What lies beneath: how can we study the inner workings of volcanoes and their plumbing systems?

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Abstract

Craig Magee and **Chris Jackson** examine how geophysical seismic reflection data can be used to image volcanoes and magma plumbing systems.

Volcanoes are awe-inspiring natural phenomena found throughout the Solar System. They fascinate and enthuse children and adults alike, providing an important route into geoscience for young adults. Beyond being photogenic, we study volcanoes for a variety of reasons (e.g., Martí and Ernst, 2008, Sigurdsson et al., 2015): (1) volcanoes provide important habitats for life on Earth, whereas their eruption can threaten the very life they harbour; (2) volcanic degassing, which may occur during major, catastrophic eruptions or during inter-eruption periods of relative calm, can influence the global climate, and in the past have driven mass extinctions; (3) the chemistry of igneous rocks, the products of magma (molten rock) moving through the crust to be erupted at volcanoes, can provide crucial insight into plate tectonic and deep Earth processes through time; and (4) the development of magma plumbing systems, which modulate volcano growth and eruption, is intimately linked to the accumulation of the many natural resources (e.g., minerals and metals) required to build a sustainable future. We have also taken to examining volcanoes on other planets, such as Mars, to see what they can tell us about planetary evolution. Given the importance of volcanoes to human life and development, we have made great strides in understanding their origins and formation.

We typically study active volcanoes by measuring their surface morphology and/or examining the chemistry or mineralogy of erupted material (e.g., lavas or gas). These studies help unravel how volcanoes have grown and evolved, and how magma is currently behaving beneath them (e.g., Grosse et al., 2009, Grosse et al., 2014, Cashman and Sparks, 2013). By coupling this information with studies of ancient volcanic centres, where erosion of the volcano has allowed access to the network of pipes and conduits that deliver magma through Earth's crust to the surface, we can identify tell-tale signs of magma movement (e.g., earthquakes and ground deformation); this helps us better understand their subsurface structure and potential hazard (e.g., Sparks et al., 2012, Segall, 2013, Ebmeier et al., 2018, Biggs et al., 2013, Biggs et al., 2011, Chouet and Matoza, 2013). Although we can go to the field and study ancient magma conduits (intrusions), which typically have vertical (dykes) or horizontal (sills) sheet-like geometries, we can only directly measure their intersection with Earth's surface. This limitation in access to magma plumbing system structure led to the paradigm that rock melts at depth towards the base of the crust, magma is transported vertically upwards, and builds up in subsurface (magma) 'chambers' from which it is erupted (e.g., Cashman and Sparks, 2013); this is what we call the 'textbook' scenario (Fig. 1A). However, this simplistic view of vertically arranged conduits and voluminous reservoirs of liquid is being replaced by a vision of transcrustal plumbing systems dominated by 'mush', i.e. a crystal framework with pores containing melt, through which small volumes of magma migrate and accumulate (Fig. 1B) (e.g., Cashman et al., 2017, Magee et al., 2018, Cruden and Weinberg, 2018). Key to realising this new paradigm of magma plumbing systems has been the integration of cutting-edge petrological and geochemical work with: (1) geophysical techniques that can image zones of mush and magma within the crust (e.g., seismic tomography); and (2) geodetic methods that can invert ground deformation patterns to model the location, geometry, and dynamics of subsurface magma movement (see Magee et al., 2018 and references therein). Here we discuss how we, and others, have used reflection seismology, a technique traditionally applied to finding oil and gas, to contribute to the evolving paradigm that describes how magma plumbing systems and volcanoes are constructed. For example, we show how seismic reflection data, coupled with structural and chemical analyses of sills exposed at Earth's surface, has helped demonstrate that volcanic systems may not be vertically stacked, but instead comprise laterally extensive intrusion networks (Fig. 1C) (Magee et al., 2016). We also take a brief look at two areas of reflection seismology that look to advance our understanding of volcanism across the Solar System in the near-future.

