Geological and Petrophysical Information in Geophysical Inversion Problems

by

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Abstract

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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.

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Chapter 1

Introduction

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 the physical properties of the rocks 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 that produce exploration vectors to the target. 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 typically 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 must 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, 2001) among other).

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

- smoothly varying models
  - Li and Oldenburg (1996) 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.
- sharply varying models

- Last and Kubik (1983) instead of regularizing by smallness and smoothness, they regularize compactness, essentially demanding that the model be as small as possible while still fitting the data.
- Portniaguine and Zhdanov (1999) extends Last and Kubik (1983) by adding a minimum gradient support functional. It minimizes the gradient such that gradient values below a threshold do not contribute to the the objective function. Whereas values above the threshold all contribute equally. This allows for sharp boundaries and blocky models because once the algorithm determines a boundary as necessary to fit the data there is little to constrain the the physical property contrast across the boundary.
- Rudin et al. (1992) and Vogel and Oman (1998) Propose total variation, in other words the use of L_1 norms to regularize, instead of L_2 norms as in Li and Oldenburg (1996) and Li and Oldenburg (1998). Since minimizing L_1 norms promote sparsity, regularizing by them will have a comparable effect (blocky models with sharp boundaries) as the method used by Portniaguine and Zhdanov (1999).
  - Total variation has been used more specifically in the context of geophysical inversion, such as with Guitton (2012)
- Farquharson and Oldenburg (1998) also report ways of achieving sharp contrast by implementing non-L_2 norms such as Ekblom and Huber norms.
- Fournier (2015) implements a method of minimizing the general L_p (smallness) and L_q (smoothness) norms for any p and q (typically values between 0 and 2) allowing an inversion to recover compact or blocky models in different directions and amounts.

* models with dipping anomalies
  - Li and Oldenburg (2000) extends the method in Li and Oldenburg (1996) and Li and Oldenburg (1998) by rotating the model objective function to allow for linear features in the recovered model to be in a direction not in line with the mesh grid

- Lelièvre and Oldenburg (2009) generalizes the methods in Li and Oldenburg (2000) to the 3D case
- Chasseriau and Chouteau (2003) creates a very general method of acquiring anomalies of almost any shape by weighting the smallness term with a covariance matrix of the model, i.e. a matrix with the covariance of each cell versus every other cell in the model. The covariance matrix can be generated from bore hole or surface sample data or from a synthetic initial model. Depending on the covariance matrix, the inversion can be biased toward an anomaly of almost any shape.
- Guillen and Menichetti (1984) extends the method in last1983compact to minimize the moment of inertia instead of volume. By specifying an axis of rotation to determine the moment of inertia they put dip information into the regularization.
- Barbosa and Silva (1994) and Barbosa and Silva (2006) generalize the method even further allowing multiple axes of rotation. The second paper also describes a GUI to interactively test the fit of various axes of rotation.

• Stochastic Inversion

- Bosch et al. (2001) directly inverts for lithologies. Forward modeling of physical properties is done by a probabilistic relation of the physical property to the lithology. New lithology distributions are created using a pseudo-random walk. *A priori* information is included partial in the probabilistic model that links the lithology to the physical properties but also as the initial probability distribution of the lithology model.
- Guillen et al. (2008) implements the method described in Bosch et al. (2001) in 3D.

• Fuzzy C-Means:

- Paasche et al. (2006) uses FCM clustering of recovered models to derive membership functions of model cells in several clusters. The clusters are then used with *a priori* porosity data to create a likely porosity of each cluster and a porosity model is created from these results.

  - Sun and Li (2015) Instead of clustering after an inversion to achieve the effect of a cooperative inversion like Paasche et al. (2006), the authors use the FCM function as an extra term in the model objective function. This allows them to simultaneously invert slowness and density by linking them through the FCM clusters. It also allows them to guide the FCM cluster physical properties in a way that allows the introduction of petrophysical measurements of geological units.

