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Optimal likelihood-based matching of volcanic sources and deposits in the Auckland Volcanic Field

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In monogenetic volcanic fields, where each eruption forms a new volcano, focusing and migration of activity over time is a very real possibility. In order for hazard estimates to reflect future, rather than past, behavior, it is vital to assemble as much reliable age data as possible on past eruptions. Multiple swamp/lake records have been extracted from the Auckland Volcanic Field, underlying the 1.4 million-population city of Auckland. We examine here the problem of matching these dated deposits to the volcanoes that produced them. The simplest issue is separation in time, which is handled by simulating prior volcano age sequences from direct dates where known, thinned via ordering constraints between the volcanoes. The subproblem of varying deposition thicknesses (which may be zero) at five locations of known distance and azimuth is quantified using a statistical attenuation model for the volcanic ash thickness. These elements are combined with other constraints, from widespread fingerprinted ash layers that separate eruptions and time-censoring of the records, into a likelihood that was optimized via linear programming. A second linear program was used to optimize over the Monte-Carlo simulated set of prior age profiles to determine the best overall match and consequent volcano age assignments. Considering all 20 matches, and the multiple factors of age, direction, and size/distance simultaneously, results in some non-intuitive assignments which would not be produced by single factor analyses. Compared with earlier work, the results provide better age control on a number of smaller centers such as Little Rangitoto, Otuataua, Taylors Hill, Wiri Mountain, Green Hill, Otara Hill, Hampton Park and Mt Cambria. Spatio-temporal hazard estimates are updated on the basis of the new ordering, which suggest that the scale of the 'flare-up' around 30 ka, while still highly significant, was less than previously thought.

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1. Introduction

Volcanic fields are areas of distributed volcanism, where each new eruption typically occurs in a new location, rather than at an existing vent (Connor and Conway, 2000). Prominent examples include Harrat Rahat in Saudi Arabia (El Difrawy et al., 2013), Jeju Island in South Korea (Brenna et al., 2012) and Auckland in New Zealand (Kermode et al., 1992; Allen and Smith, 1994). The main hazard to life is base surge (a lateral blast-like high-velocity flow of pyroclastic material) (Sandri et al., 2012) within 2-4 km of a new vent. In addition, other effusive and explosive eruptions produce lava flows and/or tephra columns that rise kms to tens of km into the atmosphere, before being dispersed by the wind. Tephra fall constitutes a hazard to infrastructure, agriculture and human health (Cronin et al., 1998). Tephra can also disrupt transport links, especially aviation, even in small amounts (Miller and Casadevall, 2000).

The next eruption of a particular volcanic field will most likely occur at a new location, thus hazard estimation requires a spatial, as well as temporal, component. In particular, the estimation of spatial intensity is important for evacuation and land use planning purposes (Marzocchi and Bebbington, 2012). While the locations of many previous vents are usually available, the aim of estimating present day hazard is critically dependent on an assessment of any spatio-temporal dependence in the record. It is actively detrimental to have a forecast weighted towards past, rather than future, behavior. Assessing such dependence requires a record of vent ages, not just locations. In order to avoid complicating factors such as multiple-vent eruptions (Runge et al., 2014) or multiple eruptions from a central volcano as at Jeju, we will consider as an example the (relatively) well dated Auckland Volcanic Field (AVF).

The AVF consists of approximately 50 volcanoes, formed over the last 250 kyr or so. Based on different age reconstructions, very different hazard models have been suggested. Magill et al. (2005) arrived at a model where eruptions occurred in episodes concentrated in time and space. In contrast, Bebbington and Cronin (2011) found no spatio-temporal dependence, and modelled eruption occurrence as a product

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of dependent spatial and temporal terms, which were themselves independent. Critically, the spatio-temporal dependence was built-in to the former work, with nearby vents being assumed to have erupted consecutively. Spatio-temporal models (Connor and Hill, 1995) concentrate present-day hazard relatively more in the vicinity of recent eruptions. While the most recent eruptions are known to include Rangitoto and Mt Wellington, the effect decays slowly enough in time (Bebbington, 2013) that the hazard is strongly influenced by the last 20-30 kyr record. For example, if a center is only 15 ka, rather than 30 ka, the hazard contribution in its vicinity doubles. Other models such as that of Magill et al. (2005) use the order of events to separate the record into clusters. A change in age of a single event changes the clustering assignment, and hence the fitted cluster size distribution and the spatial transition between clusters.

To produce an age-order model, we need to construct the best possible volcanic record of times and locations of past volcanic events from a field. There have been many attempts to directly determine the ages of the volcanoes in the AVF, summarized by Lindsay et al. (2011). However many of the determined ages are contradictory. Palaeomagnetic determinations, which limit the possible age of some volcanoes to a short excursion of the magnetic pole, based on the magnetism in the lavas, also contradict many of the ages. One unambiguous source of data is stratigraphy from overlaying lavas. When two lavas from distinct vents overlap in the field, the source volcano which corresponds to the bottom layer must have erupted first. We can hence reliably determine the age order of some events in the field, and thus constrain their ages.

