Extended commentary of the target answers in the Kolumbo elicitation

Supporting Material 8 to:
Kolumbo Volcano, Greece: expert elicitation findings supporting volcanic hazard and risk assessment

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In this Supporting File we report the commentary of target answers that were not discussed in the main text for the sake of brevity. These answers were collected in the first elicitation workshop held on Santorini, 9-12 May 2023, and in the second, follow-up elicitation workshop, held at INGV Pisa, Italy, 18-19 October 2023.

Q2a-b. 1650 CE eruption - initially extrusive/explosive probability

These two items should give complementary results with central values summing to nearly 100%, which is the case. The results look robust with very wide uncertainty in the DM reflecting limited evidence and substantial uncertainty concerning the pre-1650 structure and initial water depth. A particular difficulty is that the central region of the pre-1650 edifice was destroyed in the eruption, and this might have included an early dome. Here it is worth observing that explosive eruptions that start with dome formation are common and sometimes the initial dome is then destroyed. One suggestion in discussions was that early dome fragments should have been preserved. However, it is a moot point whether the earliest deposits have been inspected or yet sampled. In the Equal Weights results there are clearly two schools of thought, the majority favouring an initial effusive stage and a minority of five experts favouring an explosive start. These results reflect a wide spread of uncertainty which is unlikely to be reduced by further discussion, although nee evidence might decrease the uncertainty. The elicitation finding of a 2-to-1 likelihood in favour of an initial dome reflects [a] global observations that dome growth commonly precedes onset in explosive eruptions and [b] the lack of definitive data on this question for the 1650 CE eruption.

Q3a. Paroxysmal explosive eruption 1650 CE - Duration

The 1650 CE eruption duration is fairly well constrained from historic reports and this is reflected in the elicitation results. The duration of the paroxysmal phase is, hence, judged relatively precise with a median of 10 - 11 hours and approximate uncertainty range of 3 to about 30 hours.

Q3b. Paroxysmal explosive eruption 1650 CE - Volume (DRE)

This result shows quite wide uncertainty in the volume of the paroxysmal phase of the eruption. The Equal Weights and Cooke-weighted results are in close agreement. Comparing with Q1, the 50th percentile values give almost the estimate (40-50%) of the paroxysm being 50% of the total DRE volume erupted, which was discussed by the group during the elicitation workshop in Santorini. While the ranges of individual experts varied considerably, their differences averaged out. The final outcome using the Equal Weights DM is a median of 1.1 km^3 with uncertainty interval of 0.4 to 2.9 km^3. See Figure 2.32.

Q3c-e. Paroxysmal explosive eruption 1650 CE - Magma discharge rate, peak column height, mean column height

These questions are considered together because there is a well-established power law fit between column height and discharge rate (Mastin et al. 2009). There is quite good agreement between the Equal Weights and Cooke DM results. Individually, many experts gave rather narrower ranges and these are quite scattered. Although the questions were considered separately in the elicitation, many in the expert group will have been aware that their responses should be consistent with an empirical power law. The Cooke DM result for Q3c is internally consistent with the collective responses to Q3d and Q3e. While a wide range of discharge rates (Q3c) reflects large uncertainty, the group considered the 29th September eruption to have most likely accorded with the boundary between sub-Plinian and Plinian intensity eruptions (Q3c) and to have reached the stratosphere (Q3d). The mean column height of about 15-17 km were informed by modelling results which are consistent with eastward prevailing winds expected in the Autumn season up to about that height but not above it.

A few individual judgments are not consistent with the widely known empirical relationship of plume height with intensity. Remarkably though, the elicited mean column height and mean discharge rate sit within on the best-fit line through the empirical data compiled by Mastin et al. (2009) and within the range given by the widely used PLUMERA model. This consistency provides confidence in the ability of the elicitation procedure to create an expert group synthesis that performs better than most individual experts.