Reflection seismology

Reflection seismology is a technique that involves firing acoustic energy (i.e. seismic waves) from a source down into the subsurface (Fig. 2). When this acoustic energy encounters boundaries between materials with different physical properties, some energy is transmitted onwards deeper in the Earth, whilst some is reflected back to the surface (Fig. 2). By measuring the arrival times (i.e. the travel-time) and amounts of reflected energy returned to the surface, we can build an image of Earth's subsurface structure. Depending on the seismic reflection survey design, these images may either: (1) constitute extensive 2D cross-sections capable of imaging 10's of kilometres below Earth's surface across 100's of kilometres distance; or (2) form part of a dense grid of seismic lines that can be interpolated to image the Earth's subsurface structure in 3D, typically over a small area than 2D techniques. Traditionally, these seismic reflection techniques have been used to explore for hydrocarbons in basins comprising thick accumulations of sedimentary rocks. However, igneous rocks typically have very different physical properties (e.g., densities of >2.5 g/cm^3 and acoustic velocities of >4000 ms^{-1}) compared to surrounding sedimentary rocks (e.g., densities of 1.6–3 g/cm^3 and acoustic velocities of >2000–5000 ms^{-1}) (Fig. 2). Due to these difference in the physical properties of igneous and sedimentary rocks, volcanoes and their crystallised magma plumbing systems are thus commonly well-imaged in seismic reflection data (e.g., Fig. 2).

Seismic reflection imaging of volcanoes

Most volcanoes studied using seismic reflection data are ancient and have long since been buried by layers of younger sedimentary rock (e.g., Fig. 2). Importantly, these encasing sedimentary strata protect the volcanic edifices from erosion and thereby preserve external volcano morphologies (Jackson, 2012). By interpreting the top surface of volcanoes in seismic reflection data we can create a topographic map of ancient volcanic fields (e.g., Fig. 3A), comparable to imaging modern volcanoes using satellite or bathymetry techniques. From these maps we can extract and quantify the shape of ancient volcanoes (e.g., Sun et al., 2020, Magee et al., 2013b, Reynolds et al., 2018). Such quantitative information on edifice morphology has been used to reconstruct how modern volcanoes may grow, by assuming small volcanoes become large volcanoes (e.g., Grosse et al., 2014, Grosse et al., 2009, Rossi, 1996). For example, Grosse and Kervyn (2018) compile data from a range of shield volcanoes and developed a complicated framework to describe the controls on how they may grow and erupt. A key limitation to these studies of modern volcanoes is that interpreted growth models cannot be easily validated; i.e. we cannot see the inner geometry of modern and commonly still-active volcanoes to test how they grew. Seismic reflection data circumvents this lack of access because, in addition to imaging their external morphology, internal layers can also be imaged (e.g., Figs 2 and 3B) (e.g., Sun et al., 2020, Magee et al., 2013b, Reynolds et al., 2018). Several studies have used seismic reflection data to examine how the external morphology of ancient volcanoes compares to their internal architecture, showing that many appear to grow via a commensurate increase in summit height and basal diameter (e.g., Fig. 3B) (e.g., Sun et al., 2020, Magee et al., 2013b, Reynolds et al., 2018). Overall, seismic reflection data offer an opportunity to examine the external and internal morphology of volcanoes for the first time.

Seismic reflection imaging of magma plumbing systems

A major benefit of reflection seismology is that not only can we image the external morphology and internal architecture of volcanoes, but we can see their underlying magma plumbing system (e.g., Fig. 2). Because seismic reflection data is compiled from acoustic energy returned to the surface, this technique favourably images sub-horizontal-to-moderately inclined magma conduits and related rock bodies (e.g., sill, inclined sheets, and laccoliths; Smallwood and Maresh, 2002, Jackson et al., 2013, Magee et al., 2016, Eide et al., 2018). Over the last two decades, seismic reflection-based studies have shown that many intrusive components of magma plumbing systems within sedimentary basins have a saucer-shaped morphology (e.g., Thomson and Schofield, 2008, Thomson and Hutton, 2004, Schmiedel et al., 2017, Magee et al., 2013a, Planke et al., 2005); these are imaginatively called ‘saucer-shaped sills’ and comprise a relatively flat inner base surrounded by inwardly dipping sheets (Fig. 4A) (e.g., Malthe-Sørenssen et al., 2004, Polteau et al., 2008). These saucer-shaped sill reflections commonly contain discrete vertical offsets that are broadly linear in map-view (Fig. 4A) (e.g., Schofield et al., 2017, Schofield et al., 2012a, Magee et al., 2014, Magee et al., 2013c). By studying similar features in sills exposed in the field, these vertical offsets have been interpreted to represent the seismic expression of ‘steps’, ‘bridges’, or ‘magma fingers’ (Magee et al., 2019c, Schofield et al., 2012b, Hutton, 2009). These steps, bridges, and fingers form during magma injection (e.g., Hutton, 2009, Pollard et al., 1975, Schofield et al., 2012b, Schofield et al., 2010, Galland et al., 2019) and although they form in response to different processes, their long axes all sub-parallel the magma propagation direction (see Magee et al., 2019c and references therein). Mapping vertical offsets in sill reflections related to step, bridge, or finger formation thus allows us to reconstruct how magma once flowed through the host rock (e.g., Fig. 4A) (Schofield et al., 2017, Magee et al., 2014, Schofield et al., 2012a). Critically, the interpretation of sills and magma flow patterns across parts of sedimentary basins has shown that sills may be interconnected (i.e. forming a sill-complex) and facilitate magma transport across 10’s kilometres vertically and 10–100’s kilometres laterally (e.g., Fig. 1C) (Magee et al., 2016). The recognition that sill-complexes can transport magma laterally over vast distances, which has been corroborated by studies of sills exposed at Earth’s surface, questions long-held assumptions that volcanic systems are vertically stacked and that eruption sites broadly overlyie deep zones of melt generation (Fig. 1) (Magee et al., 2016).

