Summary
In recent years new methods and tools were developed in seismic survey design to address the increasing complexity of geophysical and geological problems that seismic exploration is faced with. In this paper we discuss three of these new developments: the application of point-spread functions for seismic resolution analysis, seismic survey design based on Bayesian methodology, and the generation of the seismic response for a fractured reservoir using 3D elastic general anisotropic finite-difference modeling. We demonstrate that these methods can be used effectively for seismic survey design.

Introduction
Common geological and geophysical problems that we face today include five categories:
- Imaging reservoirs below complex overburdens, for example, salt, basalt or carbonate layers
- Detecting reservoir changes and characterizing the reservoirs for development purposes
- Imaging and characterizing fractured reservoirs
- Development of unconventional reservoirs based on seismic data
- Identification of drilling hazards from seismic data

In the last decade significant developments were made in seismic exploration for both land and marine acquisitions to address these challenges. For land acquisition technology the most important developments were:
- Seismic systems with very large number of channels and point receivers
- Cable-less systems
- The use of simultaneous sources

For marine acquisition advances include:
- Wide-azimuth and full-azimuth towed-streamer acquisition
- Dual-sensor hydrophone-geophone cable systems
- Broadband towed-streamer acquisition based on single-pressure measurements (slant cable or flat deep cable)
- Broadband acquisition based on dual-pressure measurements (over-under streamers and over-under sources)
- Multimeasurement towed-streamer systems

Designing a seismic survey to address exploration challenges with the new acquisition technologies requires more comprehensive methods and workflows for survey design. In this paper, we discuss three of these new methods developed in the last five years.

Resolution analysis based on point-spread functions
In seismic survey design we are interested in determining seismic resolution at the subsurface target of interest. The typical method estimates vertical and horizontal resolution of seismic data using equations 1 and 2, respectively (Vermeer, 2002).

\[
R_x = \frac{c v}{2f_{\text{max}} \sin(\theta_{x,\text{max}})} \quad (1)
\]
\[
R_z = \frac{c v}{2f_{\text{max}}} \quad (2)
\]

Where \( c \) = proportionality factor, \( v \) = velocity, \( f_{\text{max}} \) = maximum frequency and \( \theta_{x,\text{max}} \) = angle between the vertical and the ray path from the output point to the farthest shot/receiver pair (scattering angle).

A more comprehensive way to analyze the seismic resolution is to take into account the full acquisition geometry, the source wavelet, the propagation of the seismic waves through the overburden, and the detailed reflectivity of the reservoir. This can be achieved if full 3D finite-difference modeling is performed using the acquisition geometry we want to analyze, followed by processing and imaging. Although current computing power allows us to do this type of resolution analysis, the cost is quite high if a large volume of data must be modeled, processed and imaged. If we are modeling high frequencies, this method becomes prohibitive. An alternative method was presented by Lecomte (2008) and is based on raytracing to compute point-spread functions.

The point-spread function (PSF) is defined as the impulse response of an imaging system. PSFs can be calculated based on two-way wave-equation modeling (Fletcher et al., 2012) or based on ray tracing (Lecomte, 2008). We will follow the methodology presented in Lecomte’s paper for calculation of PSFs, and we will use Norsar-SeiRoX software for resolution analysis. The main steps in this type of analysis are:
- Generating the overburden earth model and the detailed reservoir model; elastic rock properties (Vp, Vs and density) are required.
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- Calculating reservoir reflectivity (normal incidence or angle dependent)
- Defining the survey geometry; P190 or SPS files can be used to define the acquisition geometry
- Generating point-spread functions at selected locations, based on 3D ray tracing illumination vectors and a source wavelet
- Convolving the reflectivity model with the PSF to create a prestack depth-migrated (PSDM) volume

To illustrate how this methodology works for seismic resolution analysis we use a simple earth model (Figure 1).

Figure 1: Earth model showing the overburden, the reservoir and analysis location.

Two types of geometries were analyzed: full azimuth and narrow azimuth. We discuss here only the results for full-azimuth geometry. In Figure 2a the zero offset reflectivity calculated for the reservoir is shown. Figure 2b and 2c show PSDM seismic images of the reservoir calculated for the full-azimuth geometry using a 20-Hz and 40-Hz Ricker source wavelet, respectively.

The results show, as expected, that a broader source wavelet improves the resolution. However, the effect of frequency attenuation must be considered during survey design resolution analysis when determining the maximum frequency that can be recovered, after imaging, at the reservoir level. An important part of survey design is to analyze the effect of processing, particularly the seismic inversion process. The inversion process is usually performed in the time domain. Fletcher et al. (2012) introduced a method to perform PSF-based inversion in the depth domain. One advantage of this method is that acquisition and processing effects are incorporated in the PSF and by performing PSF-based inversion we can compensate for some of those effects. We used the PSF depth inversion method to perform inversion of the 20-Hz PSDM cube and the result is presented in Figure 3.

Figure 3: PSF based-depth inversion of the 20 Hz PSDM reservoir cube

This result shows that if source bandwidth was reduced due to various propagation effects, it is still possible to recover a higher-resolution image by performing PSF-based inversion. We consider that further research is needed to investigate how PSF-based inversion performs when processing artifacts are left in the PSDM cube, for example, residual multiples or random noise. This type of resolution analysis can be very useful when the overburden or the reservoir models are complex. One advantage of PSF-based resolution analysis is that both, horizontal and vertical seismic resolution, can be assessed.

