The Use of Geological and Petrophysical Information to refine the Model Objective Function of Geophysical Inversion Problems

by

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Abstract

Preface

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Glossary

This glossary uses the handy `acroynym` package to automatically maintain the glossary. It uses the package's `printonlyused` option to include only those acronyms explicitly referenced in the LaTeX source.

MOF Model Objective Function

GIF Geophysical Inversion Facility

Acknowledgments

Thank those people who helped you.

Don't forget your parents or loved ones.

You may wish to acknowledge your funding sources.

Chapter 1

Introduction

In all cases these are first guesses at what needs to be in each section more or less detail need to be added.

1.1 Research Motivation

In mineral exploration there are many form of information that can be used to determine the location of a deposit. These can be divided broadly into geological and geophysical data. Geological data refers to the actual study of the rocks in a region through surface samples, bore holes, and a understanding of how rock units interrelate under the surface. Geophysical data refers to the recovery of the value of some field above the ground that will be related to some discriminative property of the deposit. For exploration to be as effective as possible, we need to find ways of combining the geological and geophysical information. One of the major tools in using geophysical data to create geologically significant interpretations is inversion.

The overarching goal of geophysical inversion is to recover distributions of physical properties in the ground to aid in mineral exploration. To be useful to this end the distribution of the physical property (the geophysical model) needs to both fit the geophysical data and match existing geological interpretations.

Since geophysical inversions are by their nature non-unique (because of data uncertainty and there being many more model parameters than data) more a priori information needs to be added to provide a model that matches the geology of a deposit. Much work has been done to create a mathematical framework to allow the inclusion of geological and petrophysical information into geophysical inversions (for example Li and Oldenburg (1996)). However, an area where more work can be done is the creation of tools to take the petrophysical and geological data in the forms that are generally provided and create constraints that can be used in inversions.

The research in this thesis will attempt to do exactly that, provide new tools in an integrated framework that will allow the incorporation of non-trivial a priori information into geophysical inversions. As stated above, the inclusion of a priori information in inversions is not novel. Many researchers before me have used the mathematical framework to add geological and petrophysical information to inversions (Lelievre (2009),Phillips (2002) among other (still need to add more)).

In addition, in Williams (2008) Williams develops a software package to create constraints for inversions. What is novel in this thesis is the creation of a suite of tools (created by me and the rest of the Geophysical Inversion Facility (GIF) group) to make the incorporation of geological and petrophysical data into GIF inversions easy even in non-trivial cases. The interface by which a priori information can be incorporated has been much updated from Williams (2008), and tools to incorporate new forms of data into inversions have been added.

1.2 Literature Review

1.3 Types of Data Included

Chapter 2

Solutions to Including Geological Maps Into Mode Objective Functionsl

It is often the case that geological information is provided in the form of geological maps either cross section or plan view. These maps are of particular use since they provide a great deal of information over their entire surface. Cross sections can provide a great deal of information at depth and constrain as whole region often within the center of a target of interest. While plan view maps cannot provide information at depth they can constrain the entire surface of an inversion. Constraining the surface of an inversion is of particular interest since the sensitivity of the data to the top cells is particularly high which can lead to artifacts on the surface. For the next section the plan view model is from the El Poma case study and the cross section model is from TKS specifically the map from (Harder et al., 2006a)

Below in point form is the method I use to incorporate a pixel map

2.1 Loading Images into GIFtools

- load image into the GIFtools format (Figure 2.1)
    - determine image format

- load image using MATLAB utilities
- convert image into .png style representation for faster computation
- using .twf file (world file) assign location and spacial resolution to the image
- assign a legend assigning pixel RGB values to geological unit
- assign topography (either number or GIFtools TOPOdata item) for visualization
  * In the case of a cross section image, instead of topography, information for the location of the cross section in 3D or 2D space is required (Figure 2.2)

