Australian Earthquake Engineering Society
2022 National Conference, 24-25 November 2022
Mount Macedon, Victoria, Australia

The challenge of characterising earthquakes in a dormant volcanic field, Queensland, Australia

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Abstract

Undara Volcanic Field in Northern Queensland lies in an area of extremely low historical seismicity but has erupted in the Holocene (c.7ka) and has an eruptive recurrence interval of c.22 ± 15 kyr. The field forms a large, very low angle volcano that overlies a northeast-striking major crustal boundary, the Etheridge-Greenvale Fault. In the context of Quaternary volcanism, the fault should be considered capable of producing major earthquakes during volcanic episodes. We use estimated area and thickness of the volcanic edifices with empirical relationships between intrusion and extrusion volumes to estimate the aggregate intrusion volume. Published relationships between intrusion volume and moment release then allow an estimate of the aggregate seismic moment. We apportion that seismic moment over a number of events consistent with the recurrence interval suggested by dating of the volcanics. Monte Carlo simulation of the uncertainties in input parameters yields a characteristic earthquake of Mw 6.7 (5.9-7.4), on a fault with a slip rate of 0.01-0.12 mma^{-1}.

Keywords: Undara Volcanic Field; earthquake; Monte Carlo.

1 Introduction

Quaternary volcanics are found across much of eastern and southeastern Australia. Most basaltic volcanic fields experience a period of heightened seismicity in conjunction with a volcanic crisis. This volcano-seismicity may reactivate faults that are favourably oriented for dilation. Volcano-seismicity thus contributes significantly to seismic hazard in areas with otherwise low evidence for seismic hazard, like parts of the Newer Volcanic Province (Mote and So, 2014).

the Kidston Pumped Hydro Energy Storage (PHES) site, which is presently under construction in northern Queensland, is an open-pit mine conversion with a turkey's nest upper reservoir impounded by a c.5 km long embankment. The embankment is formed largely of interconnected waste heaps. The scheme lies between the Undara Volcanic Field (or McBride volcanic province - one of the most well-known, longest-lived and recently active fields in Australia, centred c.70 km NE of Kidston), and the Chudleigh Volcanic Province (located southwest of Kidston). Together, the two provinces contain around 130 Late Tertiary to Quaternary volcanic vents within a 100 km radius of Kidston. Out of these vents, only 37 are dated (Cohen et al., 2017; Griffin and McDougall, 1975). Of these dated vents, 21 are Quaternary, four are younger than 200 ka and one erupted only 7 kyr ago (Figure 1).

This paper uses the Undara Volcanic Field as an example to demonstrate a method for quantifying volcano-seismic earthquake parameters in a dormant, relatively aseismic volcanic field. This study, undertaken in the context of the design of the Wises Dam embankment for the Kidston PHES, has implications for other areas globally with low perceived seismic hazard accompanied by dormant volcanism.