In addition to being able to map intrusion geometries and magma flow patterns using seismic reflection data, we can also image the deformation (folding and fracturing) of the rock around sills that is generated to make space for magma injection. By examining host rock deformation around intrusions, we can unravel when and how magma injection occurred (e.g., Trude et al., 2003, Hansen and Cartwright, 2006). Typically, space for shallow-level intrusions is generated by uplift of overlying rock and free surface (e.g., Koch et al., 1981, Pollard and Johnson, 1973). Analysing such intrusion-related uplift of Earth's surface is key to hazard assessment at active volcanoes as it allows us track magma movement and accumulation in near real-time (e.g., Sparks et al., 2012, Segall, 2013, Ebmeier et al., 2018, Biggs et al., 2013, Biggs et al., 2011). In particular, surface uplift can be inverted to model underlying the shape and location of underlying intrusions, but this relies on assuming that space for the intrusion is solely generated by uplift (e.g., Pritchard and Simons, 2004). Seismic reflection-based studies of ancient intrusions, coupled with field analyses and laboratory modelling, confirm that uplift of rock above sills can spatially accommodate their intrusion (i.e. uplift produces structures called 'forced folds'; e.g., Fig. 4A) (e.g., Jackson et al., 2013, Hansen and Cartwright, 2006, Magee et al., 2013a). However, studies have also shown that other host rock deformation processes, such as collapse of pore spaces, can also generate space for intruding magma; where these processes and uplift occur, the height of forced folds can be significantly less than intrusion thickness (e.g., Magee et al., 2019b, Magee et al., 2013a, Jackson et al., 2013, Galland, 2012, Morgan et al., 2008). This potential difference between forced fold shape and size compared to that of the underlying intrusion implies inversion of surface uplift patterns may underestimate magma volumes if no other processes are considered to provide space for magma injection (e.g., Magee et al., 2018).

To-date, a major limitation of seismic reflection data has been our relative inability to seismically image buried, near-vertical sheet intrusions (dykes), which are expected to play a dominant role in transporting magma through the crust to be erupted at the surface (e.g., Fig. 1). This problem occurs because near-vertical dykes reflect only a limited amount of acoustic energy back to the surface and are thus typically poorly imaged in seismic reflection data (Smallwood and Maresh, 2002, Planke et al., 2005, Thomson, 2007, Wall et al., 2010, Eide et al., 2018). Where dykes have been rotated due to later deformation, they may be imaged in seismic reflection data (e.g., Fig. 4B) (e.g., Phillips et al., 2018, Abdelmalak et al., 2015). For example, Phillips et al. (2018) identify a swarm of dykes offshore southern Norway, which were originally near-vertical but since their intrusion have been tilted (Fig. 4B). These data revealed for the first time how dyke swarm geometry varies with depth, particularly showing that only dykes within the centre of the swarm ascended to shallow levels (Fig. 4B) (Phillips et al., 2018). A swarm of vertical dykes has just recently been discovered in seismic reflection data from offshore North-west Australia, i.e. the Exmouth Dyke Swarm, where individual dykes correspond to thin near-vertical zones where reflections from the flat-lying sedimentary rocks are disrupted; i.e. the dykes are co-located with areas where less seismic energy is returned from, such that they appear in seismic reflection data as zones of poor or no imaging (Fig. 4C) (Magee and Jackson, 2020a). The Exmouth Dyke Swarm is perhaps up to ~500 km long and ~300 km wide, and provides a unique opportunity to examine the 3D geometry of a vertical dyke swarm (Fig. 4C) (Magee and Jackson, 2020a). In addition to the dykes themselves, the seismic reflection data imaging the Exmouth Dyke Swarm also captures overlying host rock deformation structures related to its emplacement (Fig. 5) (Magee and Jackson, 2020a). These host rock deformation structures include (Fig. 5): (1) dyke-induced faults, where rock has fractured and slipped along inclined surfaces (normal faults) that extend along the length of and dip towards the dyke tops; and (2) pit craters, sub-circular depressions that are underlain by a vertical pipe connected to dyke tops or dyke-induced faults (Magee and Jackson, 2020a). Dyke-induced faults form because space for the underlying dyke is generated by extension of the host rock, but because magma does not reach the surface, the host rock extension above the dyke instead manifests as faults (e.g., Pollard et al., 1983, Rubin, 1992, Trippanera et al., 2015b). The origin of pit craters has remained enigmatic (e.g., Wyrick et al., 2004), but seismic reflection data from offshore

