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Okataina Volcanic Centre, Taupo Volcanic Zone, New Zealand: A review of volcanism and synchronous pluton development in an active, dominantly silicic caldera system

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ABSTRACT

The Okataina Volcanic Centre (OVC) is one of eight caldera systems, which form the central part of the Taupo Volcanic Zone, New Zealand. During its ~625 kyr volcanic history, which perhaps equates to ~750 kyr of magmatic history, the OVC has experienced two definite periods of caldera collapse (Matahina, ~322 ka, and Rotoiti, for which dates of 61 and 45 ka have recently been published), one probable collapse (Utu, ~557 ka) and one possible collapse (Kawerau, ~33 ka). Each collapse accompanied voluminous ignimbrite eruptions. Rhyolite dome extrusion and explosive tephra eruptions have occurred throughout the history of OVC.

This paper reviews volcanological observations, and geochemical and geophysical data that provides evidence for the nature and evolution of the mid- to upper crustal magma system below OVC. The chemistry of the largely rhyolitic juvenile pyroclastic deposits and lavas (most with 73–78 wt.% SiO_2) is reviewed, together with evidence provided by plutonic and mafic lithic blocks found within some pyroclastic deposits to reconstruct reservoir development. Detailed studies of zircon crystals provide age control for the longevity of the supersolidus state of the magmatic system of the OVC, while geophysical measurements, in particular resistivity and magnetotelluric (MT) data, suggest the present day existence of partial melts at depths of between 8 and 15 km. A comparison with older exposed high-level plutonic systems helps explain some of the features found in the erupted plutonic lithic blocks at OVC, and provides an indication of the potential longevity of the system. An integration of these disparate datasets allows a model to be developed in which an extensive, intermediate composition 'mush' zone occurs at 8–15 km depth, from which more silicic melt fractions periodically rise to higher level sill or laccolith-like 'pods' in the crust. Sometimes one of these pods may erupt to produce lava or pumice of a single composition, while at other times a number of pods are tapped to form large-scale, caldera-forming eruptions. Periodically, the magmatic system reaches its solidus or near-solidus, which allows ascending basalt to reach the shallow magmatic system. In the last 50 kyrs, some of these basalts have reached the surface, for example during the 1886 AD fissure eruption from Tarawera volcano.

A comparison with other active caldera complex systems in TVZ and overseas suggests that while the general model may apply, there are variations because of different tectonic setting, crustal thickness and age of the system. However, the general model has implications for geothermal reservoir evaluation and studies of epithermal ore deposition. The high crustal level magma system beneath OVC is probably part way through its evolution, so further intrusions and eruptions can be expected in the future, with clear implications for hazard evaluation.

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1. Introduction

There have been many studies of caldera structure and evolution (e.g. Smith et al., 1961; Bailey et al., 1976; Walker, 1984; Lipman, 1997, 2000; Cole et al., 2005), and it has been recognised that an understanding of the relationship between caldera volcanism and contemporary plutonism is important (e.g. Hildreth, 1981; Lipman et al., 1997; Metcalf, 2004; Quick et al., 2009; Sewell et al., 2012). However, few single studies can offer comprehensive models of sub-volcanic plumbing systems in the upper crust beneath caldera volcanoes.

Magma systems undergo a complex series of processes from their source, commonly in the mantle, to eruption and solidification at the Earth's surface. Our understanding of these processes comes from a study of both volcanic and plutonic rocks. These represent different stages of the process, with plutonic rocks representing either magmas which have completely solidified in the crust or what is left in the crust after a portion of the magma rises to the surface during an eruption (e.g. Bachmann and Bergantz, 2008).

