Elicitation of potential future explosive silicic eruption scenarios at Corbetti and Aluto volcanoes, Ethiopia

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Expert elicitation, volcanic hazards, Main Ethiopian Rift.

Front cover

Multiple flow and fall units at Corbetti volcano, Ethiopia. Photo credit Samantha Engwell

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Foreword

This report is the published output of an expert elicitation run by the British Geological Survey (BGS) using national capability funding to support research in the Rift Volcanism: Past, Present and Future (RiftVolc) project. RiftVolc is a five-year NERC funded project, which is investigating volcanism in the Main Ethiopian Rift (MER), part of the East African Rift System. BGS leads a work package investigating volcanic hazards from potential future eruptions from the central MER volcanoes and lava fields.

Expert elicitation is a tool to support uncertainty analysis of parameters and information required for quantitative models. A group of scientific experts is guided through a series of set questions to enable rational individual judgements to be made based on available knowledge, even if the uncertainties are large. How the results of an elicitation are used may depend on the scale of the uncertainties.

BGS ran an expert elicitation using the SHeffield ELicitation Framework (SHELF) at the Lyell Centre, Edinburgh on 26th April 2018 to derive recurrence rates and their uncertainties for what are considered the most likely future explosive eruption types at Corbetti and Aluto central volcanoes. This exercise also served as training for BGS staff to run the SHELF methodology, and training for designing and hosting expert elicitations. This report describes the question design, elicitation procedure, and the discussions held during the elicitation. The results are presented as distributions, from which we derived frequency-magnitude relationships. Key points arising from the discussions and lessons learnt are highlighted.

Acknowledgements

The authors would like to thank the elicitation participants and observers, Karen Fontijn, Keri McNamara, Ben Clarke and Getnet Mewa, who gave their time to take part in the elicitation and helped design the questions through discussions. We would also like to thank those who helped us prepare for the elicitation through discussions and meetings but were unable to attend the elicitation workshop: Eliza Calder, David Pyle, Susanna Jenkins, Tamsin Mather, Elias Lewi and Gezahegn Yirgu. Much of the background and geological data were compiled from the work of Karen Fontijn, Keri McNamara, Ben Clarke, Will Hutchison, Sam Engwell and Vladislav Rapprich. Finally, we would like to thank Anne Galbraith and Louise Clapperton for logistical support.

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This report describes an expert elicitation on the recurrence rates of potential future explosive silicic eruptions at Corbetti and Aluto volcanoes in the Main Ethiopian Rift (MER) and their uncertainties. This work represents BGS national capability support for research the BGS Volcanology team is leading in the RiftVolc project on future volcanic hazards in the MER.

Field campaigns have contributed to a step-change in knowledge from 2015 when the Global Assessment of Risk report (GAR15) highlighted the lack of data on volcanoes in Ethiopia (Brown et al., 2015). New data acquired through the RiftVolc project have increased our understanding of past volcanism and magmatism, particularly at Aluto and Corbetti central volcanoes in the MER. However, the data and knowledge are still limited, constrained by a lack of dateable material and resources to map and correlate volcanic deposits at these complex volcanoes.

In RiftVolc, we are developing several approaches to better understand hazards and the associated uncertainties. A key part of our planned tephra fall hazard assessment requires a judgement of the likely characteristics and recurrence intervals of future explosive silicic eruptions. Such inferences are at least partly reliant on eruption histories derived from the recent RiftVolc geological and geochronological fieldwork (e.g. Fontijn et al., 2018; McNamara et al., 2018; Siegburg et al., 2018). In addition, to support the development of event trees for probabilistic hazard assessment, we need to explore the probabilities of occurrence of particular eruptive scenarios. In order to meet both of these objectives, we have elicited the judgement of a group of five experts, using the SHeffield ELicitation Framework (SHELF; Oakley and O'Hagan, 2010) method, on the recurrence rate of future explosive silicic eruptions at Aluto and Corbetti volcanoes.

The first part of the report introduces the RiftVolc project and describes the expert elicitation procedure. This includes a description of the questions to be elicited. Section 2 of the report presents the elicited distributions of individuals and the group consensus for each question, as well as a summary of discussions held by the experts, which enabled them to agree on a final distribution. The recurrence rates for potential future eruptions at Corbetti and Aluto volcanoes derived from the group distributions are provided in Section 3. Sections 4 and 5 summarise the key points raised during discussions and highlight lessons learnt which should be taken into consideration in future expert elicitations of volcanic activity. Finally, a summary and conclusions are provided in Section 6.

1 Introduction

The NERC-funded Rift Volcanism: Past, Present, Future (RiftVolc) project began in 2014 to investigate volcanism, magmatism and the dynamics of rifting in the Main Ethiopian Rift (MER) through three work packages focusing on past, present and potential future activity. The project aims to improve understanding of the mechanisms behind rift volcanism and the potential for future volcanic hazards by studying a) past eruptions through analysis of the characteristics of deposits (tephra fallout and pyroclastic density current (PDC) deposits, and lava flows), geochronology and geochemistry, and b) geophysical monitoring information which reveals signs of unrest (deformation and seismicity). BGS leads the 'future' work package, and will build on knowledge gained throughout the RiftVolc project, and a World Bank study on volcanic risk in sub-Saharan Africa carried out in 2015 (Jenkins et al., 2015) to consider hazards in the Main Ethiopian Rift.

As part of the task to look towards future volcanic hazard in Ethiopia, BGS aim to undertake probabilistic hazard assessment for a number of hazards, including tephra fall and pyroclastic density current propagation. Probabilistic hazard assessment requires the application of numerical models, and assumptions on the relationship between frequency and magnitude of future eruptive events. Such assumptions are commonly based on information of past eruptive activity in the geological record. In addition to frequency-magnitude information, numerical models also require information on the characteristics of eruptions and their eruptive products, for example eruptive plume height, and the physical characteristics of eruptive products, for example grainsize.

Knowledge of historical activity at central volcanoes in the MER (Corbetti, Aluto, East Zway, Fentale, Kone, Boset, Beru) is limited, and while there have been focused efforts on improving understanding of Holocene eruptions, there are still substantial knowledge gaps. Eruption magnitudes are subject to significant uncertainties due to limited exposure of deposits, issues of preservation and difficulties correlating deposits. Eruption frequencies are also subject to uncertainties for the same reasons and because there is limited material available and suitable for dating. Such information is nevertheless crucial to understand and model future volcanic hazard, both in time and space.

We have focused on two volcanoes that have benefited from the most fieldwork during the Riftvolc project: Corbetti and Aluto. Using all available evidence, we have elicited the judgement of a group of five experts using the SHeffield ELicitation Framework (SHELF; Oakley and O'Hagan, 2010) method on the recurrence rate of explosive silicic eruptions at Corbetti and Aluto volcanoes. The elicitation enabled us to express the uncertainty about recurrence rates in terms of statistical distributions. These volcanoes were also selected because they are active systems with ongoing deformation and seismicity (Biggs et al., 2011; Hutchison et al., 2016a; Wilks et al., 2017) and they are situated in areas of high population density; more than 500,000 and more than 300,000 people live within 30 km of Aluto and Corbetti volcanoes respectively (GVP, 2013; Brown et al., 2015).

Based on their expertise of volcanism in the East African Rift, and current research on the MER central volcanoes, the five experts elicited were Karen Fontijn (University of Oxford), Samantha Engwell (BGS), Julia Crummy (BGS), Ben Clarke (University of Edinburgh) and Keri McNamara (University of Bristol). The elicitation was facilitated by Ben Marchant (BGS) and Julia Crummy. Daniela Cuba (BGS) ran the elicitation software. Sue Loughlin (BGS) and Getnet Mewa (Addis Ababa University) observed part of the elicitation. Pablo Tierz (BGS) observed and documented the discussions.

1.1 QUESTION DESIGN AND PREPARATION

The elicitation questions were designed by BGS (Julia Crummy, Samantha Engwell, Sue Loughlin, Pablo Tierz and Ben Marchant) with input from Eliza Calder and Ben Clarke during discussion and iteration through email and in person. Previous expert elicitations led or co-led by BGS Volcanology have posed questions using the Volcanic Explosivity Index (VEI; Newhall and Self, 1982) as a measure of the size of the eruption (e.g. Jenkins et al., 2015; Vye-Brown et al., 2016). The VEI scale is very broad and therefore experts can have differing opinions on what is included in each VEI, for example, the entire eruption from unrest to returning to background activity, or a single explosive phase. During the previous elicitation exercises, results of individual opinions varied widely. In addition, eliciting on VEI requires a series of linked questions, with repeated questions for each VEI category of interest. This can result in too much weight on the first question, which, if incorrect, propagates through the whole elicitation. Eliciting on each VEI sequentially is a long, repetitive and exhausting process. Previous elicitations have demonstrated that towards the end of the elicitation the experts can stop considering the volcano in question and focus more on ensuring the numbers fit with the earlier questions (i.e. if VEI 2-4 add up to 80% of all eruption, the VEI 5 must be 20%). It was therefore decided to trial a different approach with questions based on eruption scenarios for which there is field evidence.

Fieldwork at Corbetti and Aluto volcanoes during the RiftVolc project revealed difficulties in correlating and interpreting silicic explosive eruption deposits, which in turn led to difficulties in assigning a magnitude or VEI. However, fieldwork did identify specific eruptive events observed at both volcanoes – pumice-cone forming eruptions with localised tephra dispersal (termed 'violent Strombolian') and larger 'sub-Plinian' to 'Plinian' type eruptions with widely dispersed tephra fall. Through discussions with the expert group, questions were designed based on these two eruption scenarios.

In addition to the elicitation, feedback was sought on our assumptions on eruption source parameters (see Appendix 1) for the tephra fall hazard analysis which forms part of BGS' research on understanding potential future activity at these volcanoes. Participants (the elicitation participants as well as a small number of experts including Ethiopian partners) were asked to fill out a questionnaire providing comments on our assumptions and suggest improvements or refinements where appropriate.

In preparation, all participants were sent five documents two weeks in advance of the elicitation: 1. SHELF pre-elicitation form; 2. Background evidence; 3. Elicitation questions; 4. Assumptions; and 5. Elicitation briefing document (see Appendices 1-4). The SHELF pre-elicitation form is a requirement for the process, for the experts to declare any interests and to provide background on their expertise and any relevant evidence concerning the questions to be elicited i.e. key documents and studies they have been part of or are aware of. Documents 2, 3 and 4 contained information required to inform discussions around the questions, while document 5 described the expert elicitation process and the SHELF method. In addition, a link to an online training module on the SHELF method was provided. A meeting was held with the participants two days prior to the elicitation to ensure participants fully understood and had a shared understanding of the questions and were comfortable with the methods of SHELF.

1.2 METHOD

Elicitation is based on the premise that an expert has a mental model of uncertain quantities, reflecting their understanding and experience. In the terminology of SHELF, this model is referred to as an expert's subjective belief distribution. The expert, through his or her experience, has an intuitive sense of the likely distribution of variable quantities in their field of expertise. Elicitation is a method to extract this tacit model.

Elicitation methods have been developed through research by statisticians and psychologists, and are now widely used. They have been applied in volcanology (e.g. Aspinall and Cooke, 1998; Aspinall 2006), medicine (e.g. Mason et al., 2017; Kip et al., 2018) by the World Health Organisation (e.g. Hald et al., 2016), and for risk assessment in the nuclear industry (e.g. Siegel et al., 2018), in meteorology (e.g. Mearns et al., 2017) and in finance (e.g. Gottschalk and Gunnesdal, 2017). The SHELF method does not use weightings of experts through an algorithm, but aims, after an elicitation of individual opinions, to form a group aggregate view through discussion. The experts are not necessarily expected to change their beliefs to agree with a single model. Instead, the group aggregate model represents the model that a rational independent observer might form having witnessed the discussions and accounted for the views of all of the experts.

In the SHELF method, a group consensus is formed on the minimum and maximum values (1st and 99th percentiles) to give a range within which opinions on the median and quartile values are elicited. Each expert then writes down a median value and quartiles (25th and 75th), and these are used to fit distribution functions. The different distribution functions are discussed in the group and the reasons for any differences in opinions are highlighted. Finally, the group are asked to step into the shoes of a rational independent observer and agree on the median and quartile values that would best reflect the beliefs that this observer would have formed having witnessed the discussion. A final distribution function is then fitted with these group probability values.

1.3 ELICITATION QUESTIONS

In order to derive information on the frequency of potential future eruptions at Corbetti and Aluto volcanoes, the following questions were elicited. Each question was accompanied by the description below. Each expert was provided with the source data in a background document (Appendix 3).

1. Consider Corbetti volcano. In a 100,000 year period, how many *silicic* eruptions of any size would you expect at the volcano in question?

This includes effusive, explosive, mixed and phreatomagmatic eruptions from the Corbetti volcanic system, and related off-edifice monogenetic eruptions. A stratigraphy is provided in the accompanying background document. The current stratigraphy was compiled from existing literature (Rapprich et al., 2016; Martin-Jones et al., 2017) and field characterisation and geochemistry during the current project (Fontijn et al., 2018; Samantha Engwell, pers. comm.; Ben Clarke, pers. comm.). Correlation of tephra layers is problematic so the current known stratigraphy should be seen as a minimum estimate of frequency. Frequency-magnitude relationships based on the current stratigraphy are provided in the background document, as are global data, and current and recent weather (rainfall and wind) data. When answering this question, any 100,000 year period should be considered.

2. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a ‘violent Strombolian’ type eruption (total erupted tephra volume 0.01 to 0.1 km^3)?

Small to moderate magnitude eruptions may pose a realistic, potentially high likelihood, scenario on Corbetti. These eruptions are presumed to be ‘violent Strombolian’ type eruptions producing column heights of up to 8 km above sea level (a.s.l.), with tephra fallout, and can be associated with pyroclastic density currents and lava flows (see Assumptions document, Appendix 1).

3. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a ‘sub-Plinian’ to ‘Plinian’ type eruption (total erupted tephra volume 0.1 to 1 km^3)?

Sub-Plinian and Plinian eruptions are presumed to be entirely magmatic eruptions producing a moderate to large volume of tephra (0.1 – 1 km^3 after Newhall and Self, 1982). It is assumed that most moderate to large eruptions will have left some record in the stratigraphy. During fieldwork, the RiftVolc team identified at least seven pyroclastic fall deposits (VEI 3 and 4; Fontijn et al., 2018) interbedded with palaeosols in the last 7-8 ky, four of which have been correlated across multiple sites (Fontijn et al., 2018; Sam Engwell, pers. comm).

4. Consider Aluto volcano. In a 100,000 year period, how many *silicic* eruptions of any size would you expect at the volcano in question?

This includes effusive, explosive, mixed and phreatomagmatic eruptions from the Aluto volcanic system, and related off-edifice monogenetic eruptions. A stratigraphy is provided in the accompanying background document. The current stratigraphy was compiled from existing literature (Gibert et al., 1999; Chalié and Gasse, 2002; Gibert et al., 2002; Hutchison et al., 2016b), as well as field characterisation and geochemistry undertaken during the current project (Fontijn et al., 2018; Ben Clarke, pers. comm.; McNamara et al., 2018). Correlation of tephra layers is problematic so the current known stratigraphy should be seen as a minimum estimate of past silicic eruptions. Frequency-magnitude relationships based on the current stratigraphy are provided in the background document, as are global data, and current and recent weather (rainfall and wind) data. When answering this question, any 100,000 year period should be considered.

5. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'violent Strombolian' type eruption (total erupted volume 0.01 to 0.1 km^3)?