- Implementations of Constrained inversion
  - Phillips (2001) Uses bore hole densities and susceptibilities to bound a gravity and a magnetic inversion
  - Farquharson et al. (2008) uses density bore holes to create a reference model for a gravity inversion. Shows the effect of having many bore holes versus only a few
  - Williams (2008) Easily the most extensive review of this subject. Creates a software package to integrate a phenomenal number of types of geological and petrophysical data. Uses these tools to make detailed susceptibility and density constraints
  - Lelievre (2009) discusses the use of surface sample and bore holes in constraining a synthetic example. He also goes into the use of orientation information of linear features as a geological constraint

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)

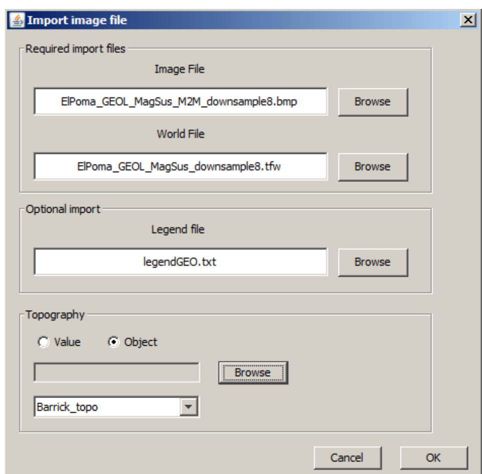

Figure 2.1: GUI for importing plan view image

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

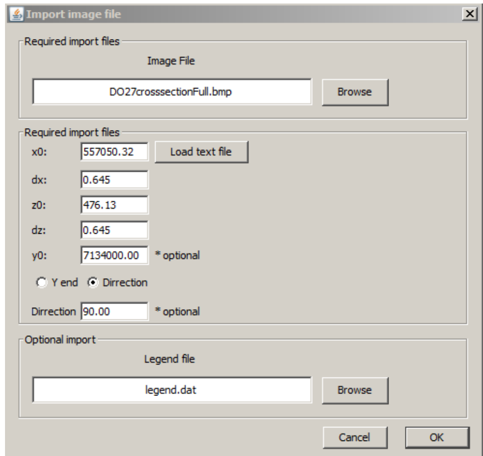

Figure 2.2: GUI for importing cross section image

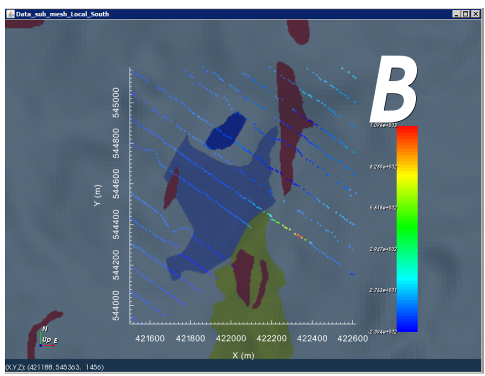

Figure 2.3: Example of magnetics data being viewed with a map overlaid

- 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

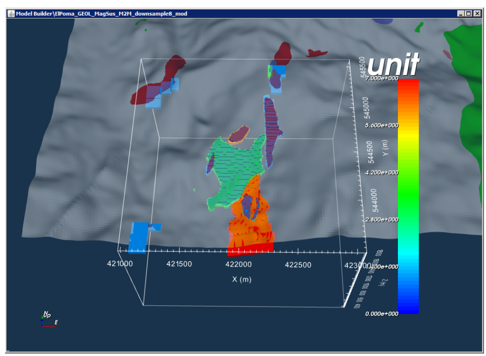

Figure 2.4: Example of a geology model created from a map with the map overlaid

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.

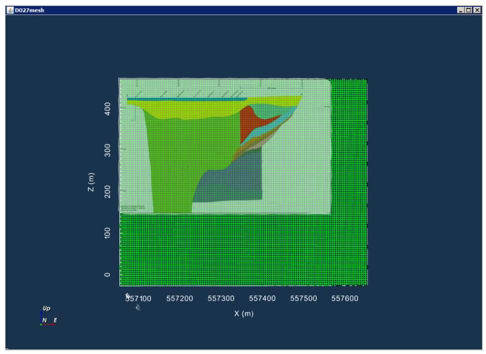

Figure 2.5: Example of a 2D mesh with the map overlaid

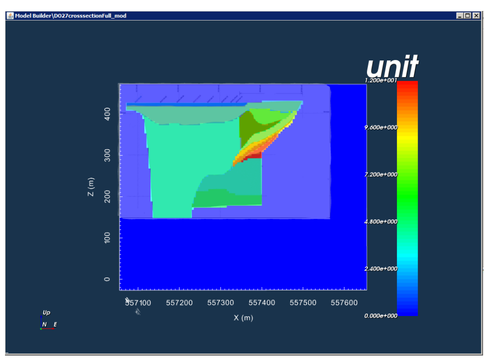

Figure 2.6: Example of a 2D geology model created from a cross section map with the map overlaid