Seismic survey design based on the Bayesian optimization method

It is now rare that new seismic data is acquired in an area with no pre-existing legacy data. For instance, in deepwater Gulf of Mexico seismic data were acquired with narrow-azimuth and wide-azimuth marine towed-streamers and, in limited areas, with full-azimuth dual-coil and node acquisitions. When we design a new survey in these areas, where advanced acquisition was already conducted, we should consider a target-oriented type design. Figure 4a shows a subsalt prospect in the Gulf of Mexico that was not illuminated by a wide-azimuth (WAZ) survey due to limited offsets and azimuths ranges of the WAZ geometry. For this case new seismic data must be acquired to improve
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The optimal Bayesian survey design algorithm was modified to allow the comparison of different acquisition geometries (Coles, 2013). The same input data are required for this method as was described before, but the uncertainty is the same for the entire target horizon. We performed survey evaluation based on the Bayesian method to compare a WAZ geometry with an areal grid geometry for a subsalt Gulf of Mexico prospect that is presented in Figure 5a. The target is the subsalt horizon. The WAZ geometry was a 2x4 configuration (Moldoveanu and Kapoor, 2009) and the areal geometry was designed with a 400-m x 400-m receiver grid, each receiver being surrounded by a 14-km x 14-km shot grid, with shots every 50 m x 50 m. The result of this analysis is presented in Figure 5b and it represents the objective value variation as a function of the number of measurements recorded with each source-receiver pair. The areal geometry gives a higher objective function than the WAZ geometry due to the full azimuth and a minimum maximum offset of 14 km. The variation of objective function with each measurement reveals also that some areal geometry measurements have minimal or no contribution to reduction in the uncertainty. This graph could be considered a performance graph of the survey.

Optimal Bayesian survey design methodology can also be helpful in planning the acquisition or data processing, by prioritizing the shots that will have the maximum contribution for the target area.

Figure 5: Subsalt target horizon used in Bayesian survey evaluation analysis (a) Variation of the objective function with each source-receiver pair measurement (b)

3D elastic anisotropic finite-difference wave-equation modeling of fractures
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Many reservoirs around the world, in clastics or carbonates, are affected by naturally occurring fractures. As seismic wave propagation is affected by fractures, it is important to model and understand the seismic response. This could help the seismic data processors and interpreters to determine fracture orientation and fracture density, and survey designers to design seismic surveys suitable for the processing, mapping and characterization of fractured reservoirs data.

Finite-difference modeling of both fractures and discrete faults is typically based on equivalent medium theory (Coates and Schoenberg, 1995). Den Boer and Sayers (2011) developed an algorithm that computes elastic properties and permeability of a fractured reservoir for discrete fracture networks (DFNs), and upscale these properties into a 3D Cartesian grid. As a result, the elastic stiffness tensor $C_{ijkl}$ is calculated for the entire reservoir in the grid required for 3D finite-difference modeling.

Modeling a fractured reservoir, based on the den Boer and Sayers method, requires performing the following steps:

- Create a discrete fracture network (DFN) from existing seismic and well information, using an interpretation software
- Determine fractured rock properties from well information: compliance or stiffness, density and permeability
- Determine the required resolution (grid size) for finite difference modeling
- Upscale DFN to cube to calculate the stiffness tensor $C_{ijkl}$ and density in a Cartesian cube, at the required resolution; extend the cubes to cover the full survey area
- Generate Cartesian cubes for velocities-$V_p$ and $V_s$, densities, and seismic attenuation (if visco-elastic modeling is required)
- Define the source wavelet
- Use a 3D visco-elastic general anisotropic wave-equation algorithm to simulate the seismic data

We include in the abstract a simple example to illustrate the propagation of seismic waves in a fractured reservoir and to compare with the propagation in an isotropic reservoir. We used the DFN created for the Tensleep reservoir model of Teapot Dome, Louisiana (Sayers and den Boer, 2011). As a result of DFN upscaling, 21 $C_{ijkl}$ cubes were generated. Figure 6a shows the cube corresponding to the stiffness tensor component $C_{2222}$. In Figure 6 we show the time slices through the wavefront generated from a source for the isotropic medium (6b) and generally anisotropic triclinic medium (6c). The same source type and location were used for both simulations. These results show that the propagation through the fractured reservoir produced an elliptical type wavefront. We plan to analyze the response of the fractured reservoir for different acquisition geometries and different types of anisotropy, corresponding to different types of fractures.

Figure 6: The $C_{2222}$ component of the stiffness tensor (a) time slices through the wavefronts for an isotropic reservoir (b) time slice through the wavefront for a general anisotropic triclinic fractured reservoir (c)

Discussions and conclusions

In addition to seismic resolution, signal-to-noise ratio is another important component of seismic survey design. Both aspects can be included in the optimal Bayesian survey design formulation. This will enable the design of seismic surveys that will maximize the amount of information gathered, considering both the seismic resolution and the signal-to-noise ratio.

Recent improvements in the performance of finite-difference algorithms and computer power, is just beginning to make possible the simulation of seismic data for an entire survey using 3D visco-elastic general anisotropic wave-equation propagation. Because fractured reservoirs are important components for unconventional oil and gas plays, seismic modeling of fractures for surface and borehole seismic acquisition, could help to calibrate seismic and reservoir data and, consequently, enable the use of seismic data to guide horizontal drilling.

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EDITED REFERENCES
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REFERENCES

Coles, D., 2013, Personal communication.


