

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

by

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Abstract

Preface

Table of Contents

| | |
|---|-------------|
| Abstract | ii |
| Preface | iii |
| Table of Contents | iv |
| List of Tables | vi |
| List of Figures | vii |
| Glossary | viii |
| Acknowledgments | ix |
| 1 Introduction | 1 |
| 1.1 Research Motivation | 1 |
| 1.2 Literature Review | 2 |
| 1.3 Types of Data Included | 2 |
| 2 Solutions to Including Information Into Model Objective Function (MOF) | 3 |
| 2.1 Forms of A Priori Information | 3 |
| 2.1.1 Bore Hole Data and the Use of Koenigsberger Ratios to Correct Bore Hole Susceptibility Measurements | 3 |
| 2.1.2 Surface Sample Data | 3 |
| 2.1.3 Geological Maps | 4 |

| | | |
|----------|--|-----------|
| 2.2 | Using Multiple Data Types, with Clustering | 4 |
| 3 | Case Study #1 El Poma | 5 |
| 3.1 | General Overview of El Poma | 5 |
| 3.2 | Overview of Deposits | 5 |
| 3.3 | Discussion of the Geophysical Data Given | 5 |
| 3.4 | What Information is Available | 5 |
| 3.5 | Synthetic Model | 6 |
| 3.6 | Blind Inversion of the Synthetic Model | 6 |
| 3.7 | Determination of Magnetization Dirrection | 6 |
| 3.8 | Creation of Constraints | 6 |
| 3.8.1 | α coefficients | 6 |
| 3.8.2 | Reference Models | 6 |
| 3.8.3 | Weighting matrices | 7 |
| 3.8.4 | Bounds | 7 |
| 3.8.5 | $L_p L_q$ weights | 8 |
| 4 | Case Study #2 TKC | 9 |
| 4.1 | Overview of Deposits | 9 |
| 4.2 | Discussion of the Geophysical Data Given | 9 |
| 4.3 | What Information is Available | 9 |
| 4.4 | Synthetic Model | 10 |
| 4.5 | Blind Inversion of the Synthetic Model | 10 |
| 4.6 | Determination of Magnetization Dirrection | 10 |
| 4.7 | Creation of Constraints and Types of Data | 10 |
| 4.7.1 | α coefficients | 10 |
| 4.7.2 | Reference Models | 10 |
| 4.7.3 | Weighting matrices | 11 |
| 4.7.4 | Bounds | 12 |
| | Bibliography | 13 |
| A | Supporting Materials | 15 |

List of Tables

List of Figures

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 [8]). 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 ([6],[10] among other (still need to add more)).

In addition, in [12] 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 [12], 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 Information Into Model Objective Function (MOF)

As Far I as I can tell This section should organized by data type as well.

2.1 Forms of A Priori Information

2.1.1 Bore Hole Data and the Use of Koenigsberger Ratios to Correct Bore Hole Susceptibility Measurements

I think there is some use in describing how GIFtools does it now. Much of this work was done in [12]. Mostly what I have done is the inclusion of lithologies and the use of Koenigsberger

2.1.2 Surface Sample Data

Again [12] did much of this. I think the Surface Samples will be promary use in proving physical properties for the map in El Poma

2.1.3 Geological Maps

This is novel as far as I can tell. I will describe the map to model software and I will describe the use of the “add face weights along line” tool to add faults in

2.2 Using Multiple Data Types, with Clustering

There is interesting things to discuss in the storing of multiple inversion in GIFtools, and in the use of clustering algorithms used and then ability to take geological models and make reference models and non-trivial face weighting.

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 [3]

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 Español (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 direction 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 $L_p L_q$ weights

allows the more fuzzy placement of faults. By rotating the 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 direction 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 Direction

Correlation of Vertical and Total Gradients of Half RTP field [3]

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 direction 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 (created 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 direction.

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_n s 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 chargeability) 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 [5] 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,I put lower weights along this surface. (show face weight model)

using clustering between density and mag (and conductivity and chargeability) 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

Bibliography

- [1] D. Clark and D. Emerson. Notes on rock magnetization characteristics in applied geophysical studies. *Exploration Geophysics*, 22(3):547–555, 1991. → pages
- [2] D. Collinson. Methods in rock magnetism and palaeomagnetism, 503 pp, 1983. → pages
- [3] N. Dannemiller and Y. Li. A new method for determination of magnetization direction. *Geophysics*, 71(6):L69–L73, 2006. → pages 6, 10
- [4] D. Fournier. *A cooperative magnetic inversion method with L_p -norm regularization*. PhD thesis, University of British Columbia, 2015. → pages
- [5] M. Harder, C. Hetman, B. Scott Smith, and J. Pell. Geology of the do27 pipe: a pyroclastic kimberlite in the lac de gras province, nwt, canada. In *Long abstracts, Kimberlite Emplacement Workshop, Saskatoon, Sask.* Available at <http://www.venuewest.com/8IKC/files/14%20Harder.pdf> [accessed 18 June 2008], 2006. → pages 11
- [6] P. G. Lelievre. Integrating geologic and geophysical data through advanced constrained inversion. 2009. → pages 2
- [7] P. G. Lelievre and D. W. Oldenburg. Magnetic forward modelling and inversion for high susceptibility. *Geophysical Journal International*, 166(1): 76–90, 2006. → pages
- [8] Y. Li and D. W. Oldenburg. 3-d inversion of magnetic data. *Geophysics*, 61(2):394–408, 1996. → pages 2
- [9] D. W. Oldenburg and Y. Li. Inversion for applied geophysics: A tutorial. *Investigations in geophysics*, 13:89–150, 2005. → pages
- [10] N. D. Phillips. Geophysical inversion in an integrated exploration program: Examples from the san nicolas deposit. 2002. → pages 2

- [11] M. Pilkington. 3-d magnetic imaging using conjugate gradients.
Geophysics, 62(4):1132–1142, 1997. → pages
- [12] N. C. Williams. Geologically-constrained ubc–gif gravity and magnetic
inversions with examples from the agnew-wiluna greenstone belt, western
australia. 2008. → pages 2, 3

Appendix A

Supporting Materials

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