New Method of Mapping Sub-Volcanic Geology Using Magnetic Data*

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Abstract

The Gawler Range Volcanics (GRV) province of the Western Gawler Craton in South Australia is an under-explored area covered by good quality, open file magnetic data. Using these data, a test study was conducted for the government of South Australia to map the thickness of volcanics and sub-volcanic geology over an area of 220km by 75km. The test area was chosen over the southern margin of the GRV where the thickness of volcanics was unknown, outcropping basement and basement with thin cover. Beneath the volcanic cover, basement configuration is unknown as there are a limited number of holes drilled, with only one penetrating through the volcanics. The main aim of this study was to map the base of volcanics, depth to sub-volcanic basement and delineation of structures underlying the GRV from the magnetic data. This test was also used to assess our new technique together with other methods concurrently being used to map subsurface geology, such as passive seismic.

To map base of volcanics and underlying basement, the Automatic Curve Matching (ACM) method was applied to located magnetic data. This method detects magnetic sources within different rock units of the crust, such as volcanics and the underlying basement. The ACM method was used to analyse and interpret millions of individual magnetic anomalies along profiles, detecting causative magnetic sources providing depth, location, geometry and magnetic susceptibility. To image the GRV in 3D, the high-frequency component of the magnetic field was targeted. The Total Magnetic Intensity (TMI) data was analysed using separate geophysical algorithms to simulate subhorizontal volcanic lava flows, and to model complex basement geology more effectively. The magnetic susceptibilities detected by ACM indicated the geochemistry of volcanics of different
ages. This allowed the imaging of separate lava flows and differentiation of the volcanics from the underlying basement. Using different visualisation techniques for the results from each algorithm, the base of volcanics was mapped along 75km NS profiles, spaced 1km apart over a distance of 220km, covering an area of 16,500km$^2$. The results were gridded, and an image of the base of volcanics was generated.

This procedure was used to map the top of the sub-volcanic magnetic basement. The Proterozoic basement magnetic susceptibilities and the magnetic source distribution pattern were used as key determinants to interpret the depth to the top of basement. The results were gridded and an image of the basement configuration was generated. In some areas, the base of volcanics coincides with the basement, whereas in other areas, there is a difference between the two, which could be due to the presence of sub-volcanic sediments. The results show that the volcanics are on average 700m-900m thick with a very thick section exceeding 3.4km in the east, and around 1.5km in the west of the study area.

The mapped volcanics thickness was validated by comparison with numerous drill holes (intersecting the base of volcanics or terminating within the volcanics). All the results matched the drill-hole data extremely well. After project completion, a passive seismic survey was conducted at the eastern end of the test area, indicating a base of volcanics of about 4km, which further confirms our results. The results achieved show that this process of mapping sub-volcanic basement can be applied in other volcanic provinces worldwide, and provide valuable and, perhaps, crucial information for mineral and petroleum exploration. Based on the imaged base, thickness and magnetic susceptibilities of volcanics, the magnetic influence of volcanics can be modelled and subtracted from the acquired magnetic data, thus enabling interpretation of magnetic anomalies arising from sub-volcanic crust. This can be done over sedimentary basins where thick volcanics mask seismic signals and prevent mapping of sub-volcanic geology. Our new method can assist solving challenges in sub-volcanic petroleum exploration in India.

**Selected References**


New Method of Mapping Sub-Volcanic Geology using Magnetic Data

Authors: I Kivior, S Markham, L Mellon, F Vaughan, David Boyd
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III. ACM Method

IV. Imaging Volcanics in 3D

V. Stripping off Volcanics from Total Magnetic Field
   - 3D-voxel Synthetic Model of Volcanics
   - Magnetic Field of Volcanics
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How we can Map Sub-volcanic Geology?
Description of the New Method

To uncover the Sub-Volcanic Geology, Magnetic Anomalies from Volcanics have to be attenuated & subsequently Magnetic Field of Sub-Volcanic Crust computed.

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\text{TMI} - \text{‘Volcanics MAG’} = \text{‘Sub-Volcanic MAG’}
\]
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ACM Method

Imaging Volcanics in 3D
ACM: Automatic Curve Matching Method

- The ACM method is applied to located magnetic data
- Analyses individual magnetic anomalies in purely automatic manner
- For each anomaly, ACM detects Magnetic Source: depth to the top, geometry & magnetic susceptibility
- Magnetic Sources visualise magnetisation of the crust: sediments, basement, intrusions & volcanics.