North-west Australia provides the first conclusive evidence that they may extend down and likely form in response to dyke intrusion (Fig. 5) (Magee and Jackson, 2020a).

Ongoing and future developments

There is a vast amount of seismic reflection data available that image volcanoes and their magma plumbing systems, but relatively few scientists utilising these data. In addition to progressing our understanding of the structures and processes described above, there are two novel applications of seismic reflection data worth mentioning here. The first concerns how we can use seismic reflection data to understand the subsurface structure of other planetary bodies. For example, dyke-induced faults and pit craters have been recognised in magmatic settings not only on Earth, but also on other planetary bodies such as Mars (e.g., Mastin and Pollard, 1988, Rubin and Pollard, 1988, Pollard et al., 1983, Trippanera et al., 2015a, Whitten and Martin, 2019, Frumkin and Naor, 2019, Okubo and Martel, 1998). Before their recognition in seismic reflection data, we have typically only been able to access the surface expression of these natural features and thus have had to infer their subsurface structure (e.g., Mastin and Pollard, 1988, Rubin and Pollard, 1988, Pollard et al., 1983, Trippanera et al., 2015a, Whitten and Martin, 2019, Frumkin and Naor, 2019, Okubo and Martel, 1998). From these inferences of subsurface structure, we have identified how the surface expression of these features could be used to estimate subsurface properties; e.g., the measured distance between and dip of a dyke-induced fault pair at the surface has been used to estimate depths to dykes (e.g., Hjartardóttir et al., 2016, Wilson and Head, 2002, Trippanera et al., 2015b). Seismic reflection data allow us, for the first time, to test these assumptions of how the surface expression of natural dyke-induced faults and pit craters may reflect subsurface structure (e.g., Fig. 4C and 5) (Magee and Jackson, 2020a, Magee et al., 2019a).

Unfortunately, preliminary analyses suggest it may be more difficult to invert the surface expression of dyke-induced faults and pit craters, to recover information on subsurface structure, than previously anticipated (Magee and Jackson, 2020b).

Perhaps the most exciting application of reflection seismology to volcanology is the move to generating seismic reflection images of active volcanoes. Along the East Pacific Rise, a 3D seismic reflection survey was recently acquired over the Axial Seamount volcano using a traditional acquisition design (Carbotte et al., 2020, Arnulf et al., 2014). These data have imaged magma and mush in a series of sills beneath the Axial Seamount, and highlighted the role of faults in directing magma flow pathways (e.g., Fig. 6A) (Carbotte et al., 2020, Arnulf et al., 2014). Similarly, an active source seismic experiment at Mt St Helens, conducted as part of the recent iMUSH (imaging Magma Under St Helens) project, has imaged crustal reflections that illuminate its magma plumbing system (e.g., Levander and Kiser, 2019). In addition to traditional surveying methods, reflections from passive (natural) seismicity at Krafla volcano, Iceland, have been used to image a magma reservoir proven by drilling data (e.g., Fig. 6B) (Kim et al., 2020). Acquiring seismic reflection data from active volcanoes provides a new frontier in understanding the internal workings of volcanic systems.

