Geophysical and volcanological insights into the subsurface morphology and eruptive histories of complex maar volcanoes within the Newer Volcanics Province, Western Victoria

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SUMMARY

To better characterise the eruptive histories and subsurface structures of several maar volcanoes from the Newer Volcanics Province, forward and inverse geophysical modelling is combined with a study on the geology of the volcanic centres. The maar volcanoes under investigation include the Red Rock Volcanic Complex (RRVC), Ecklin maar, the Mount Leura Volcanic Complex (MLVC).

High resolution gravity and magnetic data were acquired across each of the maars and the data was modelled in two and three dimensions to understand the subsurface morphology of the volcanoes vents.

Varied geophysical responses are observed across each of the maars surveyed, indicating the complex and variable nature of the subsurface volcanic vent, even when they present similar surface morphology. Where corresponding gravity and magnetic lows are detected across a maar crater, it is suggested that all the available magma was erupted and the maar diatreme (subsurface collapse structure) was not intruded by any dykes. The gravity low arises because of lower density lake sediments and pyroclastic debris infilling the crater. The lack of any intrusive dykes or remnant vents within the diatreme suggest that groundwater was available for phreatomagmatic explosions.

Maars with corresponding gravity and magnetic highs indicate a large volume of subsurface basalt, resulting from the ponding of magma at the surface of the vent. This results from a lack of groundwater for magma to interact with during the eruption, which facilitates magma rising upwards through the diatreme where it is fragmented at shallower levels.

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

INTRODUCTION

The Newer Volcanics Province (NVP) is an intraplate basaltic plains province comprised of over 400 eruptive centres, including shield volcanoes, scoria cones, tuff rings, maars, composite volcanoes and extensive lava plains (Joyce 1975; Cas 1989; Cas *et al.* 1993; Lesti *et al.* 2008; Cas *et al.* 2011). Volcanic products are Cainozoic in age (4.5 Ma-4.5 ka) and cover an area > 23 000 km^2 (Van den Hove 2013, in Prep), with northern areas of the province overlying the Palaeozoic metasediments and granites of the Lachlan and Kanmantoo Fold Belts and southern areas overlying the Mesozoic-Cenozoic sediments of the Otway Basin (Joyce 1975; Lesti *et al.* 2008; Cas *et al.* 2011).

Approximately 40 maars have been identified within the NVP, all with relatively intact edifices and no exposure of their underlying structures. The subsurface of maar volcano consists of a diatreme, which forms as phreatomagmatic explosions occur largely underground, excavating a deep crater which is then infilled with pyroclastic debris during and after the eruption (Lorenz 1975, 1986, 2003). Understanding the morphology of the diatreme and location of vents within the volcanoes of the NVP is important to reconstruct their eruptive history and assess hazards that may be associated with any future eruptions within the province.

Due to the infrequent and violent nature of volcanic eruptions, much of the work focussing on the subsurface structures of maar volcanoes is conducted on the inactive and often partially eroded volcanic edifice where it is not possible to link eruptive processes recorded from surface deposits with structures responsible for those processes in the subsurface (eg. White 1991; Ross & White 2006; Lefebvre *et al.* 2012). Where the volcanic edifice is preserved, geophysical modelling has the potential to provide information that is critical for linking the plumbing system of a volcano with its surficial deposits to understand eruptive histories and processes. Maar volcanoes are also thought to be analogues to kimberlite volcanoes which are known for hosting diamonds, so an improved understanding of their subsurface morphology has important economic implications (Lorenz 1975; White & Ross 2011).

The maar volcanoes under investigation include several maars within the Red Rock Volcanic Complex (RRVC), Ecklin maar and the Mount Leura Volcanic Complex (MLVC). These maars are hosted in the weakly lithified sedimentary sequences of the Otway Basin. Ecklin maar is a small, simple maar volcano, showing dominantly phreatomagmatic eruptive styles. The MLVC consists of a large maar crater and overlapping tuff rings, with up to 16 scoria cones contained within the centre. The RRVC is one of the most complex volcanic centres within the NVP, consisting of over 40

eruption points. The complex consists of numerous poly-lobate maars and a scoria cone complex.