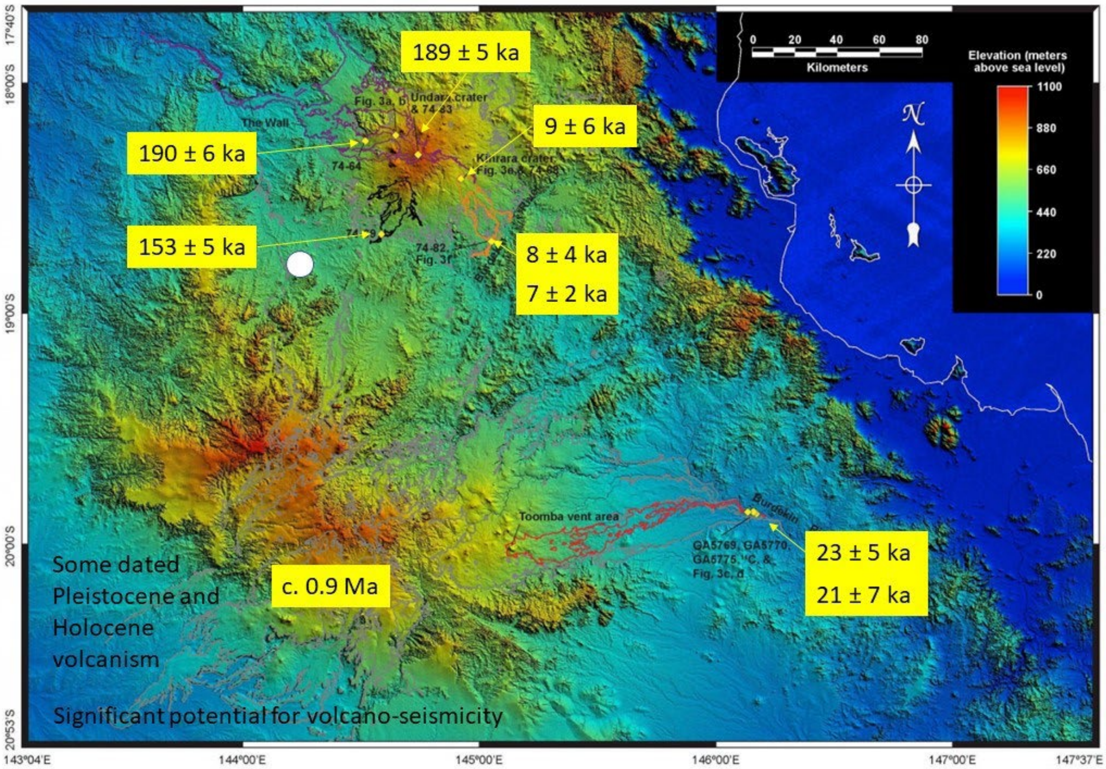

Figure 1. Location of dated volcanic flows relative to the Kidston site (white dot). Modified from Cohen et al. (2017).

2 Kidston geological setting

The Kidston PHES project is located at a geologically complicated juncture of several crustal provinces (Figure 2) (Raymond, 2018). The area is bounded to the northwest by the Jurassic Carpenteria and Cretaceous Karumba Basins and to the southwest by the Cretaceous Eromanga Basin of the Great Artesian Basin. These are draped by a thin layer of Late Cretaceous to Recent sediments of the Karumba Basin.

The basement at the PHES site consists of Paleoproterozoic rocks of the Etheridge Province. The Etheridge Province is inset by smaller Paleozoic basins such as the Gilberton Basin. About 30 km to the southeast of the site, a major NE-striking crustal boundary separates the Etheridge Province from the early Paleozoic Greenvale Province of the Thomson Orogen. This is referred to informally as the Etheridge-Greenvale fault and is crossed by a regional deep seismic reflection line (Korsch et al., 2012) which clearly shows its dip to the northwest (Figure 3).

About 60 km southeast of the Kidston PHES site, the Greenvale and Etheridge Provinces merge with the poly-deformed Broken River Province of the Silurian to Carboniferous Mossman Orogen, itself an overprint on the Thomson Orogen, at another major crustal boundary.

The crust in the Kidston area is heavily intruded by Paleozoic granitoids, including the Oak River Granodiorite that dominates much of the area surrounding the minesite, and large extents of the bedrock are covered by Quaternary volcanics of the McBride and Chudleigh Volcanic Provinces (Figure 4) (Geological Survey of Queensland, 2015a, b).

