Potential field migration for rapid interpretation of gravity gradiometry data

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Summary

We introduce potential field migration for the interpretation of gravity gradiometry data. This method is based on a direct integral transformation of the observed gravity gradients into 3D images of density contrasts in the subsurface which can be used for real-time imaging or as a priori models for subsequent 3D regularized inversion. Potential field migration is very fast and stable with respect to noise because it reduces the downward continuation of the migration field to the calculation of an analytical function everywhere in the subsurface. Hence, potential field migration avoids the numerical instabilities of other imaging methods that are based on downward continuation. We present a case study for the interpretation of gravity gradiometry data acquired in the Nordkapp Basin in the Norwegian sector of the Barents Sea. We compare the results obtained from potential field migration with those obtained from 3D regularized inversion.

Introduction

Gravity gradiometry data can provide an independent measure of 3D density distributions, or for this purpose it has become an essential dataset commonly integrated into exploration workflows. The advantage of gravity gradiometry over other gravity methods is that the data are extremely sensitive to localized density contrasts within regional geological settings. Moreover, high quality data can now be acquired from either air- or ship-borne platforms over very large areas for relatively low cost. Amongst many applications, this makes the method ideally suited to delineating salt structures in hydrocarbon exploration, and for detecting kimberlite pipes in diamond exploration.

The interpretation of gravity gradiometry data using 3D regularized inversion has been discussed in a number of publications (e.g., Li, 2001; Zhdanov et al., 2004). A variety of fast imaging techniques related to Euler decomposition have also been developed (e.g., Fedi, 2007); most of which are based on the superposition of analytical responses from specific sources. These imaging methods estimate the positions and some parameters of the sources based on attenuation characteristics. In this paper, we develop a different approach to imaging, which we base on the idea of potential field migration, originally introduced by Zhdanov (2002). The concept of the migration was developed for seismic data (e.g., Schneider, 1978; Berkhout, 1980; Claerbout, 1985). It was demonstrated by Zhdanov (1988, 2002, 2009) that this concept could be extended to electromagnetic and potential fields as well.

Potential field migration is based on a special form of downward continuation of the potential field or one of its gradients. This downward continuation is obtained as the solution of the boundary value problem of Laplace's equation in the lower half-space, in which the boundary values of the migration field on the Earth's surface are determined from the observed data. It is important to stress that potential field migration is not the same as analytic continuation, because it transforms the potential field and does not attempt to reconstruct the true potential field within the Earth. However, the migration field does contain remnant information about the original source distribution, which is why it can be used for imaging.

Potential field migration of gravity fields and their gradients

The potential field migration of gravity fields was first described by Zhdanov (2002). This was introduced as the application of the adjoint gravity operator to the complex intensity of the observed gravity field. If the profile of observed gravity fields coincides with the horizontal axis ($z = 0$), then the adjoint gravity operator is equivalent to analytical continuation of the complex conjugate of the observed gravity fields in the lower half-space. The adjoint gravity gradient operator is equivalent to the derivative of the analytic continuation of the complex conjugate of the observed gravity gradients in the lower half-space. The main difference between migration of the gravity gradients and the gravity fields involves the additional differential operation in the former, while the latter requires analytic continuation only. From a physical point of view, the migration fields are obtained by moving the sources of the observed fields above their profile. The migration fields contain remnant information about the original sources of the gravity fields and their gradients, which is why it can be used for imaging.

There is a significant difference between conventional downward analytical continuation of the observed gravity fields and their migration. The observed gravity fields and their gradients have singular points in the lower half-space associated with their sources. Hence, analytic continuation is an ill-posed and unstable transformation as the gravity fields and their gradients can only be continued down to these singularities (Strakhov, 1970; Zhdanov, 1988). On the contrary, the migration fields are analytic everywhere in the lower half-space, and migration itself is a well-posed, stable transformation. However, the direct application of adjoint operators to the observed gravity fields and their gradients do not produce adequate images of the density contrasts. In order to image the sources of the gravity fields and their gradients at the correct depths, an appropriate spatial weighting operator needs to be applied to the migration fields. We use the integrated sensitivity of the gravity fields or their gradients with respect to the density contrasts (Zhdanov, 2002).

Case study – Nordkapp Basin

The Nordkapp Basin is located in the Norwegian sector of the Barents Sea, and is an intra-continental salt basin containing over 30 salt structures. The salt is of an Early Permian age, and was mobilized by Early Triassic sedimentation. Tertiary uplift and erosion removed nearly 1400 m of Cretaceous and younger sediments (Neilsen et al., 1995). The petroleum plays are mainly salt-related traps. Only two wells have been drilled in the basin; the Pandora well which was a discovery, and the Uranus well which terminated inside salt. Recent discoveries in other nearby basins suggest potential for further hydrocarbon discoveries within the Nordkapp Basin (Hokstad et al., 2009).