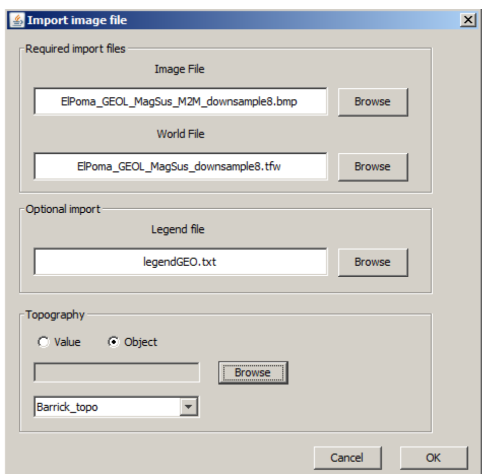

Figure 2.1: GUI for importing plan view image

Storing a map as a GIFtools object allows it's use in several ways. Notably it allows the integration of the map with models and data, allowing figures overlaying the map and data or model and allowing interpretation of the data or model with direct reference to the map (Figure 2.3).

2.2 Creating a Pixel Map Legend

Continuing on in the process of making a geological constraint

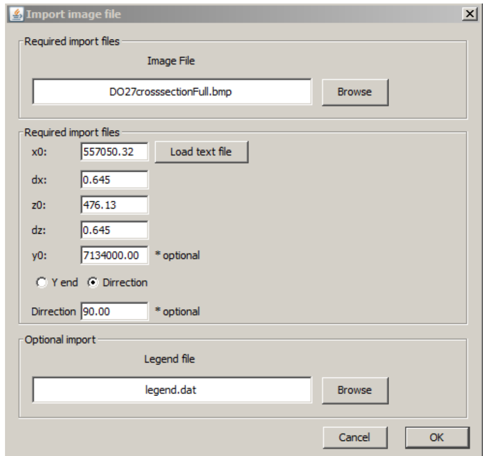

Figure 2.2: GUI for importing cross section image

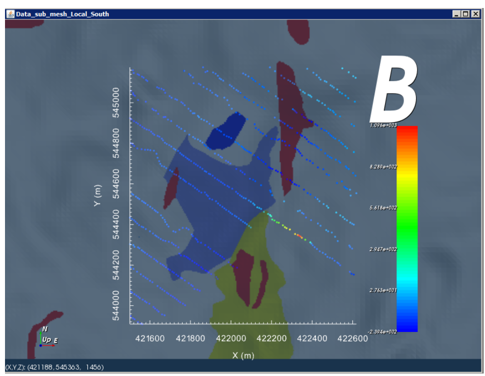

Figure 2.3: Example of magnetics data being viewed with a map overlaid

- find the geological unit represented of each pixel
  - in the .png style format as stored in MATLAB an image consists of an “image’ field’, a matrix of integers, and a “map” field, which maps the image matrix to RBG value triplets
  - Each RGB triplet is compared to the legend that was provided when the image was loaded. A map field entry is considered to represent a geological unit if all three components of the RGB triplet are within a provided tolerance of any entry in the legend

- now that we have a relation of entries in the map field to geological units in the legend, we can assign a geological unit to each pixel in the original image simply by applying the new geological map to the image field.

2.3 Making a Geology Model from Map

2.3.1 Plan View

- provide active model
  - this simultaneously provides a discretized topography for the map to lay along and also a mesh (GIF 3D tensor or OcTree)
- provide some form of depth information
  - Thickness, a certain amount of depth below topography at each point will be assigned the geological unit at each
  - Depth, the map will be used to assign a geological unit down to a fixed depth across the while model
  - Surface, if you provide another surface below topography the cells between topography and the other surface will be assigned
- crop all pixels that extend outside of the mesh or that represent the background geological unit
  - the cropping greatly speeds up the process and makes it require much less RAM
  - this also means that in the event of a mistake with coordinates the process ends almost instantly since there are almost no pixels to process
- Finally the geological model is created
  - We determine which cell of the mesh each pixel is in, including those cells below each pixel to account for thickness