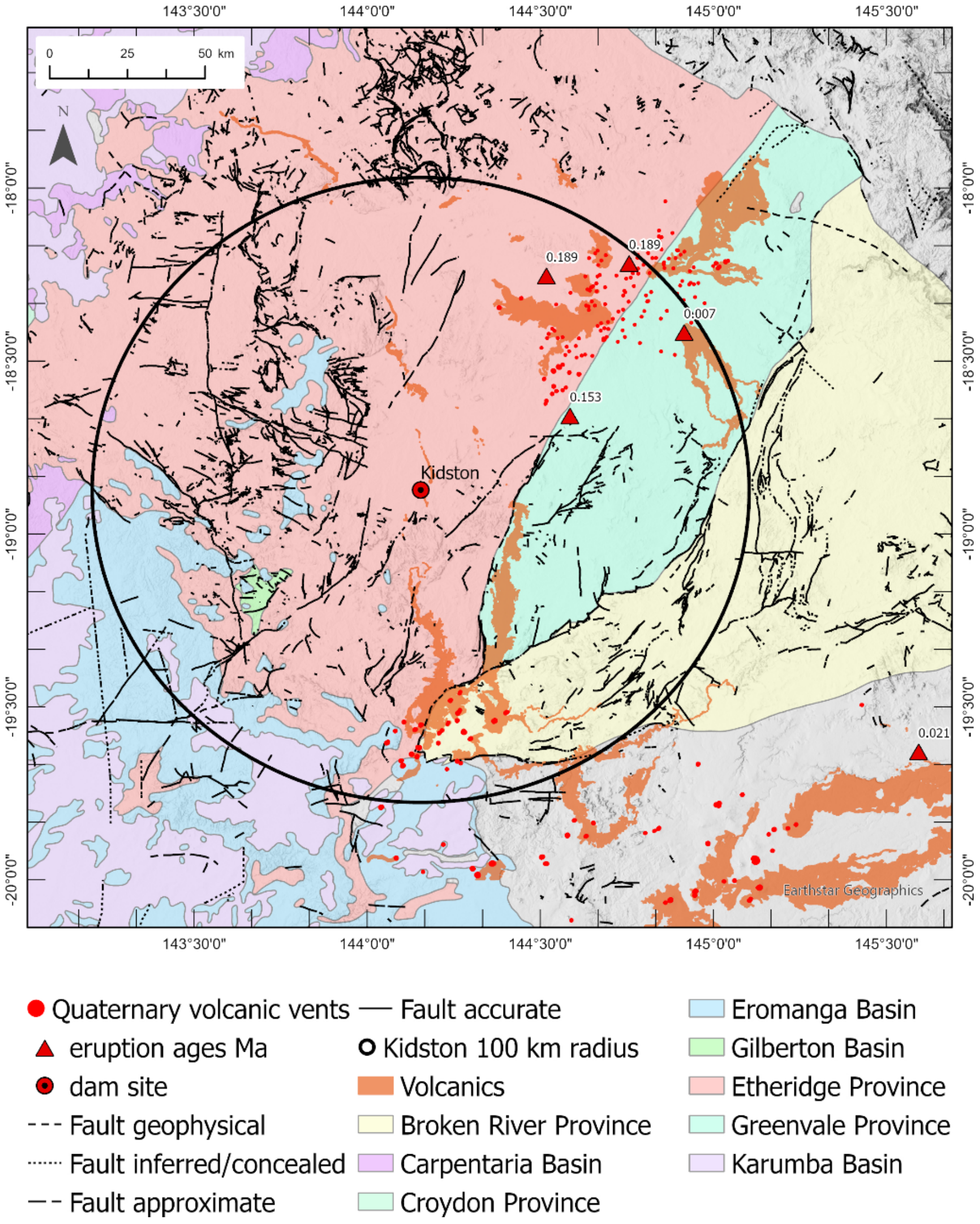

Figure 2. Northern Queensland Quaternary volcanic vents and lavas (Geological Survey of Queensland, 2015b) overlaid on 100k geological structure (Geological Survey of Queensland, 2015a) and geological provinces (Raymond, 2018). Note the proliferation of Quaternary vents 1) in the south at the intersection of the Broken River, Etheridge and Greenvale Provinces, and 2) in the northeast along the boundary of the Etheridge and Greenvale Provinces. Note also the 7-200 ka volcanism dated in this area (triangles).