Small to moderate magnitude eruptions may pose a realistic, potentially high likelihood, scenario on Aluto. These eruptions are presumed to be 'violent Strombolian' type eruptions producing column heights of up to 8 km a.s.l, tephra fallout, and can be associated with pyroclastic density currents and lava flows (see Appendix 1 Assumptions). Numerous vents (> 84; Ben Clarke, pers. comm.) for past eruptions have been identified on the edifice of Aluto volcano, the majority located on the assumed caldera ring fault (Hutchison et al., 2016).

6. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'sub-Plinian' to 'Plinian' type eruption (total erupted volume 0.1 to 1 km^3)?

Sub-Plinian and Plinian eruptions are presumed to be entirely magmatic eruptions producing a moderate to large volume of tephra (0.1 – 1 km^3 after Newhall and Self, 1982). It is assumed that most moderate to large eruptions will have left some record in the stratigraphy. During fieldwork, the RiftVolc team did not find evidence of large magnitude Plinian type eruptions around Aluto volcano. However, detailed analyses of lake sediment cores carried out by McNamara et al. (2018) as part of the RiftVolc project has revealed 24 tephras deposited over 8,990 years in Lake Abijata (25 km southwest of Aluto) and 20 tephra layers deposited over 5,439 years in Lake Langano (12 km south of Aluto). This is consistent with findings from previous studies (Gibert et al., 1999; Chalié and Gasse, 2002; Gibert et al., 2002) and suggests that despite poor preservation there have been explosive eruptions at Aluto capable of distributing tephra across large areas.

2 Discussions and Results

Prior to eliciting individual opinions for each question, the question was discussed among the participants to ensure a common understanding of the questions and language used. Discussions were also held once the individual opinions had been elicited and presented to the group, in order for the group to form a consensus on the final distribution. Relevant discussion points are summarised below. The experts were anonymised with each assigned a letter of the alphabet.

2.1 QUESTION 1

Consider Corbetti volcano. In a 100,000 year period, how many *silicic* eruptions of any size would you expect at the volcano in question?

Pre-elicitation discussions were held around the definition of an eruption i.e. a single explosive event, or a sequence of events during an eruption (as defined by GVP). Field studies at Aluto (also applicable to Corbetti) have shown that pumice cones form through a three-phase eruption cycle beginning with 'Strombolian' to 'violent Strombolian' activity forming a tuff ring, which eventually builds a pumice cone. The second phase of activity is the formation of pyroclastic density currents (PDCs) from the collapse of 'violent Strombolian' to 'sub-Plinian' eruption columns. Activity ends with the formation of obsidian lava flows (Ben Clarke, pers. comm.). The group agreed that the whole sequence would be defined as a single eruption. It was also agreed that the 100,000 year period in consideration is the next 100,000 years. Results for question 1 are given in Table 1 and Figure 1.

Range:	1 to 1000			
Expert	Median	Lower quartile	Upper quartile	Comments
A	200	77	300	Assumed 30% of all eruptions are missing from the record
B	200	80	300	
C	200	100	300	
D	150	80	250	Assumed 60% preservation
E	200	100	300	Assumed 50% preservation (200), included effusive eruptions to get upper quartile
Group probability	P(x < 190) = 0.5	P(x < 110) = 0.3	P(x > 250) = 0.4	

Table 1 Elicitation results for question 1. The range is the maximum and minimum values defined by the group for the distribution.

Syn-elicitation discussions were centred on the preservation of deposits and likelihood of the observed deposits to represent the eruption history. Experts opinions varied from 70% to 50% preservation of silicic explosive eruption deposits. A recent paper was presented to the group on the preservation of explosive eruptions in Japan, where it is estimated that up to 89% of Volcanic Explosivity Index (VEI; Newhall and Self, 1982) 4 eruptions (moderate to large) may be missing and even larger events (very large) are missing from the geological records (Kiyosugi et al., 2015). One expert suggested that under-recording at Corbetti should be less of an issue given its continental setting and larger eruptions. Some of the participants agreed with this, stating that, in their opinion, deposits in Ethiopia are well-preserved and more than likely better than in Japan. It was also noted that the main erosive agent in Ethiopia is wind, whereas in Japan it is rain. It should be noted here that the effect of flooding on deposit preservation in Ethiopia was not discussed.

The issue of variations in the rifting dynamics with time, how the dynamics can affect the volcanism, and how this can be taken into account when considering future volcanic activity was raised. It was agreed that we are assuming that the rifting dynamics will be stable over the next 100,000 year period, but that this assumption may or may not be true.

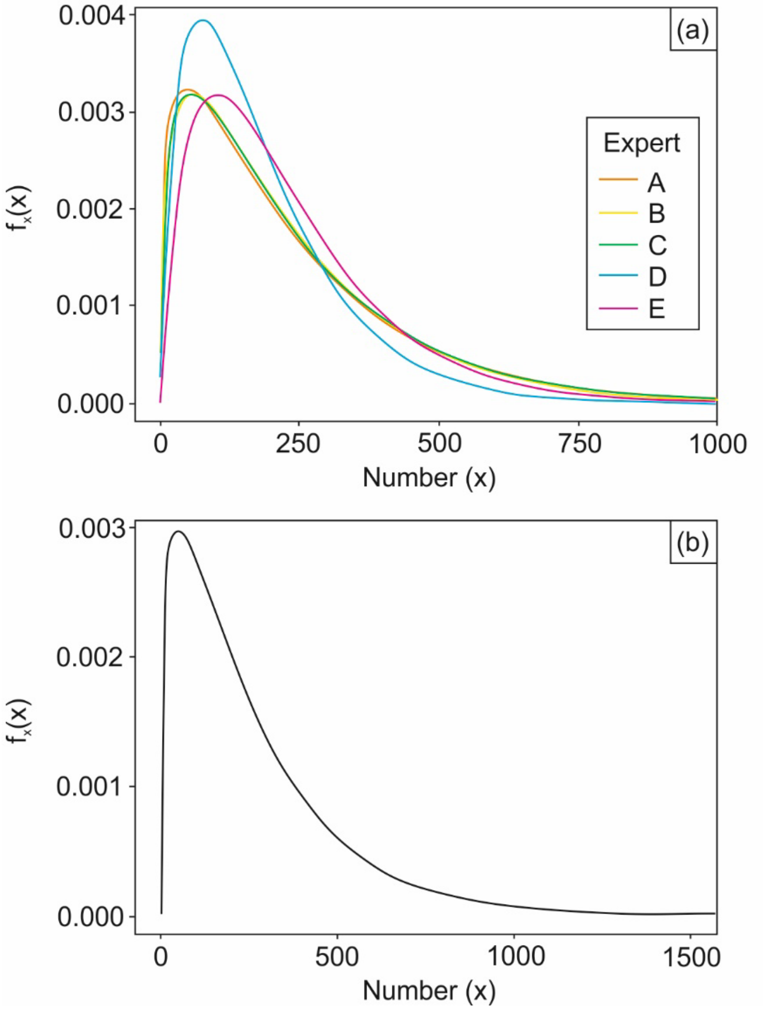


Figure 1 a. Distribution functions derived from the elicited median, upper and lower quartile values for each expert for question 1. b. Consensual group probability distribution function generated through group decision on the median, upper and lower quartile values

2.2 QUESTION 2

For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'violent Strombolian' type eruption (total erupted volume 0.01 to 0.1 km^3)?

Discussions opened with the agreement of the meaning of the question and the meaning of 'eruption'. Despite pre-elicitation preparation (design discussions, documentation and a pre-elicitation meeting), some of the experts questioned the reasoning behind eliciting on specific eruption types rather than magnitude or VEI. Some of the experts felt uncomfortable distinguishing between eruption types. See above (Section 1.1) for an explanation of this. It was also noted that pumice cones have not been observed at Corbetti; however, there is field evidence of lower magnitude eruptions that dispersed tephra locally within, and on the caldera edifice. It was therefore agreed to include 'violent Strombolian' type eruptions at Corbetti.

Range:	100 to 9500 (minimum considered 1% of all eruptions)			
Expert	Median	Lower quartile	Upper quartile	Comments
A	5500	3000	8000	
B	6000	3000	9000	
C	4000	2000	5000	Considered 5-6 categories of eruptions then calculated median for each
D	5000	3000	7000	
E	7000	3700	8500	Expects high % to be low-magnitude based on field literature as well as published literature
Group probability	P(x < 4500) = 0.4	P(x < 2500) = 0.1	P(x > 7500) = 0.15	

Table 2 Elicitation results for question 2. Results shown are the original values assigned by the experts.

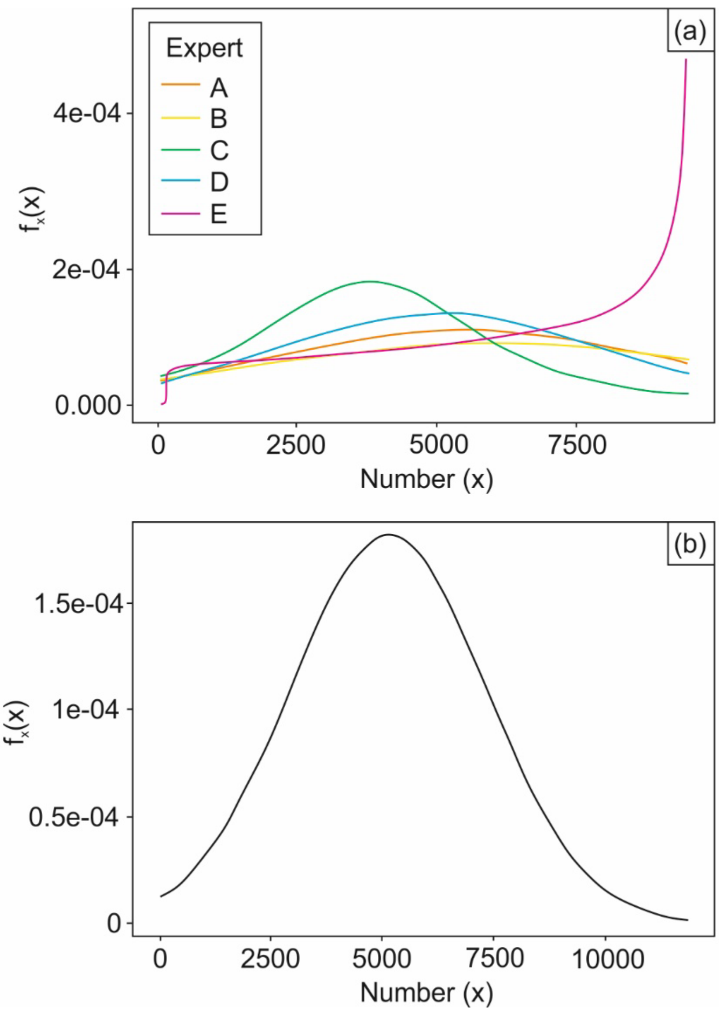


Figure 2 a. Distribution functions derived from the elicited median, upper and lower quartile values for each expert for question 2. b. Consensual group probability distribution function generated through group decision on the median, upper and lower quartile values.

Once the individual distributions were elicited (Fig. 2a), the group discussed the different possible eruption types at Corbetti and the completeness of the record. It was noted that by eliciting on only two eruption 'scenarios', there are other types and magnitudes of eruption that are not considered here i.e. effusive, phreatomagmatic and caldera-forming eruptions. Because the 'violent Strombolian' type eruptions described here include effusive activity, some of the experts included effusive eruptions when considering this question. There was discussion around how far tephra can be dispersed from a 'violent Strombolian' type eruption, and where the vent might be. Expert opinion differed on this, as some thought that almost all 'violent Strombolian' eruptions would originate from the Urji vent in the Corbetti Caldera. Other experts disagreed stating evidence of at least three off-edifice cones that may have produced 'violent Strombolian' type eruptions. There was a high degree of uncertainty among the experts, which is reflected in the different distributions (Fig. 2a). After discussion, it was considered that a sensible median would be 50% of all eruptions (Fig. 2b).

Following the group elicitation, discussions centred on the shape of the distribution and how representative it was of the uncertainty. The group attempted to get a better fit to reflect the uncertainty by altering the lower quartile; however, it was agreed that the group does not have enough information to 'fine-tune' the fitted-distribution, and it was becoming an exercise on finding a good fit rather than a realistic representation of the uncertainty.

2.3 QUESTION 3

For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'sub-Plinian' to 'Plinian' type eruption (total erupted volume 0.1 to 1 km^3)?

Discussions centred on the different individual elicited distributions (Fig. 3a) and on preservation of the deposits. One expert assumed that all records of moderate to large magnitude ('sub-Plinian' to 'Plinian') eruptions at Corbetti have been identified in the field or lake cores; therefore, chose low values (Table 3). However, not all participants agreed with this stating that it is unreasonable to assume 100% preservation (terrestrial combined with lacustrine records), especially considering that cores have not been analysed for cryptotephra. It was also noted that, based on global volcanic activity, it is unlikely that any volcano would have more than 10% of its eruptions as moderate to large magnitude Plinian eruptions. The final agreed distribution is presented in Fig. 3b.

Range:	0 to 3000 (lowered from 7000 to 5000 to 3000)			
Expert	Median	Lower quartile	Upper quartile	Comment
A	500	50	1000	
B	400	100	800	Assumed 100% preservation of all larger magnitude eruptions
C	500	100	1000	
D	750	250	1000	Considered number of eruptions with only lava flows then divided the rest between violent Strombolian and sub-Plinian/Plinian
E	2000	1000	2500	Assumed 20% could be sub-Plinian/Plinian – considered number events identified, and cryptotephra which has not been looked at
Group probability	P(x < 400) = 0.45	P(x < 200) = 0.2	P(x > 900) = 0.25	

Table 3 Elicitation results for question 3

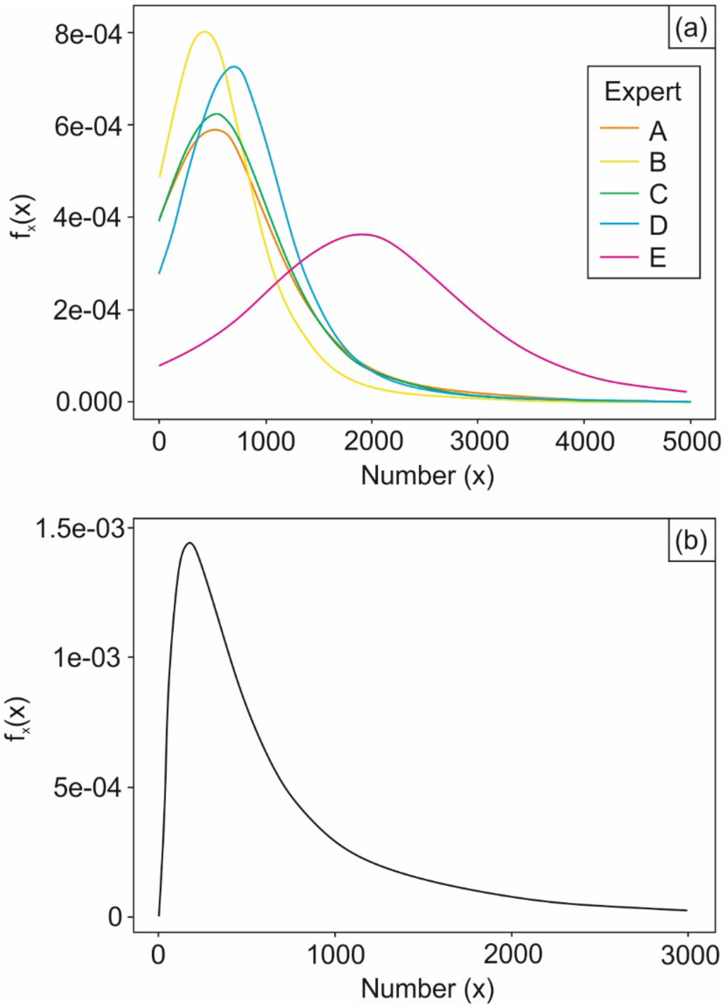


Figure 3 a. Distribution functions derived from the elicited median, upper and lower quartile values for each expert for question 3. b. Consensual group probability distribution function generated through group decision on the median, upper and lower quartile values

2.4 QUESTION 4

Consider Aluto volcano. In a 100,000 year period, how many *silicic* eruptions of any size would you expect at the volcano in question?

