Brief Communication: The effect of submerged vents on probabilistic hazard assessment for tephra fallout

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Abstract. Many volcanic systems are partially or entirely submerged, implying that vents may open underwater. The effect of submerged vents on probabilistic volcanic hazard assessment (PVHA) for tephra fallout has always been neglected, introducing potentially uncontrolled biases. We present a strategy to quantify the effect of submerged vents on PVHA for tephra fallout, based on a simplified empirical model in which the efficiency of tephra production decreases as a function of the water depth above the eruptive vent. The method is then applied to Campi Flegrei caldera, comparing its results to those of two reference end-member models and their statistical mixing.

1 Introduction

Several very hazardous volcanic systems are located very close to seas, oceans or lakes worldwide and their vents can be partially submerged by water. As a consequence, the vent of possible future eruptions for such volcanoes could be both inland or offshore, inferring the need of considering the possible different eruptive behaviour of the submerged opening vents with respect to the subaerial ones. Notorious examples of high-risk volcanoes with potentially submerged vents are, among many others, the Auckland Volcanic Field (New Zealand), Rabaul caldera (Papua New Guinea), Santorini (Greece), and the Campi Flegrei caldera (CFc, Italy).

The high risk associated with volcanic activity at some of these partly submerged volcanoes motivated many efforts to estimate the hazard posed on the surrounding high-density populated areas, for different possible hazardous volcanic outcomes (e.g. Sandri et al., 2012, at the Auckland Volcanic field). Several hazardous phenomena are associated with eruptions in shallow waters; however, in the present communication, the focus is on tephra fallout hazard which can impact very large areas far from the vent.

Tephra fallout hazard assessment is commonly achieved by using different methodologies ranging from mapping the geological record (e.g. Orsi et al., 2004) to modelling a few representative scenarios (e.g. Costa et al., 2009) or, more recently, applying probabilistic methods (e.g. Selva et al., 2010). However, in all of the studies on tephra fallout, the effect of potentially submerged vents on the computed hazard has never been explored. This motivated us to propose two new possible strategies to analyse the tephra fallout probabilistic volcanic hazard assessment (PVHA), so as to take into account the effect of the water above a submerged vent on subaerial tephra production. In particular, on one hand, we propose a new model consisting of a statistical mixing (Selva et al., 2014) of the two PVHAs based on two end-member assumptions on the efficiency of submarine vents to produce subaerial tephra: (i) the effect of the sea as null, i.e. as if every possible vent behaves as subaerial, and (ii) the effect of the sea as a cap that totally inhibits the injection of tephra into the atmosphere. On the other hand, we propose an empirically based simple model in which the efficiency of submerged eruptions in producing subaerial tephra linearly decreases as a function of the water depth above the eruptive vent, up to a maximum depth ($D_{\text{max}}$) at which such production is totally suppressed.

The goal of the paper is to explore the sensitivity of PVHA results when considering the inhibiting effect of the overlying water on subaerial tephra production, in the case that the vent opens offshore. Such sensitivity is evaluated by com-
paring the two PVHAs resulting from the proposed models with the two end-member PVHAs. We also check the sensitivity of the PVHA results of the empirically based model against the value of $D_{max}$ and against increasing values of such parameter as the size of the eruption increases. Magma–water interaction at very shallow waters has also the potential to increase the efficiency of explosion and the production of very fine ash and ash aggregates (e.g. Sheridan and Wohletz, 1983); however, here we neglect these effects in order to keep our empirical model simple and computationally cheap. This assumption is justified by the fact that the input values used to feed computational models for tephra fallout hazard assessment at many partially submerged volcanoes are commonly obtained from field data that typically account for these effects.

In order to evaluate such sensitivity, in practice we apply the proposed models to CFc, a caldera system which is approximately half-submerged, being formed by two nested calderas originated by two major collapses, the first related to the Campanian Ignimbrite eruption, which occurred about 39 ka ago (e.g. Costa et al., 2012), and the Neapolitan Yellow Tuff eruption, which occurred about 15 ka ago (e.g. Orsi et al., 1992). In the last 15 ka, CFc volcanic activity has been very intense producing about 50 eruptions (Smith et al., 2011), the last (forming Monte Nuovo tuff-cone) occurring in AD 1538 (Guidoboni and Ciuccarelli, 2011). Recently, the centre of CFc has been affected by a few major bradyseismic events, the latter two respectively in the early 1970s and 1980s, which generated almost 2 m of maximum ground deformation each (Orsi et al., 1999). Recent compositional anomalies of fumaroles together with major and minor bradyseismic events might suggest a new volcanic unrest at CFc (Chiodini et al., 2012).