METHOD AND RESULTS

High resolution ground gravity and magnetic surveys were conducted over each of the volcanic centres in order to image their subsurface structures. Details of the geophysical surveys and the techniques used for modelling internal volcanic structures are outlined in an extended abstract by Blaikie *et al*. The geophysical signatures of each of these maars are quite different even though they display similar morphological features and eruption histories. The internal structures were imaged by 2D forward and 3D inverse modelling (Figure 1) of the potential field data and were constrained by petrophysical data. In each case the depth of the maar diatreme was also constrained by examining the lithic fragments within pyroclastic deposits and determining their origin within the well constrained stratigraphy of the Otway Basin.

The geophysical signature of the Ecklin maar consists of two corresponding short-wavelength Bouguer gravity and magnetic highs in the centre of the crater which are superimposed on a longer wavelength Bouguer gravity and magnetic low. These anomalies were reproduced during forward and inverse modelling by two shallow coalesced diatremes structures (Figure 1D). The centres of the two diatremes are denser and have a higher magnetic susceptibility, representing the higher volume volcanic debris contained within the vent. The margins have a lower density and magnetic susceptibility due to higher volumes of host rock debris, which subside into the diatreme during the eruption. The overall structure of this maar-diatreme is typical of a maar volcano hosted in weakly lithified sediments. No dykes intruded into the Ecklin diatreme, or at least not to a level where they can be detected with the current parameters of the survey, and there is no evidence within the surrounding pyroclastic deposits that the maar exhibited short-lived magmatic phases that would have allowed dykes to rise to the surface and erupt in a magmatic style.

Gravity and magnetic surveys over the MLVC revealed a large Bouguer gravity high within the centre of the maar crater with a corresponding magnetic high which is related to the larger scoria cones and underlying lava flows. Magnetic anomalies are variable across other parts of the complex due to dispersed scoria cones within the coalesced maar/tuff cone craters. Magnetic highs are typically observed over the cones, however they do not always have a corresponding gravity anomalies. Modelling revealed two shallow coalesced diatremes overlain by a thick lava flow and scoria deposits (Figure 1C).

Geophysical signatures across the maars contained within the RRVC are highly variable, with some maars displaying corresponding short-wavelength Bouguer gravity and magnetic highs, others corresponding lows, and some with magnetic anomalies but no gravity anomalies. At the RRVC, alternating scoria and ash layers within the pyroclastic deposits provide evidence that the maars frequently fluctuated between magmatic and phreatomagmatic explosive activity, therefore suggesting that dykes have risen through the diatreme to the near surface and may be preserved within the diatreme. The short wavelength, positive gravity and magnetic anomalies identified within a number of maars within the RRVC suggest that this may be the case. The anomalies were reproduced during forward and inverse modelling by several sub-vertical dykes that have intruded the diatreme (Figure 1B).

Modelling of diatremes at the RRVC revealed complex coalesced structures, suggesting the eruption points frequently migrated during the formation of the complex (Figure 1A). The diatremes are shallow and bowl-shaped, indicating that the soft sediment in which the volcano is hosted influenced its final geometry, resulting in shallow broad diatremes instead of steep cone-shaped ones that are characteristic of a consolidated host rock.

CONCLUSIONS

Potential field geophysical modelling provides a means to image the subsurface structures of these volcanoes and link those structures with deposits and structures seen at the surface. Such complex subsurface structures could not be detected simply by studying the limited outcrops in the maar rims and were only revealed after geophysical modelling.

Modelling of the complex anomalies seen across these volcanoes suggest that where corresponding Bouguer gravity and magnetic lows are detected across a volcanic crater, all the available magma was fragmented by magma-water interaction and the resulting pyroclastic debris were deposited on the surface or within the diatreme. The Bouguer gravity low occurs due to low density pyroclastic debris and lake sediments infilling the crater.

Maars with corresponding short wavelength gravity and magnetic highs indicate the presence of subsurface basalt, possibly in the form of a dyke or sill. If the anomalies are broader and have a higher amplitude, it is thought that ponding of magma at the surface of the vent has occurred. The presence of dykes and/or magma ponds within the diatreme suggests a lack of groundwater was available for magma to interact with during the eruption, which facilitated magma rising upwards through the diatreme to erupt magmatically.