Magnetic Field

ACM: Vertical Gradient

Magnetic Sources
ACM
Basic Principles

Total Magnetic Intensity
Automatic Curve Matching: Theory

Total Magnetic Intensity
Profile Extraction for ACM
Profile Extraction for ACM

Profile Data Extracted from TMI
Profile Extraction for ACM

Profile Data Extracted from TMI
Profile Extraction for ACM

OBSERVED VALUES

TM [nT]
Individual magnetic anomalies of short wave-length are defined along the profiles.
Individual magnetic anomalies of short wave-length are defined along the profiles.
Individual magnetic anomalies of medium wave-length are defined along the profiles.
Individual magnetic anomalies of long wave-length are defined along the profiles.
Individual magnetic anomalies of long wave-length are defined along the profiles.
Individual magnetic anomalies of different wave-length are defined along the profiles.
Individual magnetic anomalies of different wave-length are defined along the profiles.
Individual magnetic anomalies of different wave-length are defined along the profiles.
Single anomaly is split into vertical & horizontal components, which are then represented by a pair of symmetrical & asymmetrical functions.
ACM: Goodness of Fit

OBSERVED

Vertical Component

Similarity Coefficient

CALCULATED

Vertical Component

Horizontal Component

Horizontal Component
Automatic Curve Matching: Goodness of Fit

Computed Anomaly
Observed Anomaly
Magnetic Sources

97%
Automatic Curve Matching: Goodness of Fit

- Computed Anomaly
- Observed Anomaly
- Magnetic Sources

Similarity Coefficient: 93%

< 95%
Automatic Curve Matching: Goodness of Fit

- Computed Anomaly
- Observed Anomaly
- Magnetic Sources

98%

> 95%
Automatic Curve Matching: Goodness of Fit

- Single Anomalies Interpreted Along Profile
- Computed Anomaly
- Observed Anomaly
- Magnetic Sources

Similarity Coefficient: 99%
Magnetic Sources along EW, NS, NE, NW Profiles

- Magnetic Sources
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Imaging Volcanics

Gawler Range Volcanics Province
• Test Project in the Gawler Range Volcanics province was conducted for the South Australian government.

• GRV province is located on the Western Gawler Craton in South Australia.

• GRV erupted ~1592Ma in two episodes over 100,000km² area
  - Lower GRV, felsic lavas, minor mafi at base
  - Upper GRV, felsic lavas
Mapping Base of the Gawler Range Volcanics

- Study area is covered by good quality magnetic data, used to map Base Volcanics.
- Northern part is covered by thick GRV while in the south, basement is outcropping.
- Thickness of the GRV was unknown, as there are a limited number of drill holes penetrating the volcanics.

Test Area: 16,500km²
Aim of this study was to develop a method to map Base Volcanics
ACM was applied to located magnetic data to detect Magnetic Sources within volcanics, underlying sediments & basement.
Millions of individual magnetic anomalies were analysed along profiles extracted from the TMI grid along rows, columns & diagonally.
ACM analysed individual anomalies along:
- EW & NS profiles, 100m apart; total 660,000km
- NE & NW profiles, 71m apart; total 930,000km
High & medium-frequency components of magnetic field generated by GRV were analysed using algorithms designed to simulate volcanic lava flows, and to model basement geology.
NS Magnetic Profile - Test Area

Reduction to Pole

Low-Pass Filter of Reduction to Pole

High-Frequency Component - Volcanics
GRV - Test Project

- ACM detected ~80 million Magnetic Sources within GRV & Basement
- For each Magnetic Source, ACM calculated:
  - Depth to Top
  - Model Geometry
  - Magnetic Susceptibility
  - Similarity Coefficient Factor (Goodness of Fit)
- Magnetic Sources were visualised & interpreted in 3D using Petrel
ACM Cube: Magnetic Sources
Magnetic Susceptibilities shown in colour
80 million Magnetic Sources detected by ACM
Vertical Crustal Slices of Magnetic Sources

Vertical Crustal Slice
View from West

ACM Cube
Top View

Intersection Plane

500m

Depth [m]

Northing

South

North

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Geosciences Technology Workshops 2017

Archimedes
• Key criteria used to map Base Volcanics
  i. Magnetic Susceptibility of Magnetic Sources within Volcanics are different than within Basement.
  ii. Distribution patterns of Magnetic Sources & abundance within Volcanics is different than within Basement rocks.
• Distinct boundary between Base Volcanics & Basement can be seen
VCS: Magnetic Sources

Magnetic Sources; colour shows different susceptibility values

Depth [m]

Northing

N

S

Magnetic Sources; colour shows different susceptibility values

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Archimedes
VCS: Base Volcanics

Magnetic Sources

Base Volcanics

Basement
Base Volcanics along NS Profiles

- Boundary between Base Volcanics & Basement was mapped along NS profiles & selected EW controlling profiles
- The NS Profiles were 1km to 5km apart
- Results were gridded to produce a map of Base Volcanics