Improved seismic imaging changed the structural interpretations of the salt diapirs from what were initially thought of as wide salt stocks with vertical flanks to more complex geometries with broad diaper overhanging narrow stems. Much of the exploration risk associated with these structures result from distortions in the seismic imaging, and subsequent ambiguity of the salt isopach. A full tensor gradient (FTG) survey was acquired over the Nordkapp Basin with the intent of delineating salt geometry. The Tertiary rocks in the area have a density between 2.30 and 2.38 g/cm3. The salt diapirs are characterized by negative density contrasts relative to them; hence they can be identified from the gravity gradiometry data. In this paper, we focus on results for the Obelix prospect in the southwest of the basin; particularly the G2, F1 and F2 salt diapirs shown in Figure 1.

We performed 2D migration along nine profiles of g_{zz} and g_{zx} data so as to obtain 2D images of the density contrasts, shown in Figure 2. For comparison, we show the same cross-sections obtained from 3D regularized inversion in Figure 3 (Wan and Zhdanov, 2008). We can see the same typical negative density contrasts in both of these figures. Figure 4 is the 2D gravity migration along profile A-A'. This is co-rendered with the corresponding seismic depth migration image. Salt diaper F2 is clearly identified in both the gravity and seismic migration images.

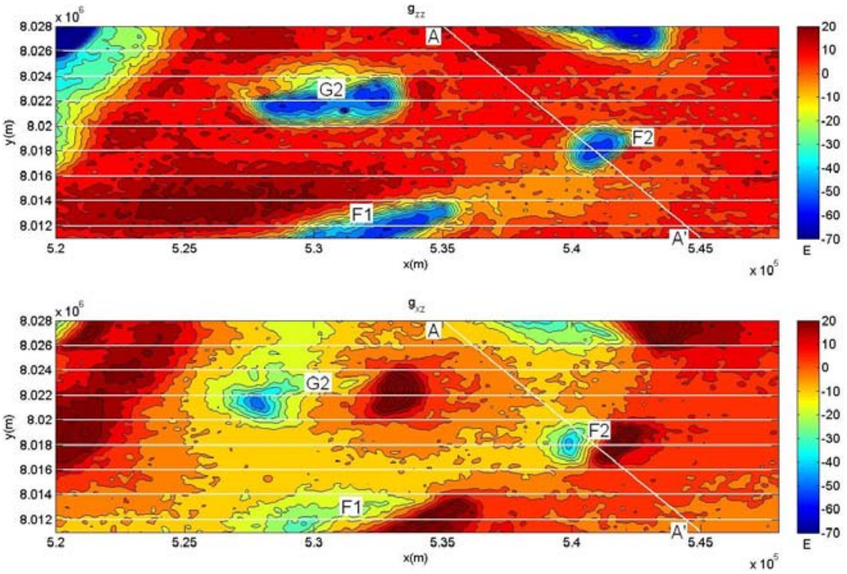

Figure 1. *g_{zz} and g_{xz} survey data for the Obelix prospect. Salt diapirs G2, F1 and F2 are shown. Profile lines are also marked in white.*

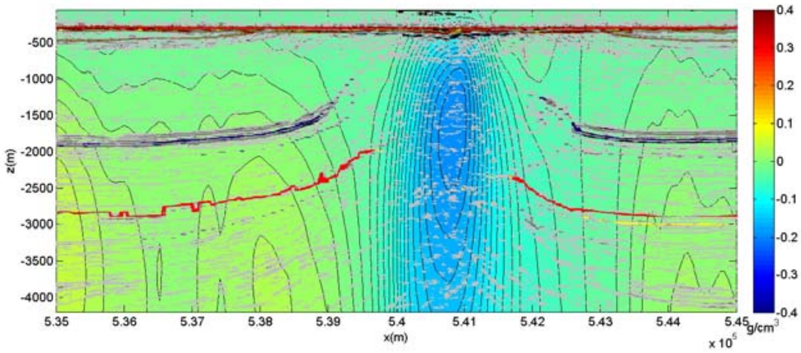

Figure 2. *2D gravity migration image along profile A-A' co-rendered with the corresponding seismic depth migration image.*

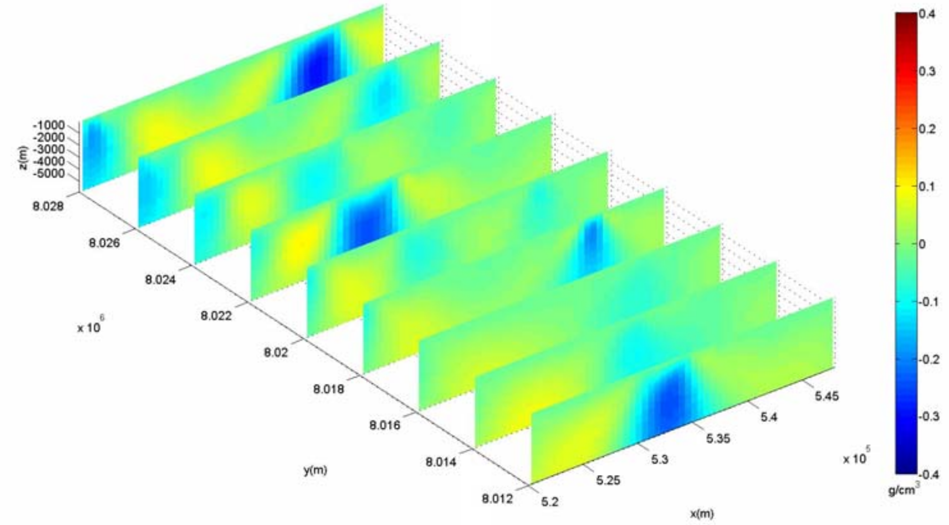

Figure 3. *2D vertical cross-sections of density contrasts obtained from 2D gravity migration of each profile.*