Conclusions

Reconstructing the emplacement and growth of volcanoes and their plumbing systems is critical to understanding eruption locations and dynamics, which feed into hazard assessments, and the distribution of magma-related critical raw materials resources. Here we show the seismic reflection data provides unique imaging of the internal architecture of volcanoes and illuminates magma plumbing systems. Although most volcanoes and intrusion imaged in seismic reflection data are ancient, and their activity long-since ceased, we show how we can peel away their layers, or map magma flow structures to reconstruct their emplacement. We also demonstrate how seismic reflection data can be used to interrogate host rock deformation processes that occur in order to generate space for intruding magma.

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Figure captions

Figure 1: The schools of thought on the structure of magma plumbing systems. (A) Volcanoes generated above vertically stacked systems of dykes connecting magma reservoirs and/or a transcrustal mush zone, occur directly above areas of melt production. (B) Sill complexes can transport magma laterally and vertically through the crust, such that associated volcanoes may be offset from areas of melt production.

Figure 2: Cartoon of Earth's subsurface structure depicting how seismic waves may reflect from rock-rock boundaries, and how we can use this to image sedimentary layers, volcanoes, sills, and associated host rock deformation (e.g., forced folds). Seismic section from the Bight Basin, offshore S Australia.

Figure 3: (A) Oblique view of the Top Volcano surface mapped across part of the the Bight Basin; note the volcanoes are all shield volcanoes but the surface is vertically exaggerated to highlight the edifices. Vertical scale is presented in seconds two-way travel-time (TWT). (B) Seismic sections through a volcano shown in (A), highlighting that internal layers within the volcano can be mapped.

Figure 4: (A) A seismic section and 3D view of a saucer-shaped sill located offshore NW Australia (modified from Magee et al., 2013a). (B) Dyke swarm imaged in seismic reflection data, offshore S Norway (modified from Phillips et al., 2018). Inset: cartoon showing the structure of the dyke swarm and explaining how basin flexure rotated the originally vertical dykes to an inclined orientation. (C) Seismic section depicting vertical dykes, and overlying dyke-induced faults, from the Exmouth Dyke Swarm, offshore NW Australia; the map shows the spatial distribution of the dykes and the dataset used to study them (modified from Magee and Jackson, 2020a).

Figure 5: 3D view of the top of a pit crater (i.e. a sub-circular depression) developed above and linked to a dyke by a vertical pipe-like structure, in which reflections from sedimentary rocks are offset downwards. Above the dyke, two dyke-induced faults are also observed that parallel the dyke trend and dip towards the dyke top (modified from Magee and Jackson, 2020a).

Figure 6: (A) Seismic sections revealing the inner structure of Axial Seamount volcano, with high-amplitude (bright) reflections interpreted to represent a magma reservoir comprising a series of sills containing melt (Arnulf et al., 2014). (B) Seismic sections spanning the Krafla volcano, Iceland, which images high-amplitude reflections shown by borehole data to coincide with zones of magma (Kim et al., 2020).

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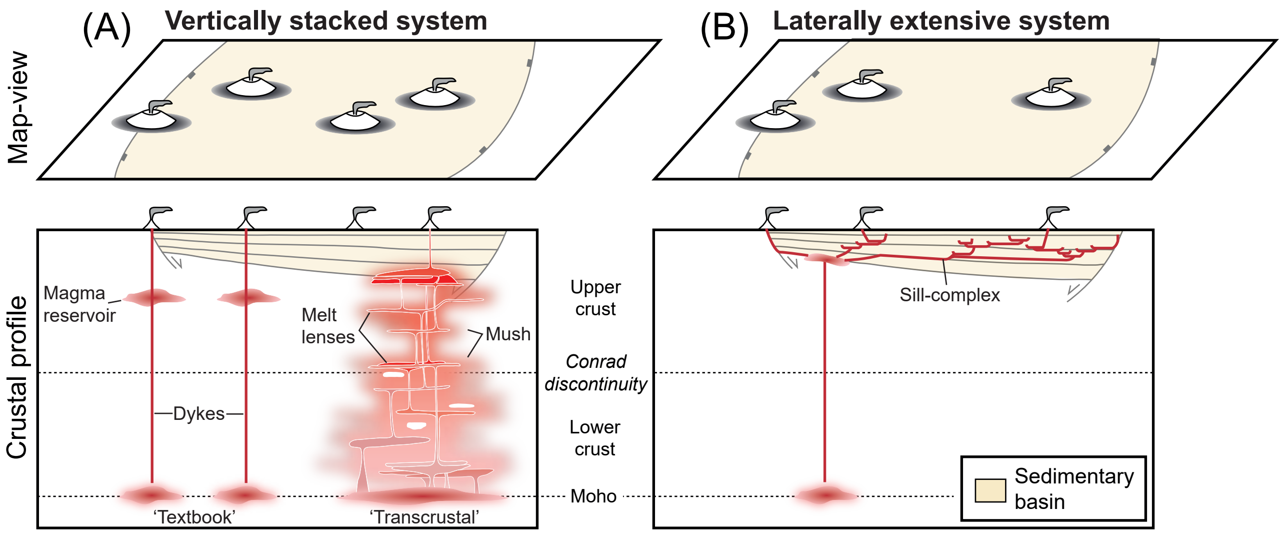
Figure 1



