Introduction

The seismic method is the most powerful tool oil explorationists have to probe the subsurface. Provided that the appropriate imaging technology and an accurate velocity model are used, the seismic method yields reliable multidimensional images, with dense spatial sampling, with which properties of the subsurface can be estimated in order to locate oil accumulations. For the relatively simple geology in which most of the known oil fields are located, conventional seismic imaging, e.g., pre-stack time migration, has been adequate to support well locations and characterize the reservoirs.

However, as the 'easy' oil fields have been almost completely explored, oil exploration has been pushed to areas of greater geological complexity, where conventional seismic imaging is inadequate. In these areas, pre-stack depth migration is mandatory and has become the industry standard for imaging the subsurface. Until recently, prestack-depth migration has been performed at the production scale by Kirchhoff algorithms, because they are fast and consistent with ray-based methods for velocity-model definition, which are the industry standards. However, the extensive use of Kirchhoff methods has exposed problems caused by the asymptotic approximation of the wavefield propagation.

With the steady growth of computational power, more robust imaging algorithms based on wavefield extrapolation have gained in importance and are now being used to produce final images, whereas the velocity-model definition still relies on migration-velocity analysis by ray-based tomography. Ray-based tomography allows flexible parametrization of the model space, such as layered models, which can improve convergence to a final velocity. However, it is widely known that in the presence of high lateral velocity variation and irregular surfaces, ray-based methods are prone to fail, because they do not describe the entire complexity of wavefield propagation, which can include band-limitation effects and multipathing. Hence, in those situations it is desirable to use wavefields to define the velocity model.

The last decade has seen the development of migration-velocity analysis (MVA) by wavefield extrapolation (**??**). Since MVA by wavefield extrapolation is solved in the image space, using tomography with wavefields as carriers of information, in this thesis it is called image-space wave-equation tomography (ISWET). Despite its theoretical superiority to ray methods, this relatively new technology has been rarely used in 3D projects because of its higher cost and because it is less flexible than its ray-based counterpart in parameterizing the velocity model. In this thesis, decreasing the cost of ISWET and incorporating ray-based strategies for model parametrization are achieved by using special wavefields: the image-space generalized wavefields.

THE GENERALIZED-SOURCES DOMAIN

Wavefield propagation is a linear process in which a source function is the input. In seismic exploration, the source function is usually represented by an array of point sources with a limited areal extent. In the far-field, the source array can be considered a point source because of the long distances traveled by the wavefields compared to the size of the array.

Applying the properties of linear, time-invariant systems enables us to consider source functions other than punctual. This characterizes generalized source functions defined in the generalized source domain. For instance, according to the superposition principle, a hypothetical experiment in which all the point sources are initiated in unison generates a horizontal plane wave. Another thought experiment would be to initiate all the sources of the seismic survey at random times, using the superposition and the time-shift properties. This concept is used in simultaneous Vibroseis acquisition, where different arrays of vibrators are initiated independently and with no synchronization between them, allowing great improvement in productivity (**?**).

Those experiments can be easily synthesized in the seismic processing environment, by combining the recorded wavefields with the same scheme as that used for point sources. In this way, the migrated image computed using the combined source functions and the combined recorded wavefields is similar to the one we would obtain by migrating the original data, provided that certain conditions particular to each combination method are fulfilled. However, the imaging cost can be smaller by orders of magnitude with generalized wavefields than with conventional wavefields.

The idea of synthesizing generalized sources during processing is not new in seismic exploration. Plane-wave synthesis (**?**), controlled illumination (**?**), and random-phase encoding (**?**) are methods that synthesize generalized sources. In the plane-wave synthesis method, linear time shifts are applied to the shot records to simulate slanted plane waves. In the controlled illumination method, a wavefield with a pre-defined shape is upward propagated and collected at the surface, defining a synthesis operator to be convolved with the original data. The generalized wavefields synthesized by the controlled illumination method tend to assume the shape of the pre-defined wavefield during the downward propagation. In the random-phase encoding method, source functions and the corresponding receiver gathers are encoded with the same random-code function, so that during migration cross-correlation of unrelated wavefields is attenuated, whereas the cross-correlation of related wavefields is minimally affected.