The central part of the Taupo Volcanic Zone (TVZ), North Island, New Zealand (Fig. 1), is the most frequently active and productive Quaternary silicic system on Earth (Houghton et al., 1995), characterised by intense, and volumetrically dominant, rhyolitic volcanism associated with large calderas and caldera complexes (Fig. 1). These represent the sites of major ignimbrite eruptions, but rhyolite domes and the products of Plinian explosive eruptions associated with the same magma systems may well extend beyond the boundaries of the calderas. At the northern end of the central TVZ (Fig. 1) is the Okataina Volcanic Centre (OVC), within which is the Okataina Caldera Complex (Cole et al., 2005; Cole and Spinks, 2010). This caldera complex represents several phases of collapse that have created a depression partially filled with intracaldera ignimbrite, younger domes and pyroclastic deposits, and lakes (Fig. 2). OVC includes all vents associated with the Okataina magma system, which extend beyond the structural boundaries of the calderas, and hence the OVC is the appropriate name to use throughout this paper.

Despite numerous individual studies of both caldera-related volcanism in the central TVZ (e.g. Brown et al., 1998; Beresford and Cole, 2000; Milner et al., 2002; Wilson et al., 2006; Gravley et al., 2007), and those of the zone as a whole (e.g. Houghton et al., 1995; Bibby et al., 1998; Rowland and Sibson, 2001; Wilson et al., 2009; Cole et al., 2010), only a few studies consider the relationship between TVZ volcanic and plutonic realms (e.g. Brown et al., 1998; Burt et al., 1998; Charlier et al., 2003). A more detailed assessment of this relationship is therefore timely.

Volcanic eruptions at the surface provide snapshots in the development of the subsurface magma chamber. Plutons on the other hand, represent portions of the magma chamber that were, for a variety of reasons, unable to erupt. Plutons are not exposed at the surface in the TVZ and can only be examined as lithic fragments (e.g. Brown et al., 1998) or in drill core (e.g. Browne et al., 1992). These plutonic rocks are extremely unlikely to represent a simple single-stage cooling event magma chamber; rather they represent the hybridized remnants of repeated magma replenishment, crystallisation, extraction and late-stage sub-solidus alteration.

This review describes the stratigraphy, geochemistry and geophysics of OVC, evaluates information that can be obtained from lithic fragments brought up from below during explosive eruptions, and briefly compares this modern caldera system with older exposed high-level plutons to produce a model for the shallow, largely silicic, magma system beneath OVC, and compares the system to other active caldera complexes in TVZ and overseas. OVC has been chosen because there has already been extensive study of its volcanic history, shallow crustal structure and petrological and geochemical evolution. It is regarded as active, with the last rhyolite eruption in 1314 AD (Nairn et al., 2001), and basalt eruption in 1886 AD (Sable et al., 2006), and has experienced frequent eruptions over the last ~625 kyrs, and hence, a better understanding of its evolution should improve hazard mitigation. The general model for sub-caldera magmatism has implications for geothermal resource evaluation and epithermal ore deposition.

2. Geologic background

TVZ is the actively rifting, on-land continuation of the Tonga–Kermadec arc (Fig. 1), formed at the convergent plate boundary between the westward subducted Pacific Plate and the Australian Plate (Cole, 1990; Wilson et al., 1995). Extension rates range from ~15 mm/y at the Bay of Plenty coast to <5 mm/y at 39°S (south of Lake Taupo) (Wallace et al., 2004). Mesozoic greywacke metasediments outcrop to the east and west of the TVZ, are found in geothermal drill holes on the eastern side of TVZ, and probably underlie the volcanic fill within most of TVZ, either as tectonically stretched greywacke crust, or as rifted greywacke blocks separated by intrusive rocks (Stern et al., 2006). Convective heat output from geothermal systems in the TVZ is exceptionally high at ~4300 MW (Bibby et al., 1995), equivalent to 26 MW/km along strike (Stern et al., 2006) and similar to hot spots such as Iceland and Yellowstone. The high heat flux causes the brittle-to-ductile transition to occur at shallow depth (~6 km) within the central TVZ (Bryan et al., 1999; Sherburn et al., 2003). Crystal and melt inclusion data indicate that rising magmas in dike-like structures