Discussions centred on the range of values and the difficulty in constraining a maximum value. Again, discussions returned to preservation of deposits. One expert noted that the recurrence rate calculated by Fontijn et al (2018) of 1 eruption every 250 years is based on the lake core record assuming full preservation of tephra layers and recording of all eruptions; however, this does not take cryptotephras or variations in wind direction into account. After some discussion on under-recording, the group agreed with an upper limit of 1 eruption every 100 years to get a maximum value of 2000 (Table 4).

There was also considerable discussion on the 84 silicic vents described in the documentation. These are described as developing post-caldera formation (Hutchison et al., 2016b). The caldera formed ca. 350 ka; however, Hutchison et al. (2016b) defined post-caldera activity as the last 60 ka, implying a 300 ka period of inactivity. One expert dismissed this hiatus in activity at Aluto because well-studied volcanoes in similar settings (e.g. Kenya) do not appear to exhibit a 200-300 ka gap in volcanism, and as such, there is no reason to have such a hiatus after a caldera-forming eruption in any rift volcanic system. It was considered appropriate, by the group, to assume that the 84 silicic vents formed at a constant rate of volcanism over the last ca. 350,000 yr.

Range:	1 to 2000			
Expert	Median	Lower quartile	Upper quartile	Comments
A	400	150	700	Assumed under-recording, but based on logs is 2x Corbetti
B	600	200	1000	
C	600	200	900	Assumed higher preservation at Aluto
D	550	150	900	
E	600	400	800	Used current knowledge for lower quartile and assumed 50% preservation for upper quartile, with median in the middle
Group probability	P(x < 500) = 0.45	P(x < 300) = 0.35	P(x > 750) = 0.25	

Table 4 Elicitation results for question 4

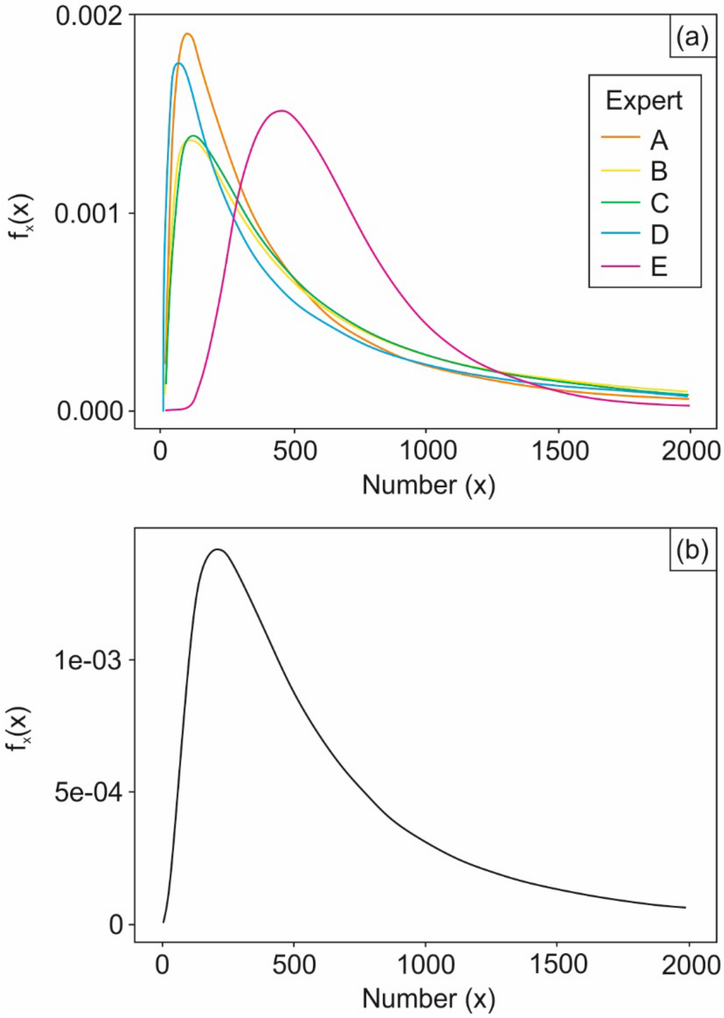


Figure 4 a. Distribution functions derived from the elicited median, upper and lower quartile values for each expert for question 4. b. Consensual group probability distribution function generated through group decision on the median, upper and lower quartile values

Following the individual elicitation, discussion again centred on the uncertainty around preservation and under-recording of explosive silicic eruptions. Although there was general agreement on the shape of the distribution, the uncertainties are reflected by the individual distributions (Fig. 4a).

2.5 QUESTION 5

For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'violent Strombolian' type eruption (total erupted tephra volume 0.01 to 0.1 km^3)?

Discussions centred on the different types of eruptions and how clearly these are defined. For example, a 'violent Strombolian' type pumice-cone forming eruption may escalate into a 'sub-Plinian' eruption. The issue of phreatomagmatic eruptions was also discussed because Aluto has a hydrothermal system and is surrounded by lakes on its northern and southern edges; therefore, eruptions could be phreatomagmatic. It was agreed that on-edifice phreatomagmatic eruptions can be included with 'violent Strombolian' as many of the eruptions have a phreatomagmatic component.

Range:	100 to 10000			
Expert	Median	Lower quartile	Upper quartile	Comments
A	7000	4000	8500	
B	6500	4000	8000	
C	5500	3000	8000	
D	7000	5000	8500	
E	6500	5000	7500	Considered eruption categories (violent Strombolian, sub-Plinian/Plinian, off-edifice phreatomagmatic, lava only) and assigned median values to each
Group probability	P(x < 6000) = 0.7 (from 0.5)	P(x < 4500) = 0.25 (from 0.3)	P(x > 7000) = 0.4	

Table 5 Elicitation results for question 5

Based on the group probability distribution (Fig. 5b), it was commented on whether the group was giving too much probability to these small/moderate eruptions because they are more benign and we 'wish' as many eruptions as possible to be this size but, nonetheless, we should not exclude bigger events.

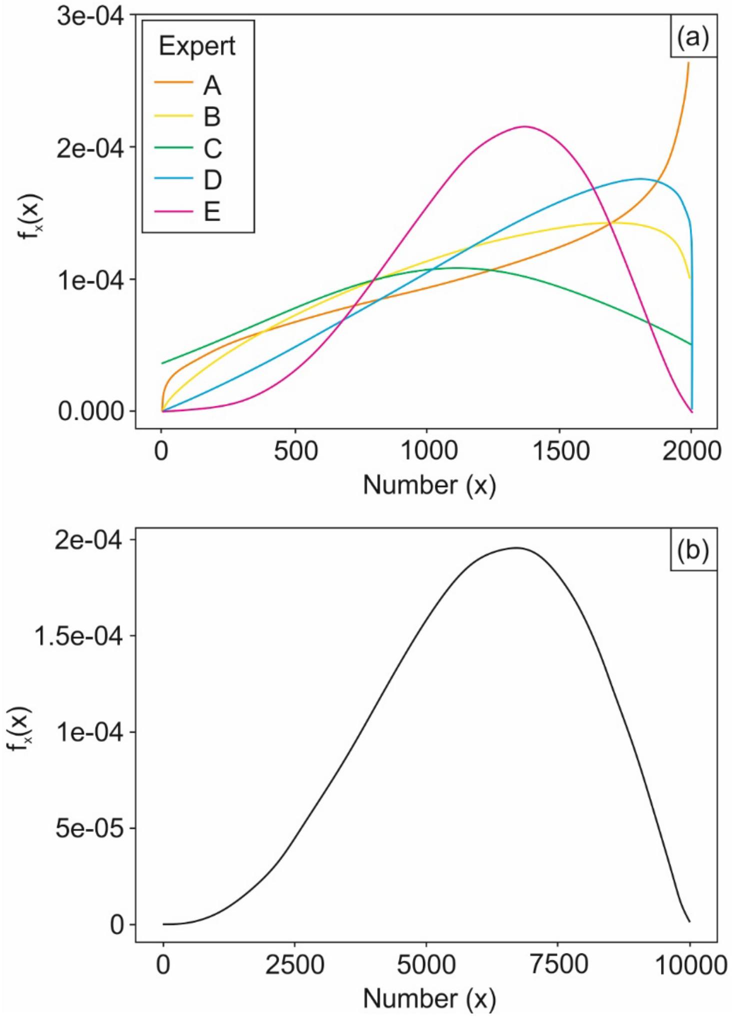


Figure 5 a. Distribution functions derived from the elicited median, upper and lower quartile values for each expert for question 5. b. Consensual group probability distribution function generated through group decision on the median, upper and lower quartile values.

Different probability distribution functions (PDF) are applied to the data to find the best-fit. There was some discussion around the choice of the PDF and whether it is appropriate to select a different PDF for each question depending on the fit, or whether a set PDF should be selected for the all questions. No decision was made, but this is something to note for future elicitations.

2.6 QUESTION 6

For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'sub-Plinian' to 'Plinian' type eruption (total erupted tephra volume 0.1 to 1 km^3)?

Discussions again centred on the difficulty between separating 'violent-Strombolian' and 'sub-Plinian' to 'Plinian' eruptions. There is too little data to enable volume estimate calculations; therefore, it is difficult to quantitatively distinguish 'violent-Strombolian' and 'sub-Plinian' to 'Plinian' events through field studies. One expert pointed out that only one 'sub-Plinian' to 'Plinian' eruption deposit from Aluto has been identified in the lake cores, which cover a time interval of 2 to 12 ka. There were discussions on whether this represents under-recording in the lake cores or reflects the true eruptive history of Aluto. It was noted that, in general, a higher frequency of small/moderate eruptions than larger eruptions is expected.

Range:	0 to 2000			
Expert	Median	Lower quartile	Upper quartile	Comment
A	300	50	700	
B	750	300	1200	
C	400	100	700	
D	500	150	700	
E	500	200	600	
Group probability	P(x < 450) = 0.5	P(x < 250) = 0.35	P(x > 650) = 0.3	

Table 6 Elicitation results for question 6.

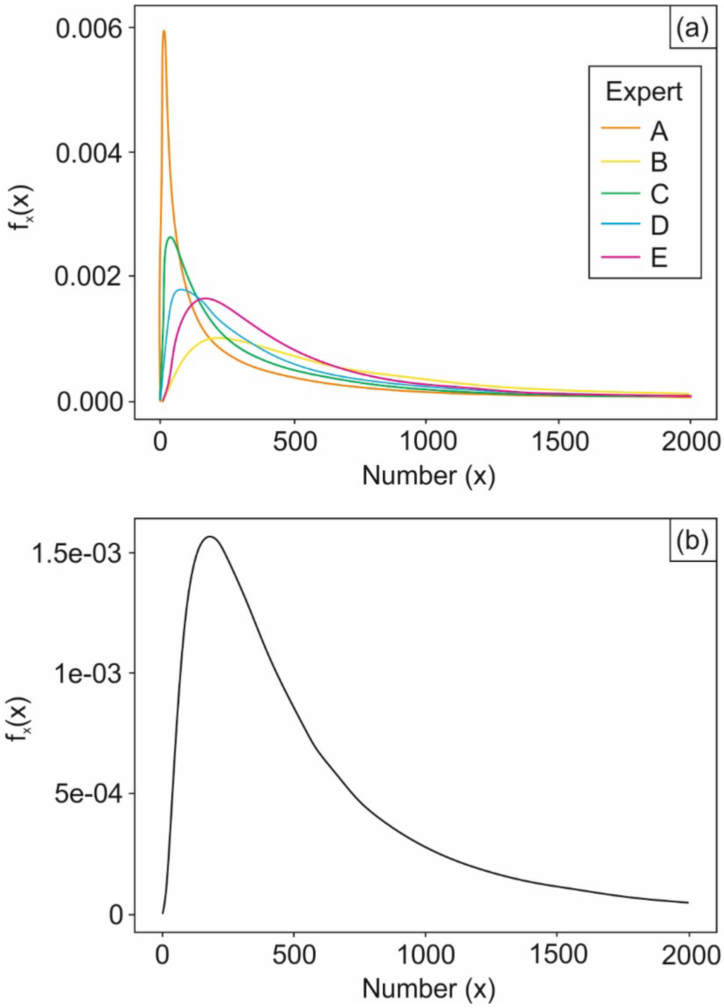


Figure 6 a. Distribution functions derived from the elicited median, upper and lower quartile values for each expert for question 6. b. Consensual group probability distribution function generated through group decision on the median, upper and lower quartile values.

3 Recurrence rates

The recurrence rate of *any* silicic eruption for Corbetti and Aluto volcanoes was calculated from the results from questions 1 and 4 on the number of silicic eruptions of *any type* in a 100,000 year period (Table 7). At Corbetti, the results indicate a median recurrence rate of 520 years, giving an annual eruption probability of 0.0019. At Aluto, the median recurrence rate is 200 years, giving an annual eruption probability of 0.005.

		Recurrence rate (years)	Annual probability
Corbetti	Median	520	0.0019
	25% quartile	909	0.0011
	75th quartile	400	0.0025
Aluto	Median	200	0.005
	25% quartile	333	0.003
	75th quartile	133	0.0075

Table 7 Recurrence rate and annual probability of any silicic eruption at Corbetti and Aluto volcanoes

The frequency of each eruption type was determined by randomly simulating 10,000 realisations from each elicited distribution. The proportion of each type of eruption was assumed to be independent of the total number of eruptions. It should be noted here that there are a suite of eruptions not included in the 'violent Strombolian' and 'sub-Plinian' to 'Plinian' eruption types elicited on here.

'Violent Strombolian' type pumice cone forming eruptions were considered 10 times more likely at Corbetti and 15 times more likely at Aluto than moderate to large magnitude 'sub-Plinian' to 'Plinian' eruptions. The 75^{th} and 90^{th} confidence intervals show the high level of uncertainty among the experts, especially towards the upper limits (Table 8). Experts considered Aluto more active than Corbetti, with a median recurrence rate for a 'violent Strombolian' type pumice cone eruption of 384 years, and 5,924 years for a 'sub-Plinian' to 'Plinian' eruption (Table 8). Experts were also more confident on the lower and upper limits for Aluto than for Corbetti.

		Median (years)	75^{th} confidence (years)	90^{th} confidence (years)
Corbetti	Violent Strombolian	1,152	388 – 5,692	266 - 13,974
	Sub-Plinian/Plinian	13,109	3,040 - 77,467	1,706 - 183,836
Aluto	Violent Strombolian	384	143 – 1,155	101 – 1,901
	Sub-Plinian/Plinian	5,924	1,560 - 23,915	967 - 44,922

Table 8 Recurrence rate of 'violent Strombolian' and 'sub-Plinian' to 'Plinian' eruptions at Corbetti and Aluto volcanoes.

