Automatic modelling and inversion for dykes from magnetic tensor gradient profiles - recent progress

Des FitzGerald (Intrepid Geophysics), Horst Holstein (University of Aberystwyth), Clive Foss (Commonwealth Scientific and Industrial Research Organisation (CSIRO))

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Abstract

We have developed an optimization method for automatic dyke delineation from observed magnetic and gravity gradient traverse data. A non-linear least squares algorithm is used to find model dyke parameters that best fit the computed gradient tensor data to the observed data. The eigen-system of the observed magnetic gradient tensor data is used to provide starting model dyke parameters for an iterative non-linear least squares solver. This greatly enhances the ability of the solver to find a plausible dyke model for matching observed and synthetic tensor gradients locally. The method works well on synthetic examples. Multiple surveys using a Full Tensor Magnetic Gradient (FTMG) signal instrument from IPHT, have been made in Southern Africa. A real case study with remanence, taken from the Platreef near Pretoria, shows that the gross observed gradient features can be recovered by our procedure, but the residuals in the gradient fit hint strongly at the need for more complex dyke models. There is more directly inferable structural geology in this tensor signal than can be found in a conventional TMI signal.

Introduction

New generation geophysical magnetic sensors trigger the need for optimally finding a "dyke" to explain some anomalies in an observed signal. In particular, a system developed by IPHT (The Institute for Photonic Technology) and Anglo American/DeBeers which has been in test for over 4 years and has flown more than 20 different surveys (Rompel 2009).

Historic Context

Phillips (2010) takes a broader look to the problem of estimating dip for both the gravity and magnetic sheet and contact. The extension to a profile of gravity observations is novel and also well overdue. He examines the use of the analytic signal, local wave-number, extended Euler and the multiple-source Werner deconvolution methods. He concludes this last method is the more useful, especially when there is more than one source interfering with the measured signal. The issue of resolving multiple sources when the observed signal is a scalar measurement such as TMI of vertical component of gravity, is rarely attempted. The estimation of dip from a profile of observed data in our experience, is the hardest part to manage, as it is related to the local phase and particularly sensitive to noise in the signal. For the scalar case, the estimated dip is an apparent one and is confined to the plane of the profile.

Gradient / Tensor Developments

With the advent and more general availability of gradiometry systems, we are able to measure all the curvature gradients directly. The challenge is to modify and extend the pioneering concepts and other similar ideas to embrace the tensor gradient signal and to remove as many of the simplifying assumptions while deducing rapidly, the best geological 2D model to explain the anomaly. Holstein et.al. (2011) gives the theory and shows simple test cases for improving the geological resolving power from measured profiles. The immediate benefits include an unambiguous measure of the local strike directly from the eigen vectors, for the magnetic case, the ability to estimate whether the body has any remanent magnetization, and if so, what is the remanent magnetic vector that best fits the observed signal. The depth to the "hot-spot" of the anomoly is also better constrained. This "hot-spot" is a top dead centre point with many estimated measures, namely position (X,Y,Z), thickness, depth, susceptibility and in the case of magnetics, the local field vector. The current strategy adopted uses 3 parts. First is to quickly locate the "anomaly" using a simple moving window with all tensor components. The second involves a local best fit for the unit vector of the inducing magnetic field (see Figure 1). This does include the possibility of pole reversals from the current International Geomagnetic Reference Field (IGRF). Finally, the position, thickness, depth to top and overall height are fitted, using a modern non-linear, bounded vector solver (see Figure 2).

The question of being able to resolve the thickness / susceptibility product for thin bodies was also addressed, and while the new method is relatively insensitive, the bounded non-linear solver produces realistic values.

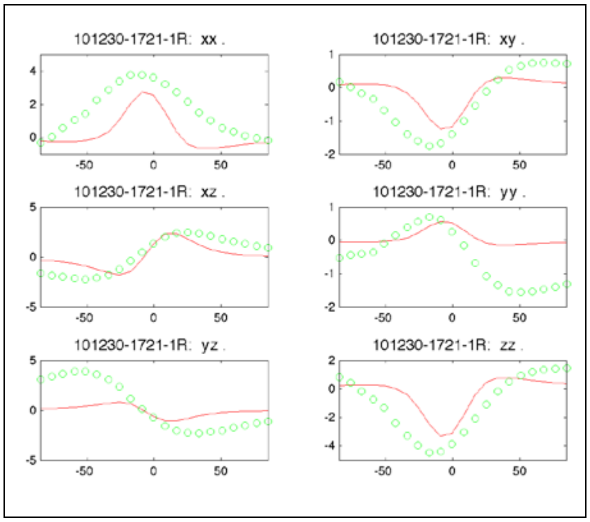

Fig 1 - Fit after preconditioning (real data)