Our PVHAs are based on the Bayesian Event Tree for Volcanic Hazard (BET_VH, see Marzocchi et al., 2010). Like in Selva et al. (2010), we use a finite number of eruptive scenarios to represent the full variability of the next possible eruption, by defining the possible vent locations (seven hundreds, Selva et al., 2012a) and a range of expected eruptive styles/sizes (dome-forming effusive, small, medium and large explosive eruptions) for CFc (Orsi et al., 2009; Costa et al., 2009). By means of BET_VH, we properly weight each eruptive scenario with its own probability of occurrence. As in Selva et al. (2010), tephra dispersal for each eruptive scenario is described using the simulation results Costa et al. (2009) obtained by applying the analytical tephra deposition model HAZMAP (Macedonio et al., 2005), for all the potential vent locations and explosive eruptive styles/sizes, and considering a statistically significant set of wind profiles. Compared to Selva et al. (2010), here we also consider the probability of eruption occurrence at CFc in 50 years as inferred in Selva et al. (2012a), obtaining the unconditioned PVHA for tephra fallout.

As we mentioned above, for the sake of simplicity, here we neglect the possible enhancement in explosivity due to magma–water interaction (e.g. Sheridan and Wohletz, 1983). However, we remark that the large proportion of fine tephra observed in CFc eruptive products (due to magma–water interaction) is, in principle, considered in the empirical total grain size distribution used as input for the HAZMAP model (Costa et al., 2009).

The final results of each PVHA are presented as Bayesian probability maps, showing the probability of exceeding a threshold of 3 kPa of tephra load in the target domain and within a time window of 50 years. We then check the sensitivity of the effect of water in the case of CFc by comparing the PVHA resulting from the presented model with the reference PVHAs and with their statistical mixing.

2 Water depth and subaerial tephra production: modelling approaches

In this section we describe how the effect of the sea has been quantitatively taken into account. In order to distinguish a possible different behaviour between inland and submarine eruptions, we introduce a variability of the probability in subaerial tephra production as a function of the vent position. In other words, the probability of tephra production at node 6 (see Fig. 1, upper panel) of BET_VH (Marzocchi et al., 2010) depends on the water depth above the submerged vent. In particular, we define four different hypotheses (namely H1, H2, H3 and H4): the first two (H1 and H2) represent the end-
member models, H3 is the statistical mixing of H1 and H2, and H4 introduces the inhibiting effect of the overlying wa-
ter for offshore vents by using some empirical considerations
(Mastin and Witter, 2000).

1. In this case we do not take into account the presence of
water above the offshore vents; in other words, we rely
on the assumption that both inland and offshore vents
have the same capability to produce subaerial tephra.
In general, this corresponds to set a uniform best guess
probability at node 6 ($P_{N6} = P_0$) for all the vents. This
is the same assumption adopted, for example, by Selva
et al. (2010) for CFc and is the most common approach
applied in tephra fallout hazard assessment up to now.

2. In this case we assume that if waters are deeper than
10 m, the production of subaerial tephra is totally sup-
pressed. The cut-depth of 10 m is here assumed as a
possible order-of-magnitude size of uplift precursor to
explosive eruptions (e.g. Guidoboni and Ciucarelli,
2011), and also a typical size of cones that form in
the first phases of eruptions. In other words, if the vent is
at such depth or shallower, in a short time before (in
case of precursor uplift) or after (due to cone forma-
tion) the eruption onset, the activity will turn into sub-
aerial, and the overall effect of water on subaerial tephra
production will be negligible (neglecting the effects of
an increase in explosivity due to magma–water interac-
tion discussed above). Following this assumption, this
hypothesis considers two typologies of eruptive vents only:
   a. inland or in shallow water (i.e. water shallower than
10 m) having a maximum capability of producing
subaerial tephra ($P_{N6} = P_0$);
   b. offshore deep water (i.e. water deeper than 10 m)
having a totally null capability of producing sub-
aerial tephra ($P_{N6} = 0$).

3. This hypothesis consists in assuming that the hazard can
be modelled by a statistical mixing of the two opposite
depend members described in H1 and H2 hypotheses. In
this view, the results obtained from H1 and H2 are statis-
tically combined into H3 by representing the latter with
a sample composed by the union of two randomly sam-
ped subsets of values (one subset from H1 and one from
H2). The relative numerosity of the two subsets is a proxy of
the relative weight assigned to H1 and H2, and
might be assigned according to the credibility of the two
hypotheses for the considered volcano: for example, de-
pending on the knowledge of the local bathymetry, if the
sea is very shallow throughout the submerged part, one
might want to assign a higher weight to H1, and vice
versa.

