Simultaneous Joint Inversion of Seismic and Gravity Data for Long Offset Pre-Stack Depth Migration in Northern Oman *

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Abstract

The problem of data-driven velocity model building for depth-imaging applications is approached from the point of view of simultaneous joint inversion of separate geophysical domains. For this purpose a general formulation of the joint inversion problem is provided. The method is then applied to a real (long offsets) seismic dataset from Omani thrust-belt where seismic travel-time residuals (first-break and Common Image Gather residuals) are jointly inverted with gravity data (in the form of Bouguer anomaly) for improving velocity model building and the corresponding depth-domain seismic image.

Introduction

Effective depth imaging through migration can be achieved only if a precise estimate of interval velocity in depth is available. The definition of a reliable velocity model for depth imaging is a difficult task especially when sharp lateral and vertical velocity variations are present. The problem becomes even more serious when the seismic data are noisy giving little chance to extract useful velocity information from the data. Geologic models can provide a guide to the velocity model building and data integration with other geophysical methods can be extremely important. Several different approaches to geophysical data integration were proposed in the past but in a very few cases the data integration problem has been handled in terms of simultaneous joint inversion of geophysical data. No applications to date, however, attempted the simultaneous joint inversion of non-seismic geophysical data and pre-stack seismic migration residuals for the improvement of seismic images in depth domain.

Formulation of the Joint Inverse Problem

A brief description of the formulation of the Joint Inversion (JI) problem in the restricted case of the JI of only two domains is provided below. The same approach can be extended to three (e.g. seismic-gravity-EM) or more domains (De Stefano and Colombo, 2006). We define an expanded model vector:

$$m = [\ m_1\ /\ m_2\ ]$$

where m_1 and m_2 are, respectively, models of two different domains (e.g. seismic velocity and density or seismic velocity and resistivity). The objective function for Joint Inversion is:

$$\phi(\mathbf{m},\mathbf{a},\mathbf{b},\mathbf{c}) = \sum_{k=1}^{N} a_k \mathbf{r}_k^T \mathbf{C}_{D,k}^{-1} \mathbf{r}_k + \sum_{k=1}^{N} b_k \left\| \xi_k(\mathbf{m}_k) \right\|^2 + \sum_{k=1}^{Nl} c_k \left\| \psi_k(\mathbf{m}) \right\|^2$$

where the first term is the weighted sum of data squared errors (a_k are weights chosen by the user, while $C_{D,k}^{-1}$ is the inverse data covariance matrix for the *k-th* domain). The second term is the weighted sum of different regularization terms, one for each domain (b_k are weights chosen by the user and ξ_k is a generic regularization function). The third term is the weighted sum of different kind of cross-parameter constrain terms between different domains (c_k are user defined weights, ψ_k are linking functions among parameters and N_l is the total number of links used); vectors **a**, **b** and **c** are composed respectively of weights a_k, b_k and c_k, k=1,2,…,N.

The term ψ_k is composed by functions imposing the structural similarity among models and/or terms linking the physical properties among parameters (e.g. empiric or analytic functions like the Gardner's equation linking P-velocity and density, or user-defined functions derived from logs). The structural similarity among models is imposed by the following cross-gradients function generalized to a 3D case:

$$\left| \mathbf{t}(x,y,z) \right|^2 = \left| \nabla m_1(x,y,z) \times \nabla m_2(x,y,z) \right|^2$$

where m_1 and m_2 are two models (e.g. velocity and density or velocity and resistivity). Joint inversion is carried out minimizing in a least-square approach the objective function with respect to the multi-parameter model vector.

Depth Imaging of Thrust-Belt Data (Northern Oman)

A seismic line was acquired in 2003 over a frontier-area complex thrust-belt environment in Northern Oman where little a-priori geological knowledge was available. The acquisition involved the use of long offsets (up to 25,000m) with the purpose of improving S/N and deriving an improved seismic image for the deep model, carbonate section. Gravity measurements were taken every 490m.

Seismic data were initially processed in time domain using well-established techniques such-as tomographic static calculation (i.e. tomostatics), multi-window deconvolution and state-of-the-art residual statics and denoising algorithms. The pre-processed data were then provided for the depth-imaging phase. Gravity measurements were processed in a robust and standard processing approach involving (among others) the calculation of terrain corrections to a suitable distance (e.g. 40km) from the measurement points and gravity reduction with a constant density of 2.500 kg/m^3.

A grid-based model parameterization was adopted. The seismic velocity and density grids were different allowing larger model cells for the gravity method for deeper layers (consistent with the expected decay of the gravity field) and by allowing additional lateral padding in the density model for taking into account border effects. The input data used for the joint inversion consisted of Bouguer anomaly, first breaks at all offsets and Common Image Gather (CIG) residuals of the post-migrated domain.

PSDM - Joint Inversion Workflow

The velocity model building was performed since the first iteration by applying the simultaneous joint inversion of first-breaks (i.e. turning ray tomography) and the Bouguer anomaly residuals. This provided a long wavelength solution of the velocity field ranging from detailed near-surface velocity determinations to macro-velocity determinations for the model section below the maximum penetration of the long offset turning rays. The gravity method was critical at this stage in extrapolating the velocity determinations to depth.