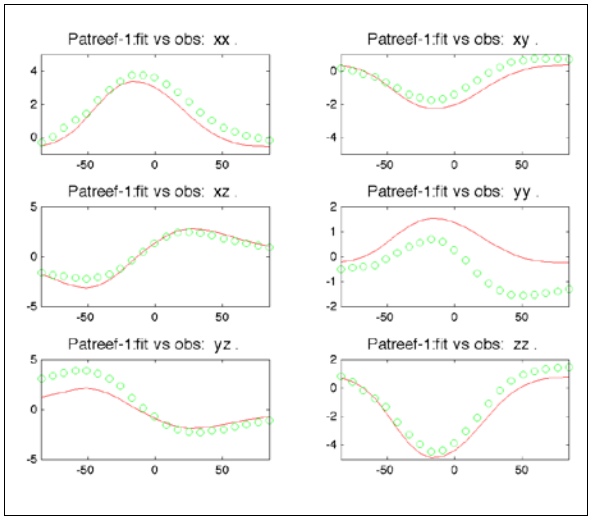

Fig 2 - Fit at end of optimization (real data)

Geometry Representation

When using variants on this "Naudy" method, many simple 2D bodies are assembled and proposed to explain the signal. This is true for scalars and tensors. Prior to this study, fundamental algorithmic work has been completed on gravitational and magnetic models of dykes and veins treated as two-dimensional geophysical structures on the scale of the survey , see Holstein (2009 & 2011). Thus, we now have the ability, using a faceted approach of representing any anomaly by a thin sheet of uniform surface density or magnetization in arbitrary orientation. We derive elsewhere the analytical zero thickness limit for the gravity potential while maintaining finite total mass. We compare the anomalies computed by the new formulae to those of corresponding finite thickness targets and to the finite difference estimates of the field and field gradient obtained from numerically differentiated thin-sheet potentials. In both cases a second order rate of approach to the limit is observed, verifying the correctness of the new formulae. The elegance and speed is enhanced by using a 2D infinite body formula for the primary solver.

Updated "HOT-SPOT" Approach

A localised approach to explaining the observed anomaly within the immediate vicinity of the survey line is appropriate, as the influence of the body now falls off with the 4th power when considering magnetic gradients.

Just two local facets in the local area are used to find the best fit in terms of location, strike, dip, thickness and susceptibility.

In a process that is sometimes described as "worming", these solutions are then resorted into a reduced and consolidated collection of thin planar sheets, spanning many lines. This is done by matching, with suitable tolerances, the tops and tails of the discrete bodies, projected from their own profiles, half-way to the next line. The now consolidated and fully connected, thin sheet representation of either the contact or a dyke, retains the individual solutions from each "hot-spot".

These worms are then exported via an ASCII, CSV file. This separates the initial definition of 2D bodies from the context of creating a comprehensive 3D geology model to explain all the other parts of creating a geological 3D model. An example of this method of specifying dyke geometrics is in Table 1(see end of this paper).

Another current development is to add formal support for generalized Dykes to GeoModeller or any other geology building technology. Both a geometric and geophysical sound way has been incorporated into this modelling tool based upon importing the "worms".

The 3D geometry takes the "hot-spot" values and translates them to contact points and "foliation" or dips. This then allows an implicit 3D function formulated to use co-krigging, with a cubic co-variance model and the mathematics of potentials, to create a parametric representation of the geological body.

Currently, the geophysical response of the dyke bodies is calculated quite independently of the "country" rock. A superposition of both responses is made and then that constitutes the estimated forward model of all of the geology elements.

Inversion Methodology

This is a vast topic that cannot be reviewed here, so it is assumed the reader has the necessary background to follow some issues that are considered different. The question here is how to measure a miss-fit with a FTMG signal that uses all elements of the signal. Very few workers have attempted this feat, and to date, it has been considered that just two or so tensor components are sufficient in a joint inversion scheme. It is possible to get somewhere using this approach, in a local spatial sense (Pratt 2009). We consider that all practical observed surveys suffer from a significant noise due to errors in the rotations (Euler Angles) from the measurement system. This is due to the lack of a compensation scheme designed to minimize this class of error in an FTG signal.

Therefore, this error spills over into a major difficulty in inversion until and when it can be shown that the signal has been compensated for attitude errors correctly. Being gradients, this effect can easily account for 1 nT/m in all the measured components near a body that you would want to invert over.

Also, as mentioned, once rotations are used formally in the mathematics, this needs to be adopted in the inversion strategy as well. The separation of concerns into amplitudes and rotations, is a close friend of the invariant properties of the tensor. This means any least squares miss-fit equations that are to be minimized, while doing an inversion, could be formulated with this in mind. The approach that has emerged involves both angular terms, positional terms, thickness/susceptibility product all grouped in a mis-fit vector. Each term is also constrained by reasonable admissibility bounds. The solver generally sorts out the position, then the dip in operation. The main convergence just takes 5 to 10 iterations for any one simple body.