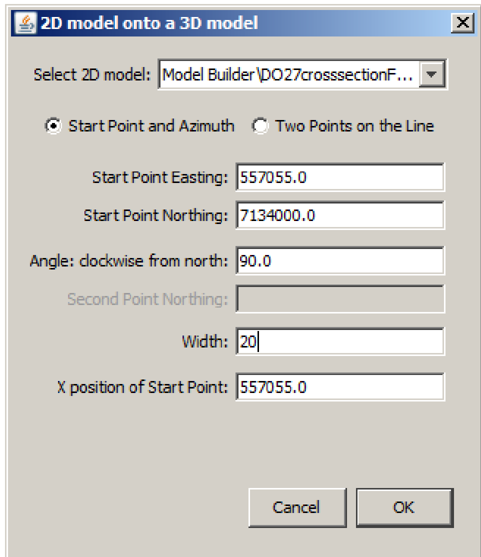

Figure 2.7: GUI for adding a 2D model to a 3D model

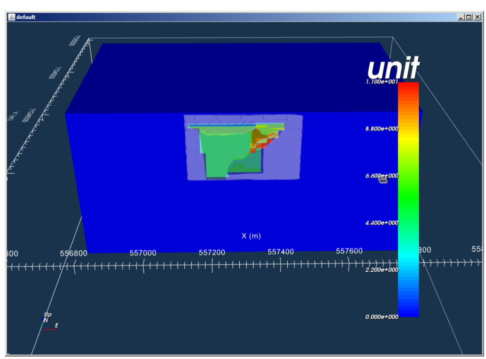

Figure 2.8: Example of a 2D geology inserted into a 3D model with the map overlaid

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.

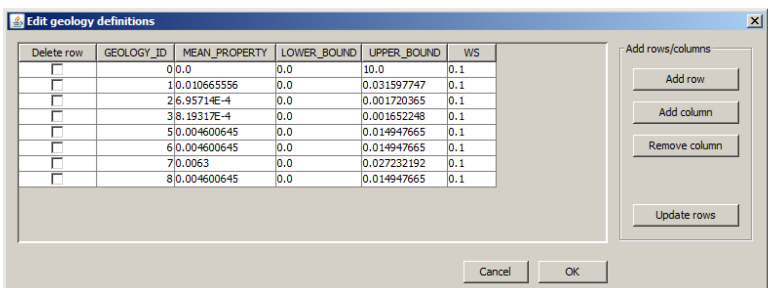

Figure 2.9: Example of a geological definition as displayed in the GIFtools GUI

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.