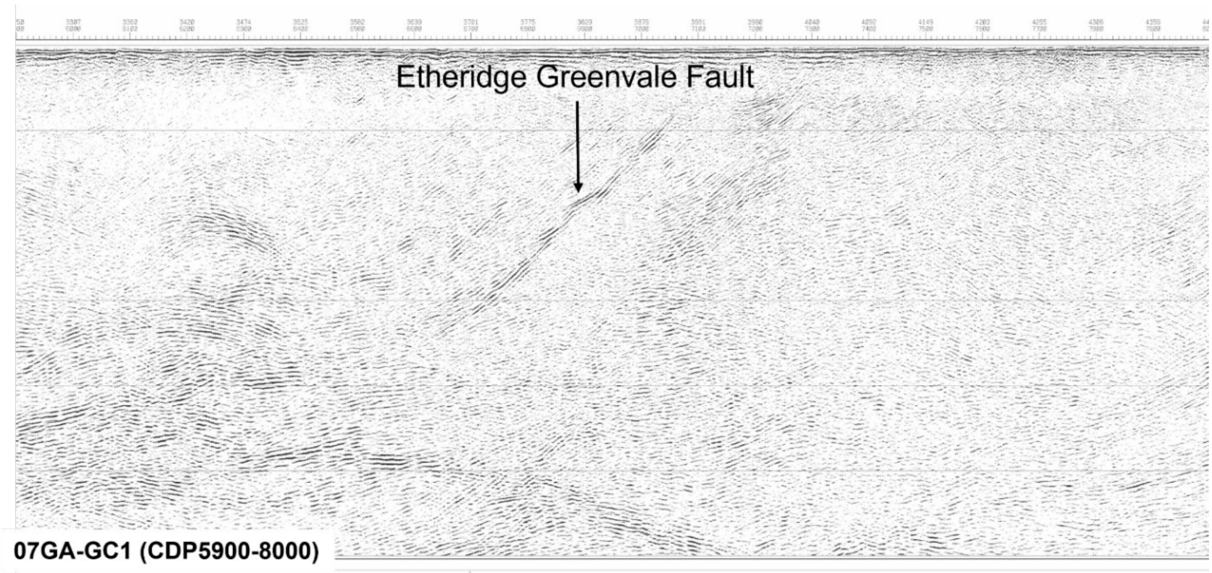

Figure 3. Part of Georgetown-Charters Towers seismic reflection section to 6s two way travel time, showing Etheridge Greendale Fault. Section is about 40 km long (Korsch et al., 2012).

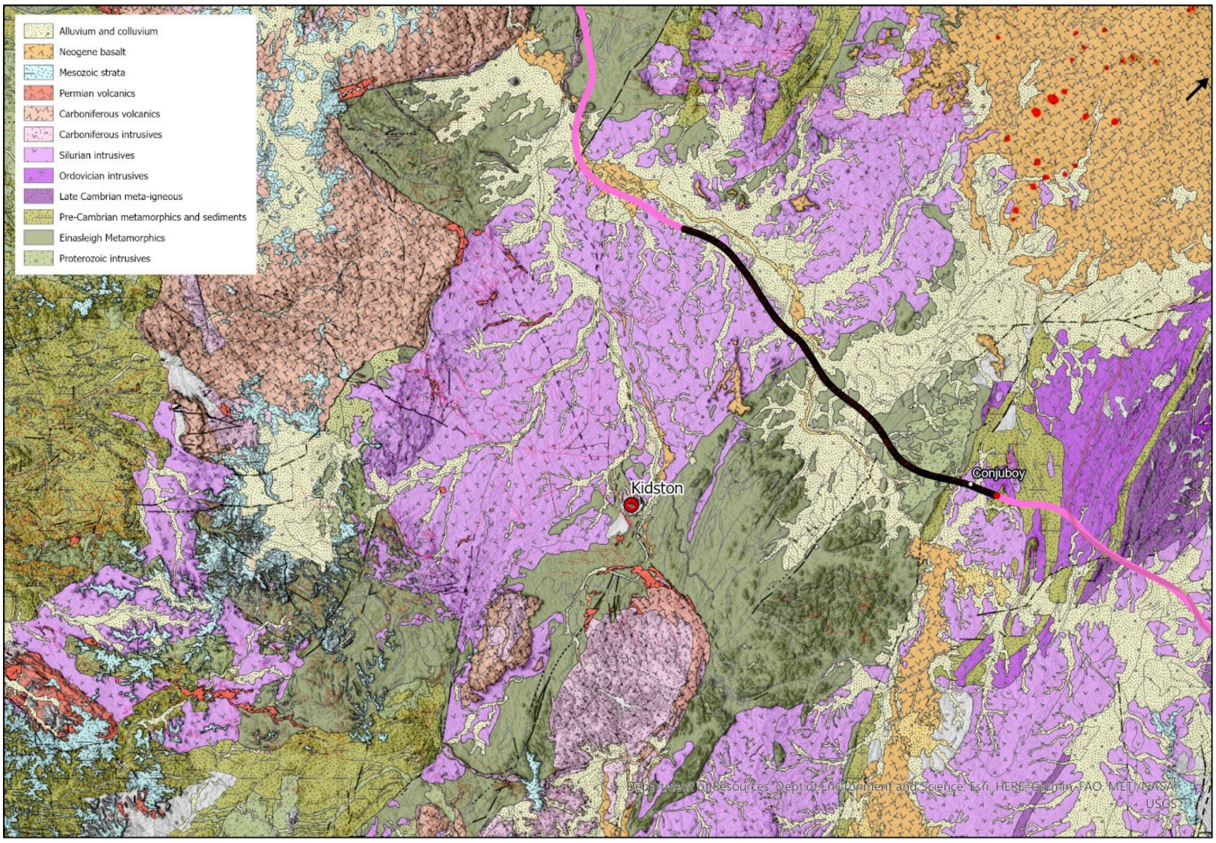

Figure 4. Simplified geology of the Kidston area, based on the Queensland seamless 100k geology map (Geological Survey of Queensland, 2015a, b). The heavy black and pink line shows the location of a regional deep seismic reflection line (Korsch et al., 2012), the black portion of which is shown in Figure 3.