CASE STUDY – Mogalakwena Platinum Mine

In mid 2008, the largest full tensor magnetic gradient survey to date was flown over the Mogalakwena Platinum Mine near Mokopane, South Africa. There were 21 separate flights with each flight collecting around 2 gigabytes of 1 kHz (high rate) data, for a total of 351 lines. The survey was flown with a towed bird at 40 m terrain clearance and 100m line spacing. This initial processing and presentation work was reported by FitzGerald (2010).

Integrating Geology and Geophysics in a common 3D model

A 3D geology model, working at the geology group level, was built from the surface geology, the digital terrain grid and a simplified section. The shuttle radar (SRTM) digital terrain grid is used to provide the surface relief. There is considerable vertical relief (300m) in this area. The observed FTMG signal is being compared to the predicted thin-body responses from the model. Faults, dykes and topographic effect associated with the Platinum reef outcrop are the immediate concern. The other magnetic features such as the Hornfels, magnetite cumulates and then remanence may follow as the model evolves. It proved difficult to easily capture the 3D dykes that are clearly seen in the survey results, for the purpose of integrating them into the geological model. The dykes are curving, plunging and weathered at the surface. It is easy enough to get an approximation of the position, but the requirement is to have a linked set of points that not only lie along the line but also include an estimate of the thickness and a plunge. For this reason, the automatic method described earlier has been developed to help easily and rapidly create the starting dyke model overlays. There are many situations where the dyke swarms can completely dominate the magnetic observed signal and it is felt that the new method will adapt in a practical way to aid rapid model building.

Discussion Points

For this case study, it is reasonable to assume that the signal from a fault or dyke could be modelled by a thin sheet with no thickness in a geometrical sense, but a thickness for the geophysical signature. This greatly simplifies the process of modelling these features. The dykes often require a variable thickness. The use of a linked list of hot-spot points allows for variable thickness along the line.

The intersection of the curving dyke sheet body with the surface digital terrain model is plagued by issues to do with smoothing. In common with most 3D geology contacts, it is the DTM surface that contributes most to the irregular line of the dyke in plan. The rugged terrain has not contributed much to the FTMG signal in this case. This is a surprising result as near surface effects contribute most of the signal. Mostly this is because the ridges are non-magnetic. All of the techniques discussed are available for practical use or project work, as they are incorporated into Intrepid and GeoModeller.

Conclusions

The 3D geology model was built to capture the terrain, group level geology units and the faults, dykes and outcropping contacts. A "Naudy" like procedure has been developed to find by inversion, a starting set of contacts, dips and thicknesses to define more formally, geological Dyke bodies. This procedure was adapted from an existing rapid depth to body solver for TMI. The adaption now covers primarily magnetic tensors but is also suitable for gravity tensor gradiometry. With the assumption of 2D bodies, the magnetic field reversals that are remanently frozen in the rock crystals in the dykes, also help date the units and sort out rock relationships.

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3D Dykes Data from naudyd. File teisa_dykes.csv											
Map Projection AUSTRALIAN_MAP_GRID_ZONE_53/AGD84											
	Dyke X	Y	Depth	Thickness	Height	Strike	Plunge	Susceptibility	Similarity	Mag Azimuth_	Mag Inclination
Dyke1	559725.97	6682805.52	1088.8	1173.7	5868	0	133.3	-0.0019	2.42	6.2	-62.8
Dyke1	559733.14	6682401.19	310.9	393.1	1965	180	48	-0.0002	2.48	6.2	-62.8
Dyke2	561598.33	6682795.23	308.8	393.1	1965	0	73.2	-0.0002	2.24	6.2	-62.8
Dyke2	561791.74	6682402.73	44.8	131.6	658	180	102.9	0.00009	1.62	6.2	-62.8
Dyke2	561801.36	6682000.08	390.7	471.7	2358	180	106.7	0.00036	2.49	6.2	-62.8
Dyke2	561731.69	6681602.33	7.2	91.4	457	0	103.9	0.00003	2.84	6.2	-62.8
Dyke3	557092.62	6682799.15	305.9	393.1	1965	0	67.7	-0.00421	1.46	6.2	-62.8
Dyke3	557023.22	6682405.43	50.9	131.6	658	180	99.9	-0.00019	1.69	6.2	-62.8
Dyke4	558189.47	6682798.75	187.7	273	1365	0	117.5	-0.00022	2.06	6.2	-62.8
Dyke4	558147	6682401.62	105.6	189.6	948	180	73.2	-0.00014	1.82	6.2	-62.8
Dyke4	558227.68	6681990.11	896.2	978.1	4890	180	118.2	-0.0073	2.12	6.2	-62.8
Dyke5	565334.8	6682799.66	141.9	227.5	1137	0	36.6	0.00033	2.61	6.2	-62.8

Table 1 - Sample of systematic way to specify complex dyke geometries and properties. This was generated by a Naudy tool. This format can also be directly imported into GeoModeller.

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