Q3f. Paroxysmal explosive eruption 1650 CE - Seawater mass fraction

Results confirm that we do not have any good constraints on water fraction, except that the group believe that some external water must have been entrained. Entrainment of water in submarine explosive eruptions is not well understood. As historical records indicate hydrovolcanic Surtseyan activity of Kolumbo on 27th and 28th September 1650, the group appeared to presume sea water was likely involved. Note that the question was referring to the paroxysmal phase of the eruption not to the initial phases. These results give a good basis for constructing the probability density function of this parameter for modelling. Note that, based on plume modelling, the upper limit of sea water fraction of about 20-30% (according to the plume velocity assumed at the vent) reflects the fact that this value is approximately the thermal limit of mixing steam with magma; above about 30% the temperature is at or below the one atmosphere boiling point and would be present as liquid water, thus significantly increasing the density of the mixture and favouring the collapse of the column.

Q3g. Paroxysmal explosive eruption 1650 CE - PDC

Results show large uncertainty and the experts' responses are bimodal. There is no unambiguous evidence for a Pyroclastic Density Current (PDC) occurring during the 1650 CE eruption. The purported PDC cause of deaths of fishermen found in a boat is a permissive interpretation. By interrogating a global database of submarine eruptions [Prof F. Maeno, pers. comm.], the group found that submarine eruptions with reported PDCs were largely confined to eruptions in shallow water with water depth of 100 m or less. Using these global data to inform judgments depends on the evidence as to how deep the vent was during the eruption. Although the pumice cone had breached the sea surface prior to the 29th September paroxysmal eruption, the explosion vent itself could still have been deep, with its action forming the present 500 m deep crater. Given such uncertainty it is not surprising that there was a wide range of opinions in the group, which amounts to the simpler statement that we do not know whether PDCs were generated in 1650 CE, or not.

Q4a1. Gas concentration in the 1650 CE source eruption fluid - H_2S

This question related to gas hazard and the deaths of tens of people on Santorini from gas poisoning. There is approximate agreement between the Equal Weights and Cooke DM, with the latter giving a somewhat larger uncertainty range. The expert group considered both the medical evidence on diagnostic symptoms of different gases [Dr P.J. Baxter, pers. comm.], information on the compositions of magmatic and hydrothermal fluids from Kolumbo volcano and chemical reactions that might take place during gas cloud transport. The group were also informed by new modelling results presented in Chap. 12.

The uncertainty range is large, but the central values are consistent with 0.1-1% H_2S in a hydrothermal fluid and, with dilution of order 5 to 20 from the models (obtained for the specific conditions assumed). The implied concentrations would still have been lethal on Santorini. There appears to be a general acknowledgment from the medical evidence that H_2S was the lethal gas and so elicited values of source H_2S concentration are largely plausible for lethal concentrations to be present in the gas cloud reaching Santorini. However, the lower range of source concentration might reflect a view that the medical evidence for H_2S is not 100% certain. The issue of H_2S concentration in a gas cloud in a future eruption comes up the responses to Q16e. See Figure 2.33.

Q4a2. Gas concentration in the 1650 CE source eruption fluid - CO_2
The question related to non-condensible gases and therefore does not include water. As expected, the group considered CO_2 should be the dominant non-condensible gas. The elicited values are not contentious, although the lower 5th percentile values of both DM values and some individual experts would require surprisingly high proportions of other non-condensible gases (H2S, SO2, HCl etc).

Q4a3. Gas concentration in the 1650 CE source eruption fluid – SO_2
Superficially, the equal weights solution to this question is consistent with much global data, i.e., that SO_2 is commonly the second most important non-condensible gas after CO_2 in arc magmas. However, looking at this response in greater detail, there is some apparent inconsistency in that, having elicited H_2S as < 1% in a separate item, SO_2, CO_2 and HCl are the only other major non-condensible volcanic gases. Since there was no discussion of HCl at the meeting, and this gas is typically subordinate to CO_2 and SO_2 in arc magmatic gases, the total of CO_2 and SO_2 should be in the high 90%'s (close to 99%). The total means of CO_2 and SO_2 are 96% for the Equal Weights solution but only about 82% for the Cooke-DM. A low total implies that a significant amount of some other gas was implicated or that that some experts did not appreciate the need to give judgments that are consistent with the typical compositions of arc magmatic fluids. The expert responses thus suggest some element of misunderstanding of the problem, especially by the more highly-weighted experts.