- each cell is assigned a geological unit based on the mode of the geological value of each pixel
- the geology definition which will allow the assignment of physical properties to each geological unit

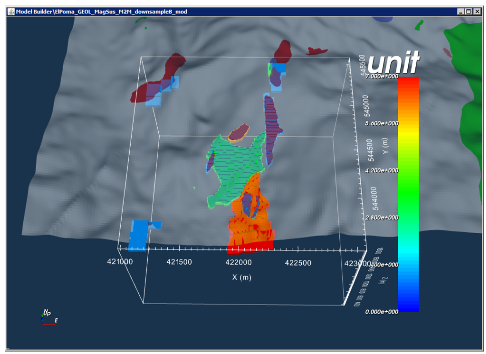

Figure 2.4: Example of a geology model created from a map with the map overlaid

2.3.2 Cross Section

The cross section case follows much the same procedure with a few exceptions. An imported cross section map is shown overlaid on a 2D mesh in Figure 2.5. Notably no parameter for the vertical extent is needed. The other notable exception is that mesh that is used is a GIF 2D mesh. The result is shown in Figure 2.6.

A 2D Geology model can be used to create constraints for a 2D inversion, it can also be used to add constraints to a 3D inversion as well. After the 2D geology model is created from the cross section map it can be inserted into a 3D mesh (GIF 3D tensor or OcTree) given a starting and ending position or a starting position and a direction Figure 2.7,Figure 2.8.

2.4 Making Constraints for an Inversion

The conversion from geological models to inversion constraints in mediated by the geology definition of the geological model. In

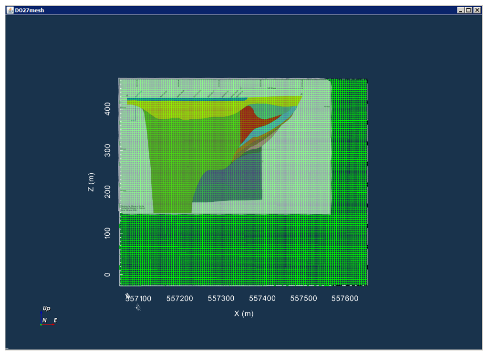

Figure 2.5: Example of a 2D mesh with the map overlaid

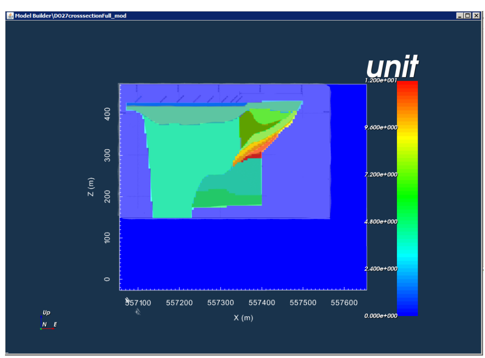

Figure 2.6: Example of a 2D geology model created from a cross section map with the map overlaid

