Three-dimensional potential field modelling of the subsurface morphology of complex maar volcanoes - Examples from the Newer Volcanics Province, Western Victoria

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SUMMARY

Potential field geophysical modelling techniques can be applied to better understand the subsurface morphology of volcanoes, and when linked with observations of surface geology can be used to develop a more complete understanding of the volcanic centres eruptive history.

High resolution ground gravity and magnetic data were acquired across several maar volcanoes located within the Newer Volcanics Province (NVP) of Western Victoria. The maar volcanoes surveyed represent a range of the different sizes and styles of eruptions observed within maar volcanoes of the NVP.

Gravity and magnetic data were subject to 2D forward and 3D inverse modelling in order to reveal details on the depth, geometry and petrophysical property distributions within subsurface volcanic structures. Gravity lows with corresponding magnetic highs are observed across the maar craters and were reproduced during modelling with the presence of a diatreme. Smaller wavelength gravity and magnetic anomalies detected in the centre of the more complex volcanic craters can be explained by the presence of intrusive dykes or vents filled with a higher proportion of denser volcanic debris.

Modelling suggests that multiple coalescing diatreme structures exist below the volcanic edifices, some containing intrusive dykes or a denser central vent filled in with volcanic debris. Multiple diatreme structures suggest a complex eruption history involving vent migration, while preserved dykes within the diatreme suggest short-lived fluctuations between phreatomagmatic and magmatic eruption styles.

Key words: Maar, diatreme, gravity, magnetics, forward modelling, 3D inverse modelling

INTRODUCTION

Monogenetic basaltic volcanoes are the most common sub-aerial volcanoes on Earth, forming from small volume magma's with short-lived eruptions. Over 400 monogenetic volcanic centres exist within the 4.5 Ma-4.5 ka Newer Volcanics Province (NVP) of south-eastern Australia (Joyce 1975; Cas 1989; Cas *et al.* 1993; Cas *et al.* 2011). Understanding their subsurface structures is an important step towards fully understanding eruption processes and assessing hazards that may arise due to future eruptions. However subsurface volcanic structures are not exposed within the NVP and potential field modelling techniques are relied upon to image the volcanic conduit (Blaikie *et al.* 2012). The application of geophysical modelling techniques to understand the subsurface architecture of volcanic systems is under-utilised given its potential to reveal detailed information on the three-dimensional structure and morphology of a volcanoes underlying vent system, but has become increasingly common in recent years (Rout *et al.* 1993; Brunner *et al.* 1999; Schulz *et al.* 2005; Blanco-Montenegro *et al.* 2007; Cassidy *et al.* 2007; Lopez Loera *et al.* 2008; Mrlina *et al.* 2009; Blaikie *et al.* 2012).

Maar volcanoes are commonly formed in monogenetic volcanic fields, and are characterised by a near-circular crater cut below the pre-existing surface and surrounded by a low, shallowly dipping tephra ring (Lorenz 1975, 1986, 2003; White & Ross 2011; Valentine & White 2012). Maar volcanoes form as ascending magma comes into contact with ground water and interacts explosively. These explosions occur largely underground, excavating a deep crater which is infilled by pyroclastic and host rock debris during and after the eruption, forming a structure known as a diatreme, which in some cases can be up to 2 km deep (Lorenz 1975, 1986, 2003).

Maar volcanoes are focussed on because their morphology is better suited to a gravity/magnetic survey than scoria cones and lava shields which often have significant topographic relief. A maar-diatreme has a high petrophysical contrast (lower density and higher magnetic susceptibility) with the surrounding host rock, making maar volcanoes ideal for gravity and magnetic modelling (Cassidy *et al.* 2007; Blaikie *et al.* 2012). Maar volcanoes are also considered as an analogue for some kimberlite pipes (Lorenz 1975; White & Ross 2011), therefore better understanding their subsurface structures and improving geophysical modelling techniques has important economic implications.