4 Key points arising from discussions

The results presented here highlight the challenges around determining recurrence rates in data-poor environments. Expert elicitation is a tool to enable us to move towards understanding of the uncertainties, but does not provide a definitive answer to the problem. As such the results should not be considered absolute. They do help to explore the sources of uncertainty and the potential biases of experts and as previously noted, the discussion between scientists with different knowledge and opinions is extremely valuable.

The SHELF elicitation method encourages in-depth discussions about data, knowledge, assumptions, biases and individual opinions. A group consensus is presented in the final distribution. Some issues were raised repeatedly in discussions throughout the elicitation and key points are summarised below:

1. Preservation of explosive eruption deposits. Numerous discussions centred on the preservation of deposits and the completeness of terrestrial and lake records. Some experts felt they were complete (100% preservation), while others felt this was unrealistic. This range of opinions was captured in the variations between individual distributions, and was particularly noticeable for Corbetti;
2. Experts struggled with the division of 'violent Strombolian' and 'sub-Plinian' to 'Plinian' eruptions. It was deemed clearer at Corbetti where there are larger volume eruptions preserved in the terrestrial stratigraphy. At Aluto, the division is less clear as the experts agreed that it is possible for pumice-cone forming eruptions to escalate from 'violent Strombolian' to 'sub-Plinian/Plinian';
3. Experts opinions did not widely vary, and experts were flexible in altering their choices which reflects uncertainty related to the geological data and known eruption histories. This was especially noticeable for Corbetti where experts had larger uncertainties;
4. Within the SHELF software, it was challenging to fit distributions at the upper and lower limits. The distribution functions used by SHELF gave quite different results; therefore, considerable discussions centred on the reason for this and how to make it fit better. It was not clear why, for example, a beta fit worked better in some instances than a log normal or a gamma fit. The question arose of whether there is a distribution function that should have fitted consistently better across all questions i.e. a log normal fit. Considerable time was spent after the group probabilities were elicited tweaking the results, within a commonly acceptable range, to get a better fit distribution until it reached a point where either the experts were happy with the distribution or felt uncomfortable to change any of the numbers further.

5 Lessons learnt

The following are a compiled list of lessons learnt following reflection on the whole elicitation process, from the preparation to analysis of the elicitation itself. These are provided to help develop and refine the elicitation methodology for further application.

1. Design of the questions, ensuring full understanding about what and who the elicitation results are for.
2. Common understanding of the questions. The experts felt that further explanation of the divisions between the eruption types would have helped. Experts were provided with documentation including the questions and definitions two weeks in advance. In addition, a pre-elicitation meeting was held to discuss the questions to ensure common understanding. However, it was apparent that not all participants read the documentation

prior to the pre-elicitation meeting, or indeed, the elicitation. In order for an elicitation to run smoothly and work well, it is imperative that all experts are fully engaged and prepared in advance. Suggestions to ensure this are:

a. Scheduling a longer pre-elicitation meeting, such as adding a half day meeting on to the elicitation, making the elicitation a 1.5 day event;
b. Keep the supporting documentation as brief as possible to encourage participant engagement;
c. Re-structure the documentation to request the experts to give feedback in advance i.e. asking questions such as what does this question mean to you? Experts were requested to submit feedback on the assumptions document and their completed pre-elicitation forms prior to the elicitation, few of them did this. Therefore, feedback requests must be structured and simplified;
d. Involve the experts more in defining the questions and the structure of the elicitation;
e. Evaluate the best way of asking questions relating to magnitude i.e. using the VEI scale or specific eruption types, or pre-defined eruption scenarios. Regardless of the wording of the question, it is useful to attach a given measure (e.g. volume) that can be used to draw comparison with results from previous expert elicitations.

3. Generally, the experts had similar perspectives on the questions and therefore similar answers. Where they did disagree, those with less knowledge of the particular issue were generally quick to acknowledge that and follow the opinions of the more knowledgeable. That all indicates a well-functioning team. The elicitation exercise could have been more interesting and challenging had the experts had more diverse and strongly held opinions. However, this could also have led to longer discussions and a struggle to complete all the questions. Perhaps there is an ideal group to elicit, for example, a group of experts with a range of expertise and experience, from early career to established researchers.

4. There was variability in the family of distributions chosen for each question or even each stage of the same question. This introduces a source of subjectivity and lack of reproducibility that could be avoided if a given type of (flexible) distribution was agreed on for each of the variables elicited before the elicitation starts. This choice could be reasoned, justified and reported in the pre-elicitation documentation.

5. There was some ambiguity in the minimum and maximum values of the distributions. It should be quite clear, and agreed before the start of the elicitation, whether these values represent the absolute lower and upper limits of the range of the elicited variable or they represent the 1st and 99th percentiles, respectively.

6. Asking the experts to agree on upper and lower limits may have pushed the experts towards consensus on their initial median and quartile values. A better way may be to elicit opinions on the upper and lower limits.

6 Summary and conclusions

Expert elicitation can be a valuable tool to understand uncertainty where there are knowledge gaps relating to limited geological and historical data. Experts are likely to have a mental model of uncertainty surrounding quantities reflecting their understanding and experience. Elicitation is a way of extracting and quantifying these opinions. We have used the SHELF method to derive frequency-magnitude relationships for potential future activity at Corbetti and Aluto volcanoes. The results reveal large uncertainties especially on the upper limits for the larger magnitude eruptions ('sub-Plinian to Plinian'), which, given the limited geological data, is unsurprising. Uncertainties are also higher for Corbetti volcano. Uncertainties are slightly better constrained for the small-moderate magnitude eruptions.

Elicitation results suggest a median recurrence rate of 520 years (0.0019 annual probability) and 200 years (0.005 annual probability) for *any* silicic eruption at Corbetti and Aluto, respectively. 'Violent Strombolian' type pumice cone forming eruptions were considered 10 times more likely at Corbetti and 15 times more likely at Aluto than moderate to large magnitude 'sub-Plinian' to 'Plinian' eruptions. The average recurrence rate for a 'violent Strombolian' type pumice cone forming eruption at Corbetti is 1,152 years with 90^{th} percentile confidence bounds of 266 and 13,974 years. At Aluto, the average recurrence rate is 384 years with 90^{th} percentile confidence bounds of 101 and 1,901 years.

The SHELF method encourages discussions to enable the experts to reach a consensus on the final distribution. Discussions are therefore a key aspect of the elicitation. Key discussion points were repeatedly raised on preservation and the completeness of the record, and on the classification of the eruption types. An important lesson learnt from the elicitation is to include all the experts in the preparation of the documentation and the design of the questions. This would ensure all experts were in agreement on the meaning of the questions to be elicited.

Through the expert elicitation we have been able to move towards constraining the frequency of low-moderate and moderate-large magnitude eruptions at Corbetti and Aluto volcanoes. The large uncertainties in the elicited distributions reflects the lack of preserved deposits, the lack of dateable material and the complex nature of these volcanic systems. Further targeted detailed geological fieldwork and further studies on quantification of uncertainties relating to frequency-magnitude relationships is recommended to better constrain recurrence rates of silicic eruptions at Corbetti and Aluto volcanoes.

Appendix 1 Assumptions questionnaire

This document describes the assumptions that we are making for the elicitation and ash fall hazard analysis. Due to the limited data available for fully probabilistic ash fall modelling we will use a scenario-based approach. Scenarios have been developed based on field evidence of previous eruption styles. We would like your feedback on the following assumptions.

Scenarios

We will model three eruption scenarios in order to account for a range of eruption styles and magnitudes that could potentially occur at Corbetti and Aluto, based on field evidence and expert opinion:

- Scenario 1: low-moderate volume silicic eruption (0.01-0.1 km^3) such as an explosive violent Strombolian type event;
- Scenario 2: a large volume silicic eruption (0.1-1 km^3) such as a sub-Plinian to Plinian type eruption;
- Scenario 3: a phreatomagmatic, off-edifice eruption

Rationale: For this hazard analysis, the focus is on the ash fall footprint and the impacts. The three scenarios have been chosen to represent the reasonable most-likely scenarios (1 & 3) and a reasonable worst-case scenario (2). There is field evidence of numerous low-moderate magnitude pumice cone forming eruptions on the flanks of Aluto and within Corbetti caldera; therefore, we propose scenario 1 as a reasonable most likely scenario. There is field evidence of moderate-large volume sub-Plinian or Plinian eruptions at both Corbetti and Aluto. The Wendo Koshe Younger Pumice (WKYP) deposit from Corbetti volcano has been mapped and described in detail by the RiftVolc fieldwork teams and the eruption volume (1.3 km^3) has been estimated by Fontijn et al. (in press). We therefore assume it is realistic to base scenario 3 on such an eruption, as a reasonable worst-case eruption scenario at both volcanoes in question.

Off the flanks of both Aluto and Corbetti edifices are monogenetic cones which have produced scoria and PDCs. The location of vents close to lakes has resulted in highly explosive phreatomagmatic eruptions producing widely-dispersed (>5 km) tephra (ash) fallout and PDCs with runout lengths of up to 6 km (Ben Clarke, pers. comm.). Due to the high population densities and development along the edges of Lake Awassa (Corbetti) and Lakes Ziway and Langano (Aluto), such an eruption could have a large impact on the local population and tourists. We will therefore model an off-edifice phreatomagmatic eruption as scenario 3.

Although we acknowledge that there have been large magnitude caldera forming eruptions in the past, and therefore may occur in the future, we believe the likelihood of such an eruption to be very small. Our focus is therefore on the more likely low-moderate and moderate-large volume violent Strombolian and sub-Plinian type eruptions.

Response:

Vent Location

For scenario 1, we assume a vent location anywhere along the rim of the caldera, for which we will use a probabilistic vent location analysis to feed into the ash fall model. For scenario 2, we assume a central vent location within the caldera at Corbetti, and a location along the caldera ring fault at Aluto. For scenario 3, we assume a vent location close to the lake, for which we will again use a probabilistic analysis.

Rationale: Geological mapping has revealed the location of monogenetic pumice-cones to be on the flanks of Aluto and Corbetti. In order to take into account the wide distribution of these monogenetic cones, and the unpredictability of the location of a future eruption, we will use a probabilistic analysis on the vent location carried out by Ben Clarke for the RiftVolc project. We will model ash fall footprints from the most likely vent locations.

In terms of impacts from ash dispersion and fall, we believe that the exact location of the vent for a larger magnitude, sub-Plinian to Plinian eruption will make little difference on the modelling results as ash will disperse widely from such an eruption. For scenario 2 at Corbetti, we have chosen to use the same source vent as the suggested location of the most recent moderate-large magnitude explosive activity: the WKYP massive pumice deposit formed < 2300 yrs BP (Rapprich et al., 2016; Fontijn et al., 2018). At Aluto, the majority of the vents occur along the assumed caldera ring fault with no obvious central vent (RiftVolc team, pers. comms. KF, BC, EC). We will therefore use a vent location probability analysis, as for the scenario 1 pumice cone events, and will simulate a sub-Plinian to Plinian eruption from the most likely vent locations.

Phreatomagmatic tuff rings and cones are observed off edifice at Corbetti and Aluto volcanoes, next to Lake Awassa (Corbetti) and Lakes Ziway and Langano (Aluto). We assume a vent location in the vicinity of these lakes to be reasonable. We will use a probability analysis on the vent location and will model ash fall footprints from the most likely vent locations.

Response:

Analogue

Due to the similarity in geology and eruption styles to Aluto and Corbetti, based on field observations during the current RiftVolc project, Pantelleria is used as an analogue for the system as a whole in order to provide information on frequency-magnitude relationships. For violent Strombolian pumice cone-forming eruptions, we use Paricutin and El Jorullo volcanoes in Mexico as analogues. For a phreatomagmatic eruption, we use the Table Rock Complex, Oregon.

Rationale: Pantelleria Island in the Sicily Channel Rift has a volcanic geology similar to Corbetti, dominated by peralkaline rhyolites with pantellerites erupted as PDCs, pumice fall or obsidian lavas (Rotolo et al., 2007). The volcano has two nested calderas, the oldest formed ca. 114 ka, and the youngest approximately 50 ka which produced the Green Ignimbrite that outcrops over most of the island (Cornette et al., 1983; Mahood and Hildreth, 1986). Orsi et al. (1991) identified at least 20 explosive eruptions in six silicic eruptive cycles since the eruption of the Green Ignimbrite ca. 50 ka. Each eruption began with explosive phases and ended with lava effusion, as we see at Aluto and Corbetti. The pumice fall deposits are not widely dispersed and have characteristics typical of Strombolian activity (Orsi et al., 1991).

Rotolo et al. (2007) revisited the explosive stratigraphy on the northern slopes of the volcano and described complex sequences of interbedded pumice fall deposits sourced from closely spaced vents. They identified eight units, erupted in the last 25,000 years. The pumice fall deposits are all associated with dome-buildings events and pantelleritic lava flows (Rotolo et al., 2007). Analysis of a deep sea core from ODP leg 160, 100 km east of Pantelleria, revealed six well-preserved tephras which have been correlated with volcanic activity of Pantelleria dated at 42.5, 127.5, 128.1, 129.1, 188.7 and 197.7 ka (Tamburrino et al., 2012).

The above correlations suggest that there have been at least 20 short-lived, Strombolian-style explosive eruptions in the last 50 ka, and eight in the last 25 ka. The deep-sea core tephra layers imply that there have been at least six sustained explosive eruptions widely dispersing tephra in the last 200 ka.

Paricutin volcano, Mexico is a scoria cone formed through violent Strombolian eruptions with contemporaneous effusive lava flow formation 1943-1952 (Pioli et al., 2008). The cone reaches a height of 2.8 km a.s.l., and although the basal tephra layers are basaltic in composition, the topmost ash blanket is andesitic (Pioli et al., 2008). The eruption column reached heights of up to 8 km a.s.l. or 6 km above the vent. Tephra accounts for an estimated 40% of the total erupted volume (Rowland et al., 2009). El Jorullo volcano, Mexico formed through similar activity from 1759 to 1775, with eruption column heights of up to 6 km and tephra fallout deposits account for 42% of the total erupted volume (Rowland et al., 2009). Although, geochemically and tectonically these volcanoes are not analogous to Aluto and Corbetti volcanoes, in terms of eruptions of violent Strombolian activity, they are well documented and provide insights into erupted tephra volumes and eruption column heights of such events. Similarly, Okmok volcano in Alaska can provide insights into violent Strombolian eruptions. Tephra volumes of 0.04 to 0.25 km^3 have been calculated at Okmok volcano using the Pyle (1989) method (Wong and Larsen, 2010). The eruption column reached heights of 8.5 to 14 km. There is also evidence of a limited degree of phreatomagmatism in the Okmok tephra deposit (Wong and Larsen, 2010), which is also observed in the tephra sequences on Aluto (Ben Clarke, pers comm).

Although there are numerous documented mafic phreatomagmatic complexes e.g. Table Rock Complex, Oregon (Brand and Clarke, 2009), Sinker Butte volcano in the Snake River Plain (Brand and White, 2007) and the Inyo Volcanic Chain, Long Valley (Miller, 1985), few have detailed studies on tephra dispersion, erupted volumes and eruption column heights. The Table Rock Complex is a mafic phreatomagmatic complex in the Fort Rock – Christmas Lake Valley Basin, South-Central Oregon, covering an area of 40 km^2 (Brand and Clarke, 2009, 2012). Brand and Clarke (2009, 2012) describe pyroclastic surge deposits formed from column collapse heights of up to 2.8 km above the vent. Their column estimates are based on the runout lengths of the surge deposits, which are greater than 5 km, similar to observations of deposits from phreatomagmatic eruptions at Corbetti volcano (Ben Clarke, pers. comm).