The methods described above for generating generalized sources are illustrated in Figures 2-4. In these figures, on the top left is the generalized source function, on the top right is the generalized receiver gather, and on the bottom is the areal-shot migrated image. In Figure 2 the plane-wave synthesis method creates horizontal plane waves at the surface. In Figure 3 a horizontal plane wave at depth 2300 m is synthesized by the method of controlled illumination. In Figure 4, the random-phase encoding method is used to combine every 20 shots into one generalized receiver gather. Migrating data from only one generalized source is not sufficient to recover a similar image quality as the migration of the original 375 shot-profiles (Figure 1). Therefore, it is usual to synthesize more generalized sources to achieve a reasonable quality. Even so, the cost of migrating generalized sources is much smaller than that of migrating the original shot-profiles.

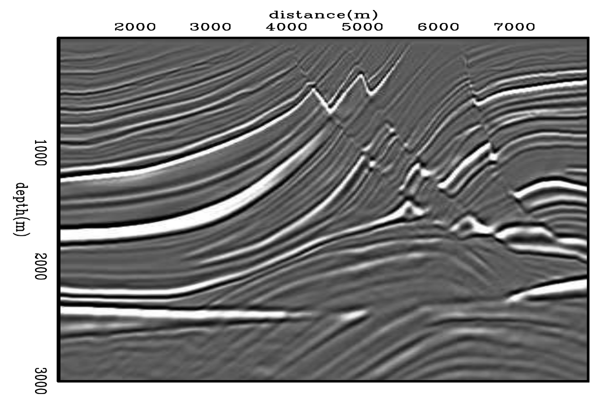

Figure 1: Migration of the original 375 shot-profiles.

