Seismic Imaging Strategies for Thrust-Belt Exploration: Extended Offsets, Seismic/Gravity/EM simultaneous Joint-Inversion and Anisotropic Gaussian Beam Pre-Stack Depth Migration

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Summary

The lateral velocity variations and vertical velocity inversions caused by near-surface overthrusted high-velocity bodies generate severe ray-path distortions. From the seismic imaging point of view, these can be handled by pre-stack depth migration if reliable velocity models can be obtained.

Extended offset geometries allow the undershooting of localized complexities while providing enhanced velocity discrimination and larger amplitudes at far offsets. The simultaneous Joint Inversion (JI) of these refracted and reflected seismic phases with multiple geophysical measurements such as gravity and magnetotellurics provide robust velocity models for depth-domain processes.

The complex velocity models characterizing thrust-belt environments also generate illumination problems of deep-seated sub-thrust targets that can be handled by multi-arrival imaging algorithms such as Gaussian Beam Pre-Stack Depth Migration (GB-PSDM). The angle-domain implementation of GB-PSDM together with hit-count trace equalization enable a number of amplitude-friendly processes of the image gathers. GB-PSDM can also be easily parameterized to handle complex anisotropy such as TTI.

The combination of extended offsets, multi-geophysical measurement Joint Inversion and specialized imaging techniques are keys to success in thrust-belt exploration.

Introduction

Seismic imaging in thrust belt is a complex problem and specific strategies need to be addressed both from the acquisition and data processing points of view. Thrust-belts are characterized by lateral and vertical velocity variations which affect the propagation of the seismic waves. Imaging in depth domain represents the most effective approach to correctly handle the irregular ray paths and provide correct positioning of seismic events through migration. Complex anisotropic effects and multipathing are other important factors affecting the quality of seismic images.

The problem of improving velocity model building and seismic imaging by exploting the properties of refracted and reflected seismic waves propagated at large offsets was discussed by various authors (Colombo, 2005; Yilmaz, 2007).

More recently, the problem of robust velocity model reconstruction has been exteded to the multiparameter model space by including gravity and magnetotellurics (MT) in Joint Inversion with seismic (Colombo et al., 2007; Colombo and De Stefano, 2007). The inversion of the multiparameter data is coupled to the seismic image residuals through a procedure called PSDM-Joint Inversion. This approach is able to minimize simultaneously the gravity field residuals, the EM (Magnetotelluric – MT) field residuals and the seismic depth-migrated image gather residuals to generate cross-consistent multiparameter models. This velocity model building approach is robust as only a limited number of models can simultaneously honour the residuals of multiparameter measurements.

Gaussian Beam Pre-Stack Depth Migration (GB-PSDM) represents an excellent tool for complex velocity fields as being an implicit multiarrival migration algorithm. It is also appropriate for steep dips, irregular acquisition geometries, and can be easily parameterized for handling complex anisotropy (e.g. TTI). The implementation of Gaussian Beam migration in angular domain adds additional value to the solution of the imaging problem via improved velocity discriminations in angle gathers, better management of migration artifacts and improved S/N ratio.

PSDM-Joint Inversion Method

Imaging through PSDM-Joint Inversion has been discussed by Colombo and De Stefano (2007). The workflow generally starts from the analysis of FB (i.e. in the pre-migrated domain) which are simultaneously jointly inverted with non seismic data (MT or Gravity). This approach has the advantage of providing robust velocity reconstructions of the shallow layers including velocity inversions or low-velocity zones which generally represent “hidden layers” for refraction seismology (e.g. diving wave tomography).

The analysis of the velocity field is extended to deeper layers by using reflection tomography from the Common Reflection Point and the residuals obtained from depth migration (Common Image Gather residuals) in Joint Inversion with the gravity and MT field residuals. The output of a PSDM-Joint Inversion workflow is therefore an optimized seismic image, a robust velocity field and robust density or resistivity fields. One interesting aspects of Joint Inversion is that the number of iterations needed to converge to a robust velocity model are generally much less than for a workflow usign seismic alone. This indicates the overall robustness of the procedure.

