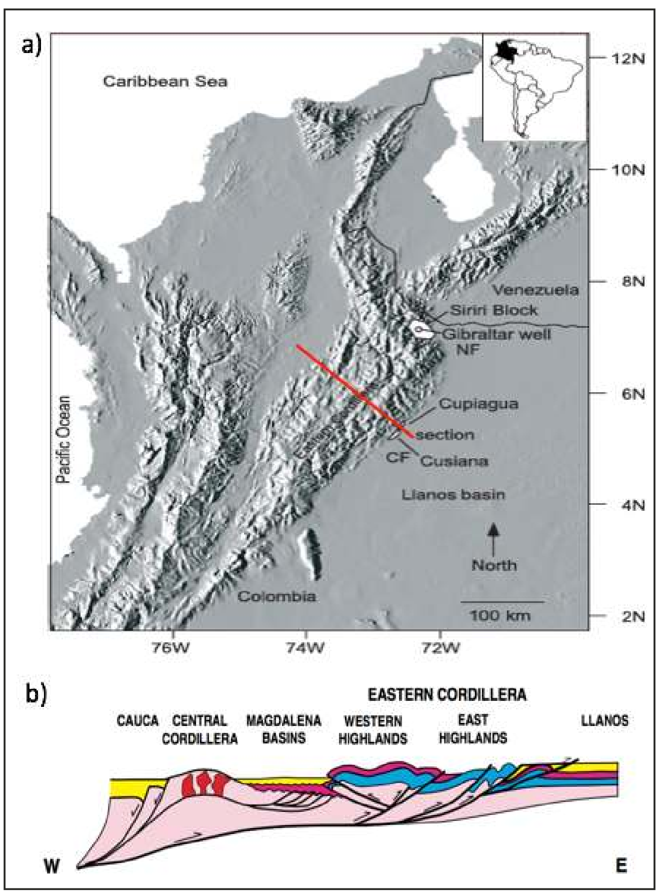

Fig. 1: The geologic area type for SEAM Foothills Model. a) Topographic map of Colombia from Villamal et al. (2004), showing the location of Llanos foothills structural trend, Cusiana and Gibraltar structure. b) Schematic cross section of the structural geology taken from Cooper et al. (1995)

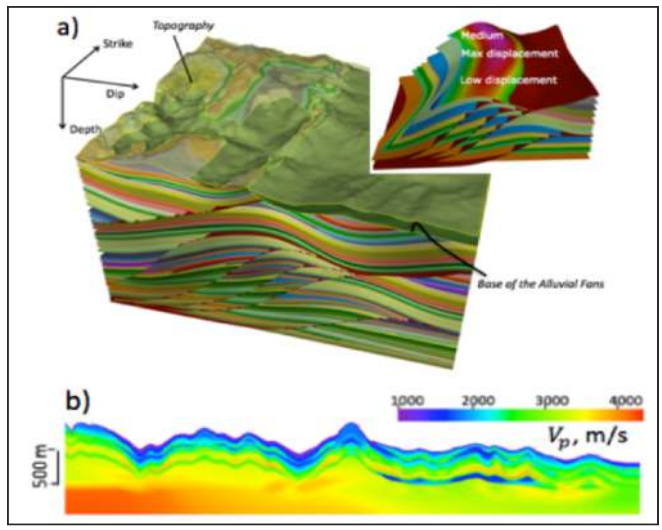

Fig. 2: Structural framework of the Foothills model. a) Displacement variation along strike for the deeper structures. b) Starting near velocity Foothills model.

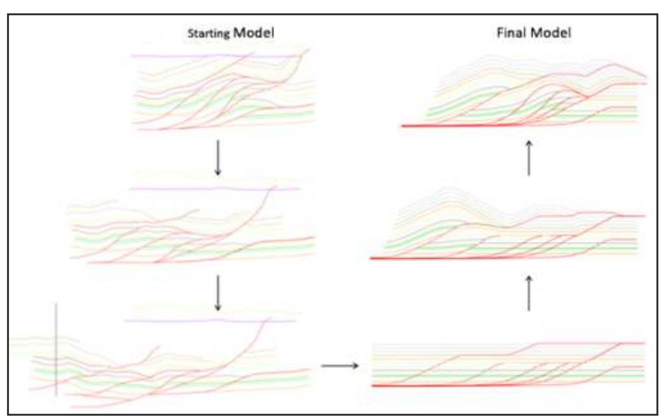

Fig. 3: Building the structural framework. Restoration and redeformation.

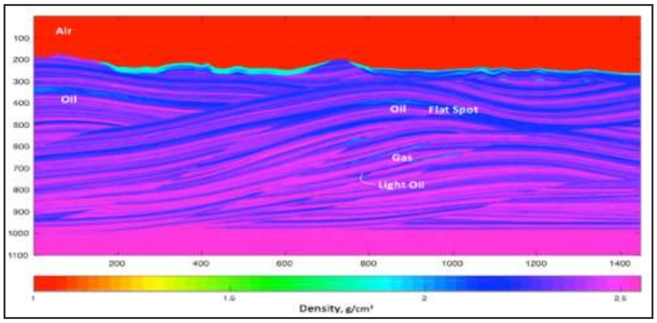

Fig. 4: Hydrocarbons. Density cross section. Elastic properties and density set to values of sediments with hydrocarbon charge. The color scale is clipped at the low end to 1.