Four volcanoes within the NVP are focussed on, including the Red Rock Volcanic Complex (RRVC), the Mount Leura Volcanic Complex (MLVC), Ecklin maar and the Anakie maar. Ecklin and Anakie are simple maar volcanoes, consisting of single elliptical craters. The RRVC is comprised of 40 eruption points including several maar volcanoes and a scoria cone complex. The MLVC consists of a coalesced maar and tuff cone crater that has been infilled by lava flows and numerous scoria cones.

METHOD AND RESULTS

High resolution ground gravity and magnetic surveys were conducted across each of the maar volcanoes mentioned above. Data were acquired along several near-orthogonal traverses across the craters with gravity station spacings every 15-20 m and magnetic data acquired at 2 second intervals. Tidal, drift, latitude, free-air, Bouguer and terrain corrections were applied to the gravity data. Magnetic data were corrected for diurnal variations and the IGRF, and subjected to despiking and filtering to remove noise caused predominantly by electric fences within the survey area. Data interpretation follows the workflow outlined in figure 1.

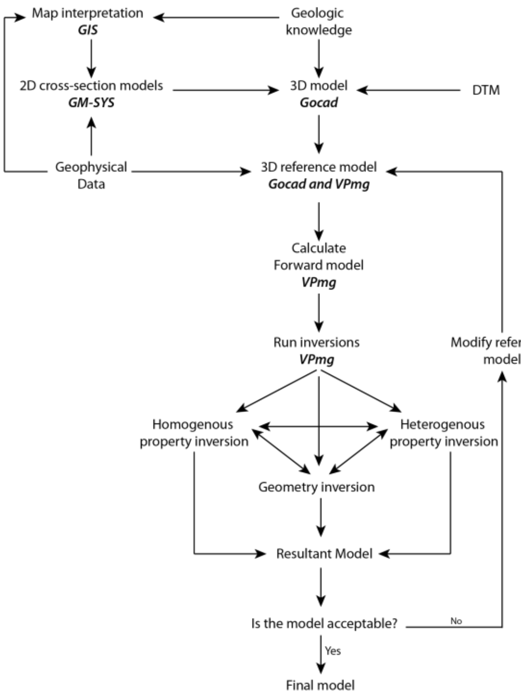

Figure 1. Modelling workflow (From Blaikie *et al.* in prep, after McLean *et al.* 2008)

Initially, the processed data was gridded and some preliminary interpretations of the observed anomalies were made. Varied geophysical responses are observed across each of the maars surveyed, indicating the complex and variable nature of the subsurface volcanic vent, even when the volcanoes are similar in surface morphology.

Anakie maar displays a simple gravity low across the crater, with no significant magnetic anomaly. Ecklin maar consists of two corresponding gravity and magnetic highs in the centre of the crater, surrounded by a gravity and magnetic low (Figure 2). The MLVC has a large gravity high within the centre of the maar crater with a corresponding magnetic anomaly, related to the largest scoria cone within the complex. Magnetic anomalies are variable across other areas of the complex due to the dispersed scoria cones within the maar crater and the variable thickness of underlying lavas. Magnetic highs are observed over the cones, however they do not always have a corresponding gravity anomaly. Geophysical signatures across the RRVC are highly variable, with some maars displaying corresponding gravity and magnetic highs, others corresponding lows, and some with magnetic anomalies but no gravity anomalies.

The gravity lows over the maar craters are attributed to the lower density pyroclastic infill of the diatreme and the accumulation of lake sediments within the crater. Short-wavelength gravity and magnetic highs indicate the presence of subsurface basalt, either in the form of dykes or magma ponds.
Following interpretation of the gridded data sets, 2D forward models were constructed to reveal information on the depth and geometry of the maars subsurface structures using GM-SYS which allows gravity and magnetic data to be jointly modelled. Each model was constrained by the regional geology, pyroclastic deposits, petrophysical properties and the interpretation of gridded geophysical data. Free air gravity was modelled so we could include topography within the model.