Q4b. Gas concentration in NE Thera 1650 CE - H2S
The Equal Weights DM and Cooke DM both agree there is quite large uncertainty associated with this gas concentration. Most experts suggest concentrations high enough to give the medical effects concluded to be H_2S. However, three experts give low values of H_2S concentration (<60 ppm for upper bound) that, based on the medical assessment, may be too low to cause the observed symptoms [Dr. P.J. Baxter, pers. comm.]. In the Equal Weights DM, the ratio of source median H_2S (Q4a1) to distal H_2S after transport is 32. In the Cooke DM the same ratio is 15. These implied dilutions are within the range calculated by the gas cloud models and indicate broad consistency in the elicitation results for Q4a1 and Q4b.

Q4b2. Gas concentration in NE Thera 1650 CE – SO_2

This item concerned SO_2 gas concentration in NE Thera on 30th September 1650. The Equal Weights DM and Cooke DM medians closely agree, with a wider uncertainty range for the latter. The concentrations, even at the high end, are much lower than the source (Q4a3) concentrations. Using the respective Equal Weights solutions, a median concentration value of 63 ppm (Equal Weights DM) can be compared with a source median of 8.6% (86,000 ppm), indicating a factor of more than 1000*x* reduction in concentration during transport. The group discussion of this item indicated the experts considered the main factors in the large decrease in SO_2 concentration on Thera were the dilution of the current by entrainment and mostly the reaction of SO_2 with water during transport.

Q6a-c. Next eruption magma composition

This trio of target items addressed the relative probabilities that the next eruption could be rhyolitic, andesitic or basaltic (see Supporting Material S4 and S6 for graphical elicitation results). Arguments concerning the three alternative compositions were discussed in the workshops; as exclusive and exhaustive alternatives, here again the DM distribution means should sum close to 100%, which is indeed the case. While the CM and EW solutions are in good agreement, they also express broad uncertainty. Roughly speaking, the collective view of the expert group is that there is slightly above 50% chance that the next eruption could be rhyolitic and slightly less than 50% chance that it could be andesitic or basaltic.

Q7b. Next eruption volume (DRE) – not located at the existing Central Volcano

The Equal Weights and Cooke DMs are in close agreement. Consideration of this question prompted a new study of the volumes of the cones in the Kolumbo volcano field in which the volumes of the 19 cones above and below the sea surface were calculated. These new results are presented in Chapter 3 and strongly informed the elicitation responses. The average cone volume from the new study was 0.24 km^3 with the largest cone being 0.77 km^3 and smallest 0.03 km^3. The Equal Weights DM mean is 0.20 km^3 with uncertainty interval 0.014 to 0.96 km^3. Note that the cone volume calculations had significant uncertainties related to the way dimensions were estimated and the absence of data on more distal deposits from cone eruptions. One feature of the responses is that several experts had ranges significantly narrower than the observed range in the cone volumes. However, the scatter in these ranges contributed to a final DM range commensurate with the observations.

Q7c. Current shallow magma chamber volume (DRE)

This topic and the initial elicitation DM solutions triggered much discussion at the Santorini workshop. There ensued a sense that not everyone had been answering the same question and there were concerns expressed about the meaning of "eruptible magma". Therefore, following discussion at the first meeting, and after some further exchanges and comments post-meeting, experts were asked to review and, if appropriate, amend or adjust their responses to allow the pattern of elicitation responses to be reworked in a more consistent manner. The revised median EW solution magma chamber volume is 2.4 km3 with 90% uncertainty interval: 0.3 to 6 km3 (see Supporting Material S5). This result is consistent with the inferred scale and nature of the geophysical anomaly under Kolumbo Volcano and with uncertainties interpreting imaging of the putative magma chamber.

Q11b. Next eruption within the next 30 years - Duration
The Equal Weights and Cooke DMs give similar wide uncertainty ranges, but there is also notable bimodality with Equal Weights DM indicating that an eruption of order 10 days is most likely while the Cooke DM has a peak of order 100 days. These responses reflect a lack of precedents and knowledge. Taken overall the results support the view that the next eruption will need planning for a potential duration of many weeks, even months.