Further refinement of the velocity model for depth migration was performed by interpreting geologically consistent horizons, determining post-migration residuals along them and performing joint inversions in conjunction with gravity (i.e. CIG residuals and gravity). The horizon-based joint inversion proceeded in a layer stripping approach from top to bottom of the model (Figure 1).

The observed gravity was sensitive to density distributions in the model located approximately between surface to about 4 km depth. The portion of the velocity model deeper than 4 km was therefore finalized using seismic data alone. The obtained depth image (Figure 2) was verified by a nearby well, which confirmed depth and position of the imaged deep carbonate structure at CDP position ~ 761 and 6,500m depth.

Conclusions

The Joint-Inversion velocity model building workflow shows various advantages over traditional approaches. Some of these are:

1) The simultaneous use of gravity data with first breaks (i.e. in the phase of turning ray tomography) provides extended depth resolution to what can be achieved from the use of the first breaks alone: from the first iterations one can solve for the macro velocities describing the whole model.
2) Gravity data are equally sensitive to low and high-density distributions whilst turning rays are more sensitive to high-velocity zones. This means that seismic-gravity joint inversion is able to retrieve near surface velocity inversions that would not be obtained by first break tomography alone.

3) In case of poor S/N ratio of seismic data, gravity can provide an important contribution to the velocity determination problem (noisy seismic cannot).
4) The inversion problem becomes less non-unique and converges more rapidly toward the correct solution (velocity model building takes many less iterations and it is more reliable).

Acknowledgements

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Reference Cited

De Stefano, M., and D. Colombo, 2006, Geophysical modeling through simultaneous Joint Inversion of Seismic, Gravity and Magnetotelluric data: SEG 76th Annual Meeting, New Orleans, Research Workshop, Integration of Seismic and Electromagnetic Measurements.