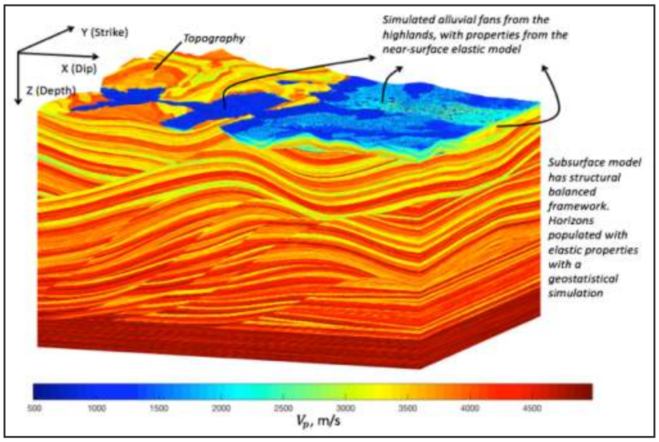

Fig. 5: Perspective view of the digital Foothills model. 3D rendering of the grid of compressional wave velocity

valleys. Structural geologists inserted a series of stratigraphic horizons into the structural framework yielding 91 distinct stratigraphic regions, representing onlaps, erosional truncations, channel features and parallel bedding. Finally, the surface-defined model was digitized into a volume with 10 m cubes containing an integer value for the 91 indexed regions.

The final merge of two models was done in two steps. First, the shallow 3D velocity grid was inserted into the indexed region representing the location of the alluvial fan layer (Figure 5). Finally, the other regions of the index grid, representing deeper sedimentary layers, were populated with fluctuating elastic properties. This population was done in a geostatistical simulation that used the statistics of petrophysical properties extracted from tree well logs of survey used to model the subsurface. For this process, it was required to develop new algorithms forcing the statistical fluctuations to conform to the model's local dip, which was estimated directly from the cube.

The merge the two geologic regions was tested with numerical seismic modeling after the full model has been populated with elastic velocities and densities.

Topography

The digital elevation map used to create the topography of the Foothills model had a coarser resolution than the final grid cell size of 10 m, and therefore was "staircased" to the grid. To avoid artifacts the topography was smoothed and interpolated during the construction of the conforming finite-element grid that was used for the numerical seismic simulations.

Numerical code to use in production was compared with codes from academia. Synthetic shots and methods were compared carefully by experts. Tests gave confidence that the finite-element method was generating accurate results for the seismic response of the Foothills model, with its sharp topography and strong velocity contrasts in the near surface.

Reservoir and Imaging Targets

The SEAM Foothills model was designed to be mainly a structural imaging challenge. As such, the model does not explicitly incorporate a reservoir model. Nevertheless, the petrophysical properties of the model were constructed in such a way as to be consistent with the charging of some sediments with hydrocarbons: light oil, oil and gas. Figure 4 shows a cross section illustrating this feature. In addition, two artificial imaging targets are built into the model. The first is a regular grid of point scatterers at a depth of 8520 m; the second is an imprint of the (old) SEG logo at a depth of 10 530 m. Both imaging targets are pure density contrasts.

Attenuation (Q)

The Foothills model includes viscoelastic attenuation—a finite value of Q—in the near-surface region. A series of modeling experiments showed that a value of Q between 25 and 100 in the near surface region, just below the topography, gave a reasonable balance between the scattered energy in surface waves and the strength of the reflections from the structures at depth, as well as a realistic rate of attenuation of the surface waves. Based on these tests, all cells in the first 50 m of the subsurface were given values of 50 for the shear (Qs) and compressional (Qp) attenuation factors, which were assumed to be constant over the simulation bandwidth. (See Carcione, 1990, for a discussion of separate attenuation factors for shear and compressional deformation, and Blanch et al., 1995, for a discussion of numerical constant-Q models). For the rest of the model, Q was taken to be effectively infinite—that is, there is no seismic attenuation below 50 m depth in the Foothills model.

Foothills Model

The digital model used for the seismic simulations is defined by three property grids— V_p, V_s and density (ρ)—and by the specification of Q given above.

Seismic Modeling Section - Survey Design and Resulting Synthetic Data Sets

The synthetic seismic survey of the Foothills model has most of the seismic shots simulated in the main 3D surface survey, which has parallel shot lines running in the strike (Y) direction in a standard 3D orthogonal survey design. Two sets of 3D synthetic data were simulated and their information is summarized in Table 1.