3 Estimating volcano-seismic parameters

The record of past volcano-seismicity is preserved now as a regional volume of eruptives. Elucidating that record requires establishing a link between eruptive volume and seismic moment release, an estimate that requires propagating uncertainty through multiple empirical relationships.

We first use eruptive volume estimates to estimate intrusive volumes

In the East African Rift Valley, the intrusive:extrusive ratio has been estimated as about 7.8±4:1 (Wadge et al., 2016). However, other global compilations put the ratio somewhat lower, with a modal value of around 2-3:1 and a median value of 5:1, reflecting considerable variability in the value (White et al., 2006). We fit the reported ratios in both sources with a log normal distribution, truncated at the 2.5 and 97.5 percentiles. This yields a modal value of 2.5 and a median value of approximately 4.5, generally consistent with the range of reported values in White et al. (2006).

We then use the empirical relationship between intrusive volume and cumulative moment release provided by White and McCausland (2016) to estimate cumulative moment release recorded in the Undara Volcanic Field. White and McCausland (2016) gave their relationship as:

$$Log V = 0.71\ Log\ \Sigma Mo - 5.32 \qquad (Eq\ 2)$$

with volume V in cubic meters and moment Mo in Newton meters.

We rewrite this in terms of Mo as:

$$Log\ \Sigma Mo = (Log V + 5.32)/0.71 \qquad (Eq\ 3)$$

We use a Monte Carlo approach to apportion the seismic moment over the eruptive history of the field. Eruptive crises typically include multiple intrusive and magma escape events, accompanied by inflation and deflation, such as the 17 events that accompanied the eruption of Krafla volcano in Iceland (Blake and Cortés, 2018), or 13 events during eruptive crises in the Afar rift (Wadge et al., 2016). Each of these would be accompanied by a seismic swarm with its own maximum magnitude. We therefore assume that more than 10 intrusions would accompany a volcanic crisis, typically 15 and we assign a somewhat arbitrary upper limit of 40 intrusive episodes.

All distributions are quoted at 95% confidence.

3.1 Eruptive and intrusive volume and cumulative moment

The McBride Volcanic Province extends over >6000 km^2. The 1020 m high peak of the Undara Crater lies 400-500 m above the elevation of peripheral flows, at the top of a low-gradient cone, superimposed on a pre-existing, granite-cored dome (e.g., Whitehead 2010). Within the McBride Volcanic Province, at least 164 volcanic centres contribute to a volume of basalt that Sutherland (1998) estimates at around 157 km^3.

The Chudleigh Volcanic Province also lies partly within the study area. It has an areal extent of around 9500 km^2 and a volume that Sutherland (1998) estimates as around 237 km^3.

Estimates of volume by Sutherland (1998) for all northern Queensland volcanic provinces imply an average thickness at the source of 0.1±0.03 km (1SD). However, the volcanic centres stand at least 300 m above the surrounding landscape and might have resulted in flexure of the crust. We consider the Sutherland estimate to be relatively low and implying of a pronounced and sustained pre-volcanic doming.

We therefore adopt an area of volcanics equal to the sum of the McBride and Chudleigh Volcanic Provinces as defined by Sutherland (1998). We calculate a conical volume based on maximum thickness at the center of the cone of 0.3±0.2 km. This yields an extrusive volume of 410-630 km^3. Applying the estimated intrusive-extrusive ratio to the extrusive volume yields an intrusive volume ranging between 690-7200 km^3. Applying the White and McCausland (2016) relationship between intrusive volume and moment (Equation 3) thus yields a cumulative seismic moment of $0.2 - 4.1 \times 10^{23} Nm$.

3.2 Recurrence characteristics

The supplementary dataset of Cohen et al. (2017) was used to evaluate the recurrence intervals of the dated volcanic episodes within 100 km of Kidston PHES, including both the McBride and Chudleigh Provinces (Figure 5). Within the constraints imposed by limited dating, the available data suggests enhanced activity in this area over the last 0.5 Myr, with periods of activity interspersed by quiescent periods of 100-150 kyr. Within the active periods multiple eruptions occur with dated recurrence intervals of c.22 ± 15 kyr. The most recent documented eruption (the 55 km long Kinrara flow, 7 ± 2/2 ka) followed an apparent break of c.108 kyr. If it follows the apparent Late Pleistocene pattern, this is likely to be the first in another phase of eruptive activity with recurrence intervals of c.22 ± 15 kyr.

