Geological and Petrophysical Information in 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.

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 forms 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 study of the rocks in a region through surface samples, bore holes, and an understanding of how rock units interrelate under the surface. Geophysical data refers to recovered measurements of some field that will be related to some physical property that will aid in the understanding of the deposit. For exploration to be as effective as possible, we need to find ways of integrating 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 spacial 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), *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 usable constraints that can be applied to 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. 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) 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 colleagues in 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

- **?** and Li and Oldenburg (1998)
  - recovers a model regularized by smallness and smoothness. Reference models and weighting matrices allow for the incorporation of geological information, making smallness and smoothness more or less significant in different parts of the model
- Li and Oldenburg (2003)
  - extends the method by also implementing bounds that can be specified for each model cell.

The methods above demand smoothness of the recovered models. There have been many attempts at allowing discontinuities in recovered models

Chapter 2

Including Geological Maps in Model Objective Functions

It is often the case that geological information is provided in the form of geological maps in either cross section or plan view. Such maps are particularly useful since they provide a great deal of information over their entire surface. Cross sections can provide information at depth and constrain a whole region often within the center of a target of interest. Plan view maps do not provide information at depth, but they do constrain the entire surface of region being inverted. Constraining the surface of an inversion is of 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 TKC, specifically the map from (Harder et al., 2006)

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

2.1 Preprocessing Images

(for the purposes of building a geological model the regions on the map have been replaced with solid colours)

2.2 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)

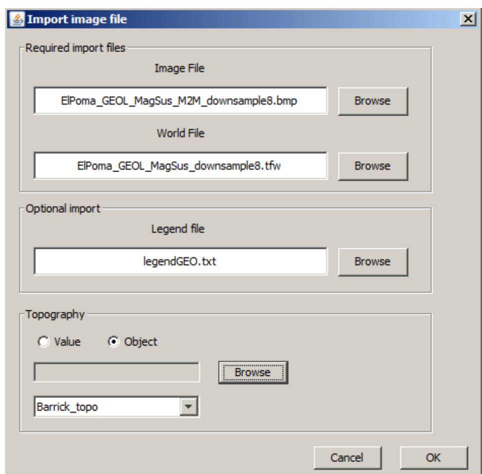

Figure 2.1: GUI for importing plan view image

Storing a map as a GIFtools object allows its 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).

2.3 Creating a Pixel Map Legend

Continuing on in the process of making a geological constraint

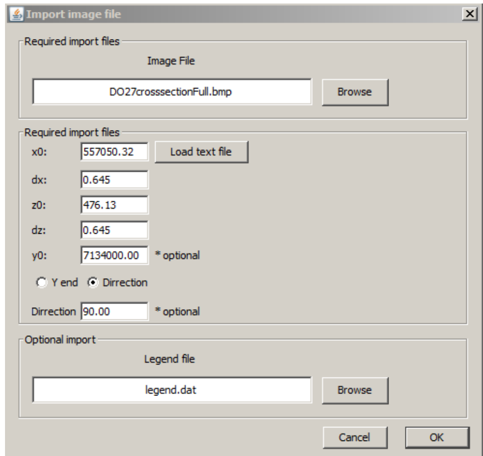

Figure 2.2: GUI for importing cross section image

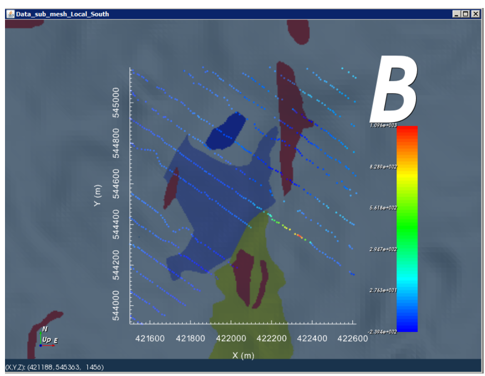

Figure 2.3: Example of magnetics data being viewed with a map overlaid

- 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.