4. This empirical hypothesis is based on the set of observa-
tions on subaqueous eruptions described by Mastin and
Witter (2000), who reported very few cases of subaque-
ous eruptions from depths greater than 100 m that have
breached the water surface, and none for water depth
over 400 m. To account for this empirical observations
we simply assume that, for submarine vents, $P_{N6}$ lin-
early decreases with the water depth $D$, from a mini-
 mum depth $D_{\text{min}}$ up to a maximum depth $D_{\text{max}}$, at
which the water column completely suppresses the pro-
deruction of subaerial tephra. This empirical relationship
can be expressed as

$$P_{N6} = \begin{cases} P_0 & D < D_{\text{min}} \\ P_0 \left(1 - \frac{D - D_{\text{min}}}{D_{\text{max}} - D_{\text{min}}}\right) & D_{\text{min}} \leq D \leq D_{\text{max}} \\ 0 & D > D_{\text{max}} \end{cases}$$

Here we set $D_{\text{min}} = 10$ m, for the same reason explained
in H2, and $D_{\text{max}} = 300$ m, after a sensitivity analysis
performed at CFc and described in Sect. 4. It is im-
portant to remark that, even though we use Eq. (1) in
the BET_VH model, nevertheless the formula is gen-
eral and can be used in other probabilistic frameworks
to compute the probability of tephra production given
an explosive eruption in submerged environments.

3 Application to CFc case study: PVHA input

As mentioned above, for our PVHAs at CFc we rely on the
model BET_VH (Marzocchi et al., 2010), which is based on
the event tree described in Fig. 1 (upper panel). Our target do-
main is a 70 km $\times$ 70 km area including CFc and the whole
area in front of the Gulf of Naples (Fig. 1, bottom panel)
where a few millions of people live. In the following we sum-
marize the definitions of the various nodes of BET_VH and
describe how we take into account the effect of the sea with
respect to the tephra production at node 6:

- Nodes 1–3 represent the probability of experiencing an
eruption in the time window $\Delta t$, that here we set to
50 years as typical for long-term hazard. As regards the
probability density function (pdf) for nodes 1–3, we as-
sume a Poissonian process with annual rate 12 times
the monthly probability of eruption computed by Selva
et al. (2012b), obtaining a best guess probability for an
eruption at CFc in 50 years of about 40 %.

- Nodes 4 and 5 represent the conditional probability to
experience a specific eruptive scenario – that is, an
eruption from a given vent position (Node 4) and of
a given size (Node 5). For the spatial probability dis-
tribution (Node 4) of vent opening we rely on results
by Selva et al. (2012a) and shown in Fig. 1 (bottom
panel). For the probability of eruptive sizes (Node 5),
as in Orsi et al. (2009) we consider four different size
classes based on the geological history of CFc (Costa
et al., 2009; Orsi et al., 2009): (i) a lava dome eruption

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Nodes 6–8 represent the impact due to a specific eruptive scenario. At Node 6 we assess the probability of tephra production given an eruption of a given size from a given vent. Such probability is parameterized according to different possible hypotheses, as explained in Sect. 2. In particular, we assume $P_0 = 1$ for all the explosive sizes and $P_0 = 0$ for the lava dome eruptions. Nodes 7 and 8 represent the conditional probability (given a specific eruptive scenario) that tephra covers different points (Node 7) in the target domain and overcomes a given intensity of tephra load (Node 8), here set at 3 kPa as a representative threshold for potential roof damage (e.g. Macedonio et al., 2005). For each explosive size, such conditional probabilities are estimated as in Selva et al. (2010), using 1000 HAZMAP simulations of tephra deposits randomly sampled from the 13 149 ones performed by Costa et al. (2009). The HAZMAP input parameters of the three reference explosive eruptive sizes are the same as listed in Table 3 in Selva et al. (2010).

4 Results and discussion

By modelling with BET_VH the water effect at CFc under the four different hypotheses H1, H2, H3 and H4, we obtain four different PVHAs for the target region, respectively labelled in the following as CF1, CF2, CF3 and CF4. CF3 is the statistical mixing of CF1 and CF2, giving equal weight to the two, as we have no evidence that one of the two hypotheses H1 and H2 could be more reliable than the other. In Fig. 2 we report the results for the four PVHAs, displayed as maps

Figure 2. PVHA based on H1, H2, H3 and H4 hypotheses at CFc are shown from top to bottom respectively (CF1, CF2, CF3 and CF4). The middle column panels show the best guess (average) value for the probability of observing a tephra load larger than 3 kPa in 50 years due to CFc magmatic eruptions, according to the PVHA model adopted. Left and right column panels show respectively the corresponding 10th and 90th percentiles.
Figure 3. Percent variation (%) between CF1 and CF2 (top left panel), between CF1 and CF3 (middle left panel) and between CF1 and CF4 (bottom left panel) relative to CF1 (in terms of average probability to overcome a threshold equal to 3 KPa in a time window of 50 years). Similarly, percent variations between CF3 and CF2, and CF4 and CF2 relative to CF2 are given in top and middle right panels, respectively. Bottom right panel shows the percent variation between CF4 and CF3 relative to CF4.

