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Controls on volcanism at intraplate basaltic volcanic fields

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ABSTRACT

A broad range of controlling mechanisms is described for intraplate basaltic volcanic fields (IBVFs) in the literature. These correspond with those relating to shallow tectonic processes and to deep mantle plumes. Accurate measurement of the physical parameters of intraplate volcanism is fundamental to gain an understanding of the controlling factors that influence the scale and location of a specific IBVF. Detailed volume and geochronology data are required for this; however, these are not available for many IBVFs. In this study the primary controls on magma genesis and transportation are established for the Pliocene–Recent Newer Volcanics Province (NVP) of south-eastern Australia as a case-study for one of such IBVF. The NVP is a large and spatio-temporally complex IBVF that has been described as either being related to a deep mantle plume, or upper mantle and crustal processes. We use innovative high resolution aeromagnetic and 3D modelling analysis, constrained by well-log data, to calculate its dimensions, volume and long-term eruptive flux. Our estimates suggest volcanic deposits cover an area of 23,100 ± 530 km^2 and have a preserved dense rock equivalent of erupted volcanics of least 680 km^3, and may have been as large as 900 km^3. The long-term mean eruptive flux of the NVP is estimated between 0.15 and 0.20 km^3/ka, which is relatively high compared with other IBVFs. Our comparison with other IBVFs shows eruptive fluxes vary up to two orders of magnitude within individual fields. Most examples where a range of eruptive flux is available for an IBVF show a correlation between eruptive flux and the rate of local tectonic processes, suggesting tectonic control. Limited age dating of the NVP has been used to suggest there were pulses in its eruptive flux, which are not resolvable using current data. These changes in eruptive flux are not directly relatable to the rate of any interpreted tectonic driver such as edge-driven convection. However, the NVP and other IBVFs used for comparison have long-term eruptive fluxes that are considerably less than definitive plume-related volcanic systems. Along with their spatio-temporal patterns and other analysis it is suggested that the NVP and the vast majority of low- and high-flux IBVFs appear to be the result of tectonic processes without requiring additional thermal input from a deep mantle source. Considering a control on volcanism by tectonic processes, the range of eruptive flux of IBVFs is related to variations in the rate of the effecting tectonic process, mantle composition, and the size of the mantle source zone where melt generation and accumulation is taking place.

1. Introduction

'Intraplate basaltic volcanic fields' (IBVFs) represent a diverse category of volcanism that cannot be readily related to plate boundary process (Schmincke, 2004). Specifically we refer to *low-flux volcanic fields* that are comprised of distributed small volcanoes that primarily result from a single eruption event and are generally mantle sourced, including mainly basaltic compositions (Cañón-Tapia, 2016; McGee and Smith, 2016). A broad variety of dynamic models are used to explain the various discrete occurrences of IBVF volcanism (Brenna et al., 2015; Demidjuk et al., 2007; Harangi et al., 2014; Kiyosugi et al., 2010; Schmincke et al., 1983; Valentine and Perry, 2007). This diversity relates to IBVFs occurring in all tectonic environments (Le Corvec et al., 2013) and showing evidence for melt sourced from either the convecting asthenosphere, static lithosphere or both within a discrete system (McGee and Smith, 2016).

Valentine and Perry (2007) discuss end-member categories of IBVFs where volcanism is controlled magmatically or tectonically. They concluded that melt generation in tectonically controlled IB-

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VFs is dependent on tectonic forces; otherwise melt would not be able to accumulate and ascend. This model is exemplified by the South Nevada 'Volcanic Field' (VF), which displays low eruptive flux that relates to the localised response of melt accumulation or production to the rates of regional tectonic processes. Conversely, melt generation in magmatically controlled fields is due to the thermal structure of the mantle and is independent of the stress field. The type example is the Eastern Snake River Plains VF, which has a very high eruptive flux. In this example, the Yellowstone mantle plume is suggested to provide sufficient melt accumulation to allow buoyancy to overcome any inhibitive forces and act independent of regional tectonic forces (Hughes et al., 2002; Kuntz et al., 1992; Valentine and Perry, 2007).

The models detailed by Valentine and Perry (2007) are specific to processes which drive the accumulation of melt and allow it to accumulate and ascend, overcoming inhibitive forces. They do not specify the need for a particular mechanism driving magmatism. However, the processes controlling magma genesis also relates to either tectonic or magmatic processes (Brenna et al., 2015). Tectonic processes that generate magma at IBVFs relate to processes that drive upwelling or focus melt already present in the upper mantle. This includes processes such as; continental extension (Aranda-Gómez et al., 2003), upward concave plate flexure (Valentine and Hirano, 2010), slab-roll back (Brenna et al., 2015), slab-window convection (D'Orazio et al., 2000), shear driven convection (Conrad et al., 2010) and edge-driven mantle convection (Demidjuk et al., 2007) and others. Magmatic control includes cases where a thermally buoyant deep mantle-plume drives magma genesis, acting independent of shallow tectonic processes (Ritter et al., 2001). However, a plume can interact with a tectonic process (Ritter et al., 2001; Tatsumi et al., 2005), as is likely the case for the Eastern Snake River Plains VF with melt derived from the Yellowstone Plume interacting with extensional structures of the northern Basin and Range Province (Hughes et al., 2002).