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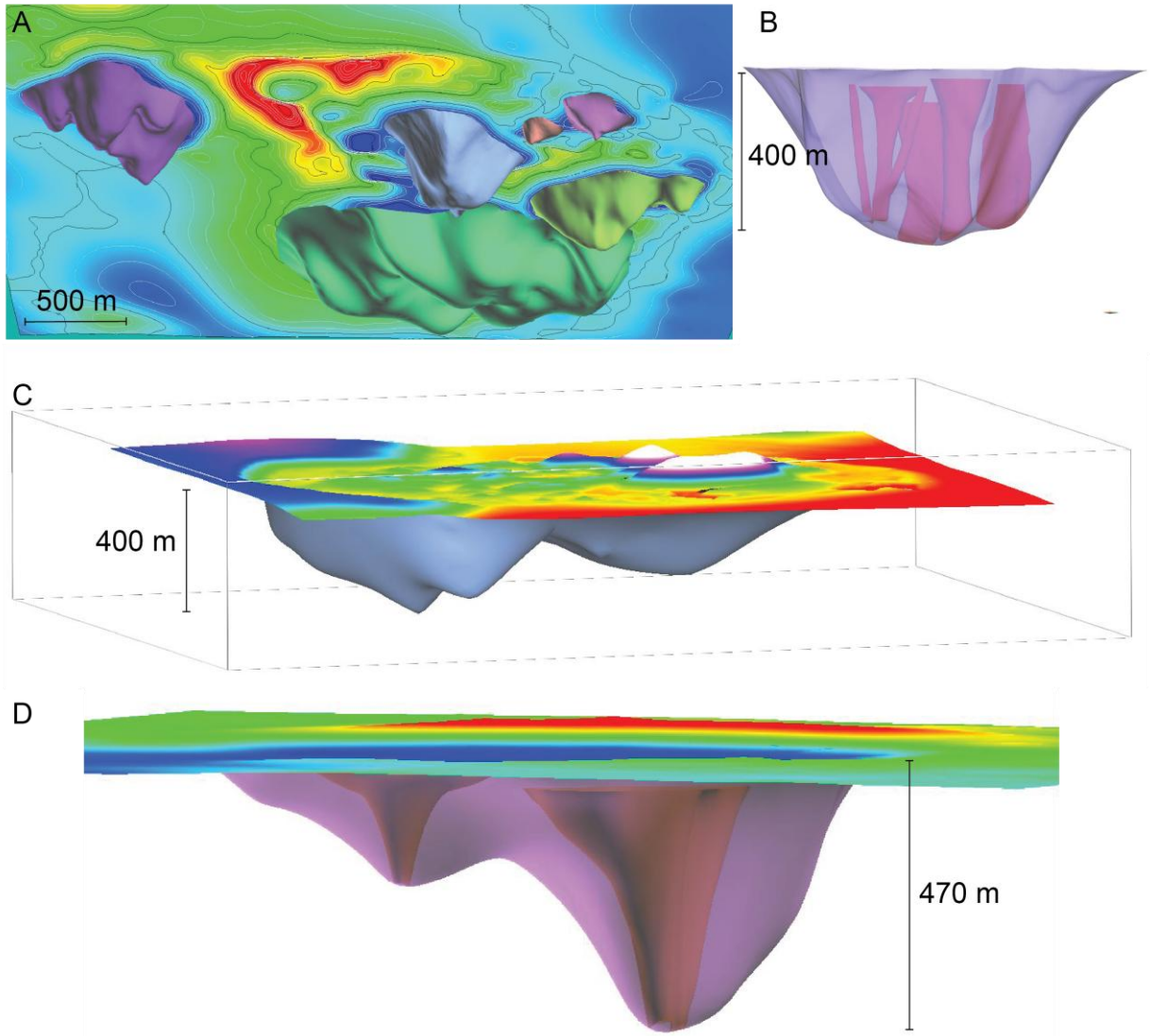

Figure 1. 3D models of the A) & B) Red Rock volcanic complex, C) Mt Leura Volcanic complex, D) Ecklin Maar (From Blaikie *et. al.* in prep)