2.4 Making a Geology Model from Map

2.4.1 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 computer memory
  - furthermore, in the event of a mistake with coordinates the process ends almost instantly as there are few 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 values of each pixel

  * The mode is used since each cell will be a particular unit. Since the property being mapped onto each cell is a geological unit, interpolation between the units will not provide the desired result

– the geology definition which will allow the assignment of physical properties to each geological unit

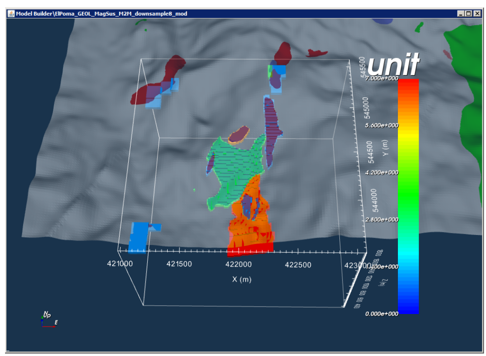

Figure 2.4: Example of a geology model created from a map with the map overlaid

2.4.2 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.

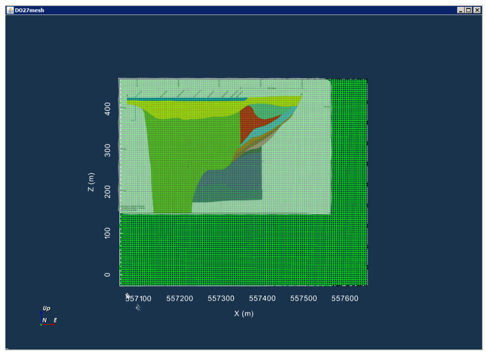

Figure 2.5: Example of a 2D mesh with the map overlaid

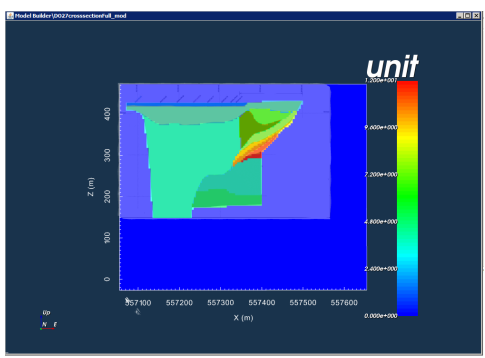

Figure 2.6: Example of a 2D geology model created from a cross section map with the map overlaid

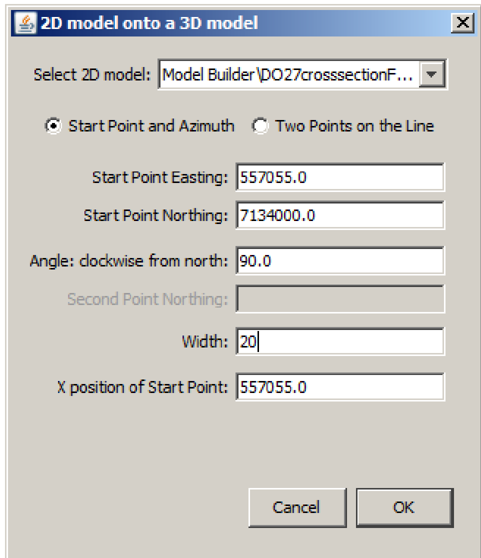

Figure 2.7: GUI for adding a 2D model to a 3D model

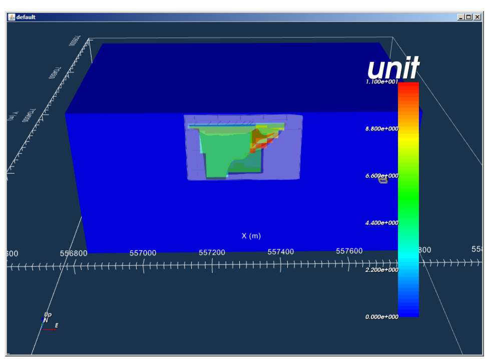

Figure 2.8: Example of a 2D geology inserted into a 3D model with the map overlaid

2.5 Making Constraints for an Inversion

The model that has been created is a geology model. That is, a model in which each cell represents a given geological unit. To be able to convert this model into a constraint for a geophysical inversion some link between between the geology and the petrophysics needs to be provided.

The link is stored in what is called a geology definition. In GIFtools this takes the form of a lookup table that contains information of a particular geological unit's property, lower and upper bounds, and optionally the smallness weight associated with each unit.

Using the geology definition we can convert a geology model that has information about the spacial distribution of geological units but not of their physical properties into constraints that are usable by an inversion. In the figures below the geological definition came from surface measurements of magnetic susceptibility within each geological unit. Figure 2.9 is an example of a geology definition in the GIFtools GUI.