(A)
Vertically stacked system
(B)
Laterally extensive system
Map-view
Crustal profile
Magma reservoir
Melt lenses
Mush
Dykes
'Textbook'
'Transcrustal'
Upper crust
Conrad discontinuity
Lower crust
Moho
Sill-complex
Sedimentary basin

Figure 2

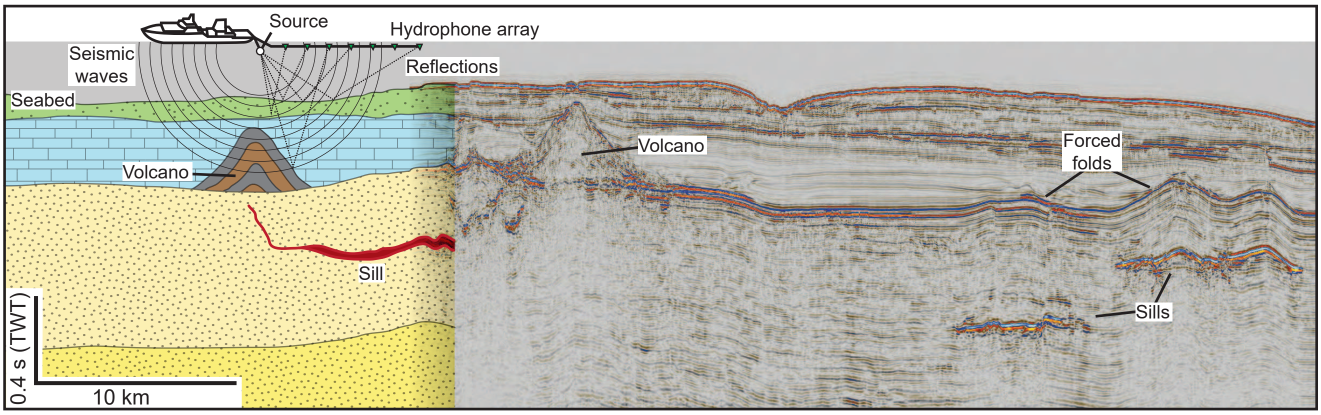
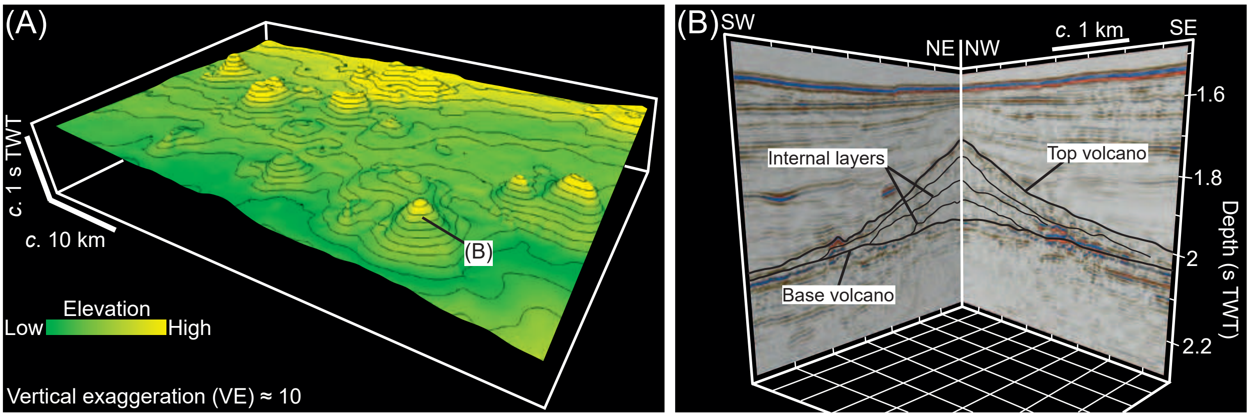
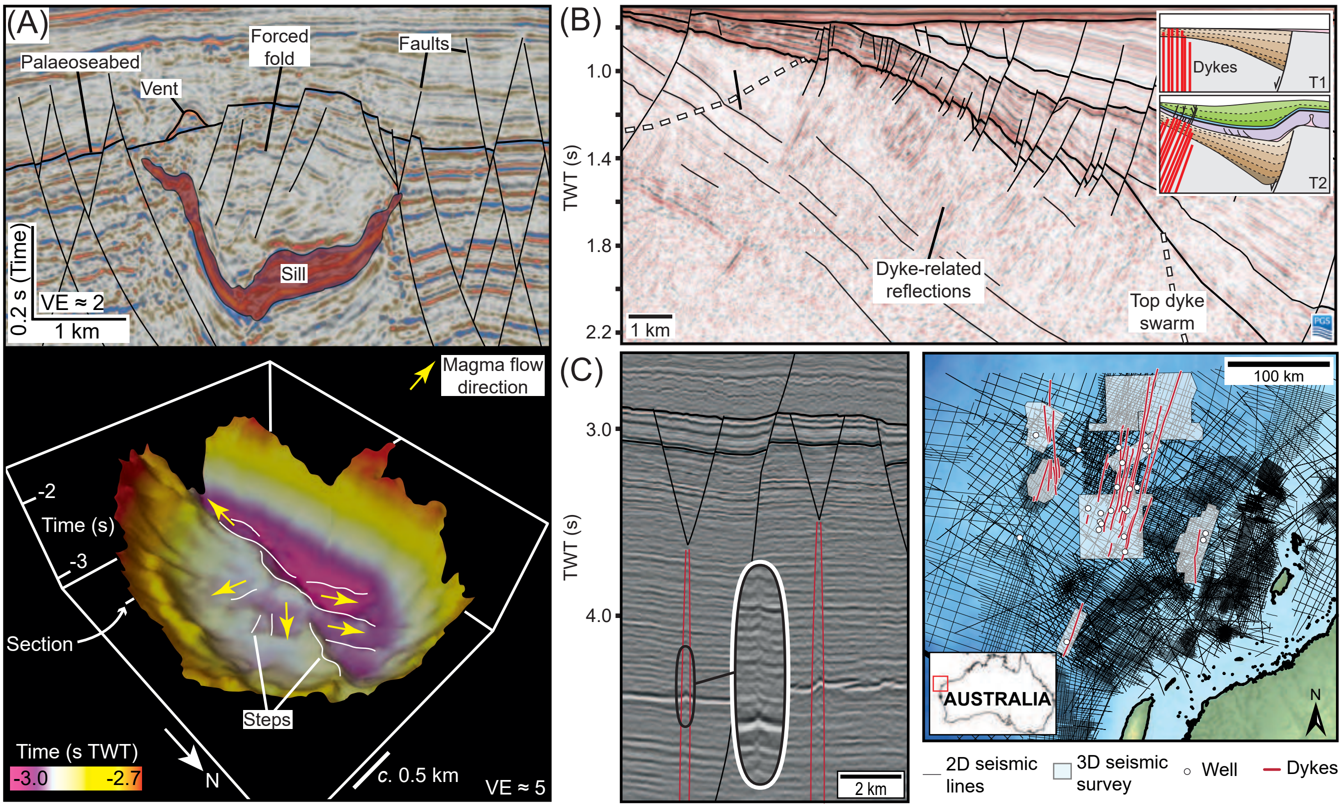

Source
Hydrophone array
Seismic waves
Reflections
Seabed
Volcano
Sill
0.4 s (TWT)
10 km
Volcano
Forced folds
Sills