Response:

Eruption column height (a.s.l.)

For scenario 1 we assume an eruption column height of 8 km. For scenario 2, we assume an eruption column height of 12 km, and for scenario 3, a phreatomagmatic off edifice eruption, we assume an eruption column height of 6 km.

Rationale: At present, there is insufficient field data to calculate eruption column heights for explosive eruptions at Corbetti and Aluto volcanoes. However, we are processing samples from the November 2017 field season and may be able to estimate eruption column heights based on maximum clasts for some of the eruptions. If so, we will use that data to assign eruption column heights. In the absence of field evidence, we will use well-studied eruptions from analogous volcanoes and the global eruption source parameters database (Mastin et al., 2009).

Violent Strombolian eruptions can produce sustained ash columns of over 5 km above the vent e.g. Paricutin, Mexico, 2 – 6 km above the vent (up to 8 km a.s.l.) (Pioli et al., 2008), El Jorullo, Mexico, 6 km (Rowland et al., 2009), Okmok volcano, Alaska, 8.5 – 14 km (Wong and Larsen, 2010) and Cerro Negro, Nicaragua, >5 km (Hill et al., 1998). We assume an eruption column height of 8 km a.s.l. is therefore reasonable for a violent Strombolian eruption. Mastin et al. (2009) describe describe silicic sub-Plinian to Plinian eruptions (VEI3 and VEI4+, i.e. S2 and S3 eruption types) as having column heights of 6-12 and 12+ km above vent, respectively.

Phreatomagmatic eruptions tend to have lower column heights than their magmatic equivalents (in terms of volume rate of production) due to the loss of thermal energy turning water to steam (Cole et al., 1995). Column collapse height estimates for phreatomagmatic eruptions at the Table Rock Complex, Oregon are 2.8 km above the vent (c.2.5 km a.s.l.) based on the long runout lengths of surge deposits from the northeast tuff ring (Brand and Clarke, 2012). Observed phreatomagmatic PDC deposit runout lengths from a tuff ring at Corbetti volcano are similar at c.6 km. However, column heights of 6-7 km a.s.l. are reported from phreatomagmatic transient eruptions at Kilauea and Ukinrek Maars, USA (Houghton et al., 2015). Therefore, we consider it reasonable to assume a column height of 6 km a.s.l.

Response:

Erupted Volume

For scenario 1 we assume an erupted tephra volume of 0.02 km^3. For scenario 2, we assume an erupted tephra volume of 1 km^3. For scenario 3, we assume a volume of 0.02 km^3.

Rationale: Volume estimates for ash fall from violent Strombolian eruptions observed at El Jorullo and Paricutin volcanoes, Mexico, reveal that the tephra fallout deposits comprise 42 and 40% of the total erupted volume (including lava flows), respectively (Rowland et al., 2009). Obsidian lava flow volumes calculated for 20 flows associated with pumice cone forming eruptions at Aluto reveal 17 have volumes of < 0.05 km^3 and 3 have volumes of > 0.09 km^3 (Ben Clarke, pers. comm.). Assuming an average lava flow volume of 0.05 km^3 and based on the tephra fall comprising roughly 40% of the total volume, we assume an erupted tephra volume of 0.02 km^3 for scenario 1.

For scenario 2, a Plinian eruption, we will base the eruption volume on the published volume of 1.34 km^3 calculated for the WKYP deposit (Fontijn et al., in press). However, because there have been no other Plinian eruptions deposits identified at Corbetti or Aluto, we propose to use a lower volume of 1 km^3. For scenario 3, we assume a similar volume to the violent Strombolian eruption.

Response:

Grain size distribution

We are assuming a normal distribution on a bounded phi scale with limits 6 phi (16 microns) to -6 phi (64 mm), with a median of -1 phi (2 mm) and standard deviation of 2 phi.

Rationale: We are currently processing samples from the November 2017 field season, from which we will get grain size distribution data, which will inform the modelling. In the absence of such data presently, we have chosen limits consistent with tephra dispersal modelling and geological studies of sub-Plinian and Plinian eruptions elsewhere (e.g. Walker and Croasdale, 1971; Woods and Bursik, 1991; Bonadonna and Houghton, 2005; Jenkins et al., 2012; Wadge et al., 2014).

Response:

Particle density

Assumed to be 1700 kg/m^3 *(*NB based on feedback provided from the experts, this has since been changed to 620 kg/m^3)*

Rationale: A mixture of pumice (average density 700-1200 kg/m^3) and lithics (2600-3200 kg/m^3) (Wilson et al., 2012)

Response:

Eruption Duration

Eruption duration is not considered by the ash fall modelling.

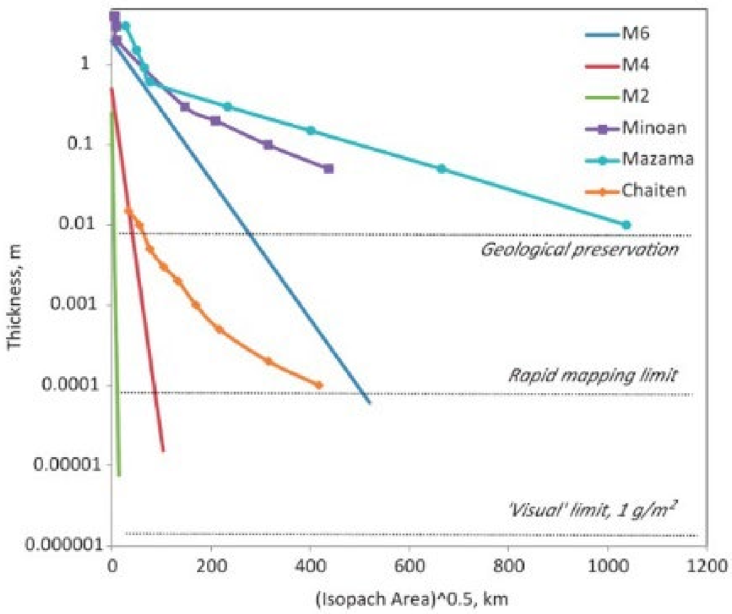
Rationale: *Tephra2* does not consider eruption duration; it assumes that parameters such as column height represent an average condition for the duration of the eruption (Connor and Connor, 2006). It also assumes that most tephra is ejected in a short duration explosive event. Therefore, each simulation is of a single explosive phase of a predefined magnitude. The resulting ash fall footprint, therefore, is of a short duration (i.e. hours) explosive event, not the footprint from a long-term eruption with multiple explosive phases. We have chosen to perform the analysis with *tephra2* as it is freely available and can be used by in-country partners to carry out further ash fall analyses.

Response:

Stratigraphy / preservation

We assume that the current known stratigraphy of Corbetti and Aluto is as complete as possible at this stage and that the absence of some deposits / lack of preservation is typical of global averages with few records of VEI 3 and lower.

Rationale: The geological record is dominated by products of thick well-preserved eruptions of magnitude (VEI) 5 and larger. Deposits from eruptions of magnitude 3 or smaller are unlikely to be preserved in the geological record (Pyle, 2016).



Schematic thickness plotted against isopach area for three typical deposits of magnitude M2, M4 and M6, assuming simple exponential decay in each case; and showing examples of more complex natural deposits (Chaiten, Minoan and Mazama; Pyle, 1989; Watt et al., 2009). Source: Pyle, D.M. 2016 Field observations of tephra fallout deposits. *In:* Mackie, S., Cashman, K., Ricketts, H., Rust, A., Watson, M. (Eds). Volcanic ash: Hazard observation. Elsevier, 300pp.

Response:

Wind

The prevailing wind direction in the central MER is to the west during January to August and blows fairly evenly between east and west in September to December. We assume that current weather conditions are representative of past conditions. We will randomly select wind profiles from a ten-year NOAA Reanalysis dataset from 1st January 2006 – 1st January 2016 to perform the simulations.

Rationale: A ten-year database of wind profiles measured 4-times daily gives 14608 possible wind scenarios. This is consistent with previous tephra dispersal modelling studies (e.g. Jenkins et al., 2012, Jenkins et al., 2015).

Response:

Appendix 2 SHELF pre-elicitation form

Pre-elicitation meeting pro forma

Volcanic hazards in the Main Ethiopian Rift

Thank you so much for offering to support this work. We have invited you to partake in this elicitation because of your expertise in some or all of the topics of interest. We are looking to define probability distributions that describe likely future eruption characteristics for volcanoes in the central Main Ethiopian Rift (MER). Please could we ask you to complete and return the following document in advance of the elicitation and provide any feedback you have on the assumptions that we make for the volcanoes as provided in document #4.

1) Background	BGS are currently conducting research to produce a local and regional volcanic ash fall hazard assessment for Ethiopia as part of the NERC-funded 'RiftVolc' project led by the University of Bristol and the University of Edinburgh. Recent work on this project has included field mapping and characterisation of deposits on Corbetti, Aluto, Kone and fentale, and geochemical and petrological research to investigate: links between magma composition, storage conditions, magma recharge, eruption timing, frequency, style and impact and whether these can be characterised through geological time. Field correlations achieved through this project have improved our understanding of past eruptions, nevertheless it is difficult to calculate the frequency and magnitude of these events. The results of this elicitation will be used to create a frequency-magnitude curve and assess the likelihood of future eruptions in the central MER. We will also ask for your feedback on some of our assumptions for hazard modelling. The elicitation research will be conducted by Ben Marchant from BGS. We will analyse the results and the outcomes will be communicated to our in-country partners as part of a broader summary of the volcanic hazards in Ethiopia. Findings will be circulated amongst all contributors.
2) Declarations of interests	[To be completed by the expert. Please identify any personal interest that you might have in the outcome of this elicitation exercise, or in the wider context specified above – whether as an employee, consultant, shareholder or in any other capacity.]

3) Parameter definitions	1. Consider Corbetti volcano. In a 100,000 year period, how many *silicic* eruptions of any size would you expect at the volcano in question? 2. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'violent Strombolian' type eruption (total erupted tephra volume 0.01 to 0.1 km^3)? 3. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'sub-Plinian' to 'Plinian' type eruption (total erupted tephra volume 0.1 to 1 km^3)? 4. Consider Aluto volcano. In a 100,000 year period, how many *silicic* eruptions of any size would you expect at the volcano in question? 5. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'violent Strombolian' type eruption (total erupted tephra volume 0.01 to 0.1 km^3)? 6. For the same volcano, given 10,000 realisations of a future *silicic* volcanic eruption, how many would be a 'sub-Plinian' to 'Plinian' type eruption (total erupted tephra volume 0.1 to 1 km^3)?
4) Participant's expertise	[To be completed by the expert. Please briefly identify your expertise in relation to estimating frequency-magnitude relationships at volcanoes with few data.]
5) Key relevant evidence	[The expert should add details of any key documents and studies that are relevant to volcanic hazard assessments (particularly with regard assigning Frequency-Magnitude relationships), and bring them to the workshop if possible.]

Appendix 3 Background Evidence

Main Ethiopian Rift Background Information and Volcanic History

The aim of this report is to provide information to inform the expert elicitation. Here we introduce the project and the Main Ethiopian Rift (section 1), and summarise background information on the two main central volcanoes, Corbetti and Aluto (sections 2 and 3), which are the focus of the elicitation. Frequency-magnitude relationships derived from the literature are given in section 4. Sections 5 summarises the palaeoclimate through the Late Pleistocene and Holocene, as observed through lake level fluctuations reflecting periods of arid and wetter conditions which may have affected tephra preservation. Current rainfall and wind data are also provided. Data from global databases, namely the Smithsonian Institution Global Volcanism Program Volcanoes of the World 4.6.6 database (VotW), are summarised in sections 6 and 7, while section 8 provides information on potential analogue volcanoes. Appendices 1 and 2 contain published and unpublished terrestrial and lake sediment stratigraphies for Corbetti and Aluto, respectively. Appendix 3 provides information on the other central volcanoes in the MER, which may be helpful when considering potential future eruptions.

Background material on the volcanic centres has been compiled from published literature as well as reports and personal communications from the RiftVolc project WP1 and WP3 teams (Karen Fontijn, Keri McNamara, Ben Clarke and Sam Engwell). For detailed information on the volcanic centres please refer to the recent Fontijn et al. (2018) paper and references therein.

1. Introduction

The five-year NERC-funded RiftVolc project began in 2014 with an aim to investigate rift volcanism in the Main Ethiopian Rift (MER) through three work packages describing past, present and potential future activity. The project aims to improve understanding of the mechanisms behind rift volcanism and the potential for future volcanic hazards through studying past eruptions (tephra, PDC and lava flow mapping and sampling for geochemistry and geochronology) and current activity (deformation and seismicity). BGS leads WP3, the future work package, and will carry out ash fall hazard analyses both at a local scale for Corbetti volcano and at a regional scale across Central Ethiopia. This will build on knowledge gained from work package 1 (WP 1, past), and a World Bank study on volcanic risk in sub-Saharan Africa carried out in 2015 (Jenkins et al., 2015).

Researchers from WP 1 have carried out fieldwork over three seasons from 2015 to 2017. BGS carried out fieldwork in 2017 alongside WP 1 researchers. Interbedded sequences of tephra, soil and/or lake deposits have been logged and sampled in road cuts and gorges near Corbetti, Aluto, Bora-Baricha, Tullu Moye, Gedemsa, Boset-Bericha and Kone (Fig. 1) (Fontijn et al., 2018). The focus of the WP3 hazards research is on the Corbetti and Aluto volcanoes.

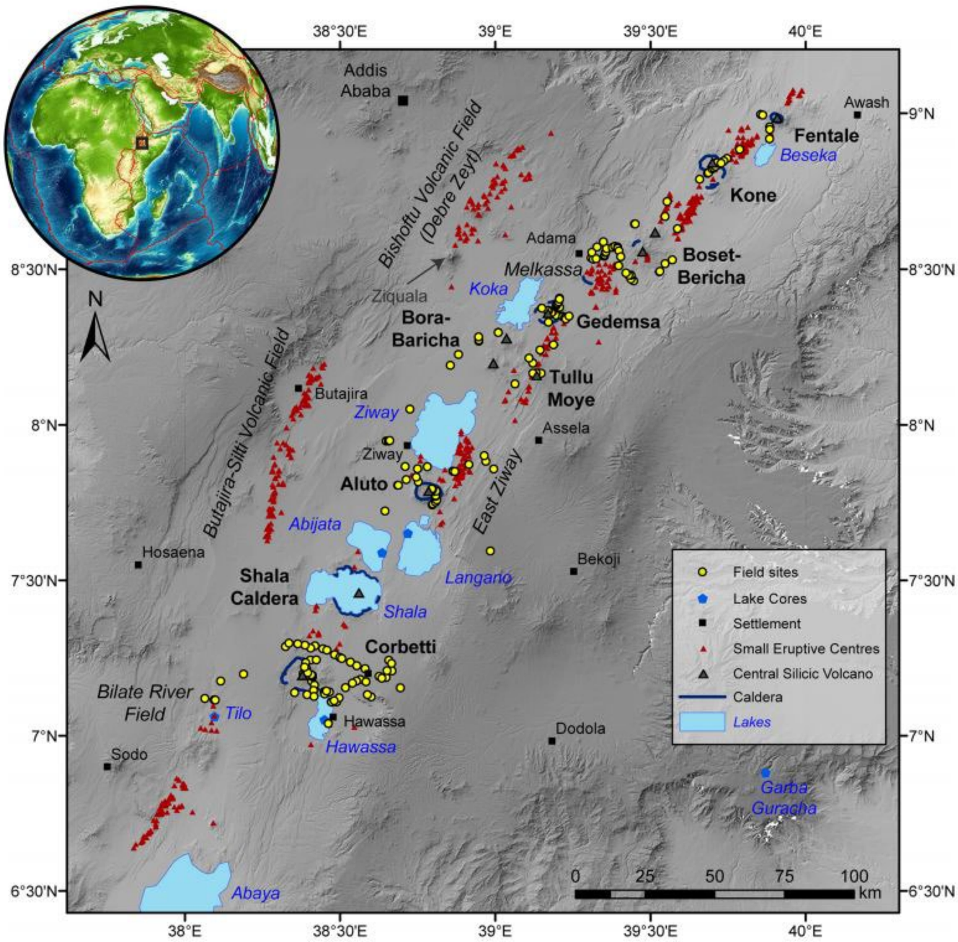


Figure 1 Location map of the Central silicic volcanoes in the MER. Figure taken from Fontijn et al. (2018).