Q12a-b. Next eruption within the next 30 years - Initially extrusive/explosive
The responses show very wide range of judgments reflecting large uncertainty, because the evidence is so poorly constrained. The Equal Weights and Cooke DMs are in close agreement. The group favour an extrusive onset rather than an explosive beginning, as illustrated by the ratio 2:1 for the median values. The two questions are complementary and should approximately add up to 100% which is the case. Similar results were obtained to Q2 for the 1650 CE eruption.

Q13. Next eruption within the next 30 years - Submarine pumice cone building
The Equal Weights and Cooke DM results are consistent with each other, with the Cooke DM having a slightly narrower range. The response is informed both by observations in 1650 and by a global dataset on submarine cone-forming eruptions which suggests cone-building can be quite rapid, with emergent islands commonly appearing within a few days. An issue for a future eruption of Kolumbo is whether the start of an eruption on the sea floor can be detected.

Q14a. Next eruption within the next 30 years (Central Volcano) - major tsunami probability. From the large variation in individual expert's median values, the range graphs (Supporting Material S4) indicate that experts' opinions vary considerably, and this contributes significantly to the overall DM distribution uncertainty. The expert group judges there to be a medium to high likelihood, i.e., ~60% probability, of a major tsunami being associated with a future eruption of Kolumbo Volcano. This response is informed both by the events in 1650 CE and by global data which show tsunamis are commonly associated with submarine eruptions. Thus, collective response of the expert group accords with a view that tsunami is a major threat from a future eruption of Kolumbo Central Volcano.

Q14b. Next eruption within the next 30 years (outside Central Volcano) - Major tsunami during paroxysmal eruption
The Equal Weights and Cooke DMs are in good agreement. The results indicate a roughly 1-in-5 to 1-in-10 chance of a major tsunami for an eruption outside Central Volcano, based on the median values. These results reflect the discussion of the smaller likely andesitic eruptions that might be expected and that extrusion eruptions appear to characterise some of the products of the smaller volcanoes. The favoured triggering mechanisms associated with the 1650 CE eruption involved either the explosive process itself or instability in the pumice cone leading to a large submarine slide. These causes are viewed as less likely for an eruption outside the Central Volcano and in relatively deep waters (cones of the Kolumbo volcanic field are typically located at >250 m water depth).

Q14c. Next eruption within the next 30 years - Tsunami during paroxysmal stage

The Equal Weights and Cooke DMs are in good agreement. There is a wide range of individual judgments, but the distributions are markedly skewed towards a high likelihood of a tsunami given a major explosive eruption occurs. The group considered there was a strong association of tsunami generation with a paroxysmal explosive stage. It can be inferred that the 1650 CE case played a major influence on experts' responses for this item.

Q15a-c. Next eruption within the next 30 years (Central Volcano) - Column height of 20 km, mean column height, paroxysmal phase duration

The Equal Weights and Cooke DMs are similar except that the Equal Weights DM extends to larger values than the Cooke DM in all three questions. There is some bimodality in Q15a based on median values, with one group believing there is less than 20% chance of reaching 20 km and the other group opting for 30 to 60% chance. The response to Q15b is consistent with previous response (Q3e) that the most likely mean column height for 1650 was about 15 km. The median responses for Q15c are similar to those for the 1650 case. It can be inferred that the 1650 eruption has strongly informed the group's responses. There is a potential inconsistency in the responses to Q15 and to Q9, both of which refer to the next eruption from the Central Volcano. Q9 indicates that the group tends to think that such an eruption is most likely represented by a scenario involving a volume that is an order-of-magnitude smaller than that of the 1650 event. On the other hand, the results from Q15, concerning judgments about explosive eruption parameters (column height and duration), jointly imply the next eruption will most likely be more consistent with a volume comparable to 1650, rather than one ten times smaller. However, it requires only a one-third increase in column height and a similar increase in eruption duration to boost total erupted volume by about a factor of ten. Thus, given Q9 entails three nominal eruption volumes – each of which could vary by half an order of magnitude, the apparent inconsistency with the likely volume when judgments are made for Q15 parameters is relatively moderate and unsurprising in the light of associated uncertainties.