Although dating studies seem to have deliberately targeted the younger flows, many young vents remain undated. The estimate of recurrence interval is based on published dating of only 37 out of 130 vents, suggesting that if the dated age distribution is similar to the overall age distribution, there may have been as many as 16 eruptions in the last 200 kyr (recurrence interval c.12,000 years). The apparent 100kyr gaps and the apparent lower activity rates prior to 0.5Ma could be accounted for by missing dates or if eruptive products at some vents were buried by younger lavas.

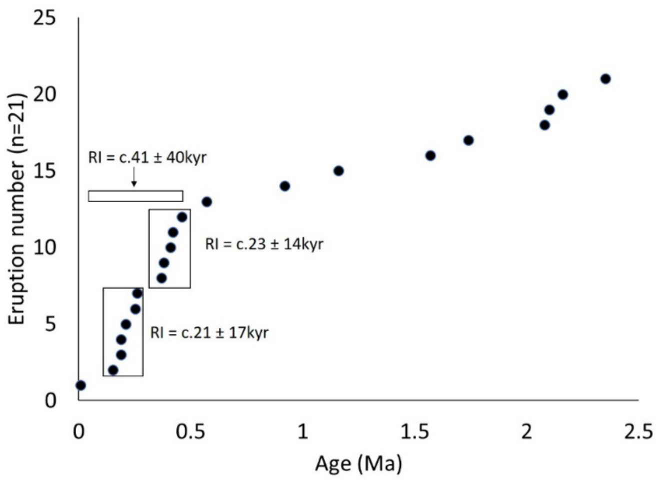

Figure 5. Age distribution and recurrence intervals of dated Quaternary volcanics within 100 km radius of Kidston mine. Data from supplementary dataset of Cohen et al. (2017).

Based on the argument above, we adopt a recurrence interval of c.22 ± 15 kyr as a reasonable estimate of recurrence interval over the late Quaternary, though we note that recurrence interval could be substantially shorter. We use the recurrence interval to obtain an estimate of seismic moment per crisis (0.005-0.5 x 10^{22} Nm). Eruptive crises may include only a single intrusive event but more typically include multiple intrusive and magma escape events, accompanied by inflation and deflation. Based on assumptions outlined previously, we assume that ten to forty intrusions would occur during a volcanic episode.

3.3 Magnitude estimate

Larger earthquakes can release most of the moment in a volcanic episode. However, in the White and McCausland (2016) catalogue, the largest earthquakes per episode only accounted for between 2% and 89% of the cumulative moment (mean 41%, st dev 23%). We therefore apportion 41±23% of the cumulative moment to the largest earthquake, yielding a largest earthquake magnitude per episode of Mw6.7 (5.9-7.4). Smaller and larger magnitudes ranging from 3.9 to 7.7 lie outside the 95%C confidence interval.

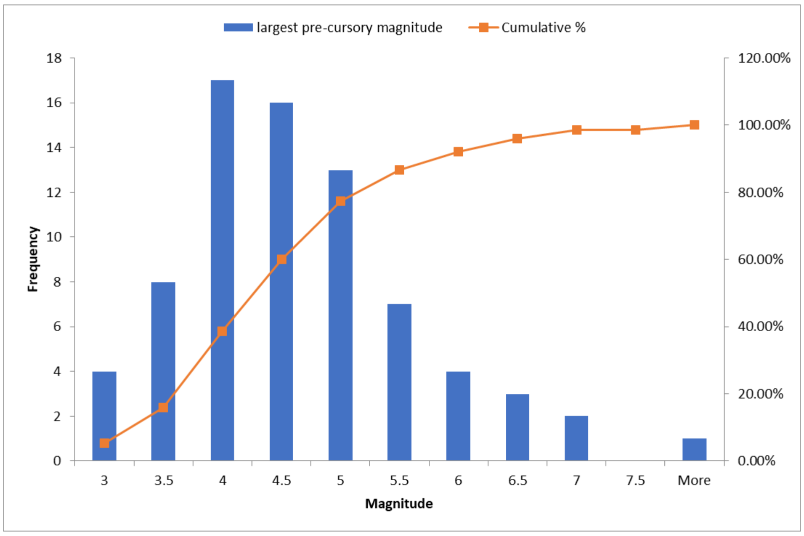

Figure 6 Magnitude frequency distribution for the largest pre-volcanic earthquakes across >100 swarms (data from White and McCausland (2016).