Besides lavas, most of the eruptions produced tephra blankets. Partial records of these are available from five deposition locations within the field formed by maars (eruptive craters infilled by sediment). Molloy et al. (2009) found 24 AVF-sourced tephras, many in more than one maar, over the last c. 70 kyr. However, there is no direct link between the deposit(s) and a particular source volcano. Shane and Smith (2000) demonstrated that intra-eruption variability in composition derived from proximal deposits covers the range of inter-eruption composition variability within the field, a conclusion which was further reinforced (Smith et al., 2008), (McGee et al., 2012) by more recent work. However, distal deposits such as those described by Molloy et al. (2009) appear from glass analyses to be more compositionally homogeneous (Shane and Smith, 2000). So only a few, or perhaps one, eruption phase is being recorded at any given distal location. This means that standard approaches to tephrastratigraphy based on geochemistry are not useful in matching source volcanoes to distal tephras in this particular situation. McGee et al. (2013) explained much of the variability in proximal trace element compositions in terms of eruption size, which will feature prominently in our analysis. The tephra layers observed in the cores are typically a few mm thick or less, and so grain size data is not available.

A first order (feasible, rather than optimal) record was constructed (Bebbington and Cronin, 2011) using a tephra thickness attenuation model (Rhoades et al., 2002) to link estimated eruption volumes with locations of source volcano and deposition location. Bebbington and Cronin (2011) used the estimated ages of the volcanoes only as constraints and did not evaluate these against the ages of the tephras. The latter were linearly interpolated, independently for each maar, by Molloy et al. (2009). An improvement on the tephra age estimates, and consequent statistical refinement of the matching (Green et al., 2014), reduced the number of AVF tephras to 22, and estimated their ages along with the associated uncertainty.

The power of our method will be derived from the novel approach of considering simultaneously all the available 'distances' between the tephras and the sources, and by defining each candidate match to be a complete set of assignments to the tephras, with each source being assigned to at most one tephra. Geochemistry being of little use beyond identifying the basaltic (i.e., AVF-sourced) tephras, the distances can be measured in time (discrepancy between the age of source and tephra) and tephra coverage (the likeliness of the observed tephra dispersal being produced by an eruption of known size, location and wind direction). There is also the negative information that if a source is not matched to a tephra, then the likelihood of large deposits in the tephra locations should be small. We will use an improved attenuation model that explicitly provides a likelihood for thickness from a single eruption (Kawabata et al., 2013) to calculate the likelihood of any combination(s) of source volcanoes and tephras. In order to include the contribution of the tephra and volcano ages into the likelihood, we will generate, by simulation, pseudo (prior) age distributions using the available age determinations for each vent, including stratigraphy. In addition to the AVF tephras, a number of rhyolitic 'marker tephras' (Lowe et al., 2013) from the Taupo and Okataina Volcanic Centres were found in the five maars. These have distinct petrological and chemical characteristics and separate the AVF events in the cores. These marker tephras are all well dated from many locations outside the AVF, and thus can be used to further constrain some combinations of source(s) and tephra(s). We will combine the resulting age likelihood with the spatial likelihood to produce the most statistically likely matching arrangement of the volcanoes and tephras through maximum likelihood estimation (MLE). Since the tephras are better dated than the volcanoes we will thus improve the age estimates of the assigned volcanoes.

The remainder of the paper is organized as follows: we will first summarize the volcano age data and maar records available for the Auckland Volcanic Field. Then we describe the attenuation model and the age model which will form our likelihood function. The calculations required to maximize this likelihood function in a linear programming framework are then derived. This will be followed by the results and discussion, the latter including an assessment of the changes in spatio-temporal behavior of the AVF suggested by the new matching.

2. Data

The Auckland Volcanic Field (Fig. 1) covers most of Auckland City in New Zealand. There have been 52 volcanoes identified (Allen and Smith, 1994; Hayward et al., 2011a) as occurring during its active phase over the last 250 kyr (Shane and Hoverd, 2002). As Grafton Volcano (Hayward et al., 2011b) is considered an earlier phase of the Domain volcano, probably within a few decades, and its estimated volume is included in that of Domain (Kereszturi et al., 2013), we will treat the combination of them as a single volcano, leaving 51 volcanoes. Apart from this, and including the two eruptions of Rangitoto (Needham et al., 2011), each volcano will be considered to have occurred in a single eruption.

The 'flare-up' indicated by an increase in the temporal density of tephra layers in cores between 32 ka and 25 ka (Molloy et al., 2009), and the relatively large number of eruptions during the Auckland excursion, suggest that there is considerable temporal dependence in the eruption record. On the other hand, there appears to be little dependence in location (Bebbington, 2013). Hence, in order to correctly evaluate the temporal likelihood of any pair of volcano and tephra, we need age distributions for the volcanoes and tephras. We will first construct prior age distributions for the volcanoes from the available record of determined volcano ages and errors and stratigraphy.

2.1. Direct volcano age determinations

Table 1 shows the available determined ages from radiocarbon dating, involving dating organic materials in the tephra, or other radiometric dating from dating rocks directly. Additional information is provided by stratigraphy. As the observed tephras in maars must postdate the eruption that formed the maar, the minimum ages for Hopua, Onepoto Basin and Orakei Basin follow from the oldest observed tephra found in their cores (Molloy et al., 2009; Green et al., 2014). We thus have direct ages, or constraints, for 24 out of 51 volcanoes. For further details see

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