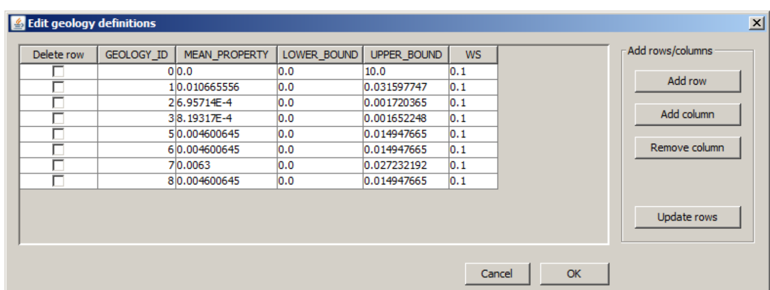

Figure 2.9: Example of a geological definition as displayed in the GIFtools GUI

Once the geology definition is provided, we can use the Combine Model Dialog (Figure 2.10) in Model Builder to create a reference model and bounds. In this case the resolution of conflicts is trivial as there is a single source of information. Less trivial examples of the creation of reference models and bounds will be discussed later. The resulting reference model is shown in Figure 2.11.

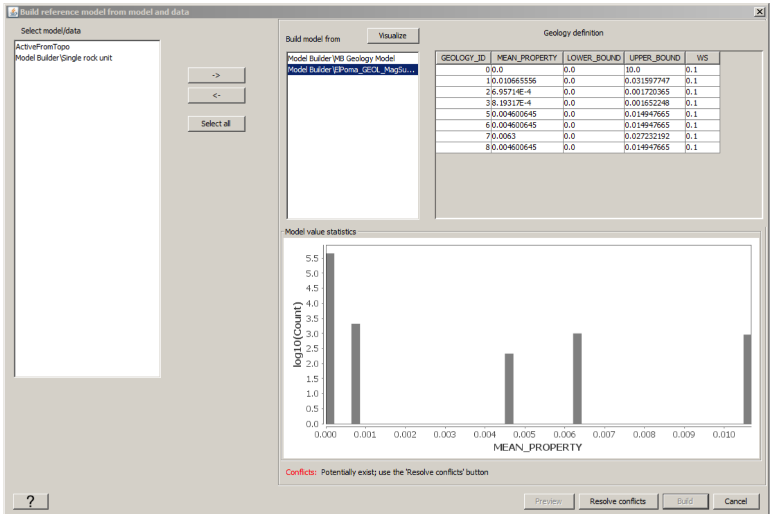

Figure 2.10: Example of a typical combine model dialog for a reference model

2.6 Inputing Fault information from Geological Maps

Another piece of information that can be in geological maps are fault locations. Again in the context of El Poma the map provided a whole complex of thrust faults as shown in the un-doctored map in Figure 2.12