Q16d1-3. Next eruption within the next 30 years - Gas density current H_2S, CO_2, SO_2 NE Thira

The Equal Weights and Cooke DMs are in broad agreement. Q16d1 response for H_2S is similar to the answer to Q4b, as illustrated by comparing median values: 115 ppm (Equal weights DM) and 80 ppm (Cooke DM) for Q16d1 compared to 192 ppm (Equal Weights) and 149 ppm (Cooke DM) for Q4b1. Q16d3 response for SO_2 is similar to the answer to Q4b2 illustrated by comparing median values: 79 ppm (Equal Weights DM) and 59 ppm (Cooke DM) for Q16d1 compared to 63 ppm (Equal Weights) and 52 ppm (Cooke DM) for Q4b2. In comparison there is much greater reduction in SO_2 relative to the source concentrations of H_2S. This difference can be attributed to the fact that the group takes into account not only the dilution in the gas cloud during transport, but also the fact that SO_2 is expected to react with water during transport, whereas H_2S concentration is expected to be conserved. There is large uncertainty in the responses. The low-end Cooke and Equal Weights DM distribution concentrations of H_2S of a few ppm or less, shown on Figure 12, may be too low to be fatal on Thira. Here the elicited concentrations are strongly influenced by the interpretation of the 1650 eruption. Note that for Q16d2 the implied dilution for CO_2 during transport using the DM median values is about 10.

Q16e. Next eruption within the next 30 years - Gas density current release duration
The Equal Weights and Cooke DMs are in broad agreement. These results yield a wide range with the group considering that any CO_2 release would like last between a few minutes and a few hours.

Q17a. CO2 hazard - next eruption
The Equal Weights and Cooke DMs are in broad agreement. However, there appears to be inconsistency between the responses to this item and those to Q16a and Q16b2, since logically in combination they are almost the same question. On the face of it, Q17a responses indicate using median values less than 1-in-5 chance of a CO_2 current while Q16a responses gives a 1-in-2 chance. Since any gas current of non-condensable gases is expected be largely CO_2 (see Q16b), the answers to Q16a and Q17a should be similar. However, for both Q16a and Q17a, the DMs (Equal Weights and Cooke) exhibit uncertainty ranges that each span almost the whole of the range from 0% to 100%. This implies there is no factual or reasoning basis for giving strong weight to the central (median) probabilities of these targets. It is not just that the medians are different, the patterns of individual responses among the experts are quite different.

Q17b-c. CO_2 hazard next 30 years - unrest with no eruption, no unrest
The Equal Weights and Cooke DMs are in broad agreement. The possibility of a CO_2 release during a period of unrest without eruption in the next 30 years is somewhat less than for an eruption: median 6.7% for Equal Weights DM and 16.9% for Cooke DM. A conundrum is that the way Q17b is phrased: the question is the probability that a CO_2 release might occur, associated with a period of unrest, in next 30 years. There is of course the possibility that an interval of unrest might occur without CO_2 release. Thus, implicitly the responses indicate that the group is making an assessment of the likelihood of unrest in next 30 years as being greater than the elicited values. It is a difficult then reconcile this response with the results from Q10 which implies a greater than 50% chance (median) that unrest will be followed by eruption. However, mutually consistent responses to these questions can be found by choosing combinations in the extremes of the ranges for these questions: Q8, Q10 and Q17b. Thus, the apparent inconsistency from comparing central results can be seen as reflecting the large uncertainty with respect to defining and understanding unrest at Kolumbo. The chances of CO_2 release unrelated to eruption or unrest in the next 30 years are considered over an order of magnitude less, of order 1%.

Q17d-e. CO_2 hazard – Volume, duration
The Equal Weights and Cooke DMs are in broad agreement. The volume results (Q17d) are, however, incoherent and represent a huge range and diversity of opinion. One can observe four individual experts who have no overlap between them in the range graph The question really

requires some modelling of the capacity of the current seawater occupying the Central Volcano submarine crater to absorb and then release CO_2 by an overturn.