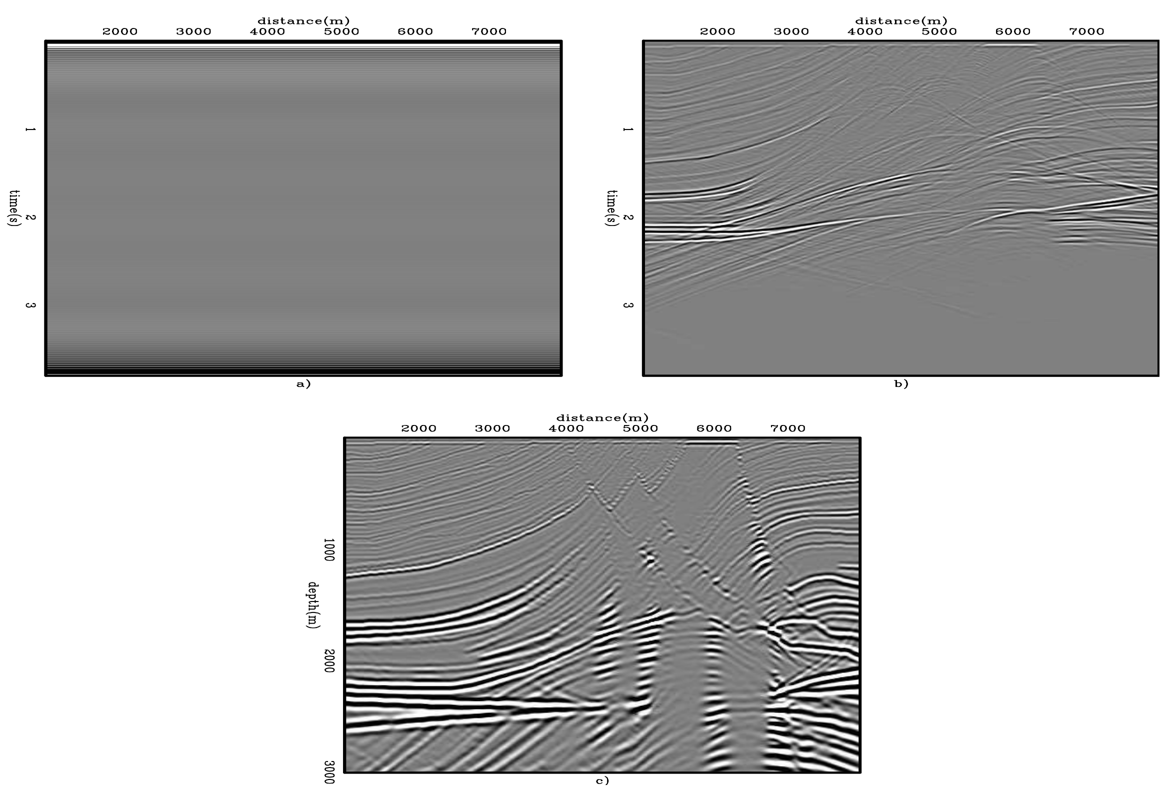

Figure 2: Horizontal plane-wave synthesis. a) generalized source function, b) generalized receiver gather, and c) areal-shot migration.

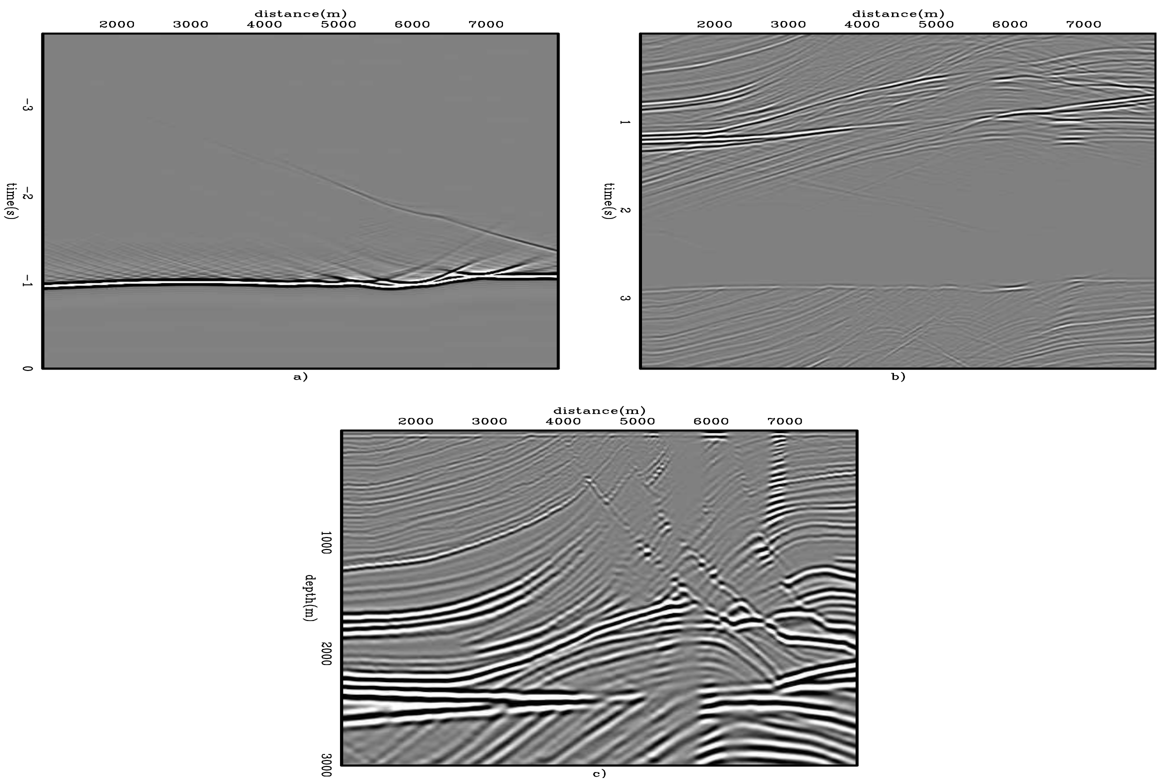

Figure 3: Horizontal plane-wave at depth 2300 m by the controlled illumination method. a) generalized source function, b) generalized receiver gather, and c) areal-shot migration.