4 Discussion

4.1 Sensitivity of magnitude to input data

The analysis presented here uses a number of empirical, inherently uncertain inputs to assess the likely magnitude range associated with volcano-seismicity in this region. Each contributes differently to the estimated magnitude range. A sensitivity analysis indicates that the intrusion-extrusion ratio accounts for much of the uncertainty, with lower ratios yielding lower magnitudes and vice versa. Improved understanding of the intrusive volumes in these fields would therefore improve understanding of the seismic hazard they pose.

4.2 Scaling fault length from Mw

Magnitude-length scaling relations are difficult to evaluate for volcano-seismicity. This is because of several reasons including 1) such scaling is only relevant if the volcanic earthquake results from shear caused by the intrusion and 2) length-magnitude scaling relationships do not account for the effects of heat and fluid.

Stirling et al. (2013) recommend the Wesnousky (2008) normal fault earthquake scaling relationships for earthquakes in volcanic regions with thick crust. The relationship is developed for the basin and range, where low fault dip allows for high fault width within the seismogenic zone. Northern Queensland is not an analogous situation and the Wesnousky (2008) relationships founder if not used within a narrow magnitude (6.6-7.0) and length range associated with the sample set. Lengths quickly become unreasonable above Mw7 and the widths become unreasonable below Mw6.6. In this Queensland case, the upper magnitude bound exceeds the maximum magnitude for which the relationship was calculated.

Volcanoes like Mt Etna provide examples of repeated coseismic surface ruptures during volcano-tectonic events. Those events follow a magnitude-length scaling relationship (e.g., Azzaro et al. 2017) that lies approximately two orders of magnitude below the equivalent Wells and Coppersmith (1994) trend (Tringali et al. 2022). However, this dataset is contained within the edifice and specifically excludes larger events. Italian earthquakes at Mw≥5 tend to follow the Wells and Coppersmith trend (e.g., Fig 11 in Tringali et al. 2022). Villamor et al. (2001)

developed a length-magnitude scaling relationship for the Taupō Volcanic Zone. That relationship lay above the Wells and Coppersmith (1994) trend.

Although the appropriateness and choice of length magnitude scaling is uncertain, the PSHA process requires definition of parameters such as fault length and slip rates that can really only be estimated by assuming shear displacement. Given the variability of the few published relationships either side of the Wells and Coppersmith (1994) relationship, we adopt that relationship to estimate a modal rupture length of 18 km (8-180 km at 95% CI; Wells and Coppersmith (1994)). The SCR dip-slip scaling of Leonard (2014) provides a similar estimate of 22 km (9-83 km at 95% CI).

4.3 Slip rates

The Wells and Coppersmith (1994) scaling relationship for normal fault displacement yields an average displacement of 0.2-1.6 m per episode. Apportioned over the volcanic recurrence interval of c.22kyr, this yields slip rates of 0.01-0.12 mma^{-1}. The Leonard (2014) SCR relationships yield a higher displacement at the 95% CI of up to 2.4 m, giving a commensurately higher slip rate of up to 0.21 mma^{-1}.

4.4 Distance from volcanic source

White and McCausland (2016) recorded distance from source for the included earthquakes. They found that volcano tectonic seismicity driven by precursory intrusions commonly nucleated on tectonic faults at distances up to tens of kilometres from the site of the eruption, rather than at the eruption site. The greatest distance that they considered was less than 40 km from the subsequent eruptive centre and their data shows a weak relationship between magnitude and distance from source (Figure 7). Earthquakes generally occurred within a mean distance to the eruptive centre of 8.5 ± 8 km. Given the slight tendency to larger earthquakes at greater distances, we might expect an earthquake to occur at up to 15 km from the eventual eruptive centre.