Table 1: Foothills Model Data Sets

Date Sets	Component	Coverage	Spacing (X,Y)	Number	Depth
35 Surface survey	Shots 1C (Z) Receivers 3C (X,Y,Z)	13.5x11.5 km 14.5x12.5 km	25 x 250m 12.5 x 250 m	25,355 117,261	On Surface On Surface

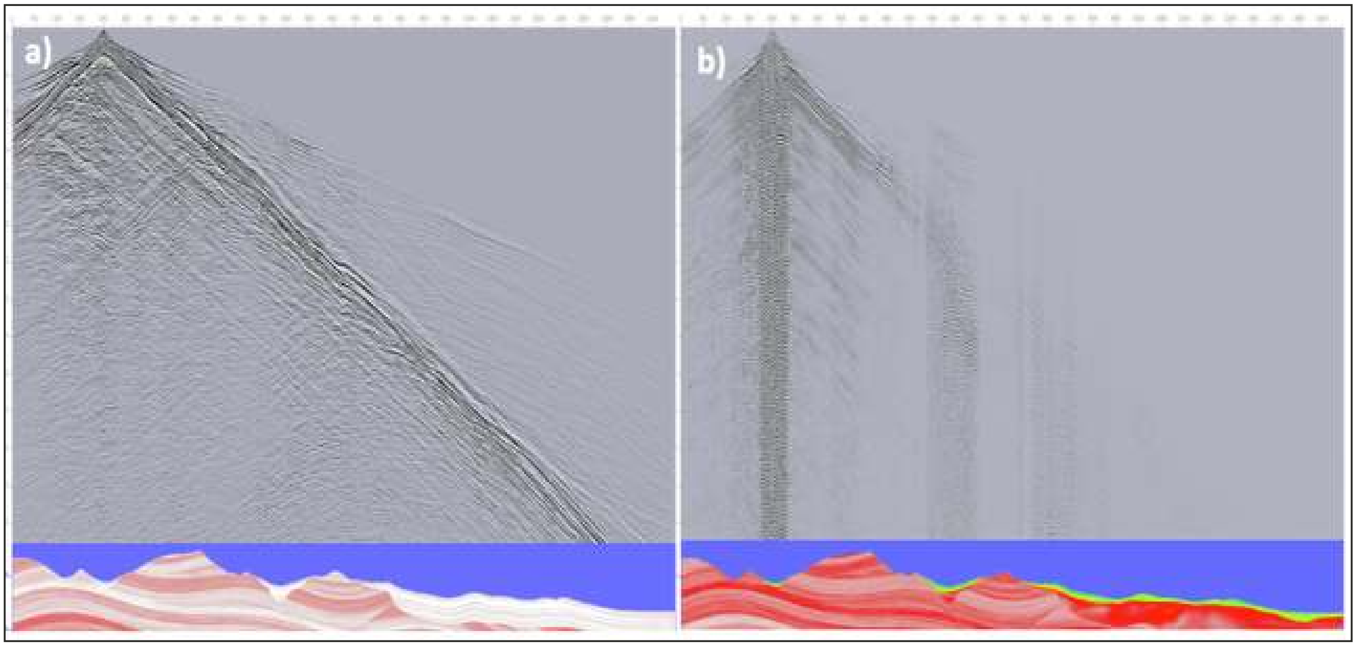

Fig. a) Synthetic shot using initial near velocity model, velocity defined by conformed layers. b) Synthetic shot from improved near velocity model including lateral variation in alluvial fan showing more scattering of surface waves and reverberation between near and subsurface features.

Seismic sources are imposed as vertical-component point forces, simulating an ideal Vibroseis source with a 40 Hz Klauder wavelet. The receiver array thus lies in a 14.5 x 12.5 km patch that essentially covers the entire model. All receivers are 3C and are located at the Earth-air interface. Each receiver is a three-component (3C) geophone recording particle velocity along the three Cartesian axes, (V_x, V_y, V_z). To accommodate the receiver patch and the absorbing boundary conditions, the computational model is extended slightly by extrapolating the values along its vertical and bottom bounding planes. Absorbing boundary conditions were used at the side and bottom bounding planes. A finite-element grid conforming to the interpolated topography was used to mesh just the solid-earth part of the model; a standard free-surface (zero-traction) boundary condition for linear elasticity was applied at the top of the model (Earth-air interface).

The source-receiver aperture depends on the source location and can be highly asymmetric for the Foothills model simulations. This design was considered to be more realistic for actual Foothills field surveys; also, there is no easy and realistic way of extending the topography and geologic structure off the edges of the model. Figure 6b shows a characteristic shot profile.

The second data set includes data from a dense receiver array, which is essentially a complete recording of the surface wavefield for all shots (117,261) in the 3D shot pattern. It was made at a fixed array of receivers at 10 m spacing in both dip and strike directions.

Concluding Remarks

Synthetic shot records show the strong disruption of propagating seismic energy. This scattering of surface waves was obtained by including topography with strong changes, variations in the alluvial fills and lateral contrast in properties between alluvial fans and deep layers reaching topography.

The newest SEAM 3D Foothills Model presents realistic near surface complexity to the expected level. The degree of attenuation and presence of geological noise in the near surface will be challenging the development and improvement of imaging solutions to better de-risk seismic exploration in mountainous regions.

The subsurface zone of the model is a realistic model which was structurally balanced during geomodeling process. Rock properties also correspond to real field proving a challenging model to geoscientists.

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