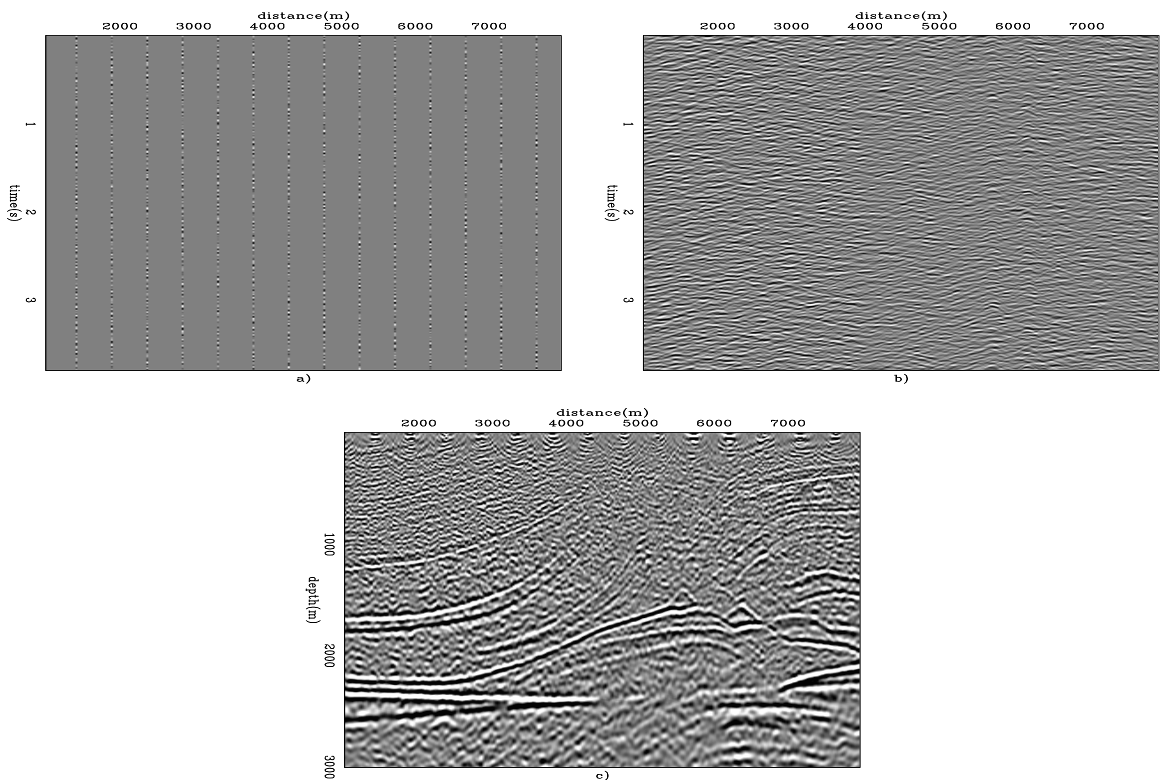

Figure 4: Random-phase encoding combining every 20 shots. a) generalized source function, b) generalized receiver gather, and c) areal-shot migration.

The methods for computing generalized sources discussed above operate in the data space, characterizing the data-space generalized sources. This thesis introduces a new category of generalized sources that are initiated from selected reflectors, using the pre-stack exploding-reflector model (PERM) (?).

PERM is an extension of the exploding-reflector model (?). Because PERM wavefields are initiated in the image space, they are called the image-space generalized sources. The image-space generalized sources are suitable for migration-velocity analysis. After optimizing for the velocity model, any migration scheme can be used to generate the final image using the original data. Figure 5a shows the Marmousi image computed with shot-profile migration using an initial velocity model, which is inaccurate below the top of the anticline at a depth of 1700 m. The inaccuracy of the velocity model is indicated by reflectors being pulled up in the center of the image below 2000 m. Figure 5b shows the Marmousi image computed with shot-profile migration using a velocity model optimized with ISWET. ISWET was performed with 11 pairs of image-space generalized sources synthesized from 12 selected reflectors and collected at a depth of 1500 m. The pull up effect has been corrected, and the reflectors are better focused. Compare Figure 5b with Figure 1, which was computed with the true velocity model. For this example, each iteration of ISWET using the image-space generalized wavefields is approximately 60 times faster than that with the conventional 375 shot-profiles.