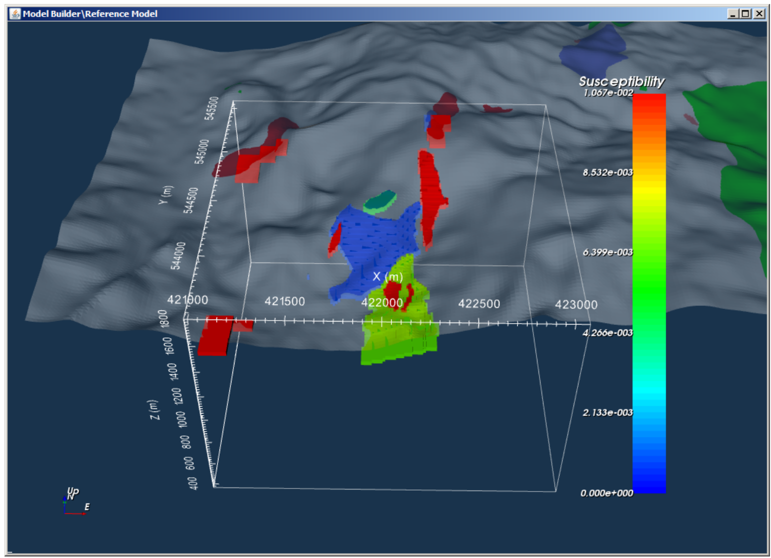

Figure 2.11: Example of a reference model created from a geological map

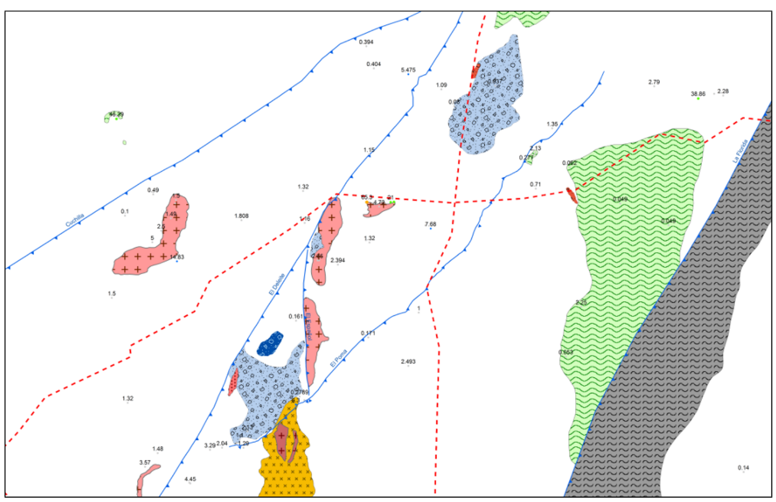

Figure 2.12: The El Poma map with fault lines (blue lines with barbs) included

The method used to insert faults into an inversion is as follows

- Determine the end points of the fault.
  - GIFtools makes this easy by reporting the location of the cursor in the data viewer allowing you to find the location (including elevation) of a point along the fault
- Using the locations provided create a box of a desired thickness (default value is based on the core mesh size) that includes the ends points of the fault and dips in the desired direction
- faces within this box are assigned a new value that is provided in the GUI Figure 2.13

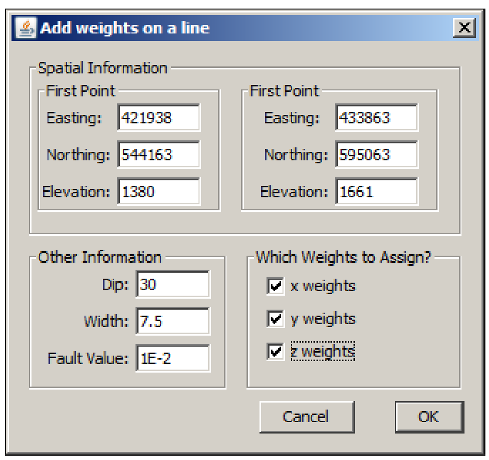

Figure 2.13: The GUI for the creation of fault weights

This process can be done multiple times to create non-trivial fault complexes as shown in Figure 2.14

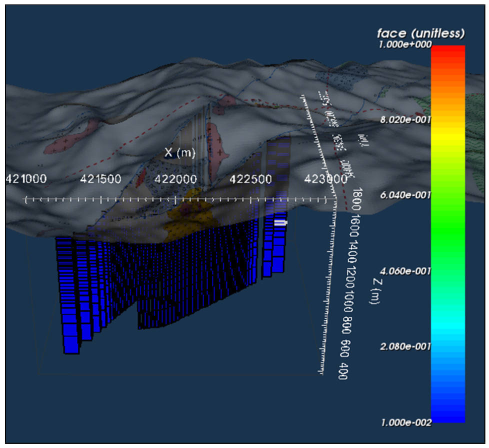

Figure 2.14: An example of fault weights that can be created with GIFtools

In this section I have shown the creation of constraints that are compatiple with GIF inversion codes. I have created these constraints from multiple types of map (Cross Section and Plan View) and have used different pieces of information from these maps (geological units and fault locations).

Chapter 3

Case Study #1 El Poma

3.1 General Overview of El Poma

3.2 Overview of Deposits

3.3 Discussion of the Geophysical Data Given

3.4 What Information is Available

3.5 Synthetic Model

3.6 Blind Inversion of the Synthetic Model

3.7 Determination of Magnetization Dirrection

3.8 Creation of Constraints

3.8.1 α coefficients

3.8.2 Reference Models

3.8.3 Weighting matrices

3.8.4 Bounds

3.8.5 L_pL_q weights

Chapter 4

Case Study #2 TKC

4.1 Overview of Deposits

4.2 Discussion of the Geophysical Data Given

4.3 What Information is Available

4.4 Synthetic Model

4.5 Blind Inversion of the Synthetic Model

4.6 Determination of Magnetization Dirrection

4.7 Creation of Constraints and Types of Data

4.7.1 α coefficients

4.7.2 Reference Models

4.7.3 Weighting matrices

4.7.4 Bounds

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Appendix A

Supporting Materials

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