Location of Vertical Crustal Slices
GRV - Test Project

- Base Volcanics was mapped using several different attributes such as:
  - TMI & VG(TMI)
  - Geophysical Model: Dyke, Plate, Edge
  - Profile Direction: EW, NS, NW-SE, NE-SW
  - Similarity Coefficient Factor

- Drill hole data was used as a guidance & to validate the interpreted results

Vertical Crustal Slice
500m Wide

Profile Location: 714050mE
GRV Project – VCS at 714050mE
Base Volcanics with VG(TMI) & Dyke+Plate+Edge Models

South

Northing

North

Depth [m]

Magnetic Sources

Base Volcanics
GRV Project – VCS at 714050mE
Base Volcanics with TMI & Dyke+Plate Model

South
Northing

Depth [m]

Magnetic Sources
Base Volcanics
Boundary of Lower & Upper GRV
Boundary of Upper & Lower GRV
Base Volcanics vs Drill-hole Data
Base Volcanics - Drill Hole MSDPO9

Drill hole MSDPO9 TD = 319m

- Base Volcanics = 174m
- Base Volcanics = 195m

195m
Base Volcanics - Drill Hole M004

Drill hole M004: TD=844m
Base Volcanics = 437m
Magnetic Sources
Base Volcanics = 430m

TD 844m
Map of the Base Volcanics generated from NS Profiles.
Volcanics are on average 700m-900m thick
Very thick section exceeding 3.4km in the east & ~1.5km in the west.

Thickness of Volcanics was validated with:
- Drillhole data showing good match
- Passive seismic in the east indicates 4km thickness
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3D-Voxel Synthetic Volcanics Model
Magnetic Susceptibility of individual voxels of the Volcanic Layer are assigned based on the Susceptibilities of Magnetic Sources detected by ACM.
Base Volcanics & Top from Topography was used to construct 3D-Voxel Synthetic Model simulating GRV.
3D-Voxel Synthetic Model of GRV

Base Volcanics & Top from Topography was used to construct 3D-Voxel Synthetic Model simulating GRV.
3D-Voxels of Synthetic GRV Model

Layer-2
Upper GRV
Layer-1
Boundary
Lower GRV
Base GRV
250m
250m
250m
Layer-1:
- Base GRV
- Top: Boundary Lower/Upper GRV

Layer-2:
- Base: Boundary Lower/Upper GRV
- Top GRV/Topography
Magnetic Field of Volcanics

‘Volcanics MAG’
Magnetic Field of Volcanics

‘Volcanics MAG’

• ‘Volcanics MAG’ is computed from 3D-voxel synthetic model of Volcanics using Magnetic Susceptibilities computed by ACM
  - Layer-1: Lower GRV; av. 0.01 – 0.05 SI units
  - Layer-2: Upper GRV; av. 0.001 – 0.01 SI units

• ‘Volcanics MAG’ is computed using in-house software
Magnetic Field of Volcanics

Magnetic Field computed from 3D-Voxel Synthetic Model of GRV
Sub-Volcanic Magnetic Field
TMI – ‘Volcanics MAG’ = ‘Sub-Volcanic MAG’
3D-Voxel Synthetic Model

TMI – ‘Volcanics MAG’ = ‘Sub-Volcanics MAG’
Magnetic Field of Sub-Volcanic Crust
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Interpretation
Sub-Volcanic Magnetic Field Examples
Sub-Volcanic Geology

Sub-Volcanic MAG used to map Basement, Sedimentary Horizons & Faults beneath thick Volcanics such as Deccan Traps

Base Volcanics
Sub-Volcanic Horizon
Sub-Volcanic Basement
Computed Sub-Volcanic Magnetic Field was analysed to map Sub-Volcanic Basement, Sedimentary Horizons & Faults in PNG & Sirte Basin in Libya.
Mapping Sub-Volcanic Basement
Mekong Delta, Vietnam

Magnetic Field

Sub-volcanic Basement

Sub-volcanic Basement
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Conclusions

- New Method presented allows magnetic anomalies of GRV to be removed from TMI field & Sub-Volcanic Magnetic Field to be computed.
- ACM detected Magnetic Sources within GRV & underlying basement.
- Magnetic Sources, visualised in 3D, allowed imaging the thickness of the Upper & Lower GRV & also the underlying Basement, for the first time.
- Base Volcanics was successfully mapped along NS profiles using: magnetic susceptibility values, distribution patterns & abundance of Magnetic Sources within GRV. Results were validated by comparison with drillholes & passive seismic.
- Magnetic Field of Volcanics was computed from 3D-Voxel synthetic model of GRV.
- This field was subtracted from TMI field to produce Sub-Volcanic Magnetic Field, which can be used to map basement, multiple sedimentary horizons & faults.
- Our New Method can assist in solving petroleum exploration challenges in India & other volcanic provinces around the world.
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Thank You