Main Ethiopian Rift

The MER forms the northern most segment of the East African Rift System (EARS), a continental rift associated with active volcanism (Ebinger and Casey, 2001). Silicic caldera complexes and central stratovolcanoes are found along the rift axis, as well as large fields of mafic scoria cones. Rifting in the MER began around 11 Ma in the north (Wolfenden et al., 2004), and around 8-10 Ma (Woldegabriel et al., 1990) or 5-6 Ma (Bonini et al., 2005) further south. At around 1.6-2 Ma, distribution of activity narrowed and active faulting and volcanism focused on the rift floor.

There are eleven central silicic volcanoes in the RiftVolc study area of the MER, which from north to south are: Fentale, Kone, Boset, Bericha, Gedemsa, Bora, Baricha, Tullu Moye, Aluto, Shala and Corbetti (Fig. 1) (Fontijn et al., 2018). There are also two volcanic fields along the western edge of the rift: Bishoftu and Butajira. The latest Pleistocene to Holocene volcanic history of these centres is poorly known; however, in recent years there has been an increased interest in understanding the volcanic systems of the MER in relation to volcanic hazards (e.g. Biggs et al., 2011; Hutchison et al., 2016a; Hutchison et al., 2016b; Rapprich et al., 2016; Vye-Brown et al., 2016; Martin-Jones et al., 2017; Fontijn et al., 2018).

For the purposes of WP3, the focus will be on eruptive activity at Aluto and Corbetti volcanoes. The presence of multiple pumice fall deposits on the edifices of Aluto and Corbetti, and numerous tephra layers in lake sediment cores suggest frequent occurrence of explosive eruptions at these centres. There have been no historical eruptions at the central MER volcanoes in living memory; however, this is not true for other volcanoes along the active EARS (e.g. Nabro, 2011; Ol Doinyo Lengai, 2008; Erta Ale ongoing eruptions). Recent eruptions together with ongoing ground deformation (e.g. Biggs et al., 2011; Hutchison et al., 2016a) and seismicity (e.g. Keir et al., 2006; Wilks et al., 2017) indicate that these magmatic systems are still active.

2. Corbetti

The Corbetti caldera lies in the central to southern MER and is the southernmost of the RiftVolc MER central volcanoes (Fig. 1). Together with Aluto, it is probably the best studied of the central MER volcanoes. The caldera formed approximately 180 ka producing a welded ignimbrite and unwelded pyroclastic deposits. Post-caldera activity is characterised by explosive pyroclastic activity and the formation of effusive obsidian lava flows. Within the caldera are three volcanic centres: Artu, Urji (Wendo Koshe) and Chabbi (also known as Chabi or Chebi). Based on morphology and field relationships, Artu is assumed to be the oldest with more recent activity alternating between effusive activity at Chabbi and explosive activity at Urji (Rapprich et al., 2016; Fontijn et al., 2018). Deposits at the base of Chabbi are dated at 20 ka (Fontijn et al., 2018).

The most widespread pumice fall deposit is the Wendo Koshe Younger Pumice (WKYP), a massive pumice fall deposit that can be traced across an area of over 1040 km^2 (Rapprich et al., 2016). Based on new field data, Fontijn et al. (2018) estimated a minimum erupted volume of 1.3 km^3 for the WKYP deposit using the Pyle (1989) method, with an estimated thickness of 0.5 m in the nearby town of Shashemene, approximately 20 km to the east of Corbetti (Fig. 2). The age of the eruption has been dated at > 2.3 ka cal BP based on radiocarbon dating of a palaeosol underlying the WKYP (Rapprich et al., 2016). At least four obsidian flows from Chabbi post-date the WKYP deposit.

Within Corbetti caldera there are at least two thick pumice fall deposits separated by multiple small-scale fall deposits: the WKYP and the Bedded Pumice (Fontijn et al., 2018). The Bedded Pumice deposit is a rhythmically bedded pumice deposit characterised by the presence of obsidian clasts. The deposit has a roughly circular pattern which has been interpreted as resulting from pulsatory behaviour of the eruption (Fontijn et al., 2018).

Off the flanks of the Corbetti edifice are monogenetic cones, which have produced scoria, PDCs and lava flows. The location of vents close to Lake Awassa has resulted in highly explosive phreatomagmatic eruptions producing widely-dispersed (>5 km) tephra (ash) fallout and PDCs with runout lengths of up to 6km (Ben Clarke, pers. comm.).

In total, Fontijn et al (2018) have identified seven pyroclastic fall deposits interbedded with palaeosols in the last 7-8 ky (Appendix 1), four of which have been correlated across multiple sites. Based on this, Fontijn et al. (2018) estimate an explosive eruption recurrence rate of 700-1000 years.

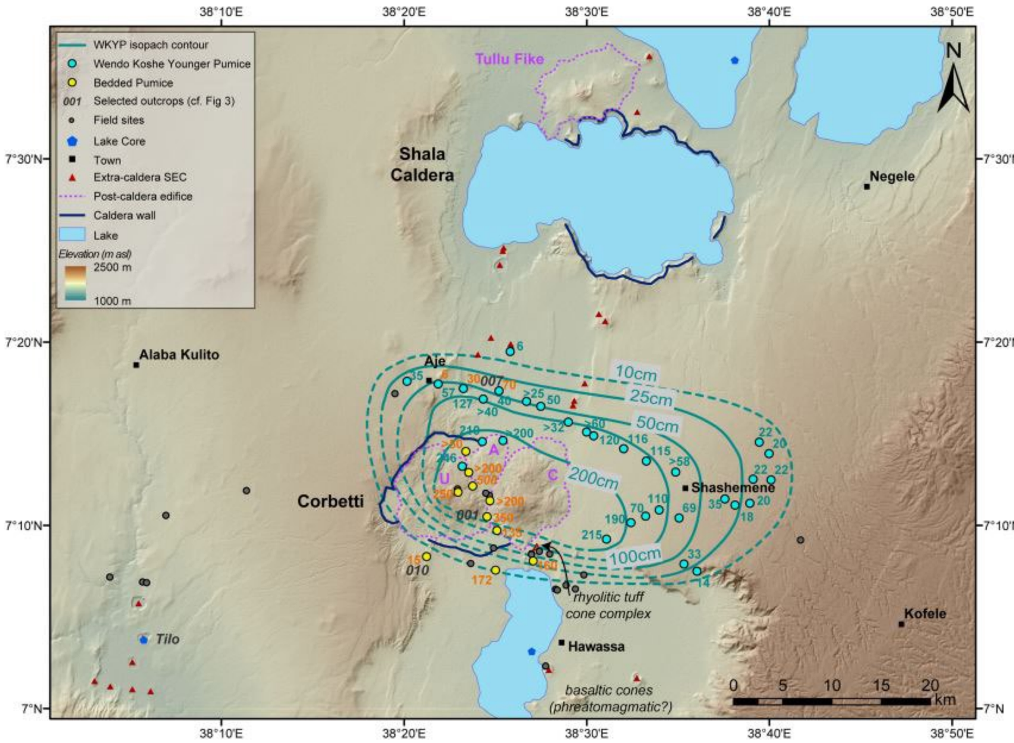


Figure 2 Location map of Corbetti and Shala calderas with isopachs for the Wendo Koshe Younger Pumice (WKYP). Figure taken from Fontijn et al (2018).

Martin-Jones et al. (2017) analysed sediment cores from Lakes Awassa (Hawassa), Tilo (40 km west of Corbetti caldera) and Chamo (170 SSW of Corbetti caldera). They dated 14 tephra layers within the last 10 ky in the Lake Tilo core. Based on geochemical similarities to tephra in cores from Lake Awassa and tephra deposits on Corbetti caldera, Martin-Jones et al. (2017) attribute Corbetti as the source volcano. They suggest a recurrence rate for explosive eruptions at Corbetti of approximately 900 years, consistent with the estimates of Fontijn et al. (2018).

3. Aluto

Aluto caldera (Fig. 3) formed around 300-320 ka (Hutchison et al., 2016b) with the eruption of at least one welded-ignimbrite. Post-caldera activity, < 60 ka, has largely filled the caldera with the eruption of pyroclastic deposits and lava forming pumice cones and obsidian lava domes on the edifice (Hutchison et al., 2016b; Ben Clarke, pers. comm.). Eighty-four vents have been identified on the LIDAR DEM across the Aluto edifice, the majority located along the caldera ring fault (Ben Clarke, pers. comm). These vents are morphologically identical to ground truthed pumice cones. The pumice cones follow a three-phase eruption cycle beginning with Strombolian to violent Strombolian activity forming a tuff ring, which eventually builds a pumice cone. The second phase of activity is the formation of PDCs from the collapse of violent Strombolian to sub-Plinian eruption columns. Activity ends with the formation of obsidian lava flows (Ben Clarke, pers comm).

Fontijn et al. (2018) described deep river gorges exposing tens of metres thick sections containing up to 20 pyroclastic fall deposits interbedded with lacustrine deposits and/or palaeosols (Appendix 2). This terrestrial record is consistent with the explosive eruptive record of 25 distinct tephra horizons in the last ~12 kyrs described in sediment cores from the nearby lakes of Abijata (Abiyata) and Langano, 25 km southwest and 12 km south of Aluto, respectively (Gibert et al., 1999; Chalié and Gasse, 2002; Gibert et al., 2002; McNamara et al., 2018).

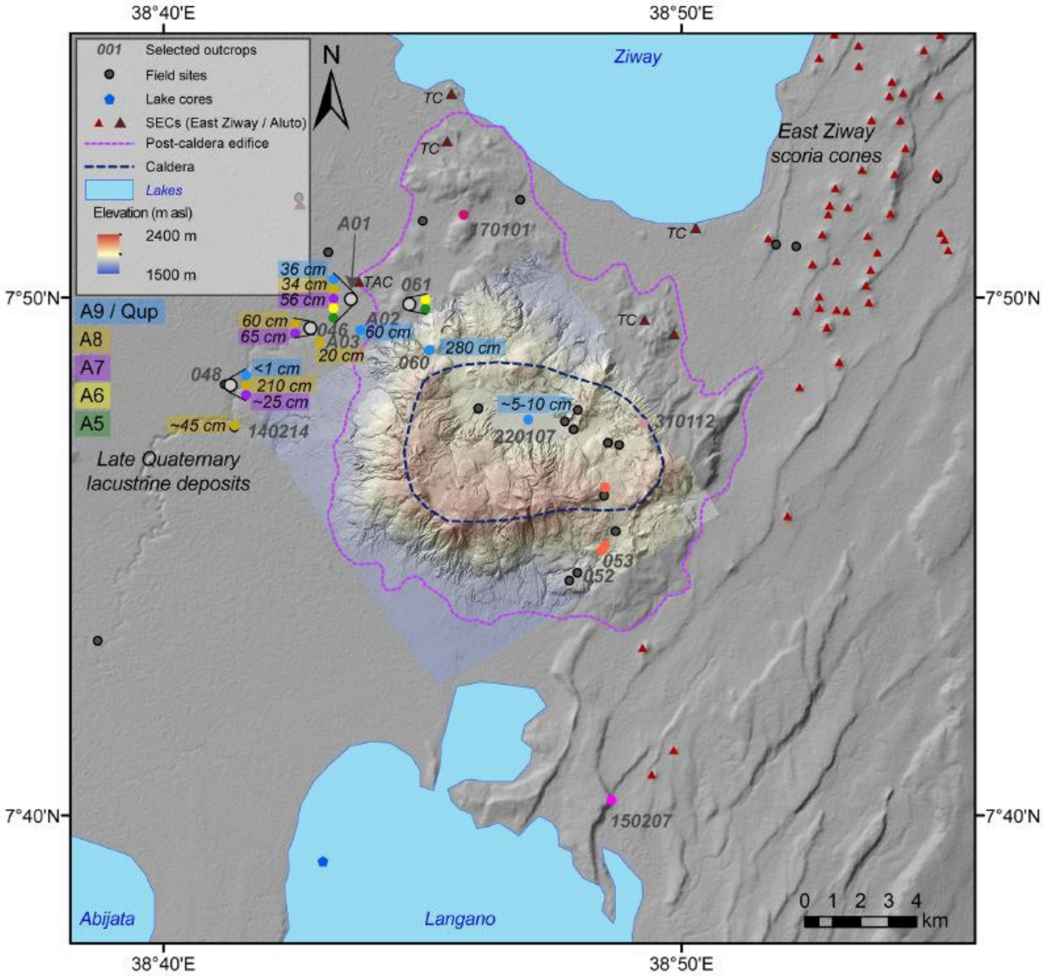


Figure 3 Location map of Aluto caldera, taken from Fontijn et al. (2018).

McNamara et al. (2018) analysed tephra layers from the sediment cores from Lakes Abijata and Langano in detail. They describe 24 tephras deposited over 8990 years in the Lake Abijata core (ABII) and 20 tephra layers deposited over 5439 years in the Lake Langano core (LLIII) (Appendix 2). The higher number of tephra layers in LLIII may be related to the more proximal location of the core to Aluto volcano (McNamara et al., 2018). Based on timing, componentry and geochemistry, five tephra layers have been correlated between the two cores.

Hutchison et al. (2016b) identified a post-caldera pumice fall deposit covering much of the Aluto edifice, which they described as forming from a single Plinian event. However, based on glass major element analyses of pumice lapilli and ash, Fontijn et al. (2018) suggest this unit comprises multiple pumice fall deposits sourced from different vents on the edifice. They associate the pumice deposits with the formation of pumice cones, which would have deposited thick accumulations of pumice locally, but would not have been widely dispersed.

Tuff cones have been identified in the vicinity of Lake Ziway, north of Aluto volcano (Fontijn et al., 2018). These have produced phreatomagmatic eruptions in the past; however, their ages are unknown.

4. Frequency-magnitude relationships

The focus of the RiftVolc fieldwork has been on the explosive silicic post-caldera eruptions of the central volcanoes; therefore, any information on frequency-magnitude relationships relates to explosive silicic activity, and in particular, the activity that results in widespread tephra fall. There have been reports of recent (the last few hundred years) effusive activity at some of the centres: Fentale, Kone and Tullu Moye. The ages of activity at the volcanic fields of Butajira and Bishoftu are unknown.