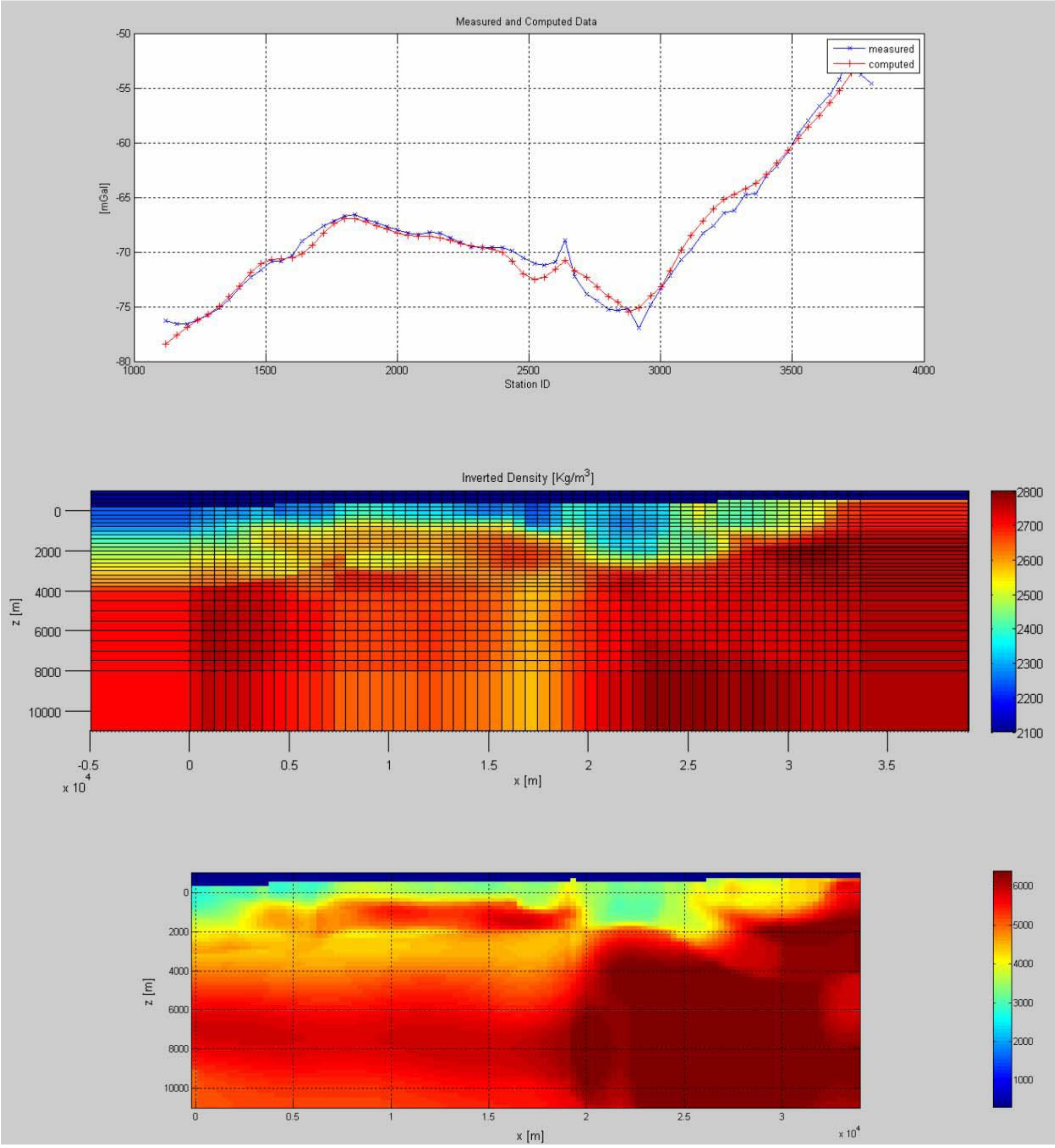

Figure 1. Velocity model building through Joint Inversion of seismic and gravity data, Northern Oman. Top: fit of calculated gravity response versus the observed gravity field at the final joint inversion iteration (r.m.s. residual = 0.66 mGal). Middle: density distribution deriving from joint inversion at final iteration. Bottom: final velocity field in depth from joint inversion.

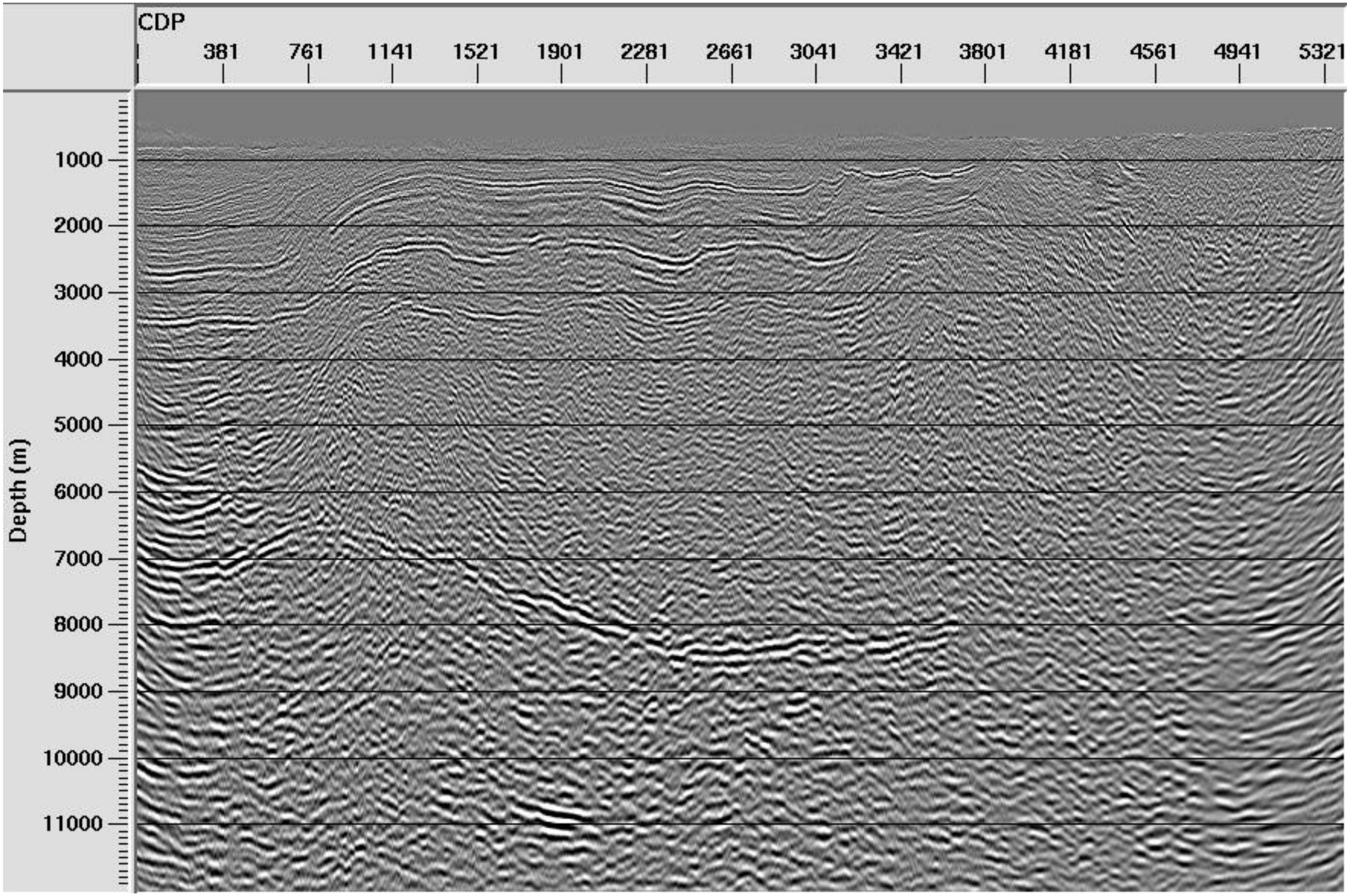

Figure 2. Pre-stack depth migration from simultaneous seismic-gravity Join-Inversion workflow (DP elev. = 1000m a.s.l.).