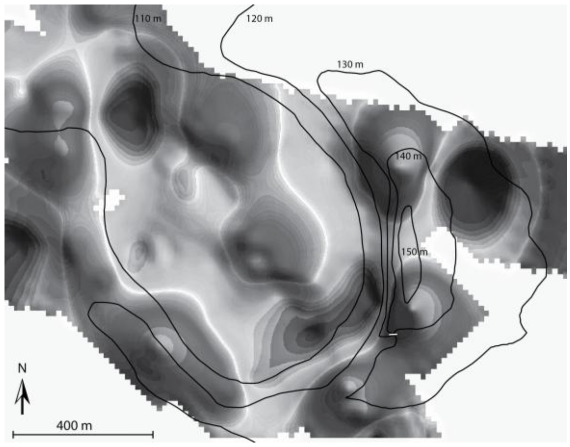

Figure 2. High Pass filter (800m cutoff wavelength) of the Bouguer gravity data over Ecklin maar Two weak gravity highs can be observed in the centre of the maar and correlate with two magnetic anomalies.

The 2D forward models across each of the volcanic centres are shown in Figure 3. The gravity lows with corresponding magnetic highs observed across the Ecklin maar (Fig. 3a) crater were reproduced during modelling with the presence of two coalesced diatreme structures containing denser vents within the centre of the diatreme. The anomalies observed at the Anakie maar were reproduced with a simple, shallow diatreme structure (Fig. 3d).

The RRVC (Fig. 3b) and MLVC (Fig. 3c) have more complex geophysical signatures, consisting of short wavelength gravity and magnetic highs superimposed on longer wavelength gravity lows. These anomalies are reproduced during modelling with multiple shallow coalesced diatremes containing dykes and magma ponds.

Multiple cross cutting forward models across each of the volcanoes were used as a constraint during the construction of 3D geologic models. The 3D models were built within Gocad and used as a reference model for homogenous, heterogeneous and geometry inversions of the gravity data performed within VPmg (Fullagar *et al.* 2000; Fullagar *et al.* 2004; Fullagar & Pears 2007). Inversions were applied to minimise the misfit between the observed and calculated data and to understand the 3D structures and density distribution within the volcanoes underlying vent systems. This was achieved through sequential homogenous, geometry and heterogeneous property inversions. Constraints were applied so that the models remained geologically plausible and could only vary within the applied petrophysical and geological constraints.

Homogeneous and geometry inversions are applied to reduce the misfit between the observed and calculated data and optimise the density and geometry of select lithological regions. Heterogeneous inversions are then applied to understand the density distribution within the diatreme. Results indicate denser regions within the centre of the modelled diatremes surrounded by lower density regions. These dense regions indicate the presence of the volcanoes vents which are filled with a higher proportion of volcanic debris. The surrounding low density material consists of a mix of collapsed host rock and pyroclastic debris.

Any geophysical model is limited in that an infinite number of solutions to the data may exist (Whiting 1986; Valenta *et al.* 1992; Jessell *et al.* 1993; McLean & Betts 2003). The examples presented here are constructed from a combination of 2D and 3D modelling techniques and are constrained by all the available geologic data, thus limiting the number of plausible solutions. However some assumptions were made throughout the modelling process, particularly in regards to the petrophysical properties of the subsurface. Surface deposits are used as an analogue since the subsurface could not be sampled, however these properties may vary considerably to the subsurface due the differences in composition and weathering and a sensitivity analysis is required to assess model ambiguity.

Sensitivity analysis is achieved by systematically altering model properties and/or geometries to identify which structures within the model have the greatest geophysical influence. Structures such as the maar diatreme and its feeder dykes are highly sensitive to changes in their properties/geometries unless covered by thick lava flows which tend to mask their geophysical signature. Because the petrophysical properties of the subsurface are inferred, 3D geometry inversions are applied to test the variability in model geometry due to variations in density within select lithological regions. Figure 4 shows the how the geometry of the Ecklin maar diatreme varies when the density of the diatreme is varied within the upper and lower bounds of the constraints.