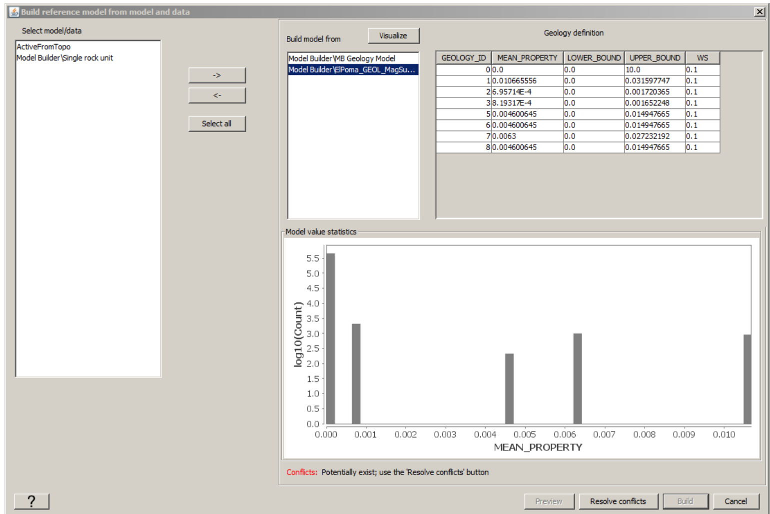

Figure 2.10: Example of a typical combine model dialog for a reference model

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

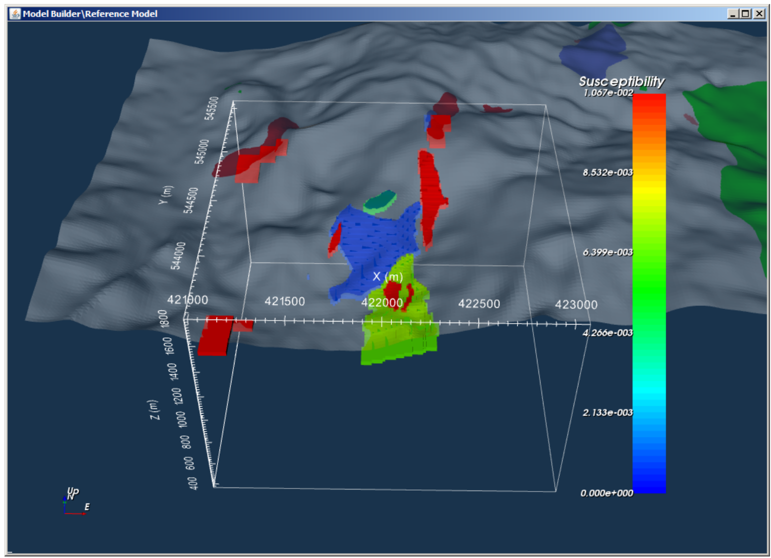

Figure 2.11: Example of a reference model created from a geological map

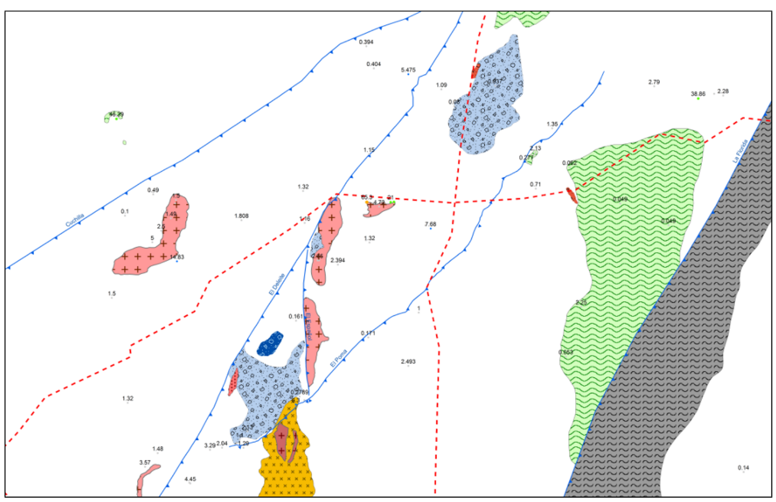

Figure 2.12: The El Poma map with fault lines (blue lines with barbs) included

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

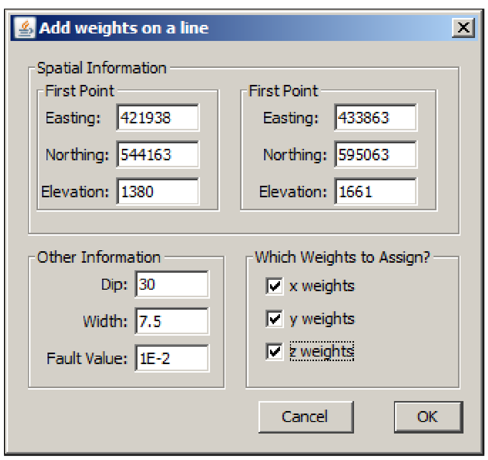

Figure 2.13: The GUI for the creation of fault weights

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

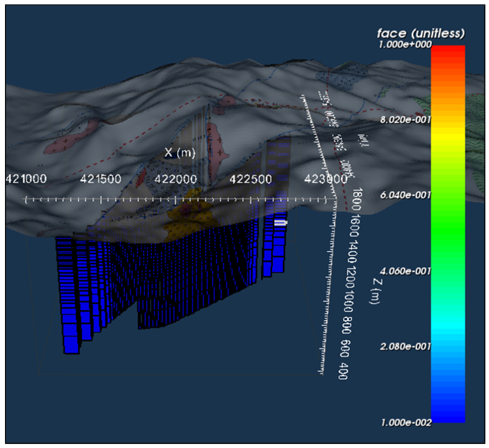

Figure 2.14: An example of fault weights that can be created with GIFtools

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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