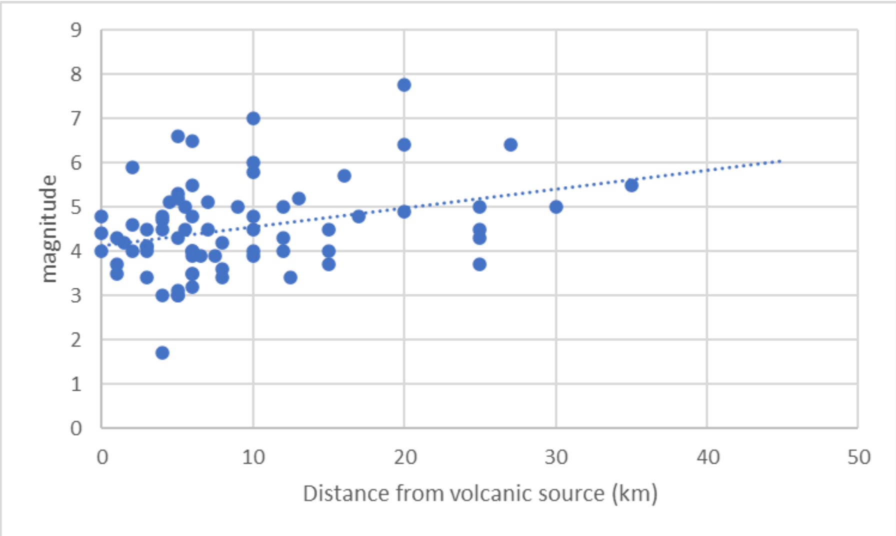

Figure 7 Plot of magnitude versus distance from source for the volcanic earthquakes in the White and McCausland (2016) dataset.

4.5 Potential volcano-seismogenic host fault

Wyatt and Webb (1970) noted that the vents of the Undara basaltic fields appear to lie on northeast trending zones up to 70 km long, which suggests that they localize along zones of crustal weakness related to major cratonic structures (Wyatt and Webb, 1970).

Figure 2 shows that the Quaternary volcanic vents either side of Kidston Mine are roughly aligned with the boundary of the Etheridge and Greenvale Provinces (the Etheridge-Greenvale Fault mentioned above). The southern part of that boundary is mapped as a major fault in the 100k scale map of Queensland (Figure 4). A fault is not mapped further northeast but examination of the topography and low-coherence magnetic data for the area indicates that the fault is obscured beneath a 70 km wide volcanic edifice centred on the province-bounding fault. Young flows radiate outward from this central high within the McBride Volcanic Province.

The smaller group of eruptive centres forming the Chudleigh Volcanic Province, including some eruptions within the last 500 kyr, are located close to the Etheridge/Greenvale/Broken River Province boundary.

Given the close association of both provinces with the Etheridge-Greenvale Fault, it should be considered volcano-seismically significant. Although the fault has no documented Quaternary significance, it does have extensive alluvium on the hanging wall on the southwest margin of the McBride Volcanic Province.

4.6 Seismic hazard of volcanic fields

Relatively little work has been done on the statistics of volcano-seismicity in the context of PSHA. The White and McCausland (2016) analysis of 136 earthquake swarms considered pre-eruptive seismicity. The distribution of the largest magnitudes in their Table 1 is shown in Figure 6 and shows that 40% of pre-cursory earthquake swarms had maximum magnitudes >4.5 and six had earthquake magnitudes >6.0. The largest was a Mw7.55 earthquake in Hawaii in the 19th century. White and McCausland (2016) only analysed pre-cursory earthquakes; the largest recorded pre-cursory earthquake at Mt St Helens was a M3.9 however the eruption was triggered by a M5.5 earthquake. Pre-cursory earthquakes thus do not capture the full extent of the hazard. Nevertheless, the estimates in our study are at the higher end of magnitude potential of the White and McCausland (2016) dataset. Reducing the recurrence interval to 12 kyr based on assumption that the temporal distribution of undated events is consistent with dated events does not greatly reduce the apparent magnitude potential.

Volcano-seismicity thus appears to dominate seismic hazard in northern Queensland, where we observe a general dearth of seismicity within 100 km of Kidston. Only one earthquake (Mb4.9 @85 km distance) and associated foreshock/aftershock sequence has been recorded within 100 km. Another poorly located event lies ~101 km distant and may have been within the radius. These are insufficient to assess earthquake recurrence. If a volcanic crisis is expected to deliver an earthquake with Mw>6.5, as suggested by Mote and So (2014) and supported by our estimates, the low seismic hazard source zone may fail to capture the real seismic hazard.

A general consideration of similar settings suggests that seismic hazard analysis for volcanic fields with long dormant intervals such as the Newer Volcanics or other Queensland fields should at least consider shallow (<5 km deep) volcanic earthquakes of Mw 6.5 or greater (Mote and So, 2014), a magnitude that would capture the upper 5% of volcanic eruptive episodes in the White and McCausland (2016) precursory-only dataset.

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