The case for both tectonic processes and mantle plumes as drivers of volcanism is made for individual IBVFs in several cases (Brenna et al., 2015; Demidjuk et al., 2007; Graeber et al., 2002; Harangi et al., 2014; Ritter et al., 2001; Tatsumi et al., 2005), which occur in a range of tectonic settings and vary in long-term eruptive flux over several orders of magnitude. Recent literature discussing tectonic controls *versus* mantle plumes in the case of such fields favour tectonic processes as the control on volcanism (Brenna et al., 2015; Demidjuk et al., 2007; Harangi et al., 2014; Mashima, 2009). These studies have used detailed volume, age and geochemistry data collected for individual volcanoes to provide the basis for establishing eruption short-term eruptive flux and spatio-temporal patterns (Brenna et al., 2015; Valentine and Connor, 2015). This method provides the best means for determining controls on volcanism; however, not all IBVFs have the appropriate data available (Valentine and Connor, 2015). Hence, it is of interest to discuss the trends of long-term eruption flux and other variables in relation to tectonic or magmatic primary controls on volcanism at IBVFs. Here we discuss how these primary controls can be established for IBVFs where no detailed volume and geochronology data exist by taking one of the more complex IBVFs as a case study; the Newer Volcanics Province (NVP) of south-eastern Australia.

We use high resolution aeromagnetic and borehole log data to map out the extent of the NVP of south-eastern Australia, similar in method to Blakely et al. (2000); from this map a new volume model is built using computer modelling software. Taking into account estimates of erosion and the available geochronology of the NVP, the mean long-term eruption flux of the system is calculated. We compare our results of the NVP with the size, eruption flux and tectonic setting with other IBVFs, and discuss the validity of the IBVFs controlled primarily by tectonic processes versus magmatic mantle plume models.

2. Geological setting of the Newer Volcanics Province

The Pliocene–Recent Newer Volcanics Province (NVP) is a large and spatio-temporally complex IBVF (Cas et al., 2016) that has been described as either being related to a deep mantle plume (Graeber et al., 2002), as well as upper mantle and crustal process (Demidjuk et al., 2007; Lesti et al., 2008). The NVP is characteristic of a low eruption frequency, basaltic plains field with >416 identified small basaltic eruption centres (Cas et al., 2016), of which 39 have been dated using a variety of methods giving a range of ages between 4.6 Ma–5 ka (cf. Cas et al., 2016 and the references therein). The number of dated volcanic centres throughout the field is insufficient to provide a detailed time-volume analysis of the field. However; the majority of the field's area and volume is suggested to have been produced between 3 and 1.8 Ma, with eruptions of this age associated with the vast tholeiitic lava plains whilst younger alkaline eruptions are associated with lesser volume edifices (Wellman, 1974; Vogel and Keays, 1997).

The NVP is subdivided into three sub-provinces; the Central Highlands, Western Plains and Mount Gambier sub-provinces based on geomorphology. Its extrusive deposits overlie Palaeozoic metasedimentary rocks and granitic rocks of the Delamerian and Lachlan Fold Belts to the north and sedimentary sequences of the Otway Basin to the south (Cas et al., 2016) (Fig. 1b). The majority of NVP deposits are composed of basaltic lavas and lesser scoria and ash deposits (Cas et al., 2016; Hare and Cas, 2005). In the regional total magnetic intensity (TMI) anomaly map, the basaltic lava flows are characterised by a high magnetic response with a distinct stippled texture (Figs. 1 and 2), which is typical of thin deposits of basaltic material near to the surface (Hare and Cas, 2005).

The NVP is an interesting example of an IBVF because it occurs within a compressional local stress-field (Le Corvec et al., 2013). Models explaining the source of volcanic activity in the NVP include: hotspot trails, post-rift diapirism, transtensional decompression, and edge-driven convection of the upper mantle (cf. Cas et al., 2016 and the references therein). Geochemical signatures and hydrous mineral-rich mantle xenoliths shows the upper mantle beneath the NVP hosts metasomatised zones necessary for melting to occur (cf. Cas et al., 2016 and the references therein).

The NVP is a juvenile IBVF and is consequently well preserved and exposed, though significant areas are covered over by recent alluvium and/or coastal dune deposits (Cas et al., 2016; Hare and Cas, 2005). Some lava plains and eruptive centres extend off Victoria's southern coast where they are submerged (Cas et al., 2016). These characteristics make it amenable to detailed 3D volume estimates.

3. Methods

3.1. Mapping the extent of Newer Volcanics Province deposits

The aeromagnetic anomaly maps of Victoria and South Australia were collected at 80 m elevation, line spacing of 200 m, and have a grid cell size of 50 m. Australian Geomagnetic Reference Field values for the NVP were: magnitude = 53806 nT; inclination = −56; declination = 5.5. Young basaltic rocks exhibit a stippled magnetic response and show the extent of the volcanic succession and the geometry of their boundaries. This enabled the total extent of deposits to be determined. The new extent was built by modifying the 'Newer Volcanic Group' polygon from the Geological Survey of Victoria (GSV) 1:1,000,000 map sheet (seamless geology 2011 edition) (Fig. 2). The scoria and tuff deposit polygons derived from 2014 edition of the seamless geology map sheets were included and modified to provide a more accurate deposit extent. The total

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