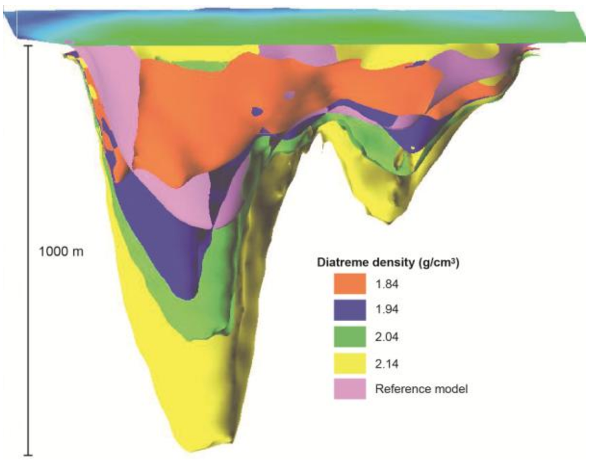

Figure 4. Results of geometric inversions of the Ecklin maar-diatreme model for variable diatreme densities. (From Blaikie *et al.* in prep)

CONCLUSIONS

Geophysical modelling techniques have been successfully applied to model the subsurface architecture of several volcanoes within the Newer Volcanics Province and help constrain their eruptive history. Models suggest that the volcanoes vents frequently migrate during the eruption, and will often switch between magmatic and phreatomagmatic eruption styles.

The aim of the modelling technique presented here is to produce multiple geophysical models through different inversion styles that are all geologically meaningful and consistent with the available geologic information, rather than seeking a single 'ideal' solution. Where no subsurface constraints are available, uncertainty in model results will always exist. However, the uncertainty can be assessed by producing a suite of models that examine possible solutions when initial constraints are varied to their upper and lower bounds.

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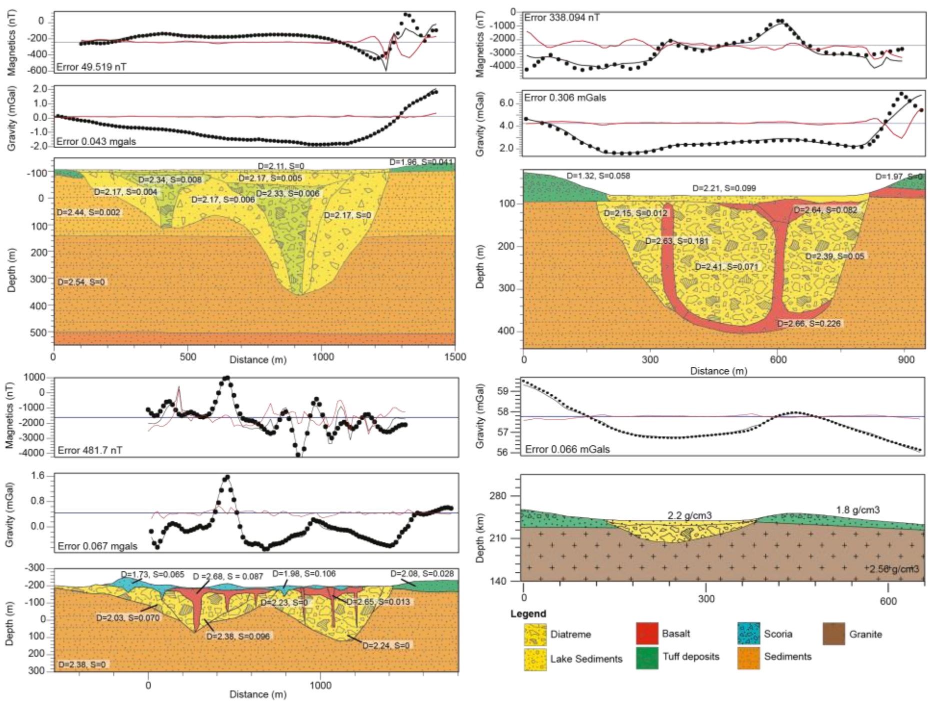

Figure 3. 2D forward models of a) Ecklin, b) Red Rock Volcanic Complex, c) Mt Leura, d) Anakie