As mentioned above, for CF4 we set $D_{\text{max}} = 300 \text{ m}$. However, in order to check the effect of this assumption we used different values for $D_{\text{max}}$ (from 200 to 400 m). Results using such different values show no significant changes in CF4 results; the same applies if we consider increasing values of $D_{\text{max}}$ as the size increases (200, 300 and 400 m for respectively small, medium and large explosive eruptions). However this insensitivity to $D_{\text{max}}$ might be due to the shallow bathymetry in the Gulf of Pozzuoli, where maximum water depth is about 150 m, and may not be generalizable to volcanic areas characterized by deeper bathymetry.

The overall feature resulting from a comparison of the four PVHAs is that the maximum of difference is to the southeast of the submerged part of the caldera. This is due to a combination of factors very peculiar to CFc: the submerged part of the caldera has a much lower probability of vent opening (Selva et al., 2010), compared to the subaerial part (see Fig. 1, bottom panel), and the prevalent wind direction is towards the SE (Costa et al., 2009), away from the coastline. This implies that the influence of the sea on the tephra fallout hazard posed by CFc eruptions is mostly relevant offshore, while on land it may be relevant only within the caldera and in the western part of the municipality of Naples. This can be better visualized in Fig. 3, where, in the left column, the relative differences in terms of PVHA are highlighted by showing residual probability between CF1 and CF2, CF1 and CF3, and CF1 and CF4 respectively, all divided by CF1 (which is
by definition, the model implying the largest hazard). More specifically, the maximum relative differences are offshore, and respectively around 50, 30 and 15 %, while inland they are about 30, 20 and 10 %. Such differences are all well captured by our estimate of the epistemic uncertainty in the most commonly used reference model CF1. However, this may be different at other (partially or totally) submerged volcanic systems (Bebbington and Cronin, 2010; Sandri et al., 2012). Similarly, we show the residual probability between CF3 and CF2, and CF4 and CF2 respectively, all divided by CF2 (see top and middle panels in the right column of Fig. 3). With CF4, we try to capture the main feature contained in the data by Mastin and Witter (2000), i.e. a decrease in explosivity as vent depth increases. In this view, the latter results emphasize the evident underestimation of model CF2 offshore and in the coastal areas of Pozzuoli and Posilipo. Moreover, we calculate the relative variation between CF4 and CF3, which shows similar results between the two, with a general underestimation of CF3 respect with CF4 (Fig. 3, bottom right panel). The maximum variation on land, although within the uncertainty estimated in each model, is below 15 % and never exceeds 25 % offshore. As a consequence of this similarity, we can argue that both CF3 and CF4 can be used to estimate the effect of the sea on the final PVHA applied to CFc. As we have stressed above, the variations found in the hazard assessment computed in this study making different hypotheses is due to the features of CFc that are not general for other volcanoes, as for example in the case of the Auckland Volcanic Field (Bebbington and Cronin, 2010; Sandri et al., 2012). In such cases, the sensitivity of PVHA to the effect of the sea might be important also at inland locations. Furthermore, the value of the differences in PVHA obtained here for CFc might not be negligible when using the hazard assessment to take rational decisions for risk mitigation based for example on cost/benefit analysis (e.g. Marzocchi and Woo, 2009), as in general they might change significantly the areas where an action should or should not be taken.

5 Conclusions

We have explored the effect of potentially offshore eruptions on the PVHA for tephra fallout, by comparing four different hypotheses for tephra production from submerged vents. The proposed models H3 and H4 seem to be a reasonable way to account for submerged vent locations, at least in our application at CFc. In such application, the differences among the four proposed PVHAs are within the epistemic uncertainty attached to the most commonly used H1 model, and are mostly confined to offshore areas. However, this might be a consequence of two peculiarities of CFc (i.e. the low probability of offshore vent opening and the SE direction of prevalent winds). In addition, such differences might not be negligible in terms of risk mitigation strategies and the effects could be completely different for other volcanoes worldwide. Both H3 and H4 models can, in principle, be applied to any other (partially or totally) submerged volcanic system. However, while for CFc they provide similar results, this might not be generalized to other volcanoes, since their results depend on local features of the considered volcano (i.e. bathymetry, spatial probability of vent opening, prevailing wind field compared to coastline direction, etc). In conclusion, we argue that a comparison with PVHAs based on H3 and H4 assumption might be a simple and computationally cheap strategy to quantify the effect of submerged vents on subaerial tephra production and related hazard.

The proposed contribution neglects possible efficient magma–water interaction at very shallow waters, that should be considered in future works on more comprehensive PVHA for tephra fallout and other phenomena, to further explore the sensitivity of hazards to such effect.

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