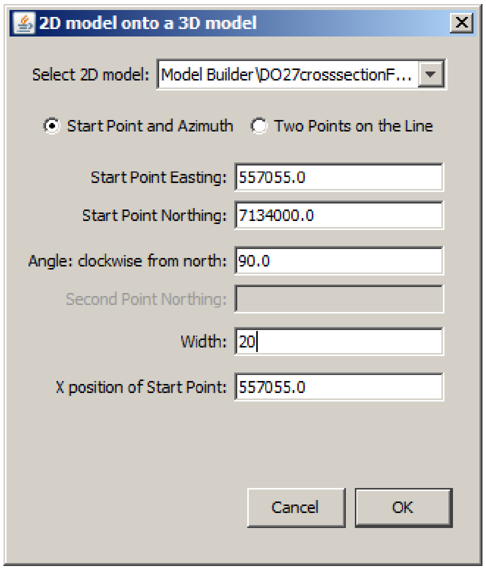

Figure 2.7: GUI for adding a 2D model to a 3D model

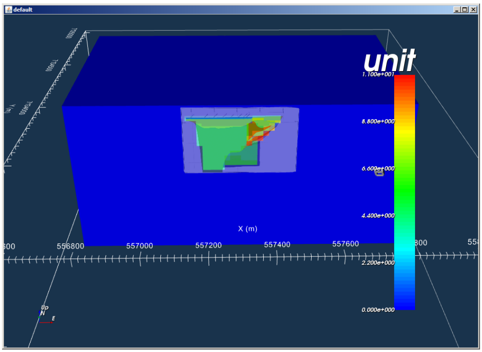

Figure 2.8: Example of a 2D geology inserted into a 3D model with the map overlaid

Chapter 3

Case Study #1 El Poma

In all cases these are first guesses at what needs to be in each section more or less detail need to be added.

3.1 General Overview of El Poma

Two anomalies. North and South.

Magnetic Anomaly. Remanent magnetization is clearly present

3.2 Overview of Deposits

3.3 Discussion of the Geophysical Data Given

Magnetics. Missing a corner over the southern anomaly

3.4 What Information is Available

Bore Hole -susceptibilities, much lower than the recovered model sue to remanent effects being present

Plan View Geological map -with susceptibility surface samples marked, in addition to surface samples and geological units, we also have a system of thrust faults over top of both anomalies.

Surface Samples -susceptibility, same as marked on map but includes many samples from outside map area as well -also have nine remanences measured with direction and K_n

3.5 Synthetic Model

TODO: Create Model - make iso-surface of Kris's result. Determine property from parametric inversion. show model discuss its creation - magnetization direction

show its fit to the field data

3.6 Blind Inversion of the Synthetic Model

Show results. Discuss how magnetization direction puts anomaly away from actual location

3.7 Determination of Magnetization Dirrection

Correlation of Vertical and Total Gradients of Half RTP field Dannemiller and Li (2006)

taking core direction from MVI result could also use parametric inversion and MVI sensitivities to provide more constraint.

apply recovered direction to the anomaly direction in MAG3D could apply anomalous dirrection locally to anomaly

3.8 Creation of Constraints

3.8.1 α coefficients

For El Españole (north south fault) we can lower the α_x to allow for greater discontinuity in general in that direction. Cannot account for other faults without rotation objective function.

(show result)

3.8.2 Reference Models

Most work to be done here.

Borehole: provides susceptibilities need to convert into effective susceptibilities. Assuming uniform magnetization direction this is not complicated. Choose a K_n and multiply susceptibility by that (maybe with +1). For MVI I need to apply the dirrection of magnetization as well. Either from the truth of the synth model from direction of the nearest remanent sample or from the bulk rem mag direction. (show reference model) (show result)

Map: geological units have susceptibilities attached. Have to convert into effective susceptibilities. Might extend the map cells down below surface to be less weighted (show reference model) (show result)

Surface Samples: used to make susc values for geological units. Can also be used for reference model directly but this provides less cover of the surface. Perhaps use surface samples in white region instead of just applying nothing. (show reference model) (show combined map and SS reference model) (show result)

(show Combined result)

3.8.3 Weighting matrices

smallness: using some measure of confidence in the measures decrease in cells with reference model specified to force the result to approximate the reference model. In case that map is extended down I will lower the W_s as model cells are further below the surface. (show smallness weight model) (show result, compare to result without)

smoothness: to spread the model values away from where they are specified I can increase the smoothness weights in the vicinity of cells with specified reference models. (show face weight model) (show result, compare to result without) The other application of smoothness weights is to allow discontinuities on the faults (perhaps with increased smoothing on either side of the fault). Need to experiment with orientations of the faults. (show result)

(show Combined result)

3.8.4 Bounds

Also useful for forcing model values to be near the specified reference model while allowing for uncertainty in our phys prop value (show result)

3.8.5 L_pL_q weights

allows the more fuzzy placement of faults. By rotating the Model Objective Function (MOF) we can place them in arbitrary directions. The trouble is having more than one fault in more than one orientation. Can't currently apply to MVI inversions, can still apply on MAG3D inversions (show result)

Need to determine if showing the field example is worthwhile at this point and how to bring it into the narrative

Chapter 4

Case Study #2 TKC

In all cases these are first guesses at what needs to be in each section more or less detail need to be added.