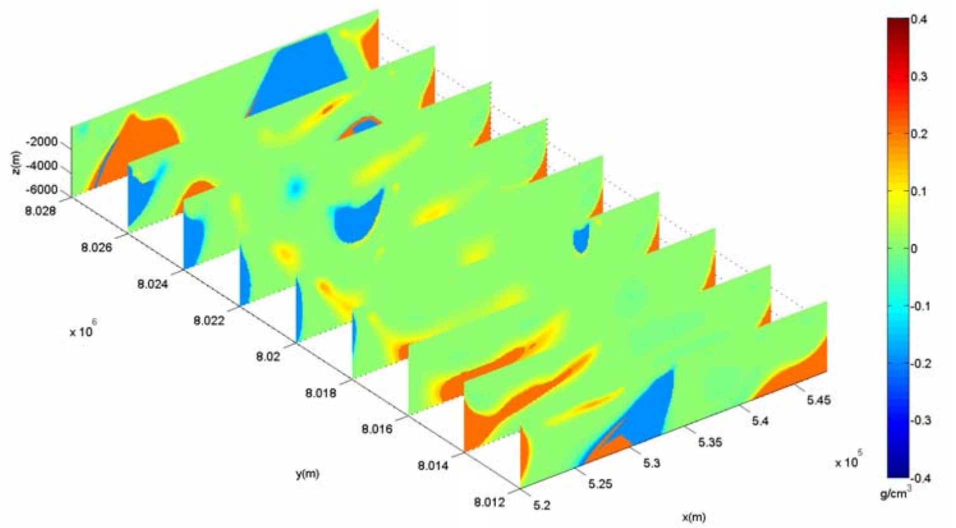

Figure 4. *2D vertical cross-sections of density contrasts obtained from 3D regularized inversion with focusing (Wan and Zhdanov, 2008).*

Conclusions

We have introduced a new method for interpreting gravity gradiometry data based on potential field migration. This method is based on an integral transformation of the gravity gradiometry data into an image of density contrasts in the subsurface. Potential field migration is very fast and stable, and can be used for real-time imaging or for preparing a priori models for 3D regularized inversion. Currently, the method is implemented for the migration of 2D profiles of gravity gradiometry data. We have demonstrated this with a case study for salt mapping from the Nordkapp Basin in the Barents Sea. The method can be naturally extended to 3D, as well as to magnetic fields and their gradients. This constitutes our future research activities.

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References

Berkhout, A.J. [1980] *Seismic Migration*. Elsevier.

Claerbout, J.F. [1985] *Imaging the Earth's Interior*. Blackwell.

Fedi, M. [2007] DEXP: A fast method to determine the depth to the sources of potential fields: *Geophysics*, **72**, L1-L11.

Li, Y. [2001] 3D inversion of gravity gradiometer data. *SEG International Exhibition and 71st Annual Meeting*, San Antonio.

Hokstad, K., Myrlund, E.A. and Fotland, B. [2009] Salt imaging in the Nordkapp Basin with electromagnetic data. *AAPG 3-P Arctic Conference and Exhibition*, Moscow.

Nielsen, K.T., Vendeville, B.C., and Johansen, J.T. [1995] Influence of regional tectonics on halokenesis in the Norkapp Basin, Barents Sea. *AAPG Memoir*, **65**, 413-436.

Schneider, W.A. [1978] Integral formulation for migration in two and three dimensions. *Geophysics*, **43**, 49-76.

Strakhov, V.N. [1970] Some aspects of the plane gravitational problem (in Russian). *Izvestiya Akademi Nauk SSSR Fizika Zemli*, **12**, 32-44.

Wan, L. and Zhdanov, M.S. [2008] Focusing inversion of marine full-tensor gradiometry data in offshore geophysical exploration. *SEG International Exhibition and 78th Annual Meeting*, Las Vegas.

Zhdanov, M.S. [1988] *Integral Transforms in Geophysics*. Springer-Verlag.

Zhdanov, M.S. [2002] *Geophysical Inverse Theory and Regularization Problems*. Elsevier.

Zhdanov, M.S. [2009] *Geophysical Electromagnetic Theory and Methods*. Elsevier.

Zhdanov, M.S., Ellis, R.G. and Mukherjee, S. [2004] Regularized focusing inversion of 3D gravity tensor data. *Geophysics*, **69**, 925-937.