Explosive eruption recurrence rates of 700-1000 years and 300-500 years have been estimated for Corbetti and Aluto, respectively, based on new field data collected by the RiftVolc project and Hutchison et al. (2016b) (Fontijn et al., 2018) (Table 1). McNamara et al. (2018) carried out cluster analysis on the tephra layers from the sediment cores from Lakes Abijata and Langano to identify any clustering in frequency of eruptions and therefore peaks in activity. Aluto appears to experience bursts of activity of five or more eruptions with an eruption frequency of at least one every 150 years (Fig. 4). These periods of heightened activity have occurred at 3.5 ka, 6.1 ka and 11 ka with eruption frequencies or recurrence rates of 103, 109 and 128 years, respectively (McNamara et al., 2018). Eruption recurrence rates of 519 and 1700 years, respectively, have been estimated for between these periods of activity (McNamara et al., 2018).

Volcano	***n* eruptions (Holocene)**	**Recurrence rate**	**VEI**	**F-M (Jenkins et al., 2015)**
Corbetti	7	1 per 700-1000 years	4 VEI=4 3 VEI=3	
Aluto	25	1 per 300-500 years	VEI=3	VEI<3 550 years VEI=3 950 years VEI=4 3600 years VEI=5 14,500 years VEI=6 65,000 years
Bora-Baricha	unknown (>11 since Late Quaternary 0.5-1Ma)	?1 per 45,000-90,000 years	unknown	
Gedemsa	unknown	unknown	unknown	
Boset	5-6	1 per 2000-2500 years	unknown	
Kone	unknown	unknown	unknown	
Fentale	unknown	unknown	unknown	VEI≤2 450 years VEI=3 460 years VEI=4 700 years VEI=5 1500 years VEI=6 3000 years

Table 1 Frequency-magnitude of post-caldera eruptions at the main MER eruptive centres. Data from Fontijn et al. (2018). The frequency-magnitude relationships derived by Jenkins et al. (2015) through expert elicitation for Aluto and Fentale are also given. Aluto was considered representative of Corbetti.

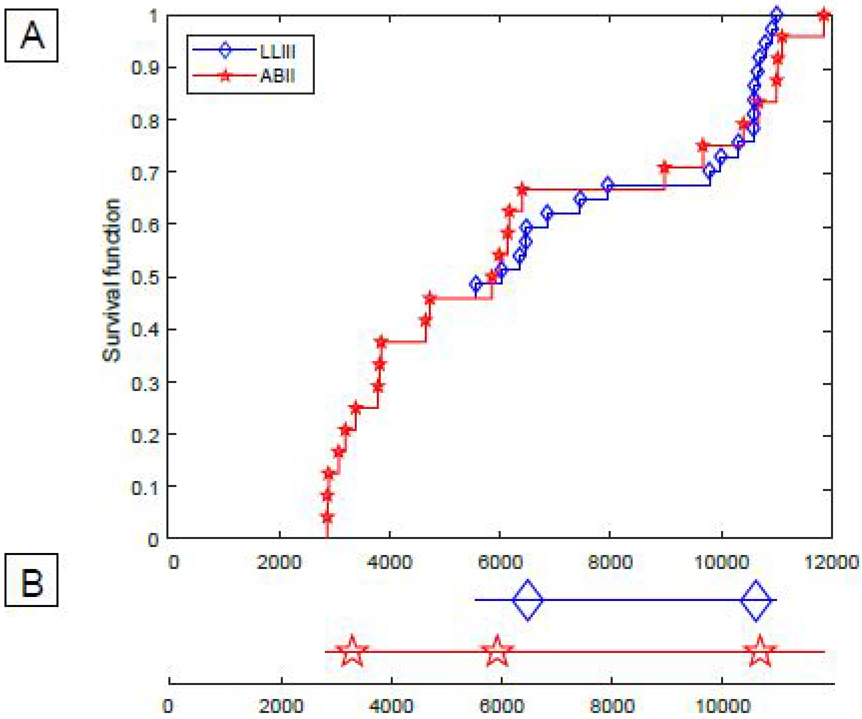


Figure 4 A) Plot of survival function with time for cores ABII (red) and LLIII (blue) showing the stepped appearance of heightened levels of activity. B) Centroids of the three main phases of heightened activity. Figure taken from McNamara et al. (2018).

Although Corbetti and Aluto are the best studied of the central MER volcanoes, the stratigraphies are still incomplete due to lack of correlatable exposures, a lack of dateable material, and preservation issues. Both volcanoes would benefit from further field analysis of both tephra and pyroclastic flow deposits. As a result, recurrence rates are minimum estimates.

Eruption magnitudes (VEI) were assigned by Fontijn et al. (2018) based on the thickness of deposits observed in the field. The Qup pumice fall deposit at Aluto is up to 3 m thick near the source vent; however, it rapidly thins to tens of centimetres or less within 5 km. Fontijn et al. (2018) therefore assigned a VEI of 3 to this eruption, and to the other 24 pumice-forming eruptions identified at Aluto. Similar scale deposits have been identified at Tullu Moye and Boset-Bericha (Fontijn et al., 2018). Thicker, metre to tens of metres, pumice fall deposits described at Corbetti (and Bora-Baricha and Boset) are consistent with larger volume, VEI 4 or 5, eruptions. Fontijn et al. (2018) assigned VEI 4 to four of the Corbetti Holocene eruptions, and VEI 3 to the remaining three (Table 1).

Based on the presence of pumice deposits on the edifices, most obsidian lava flows and coulees at Aluto and Corbetti are assumed to be associated with explosive activity (Hutchison et al., 2016b; Fontijn et al., 2018), which is consistent with other peralkaline volcanic systems. Further north however, at Tullu Moye, Boset and Fentale, there is an increasing proportion of silicic effusive activity with no obvious associated explosive volcanism (Fontijn et al., 2018).

Of the remaining central volcanoes, there is very little data to base frequency-magnitude relationships on. Fontijn et al. (2018) described at least 11 pyroclastic fall deposits at Bora-Baricha which they estimate to have erupted during the Late Quaternary (0.5 – 1 Ma). Based on this we have estimated a recurrence rate of 1 every 45,000 to 90,000 years, however this is very ambiguous. At the Boset complex, Fontijn et al. (2018) identified 5-6 pyroclastic fall deposits erupted during the Holocene, which gives a recurrence rate of 1 every 2000-2500 years. Although post-caldera explosive activity at Gedemsa has been described by Fontijn et al. (2018), there is no geochronology to constrain the ages of the eruptions. Post-caldera explosive eruptions at Kone and Fentale have not been identified.

Eruption frequency-magnitude relationships were derived through expert elicitation for Aluto and Fentale volcanoes for a World Bank project on Sub-Saharan Africa Volcanic Risk (Jenkins et al., 2015). Because of similarities between Aluto and Corbetti volcanoes, the frequency-magnitude relationship for Aluto was taken to also represent Corbetti. Due to the lack of data for Fentale, the well-studied Rungwe volcano in Tanzania was used as an analogue. The experts derived a mean estimate of recurrence rate for each of VEI <3, 3, 4, 5 and 6. Results show that uncertainties were larger for the larger magnitude (VEI 5 and 6) eruptions reflecting the potential for long periods of dormancy or the potential for the system to move towards extinction (Jenkins et al., 2015).

5. MER climate

Late Pleistocene to Holocene

Various palaeoclimatic studies have been carried out in the lakes Region of the central MER, with a focus on the evolution of the lake systems (Benvenuti and Carnicelli, 2015 and references therein). Four main phases of lake level fluctuations linked to climatic periods of drier and wetter conditions have been identified. The first phase coincides with the last glacial period ca. 100 - 22 ka, during which the lake waters inundated wide areas north of Lake Ziway. Following this was a period of dramatic shrinking, from ca. 22 – 11 ka. From ca. 11 to 5 ka lake levels experienced frequent fluctuations, but were never as high as recorded during the first phase. The final phase covers the last 5 ka, during which the previous single large lake separated into Lake Ziway in the north and Lakes Abyiata, Langano and Shala in the south. These phases have been related to global Late Quaternary weakening and strengthening of the monsoon circulation that caused drier and moister conditions over the lakes (Benvenuti and Carnicelli, 2015 and references therein).

Current Rainfall

The Ethiopian National Meteorological Agency (NMA) produces daily rainfall data from 27 stations across Ethiopia (Fazzini et al., 2015). Data from nine stations from the MER reveal annual rainfall of between 505 and 1225 mm, with between 49 and 71% falling during *kiremt*, the main monsoon-type rainy season from June to September (Table 2).

Meteo-Stations	Height (m s.a.l.)	P (mm) annual	P (mm) *belg* (Feb-May)	P (mm) *kiremt* (Jun-Sep)	P (mm) *bega (Oct-Jan)*	% *kiremt*
Adami Tulu (ATU)	1,636	756.8	186.2	447.6	123	59.1
Asela (ASE)	2,430	1225.5	321.6	762.8	141.1	62.2
Awasa (AWA)	1,750	951.5	292.9	472.6	186.0	49.7
Boricota (BOR)	1,062	505	122	309	74	61.2
Butajira (BUT)	2,000	118.1	377.7	560.6	179.8	50.1
Koka Dam (KOK)	1,595	698.8	135.6	496	67.3	71
Meki (MEK)	1,660	771.2	185.6	482.1	103.5	62.5
Metahara (MET)	947	549.2	140.2	322.4	86.6	58.7

Ziway (ZIW)	1,640	742.5	201.5	442.1	98.9	59.5

Table 2. Rainfall data for the nine NMA stations in the MER. Precipitation, P, is in millimetres. The percentage of rain that falls in the rainy season from June to September (*kiremt*) is also given. Data taken from Fazzini et al. (2015)

Current Wind Conditions

The prevailing wind direction in the central MER is to the west during January to August, and varies between east and west in September to December. Figure 5 shows wind rose diagrams for Corbetti caldera from 2015, generated from NOAA Reanalysis data. Wind data has also been downloaded for Aluto, which shows very little variation from wind conditions at Corbetti.

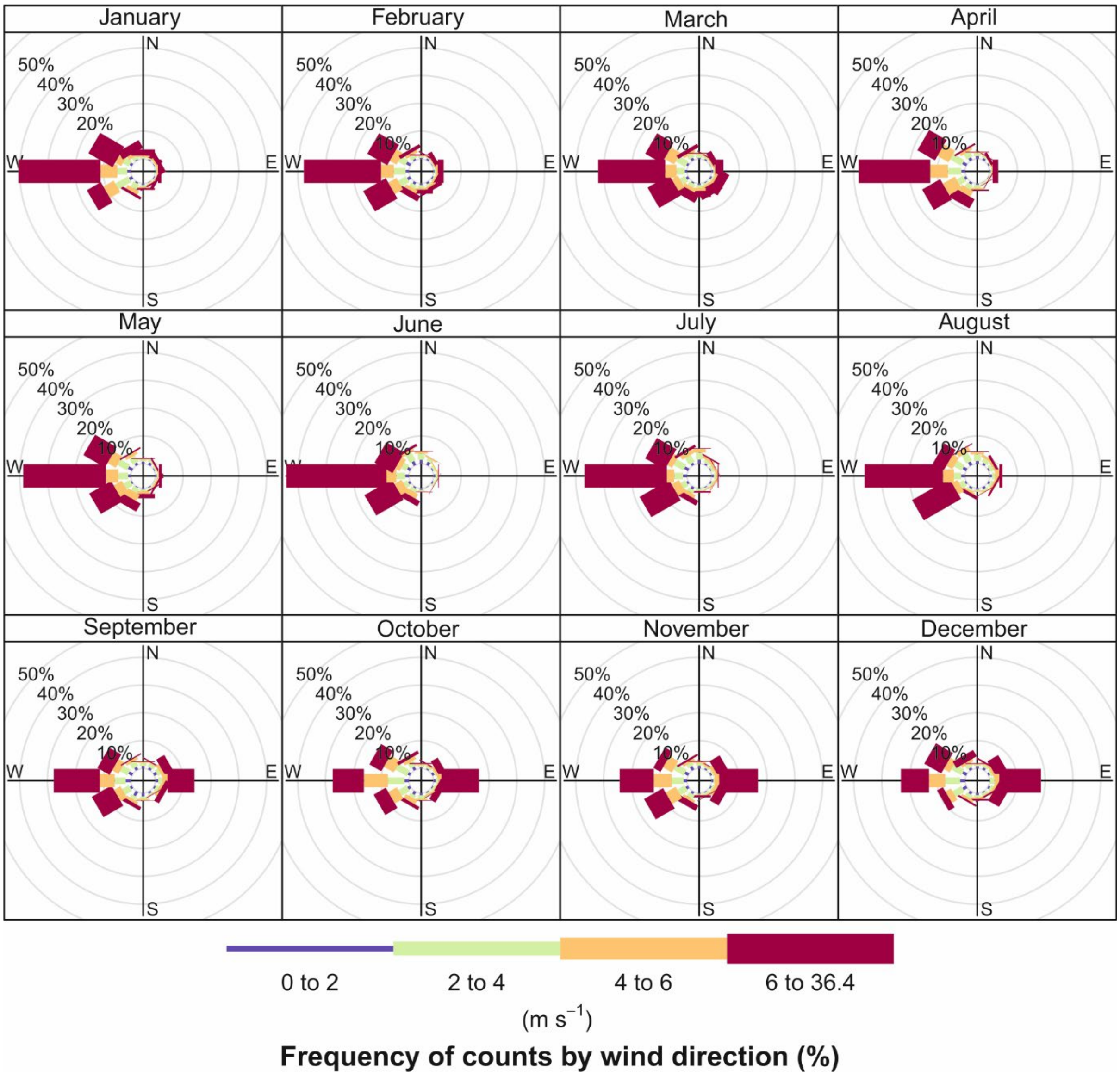


Figure 5 Wind rose diagrams from 2015 for Corbetti volcano. Coloured bars show the direction the wind is blowing to, while the colours represent the wind speed. NCEP-NOAA reanalysis2 data downloaded in November 2017 (NOAA, 2015)

6. Global Volcanic Data

According to the Smithsonian Institution Global Volcanism Program (GVP), Volcanoes of the World 4.6.6 (VotW) database there have been 9840 confirmed eruptions in the Holocene (GVP, 2013). These have been classified according to the Volcanic Explosivity Index (Newhall and Self, 1982) from VEI 0 to 7. Unclassified eruptions have also been included (Fig. 6). However, care must be taken with using the VotW database. For many years the GVP designated explosive eruptions of unknown size as VEI 2. The VEI assigned to an eruption refers to either the maximum VEI explosion produced (up to VEI 8) over the course of an eruption or the cumulative VEI calculated from the total volume of material erupted throughout the eruption. It is not always clear or stated which method has been used in the VotW database. The duration, magnitude and chronology of explosive episodes produced during an eruption can have significant influence upon the likely impacts and this important information is masked in eruptions classified only by their VEI.