Areas of application for the Joint Inversion workflow are conditions of poor S/N for seismic data, near-surface complex velocity fields, areas of insuffcient seismic coverage and problems of hidden layers or velocity inversions. Extensive applications to thrust-belt areas in Oman (Colombo et al., 2007) and other areas in the Canadian foothills, Western US (sub-basalt), Bolivia and Saudi Arabia have confirmed the extended range of applications that geophysical multi-measurements and Joint Inversion can offer to solve complex imaging problems.

Gaussian Beam PSDM in Angular Domain

Gaussian Beam PSDM has emerged as an attractive imaging tool in various geological environments including sub-salt and thrust-belt. Whilst the theory of Gaussian Beams for Pre-Stack Depth Migration has been extensively covered by various authors (Hill, 2001; Zhu et al., 2007; to cite a few), the implementation of Gaussian Beam migration in angular domain, the equalization with hit counters and the parameterization for TTI anisotropy is still a relatively new topic.

The beam of energy is propagated along the central ray which is considered as the asymptotic solution of the wave equation centered along a ray. The beam is frequency-dependent and the user can select the frequency content of the beam. This provides penetration of the energy also in complex portions of models where focussing effects determine poor coverage for the seismic energy (i.e. undershooting).

The recorded seismic data are decomposed into local plane waves through slant-stacking and the migration process back-propagates the plane waves (Gaussian beam) from the source side and from the receiver side independently (figure 1). All the contributions are then summed in angular domain to obtain the complete subsurface image. Before summing, the hit-counter equalization is applied to normalize the amplitudes based on the actual illumination of the reflector.

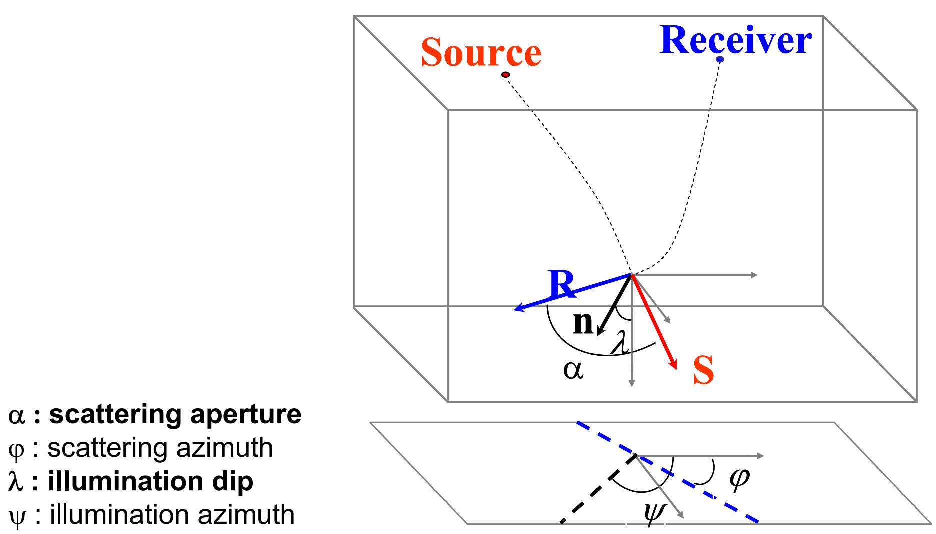

Figure1: Gaussian Beam PSDM, extraction of angle gathers.

Multi-arrivals are intrinsic on the receiver side and user-selectable from the source side. This provides great flexibility in testing different migration options. Turning ray propagation is allowed and user-defined. This allows the imaging of steep-dips and overhangs.

TTI anisotropy is parameterized and easily computed for the central ray propagation. The flexible ray-tracing scheme allows the computation of several anisotropic parameterizations from simplest VTI to more complex generalized anisotropy such as TTI. Gaussian Beam PSDM is performed in shot domain and is therefore suited for acquisition in rough topography such as thrust-belts.

Conclusions

The combined application of PSDM-Joint Inversion (with gravity/MT) and Gaussian Beam PSDM in angular domain allows the extraction of additional information from low S/N seismic data (figure 2).

Extensive application of PSDM-Joint Inversion of multi-geophysical data and the encouraging results of Gaussian Beam PSDM in angle domain are suggesting the possibility of new important tools for the solution of a range of difficult imaging problems in depth domain.