4.1 Overview of Deposits

Kimberlite Complex Two anomalies, focusing on the southern one (DO27)

Magnetic Anomaly. Remanent magnetization is likely present but largely in the dirrection of the earth's field Density Anomaly.

4.2 Discussion of the Geophysical Data Given

Magnetics: Three different surveys
Gravity: Ground mag (of usable but dubious quality), Gravity Gradiometry airborne data

much EM as well, outside the scope of this Master's Thesis

4.3 What Information is Available

Great deal of borehole data with rock units at each depth We also have Phys Props at various points along the holes. We can either mean these across the facies or take the value of each facies that the specially nearest the the measured result.

From the borehole data we also have created a surface model of each of the units again from the borehole data, we have graphical cross section maps

4.4 Synthetic Model

TODO: Create Model - Already mostly done - we have a surface from the borehole data and we can use the parametric inversion to assign the properties. show model discuss its creation - magnetization direction

show its fit to the field data

4.5 Blind Inversion of the Synthetic Model

Show results. show how model is insufficiently compact and over estimates the amount of kimberlite

4.6 Determination of Magnetization Dirrection

Correlation of Vertical and Total Gradients of Half RTP field Dannemiller and Li (2006)

taking core direction from MVI result

apply recovered direction to the anomaly direction in MAG3D could also use parametric inversion and MVI sensitivities to provide more constraint.

could apply anomalous dirrection locally to anomaly

In any case the result will be very similar to the earth's field in the location

4.7 Creation of Constraints and Types of Data

Extensive Boreholes with rock units Multiple cross sections (crreated from said bore holes) Multiple data types to cluster

4.7.1 α coefficients

not much with alphas to be done here given that we don't expect discontinuity in any one particular dirrection.

4.7.2 Reference Models

Most work to be done here.

We can create a reference model from the phys prop results from the borehole data. Perhaps we should only use some of the boreholes so that we have a more realistic amount of information than in a fully drilled example. We have two ways of applying phys prop measures to inversion and might use both. Also using K_ns to improve degree of fit between phys prop measures and effective susc recovered properties (show reference model) (show result)

with sufficient boreholes we could make a incorrect surface that approximates the "true" model used. Use this with parametric inversion for reference model (show reference model) (show result)

using clustering between density and mag (and conductivity and chargeablity) to create clusters, populate each cluster with a value either the mean value of the cluster or a parametric inversion and use as reference (show reference model) (show result)

use cross section from Harder et al. (2006b) perhaps extend away from line and down weight (show reference model) (show result)

(show Combined result)

4.7.3 Weighting matrices

smallness: using some measure of confidence in the measures decrease in cells with reference model specified to force the result to approximate the reference model. In case the cross section is extended down I will lower the W_s as model cells are further away from the cross section (show smallness weight model) (show result, compare to result without)

smoothness: to spread the model values away from where they are specified I can increase the smoothness weights in the vicinity of cells with specified reference models. (show face weight model)

with sufficient boreholes we could make a incorrect surface that approximates the "true" model used. Use this with parametric inversion for reference mode,l put lower weights along this surface. (show face weight model)

using clustering between density and mag (and conductivity and chargeablity) to create clusters, populate each cluster with a value either the mean value of the cluster or a parametric inversion and use as reference (show result)

(show result, compare to result without)

(show Combined result)

4.7.4 Bounds

Also useful for forcing model values to be near the specified reference model while allowing for uncertainty in our phys prop value. Since we have more statistical info on the (show result)

Need to determine if showing the field example is worthwhile at this point and how to bring it into the narrative

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Appendix A

Supporting Materials

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