Figure 3



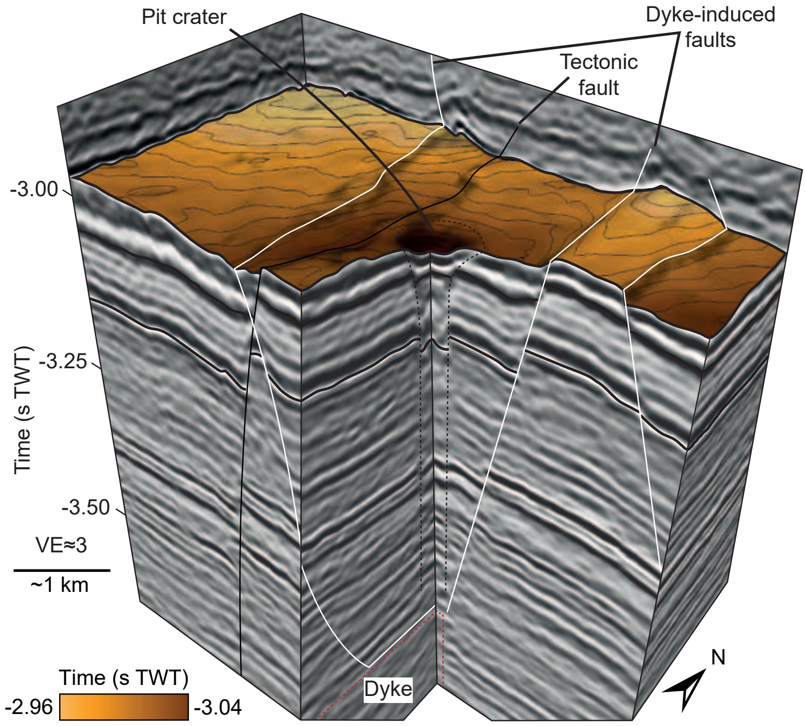
(A)
c. 1 s TWT
c. 10 km
(B)
Elevation
Low
High
Vertical exaggeration (VE) ≈ 10
(B)
SW
NE
NW
c. 1 km
SE
1.6
1.8
2
2.2
Depth (s TWT)
Internal layers
Top volcano
Base volcano

Figure 4



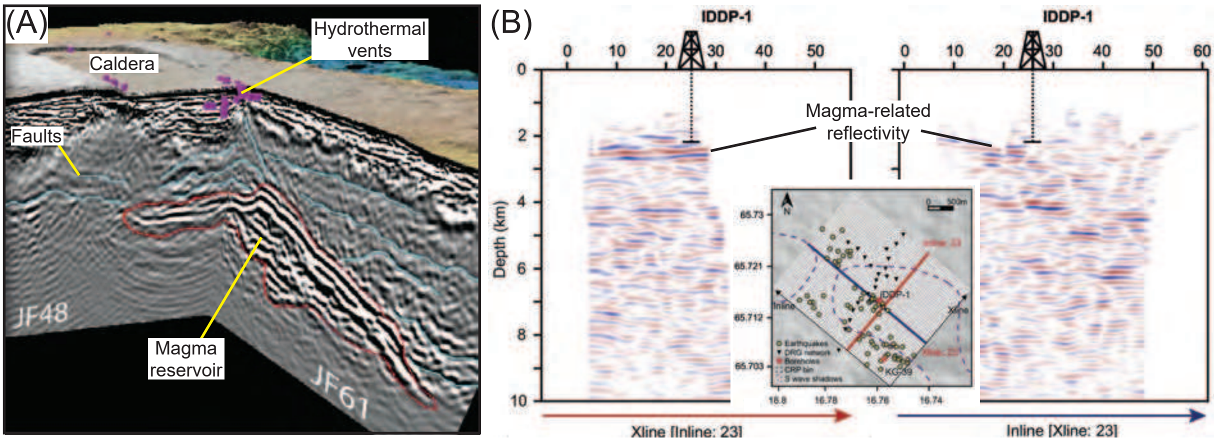
(A)
Palaeoseabed
Vent
Forced fold
Faults
Sill
0.2 s (Time)
VE ≈ 2
1 km
Magma flow direction
-2
Time (s)
-3
Section
Steps
Time (s TWT)
-3.0
-2.7
N
c. 0.5 km
VE ≈ 5
(B)
1.0
1.4
1.8
2.2
TWT (s)
Dykes
T1
T2
Dyke-related reflections
Top dyke swarm
1 km
(C)
3.0
4.0
TWT (s)
2 km
100 km
AUSTRALIA
N
2D seismic lines
3D seismic survey
Well
Dykes

Figure 5



Pit crater
Dyke-induced faults
Tectonic fault
-3.00
-3.25
-3.50
Time (s TWT)
VE≈3
~1 km
Time (s TWT)
-2.96
-3.04
Dyke
N

Figure 6


(A)
Caldera
Hydrothermal vents
Faults
Magma reservoir
JF48
JF61
(B)
IDDP-1
Magma-related reflectivity
Depth (km)
Xline [Inline: 23]
Inline [Xline: 23]