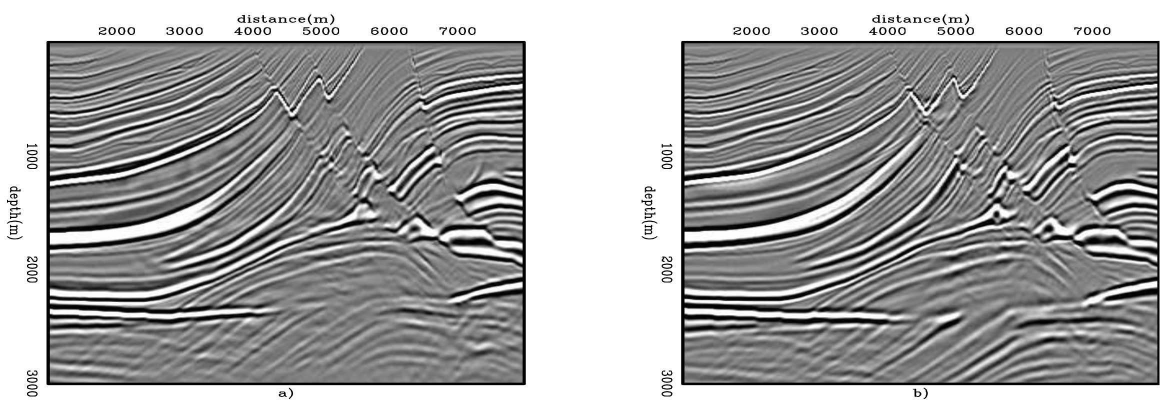

Figure 5: Shot-profile migrated images of Marmousi obtained with: a) An initial velocity model, which is inaccurate below the top of the anticline at depth 1700 m, b) a velocity model optimized with ISWET, using 11 pairs of image-space generalized sources synthesized from 12 selected reflectors and collected at depth 1500 m.

As will be shown, in 3D a dramatic data reduction is possible with these generalized sources. Since they are initiated at selected reflectors, a horizon-based strategy to parameterize the velocity model can be naturally incorporated into ISWET. Moreover, image-space generalized sources can be collected at any depth during the upward propagation, making a target-oriented approach also easily integrated. This thesis is one step forward in making 3D-ISWET a standard for depth-imaging projects in the presence of complex geology.

THESIS OVERVIEW AND CONTRIBUTIONS

Pre-stack Exploding-Reflector Model: In Chapter **??**, PERM is presented and extended to 3D. I show that if the image used as the initial condition to model PERM wavefields is computed with common-azimuth migration, the data size can be smaller by two orders of magnitude when compared to the data size obtained by 3D-plane wave synthesis.

Image-space Phase-encoded Wavefields: In Chapter **??**, to improve the data size reduction achieved with PERM, I introduce the image-space phase-encoded wavefields (ISPEWs). ISPEWs are another example of image-space generalized wavefields. They are computed by phase-encoding PERM experiments to mitigate cross-talk, which is a consequence of the further data size reduction. I describe how crosstalk is formed and propose strategies to attenuate it.

Migration-velocity analysis using image-space generalized sources: In Chapter **??**, I extend ISWET from the shot-profile domain to the image-space generalized-sources domain. In this domain, the cost of ISWET is greatly reduced by decreasing the number of wavefields to be propagated and solving it in a target-oriented manner. Also, since the image-space generalized wavefields are initiated at some selected horizons, a horizon-based strategy similar to that used in ray-based migration-velocity analysis is naturally incorporated into ISWET.

3D field-data example: In Chapter **??**, the theory of ISWET extended to the image-space generalized sources domain is applied in the optimization of the velocity model for a 3D field dataset from the North Sea. I show that using these wavefields greatly improves computational efficiency of ISWET and yields accurate velocity updates.