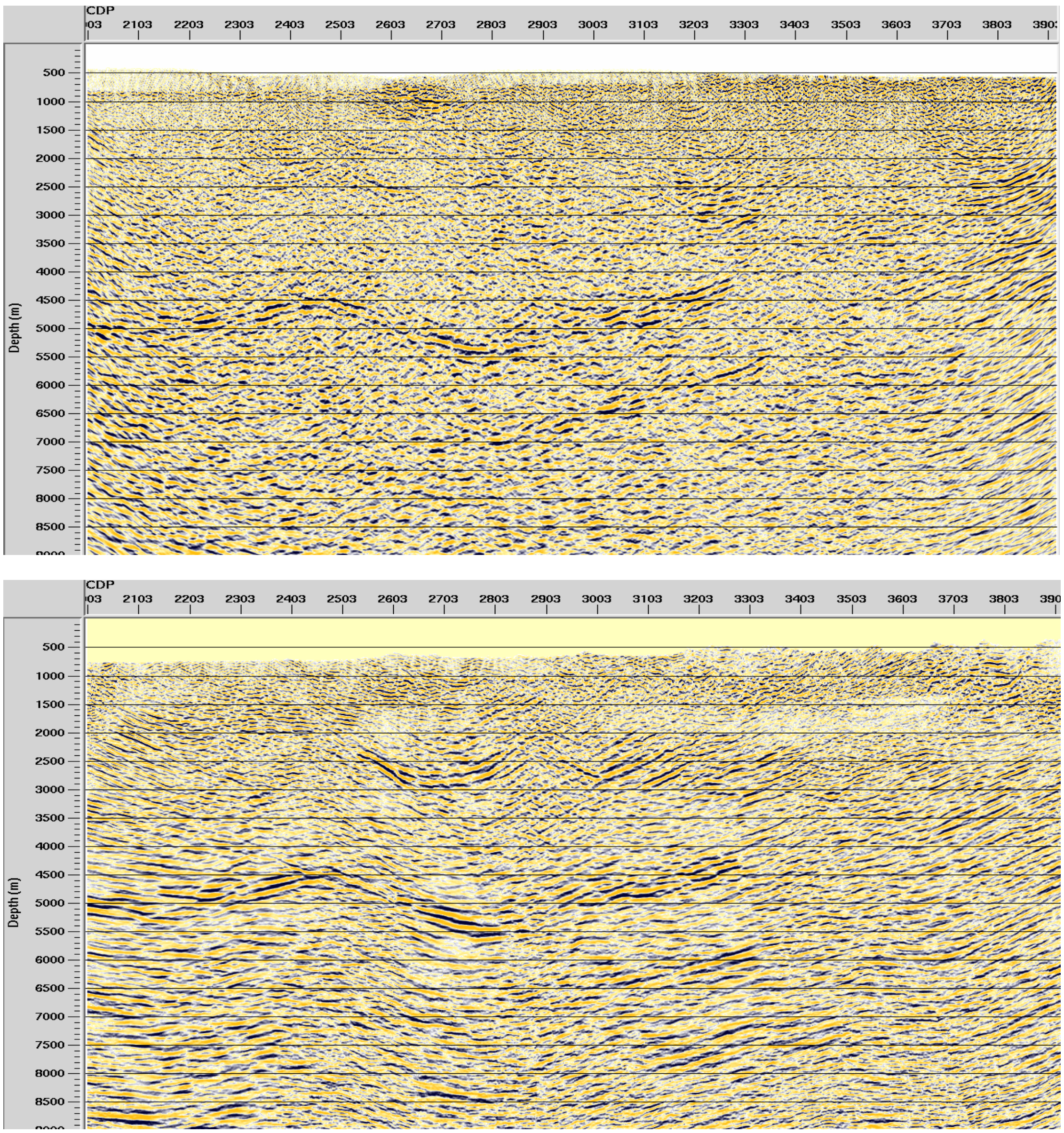

Figure2: Application to a real dataset in Oman: Kirchhoff PSDM (top), Gaussian Beam PSDM (bottom).

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