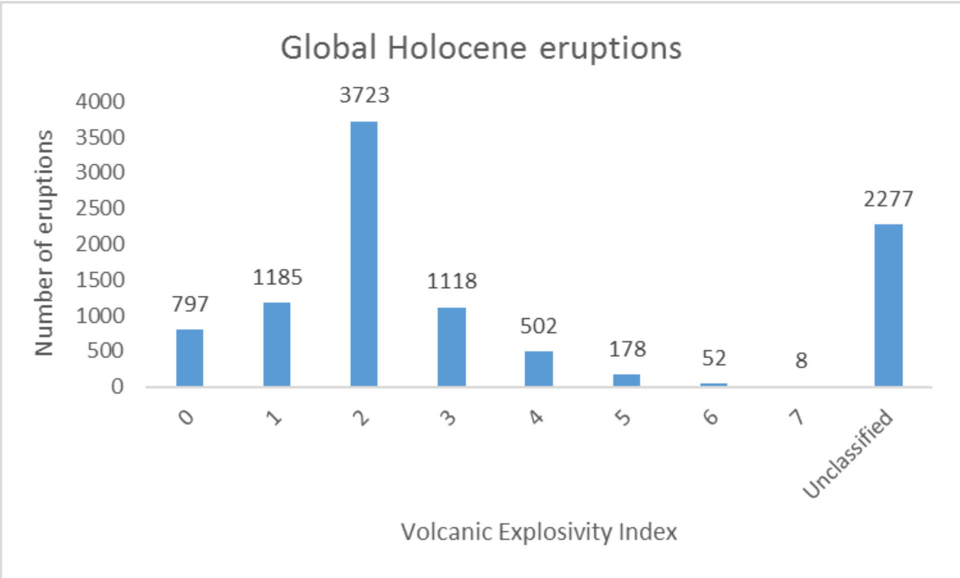


Figure 6 Confirmed global Holocene eruptions according to the VotW database (GVP, 2013)

7. Eruptive activity in Africa

Confirmed African Holocene eruptions number 166 in the VotW database (GVP, 2013) (Fig. 7). Again these have been classified according to their VEI from 0 to 6, with no recorded VEI 7 eruptions in the Holocene in Africa. Unclassified eruptions have also been included.

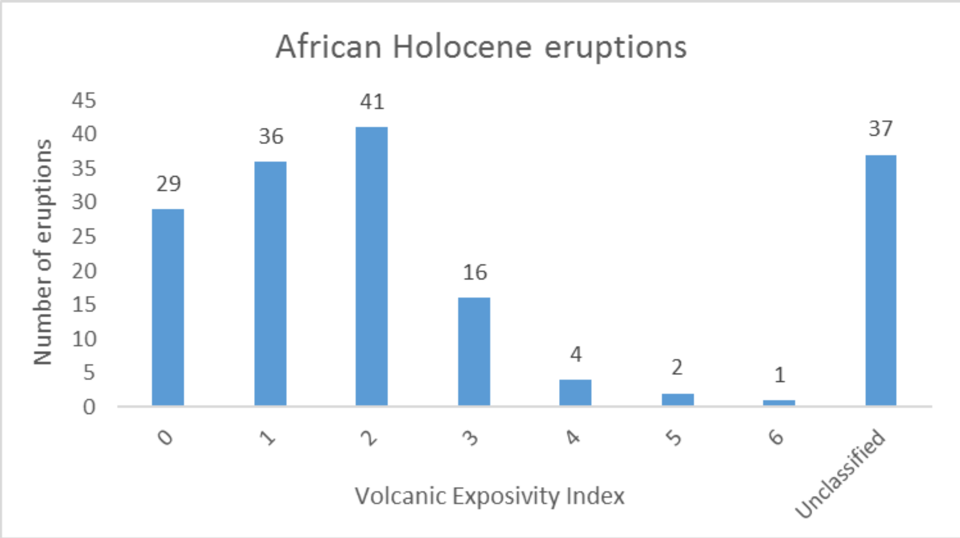


Figure 7 Confirmed African Holocene eruptions according to the VotW database (GVP, 2013)

According to the Global Volcanism Program, VotW database, there have been 28 Holocene eruptions in Ethiopia (Fig. 8). Of these, two have a VEI of 3, ten have a VEI of 2, two have a VEI of 1, six have a VEI of 0 and eight are unknown. Six Holocene eruptions are identified at the central MER volcanoes Aluto, Tullu Moje, Kone and Fentale (highlighted red in Fig. 8). Of these six eruptions, one has a VEI of 1, one has a VEI of 0 and the remaining four are unknown. All are confirmed eruptions through radiocarbon dating, anthropology and historical observations.

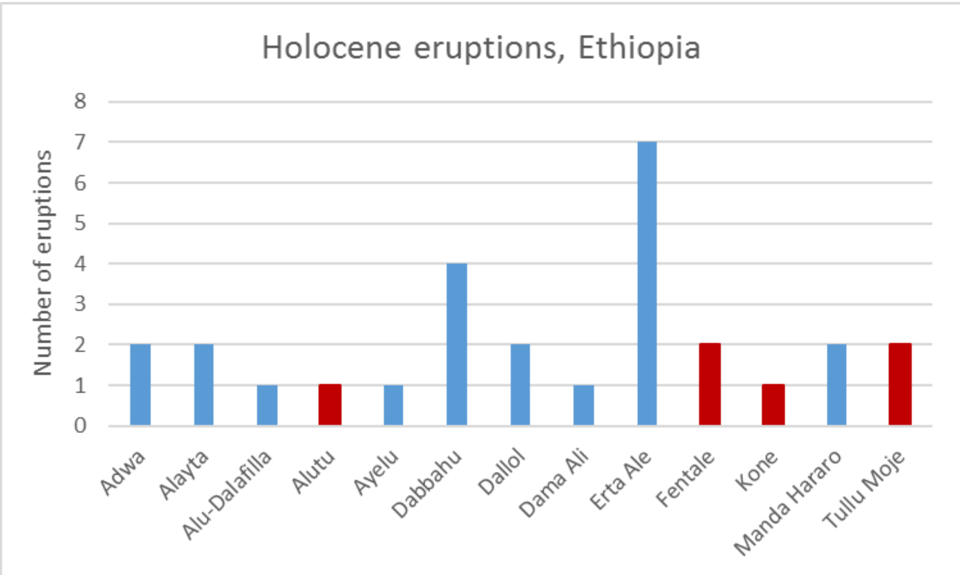


Figure 8 Global Volcanism Program, Volcanoes of the World 4.6.6 catalogue for Ethiopia. The main central volcanoes within the MER are highlighted in red. Global Volcanism Program, 2013. Volcanoes of the World, v. 4.6.6. Venzke, E (ed.). Smithsonian Institution. Downloaded 06 Mar 2018

8. Analogues

Corbetti and Aluto are peralkaline shield volcanoes, which experienced massive caldera-forming eruptions at approximately 180 ka and 300-320 ka, respectively (Hutchison et al., 2016b). Post-caldera activity at both centres is characterised by explosive pyroclastic pumice-cone forming eruptions and effusive obsidian lava flows. Mafic lava flows and phreatomagmatic eruptions are evident along regional fault structures on the rift floor surrounding the edifices. Analogous volcanoes must therefore have experienced massive ignimbrite caldera-forming eruptions and post-caldera silicic pyroclastic and effusive activity. Peralkaline rhyolite magmas tend to be water-rich and hence less viscous than their metaluminous counterparts; therefore, an ideal analogue would also be a peralkaline system. However, as with Aluto and Corbetti, the majority are under-studied and/or poorly accessible.

One well-studied example is Pantelleria, situated in the Sicily Channel Rift. Panterlleria is a strongly peralkaline rhyolite volcanic system with pantellerites erupted as PDCs, pumice fall or obsidian lavas (Rotolo et al., 2007). The volcano has two nested calderas, the oldest formed ca. 114 ka, and the youngest approximately 50 ka which produced the Green Ignimbrite that outcrops over most of the island (Cornette et al., 1983; Mahood and Hildreth, 1986). Orsi et al. (1991) identified at least 20 explosive eruptions in six silicic eruptive cycles since the eruption of the Green Ignimbrite ca. 50 ka. Each eruption began with explosive phases and ended with lava effusion, as observed in the stratigraphy of Aluto and Corbetti. The pumice fall deposits are not widely dispersed and have characteristics typical of Strombolian activity (Orsi et al., 1991).

Rotolo et al. (2007) revisited the explosive stratigraphy on the northern slopes of the volcano and described complex sequences of interbedded pumice fall deposits sourced from closely spaced vents. They identified eight units, erupted in the last 25,000 years. The pumice fall deposits are all associated with dome-buildings events and pantelleritic lava flows (Rotolo et al., 2007). Analysis of a deep sea core from ODP leg 160, 100 km east of Pantelleria, revealed six well-preserved tephras which have been correlated with volcanic activity of Pantelleria dated at 42.5, 127.5, 128.1, 129.1, 188.7 and 197.7 ka (Tamburrino et al., 2012).

The above correlations suggest that there have been at least 20 short-lived, Strombolian-style explosive eruptions in the last 50 ka, and eight in the last 25 ka. The deep-sea core tephra layers imply that there have been at least six sustained explosive eruptions widely dispersing tephra in the last 200,000 years.

Another potential analogue is Newberry volcano, Oregon, USA. Although the system is not peralkaline, there are a number of similarities in terms of eruptive style and products. Newberry volcano is a low angle shield volcano stretching 30 km east-west and 50 km north-south, approximately 60 km east of the Cascade range (Jensen et al., 2009). The summit has a caldera approximately 7 by 8 km in diameter that formed ca. 80 ka (Higgins and Waters, 1967). Activity at Newberry volcano includes mafic and silicic lava flows and silicic pyroclastic deposits from numerous eruptions within or near the central summit caldera. During the last 500,000 years there have been at least 50 rhyolitic and dacitic tephra-producing eruptions (Kuehn, 2002). These vary from locally distributed pumice rings and cones to ignimbrites and widely dispersed Plinian fallout deposits (Kuehn and Foit Jr, 2006). Kuehn and Foit Jr (2006) identified and correlated 13 tephra units, erupted between ca. 1500 and > 200,000 yrs BP, across 20 sites across five western states of the USA. Four distinct eruptive periods have been identified in the last 10,000 years, the last of which occurred approximately 1300 yrs BP. This period began with an explosive phase that produced widespread tephra fall (the Newberry Pumice), followed by the production of a small pyroclastic density current. The eruptive period ended with the production of an obsidian lava flow, the Big Obsidian Flow (Rust and Cashman, 2007). The estimated total volume of the eruption is 0.2 km^3 DRE, with an estimated 0.1 km^3

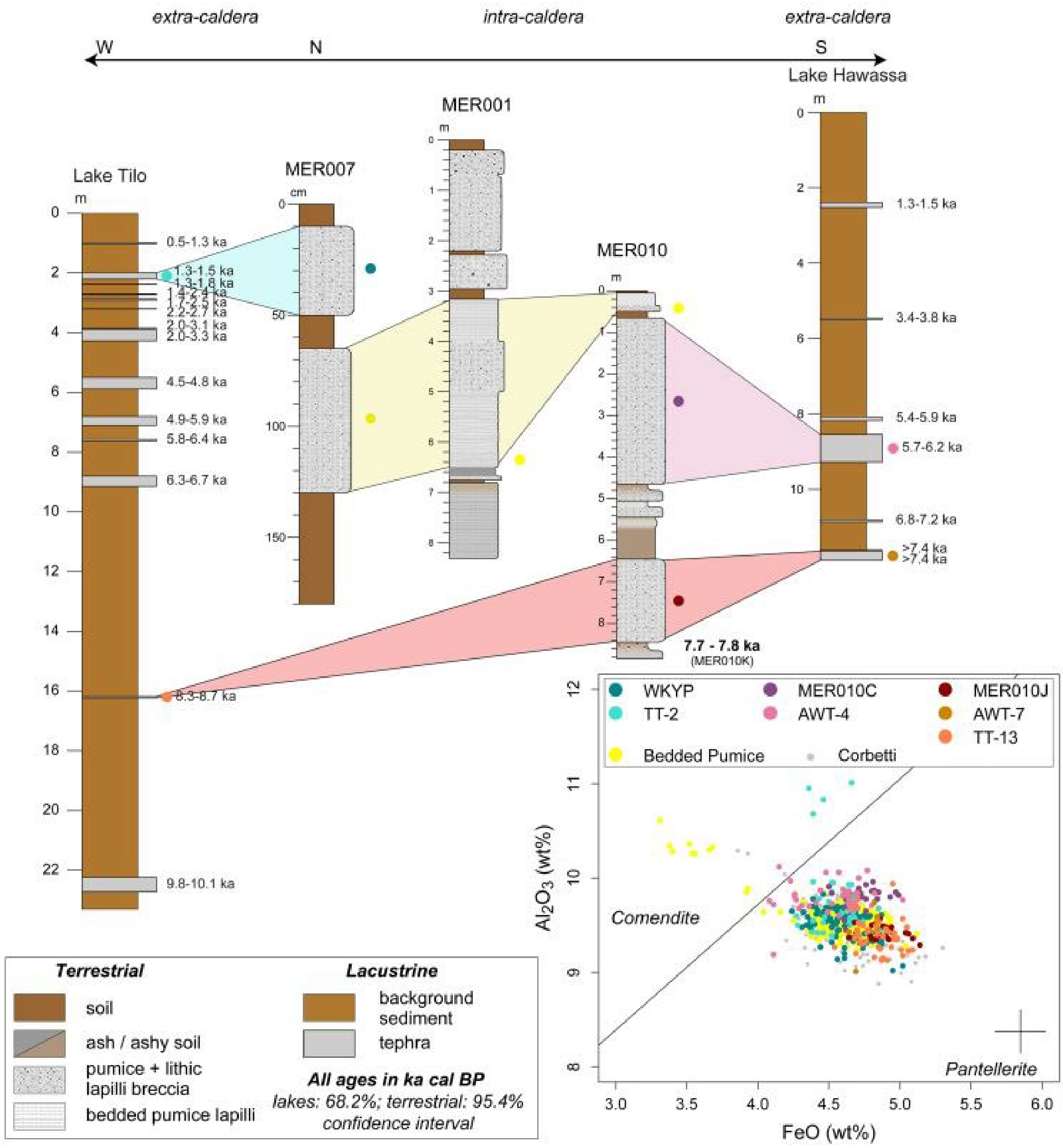
tephra fall deposit (MacLeod and Sherrod, 1988). The eruption column height was estimated to have been 21 km a.s.l. based on the method of Carey and Sparks (1986) (Gardner et al., 1998); however, Rust and Cashman (2007) suggest that this is overestimated as the elongated isopachs for the deposit suggest wind speeds of over 50 m/s. They instead suggest that the eruption was sub-Plinian, with a bent over plume resulting in a widely distributed deposit.

Corbetti and Aluto volcanoes have experienced numerous pumice cone-forming violent Strombolian type eruptions. Paricutin volcano, Mexico, is a scoria cone formed through violent Strombolian eruptions with contemporaneous effusive lava flow formation 1943-1952 (Pioli et al., 2008). The cone reaches a height of 2.8 km a.s.l., and although the basal tephra layers are basaltic in composition, the topmost ash blanket is andesitic (Pioli et al., 2008). The eruption column reached heights of up to 8 km a.s.l. or 6 km above the vent. Tephra accounts for an estimated 40% of the total erupted volume (Rowland et al., 2009). Another example is El Jorullo volcano in Mexico, which formed through similar activity from 1759 to 1775, with eruption column heights of up to 6 km and tephra fallout deposits account for 42% of the total erupted volume (Rowland et al., 2009). Although, geochemically and tectonically these volcanoes are not analogous to Aluto and Corbetti volcanoes, in terms of eruptions of violent Strombolian activity, they are well documented and provide insights into erupted tephra volumes and eruption column heights of such events. Similarly, Okmok volcano in Alaska can provide insights into violent Strombolian eruptions. Tephra volumes of 0.04 to 0.25 km^3 have been calculated at Okmok volcano using the Pyle (1989) method (Wong and Larsen, 2010). The eruption column reached heights of 8.5 to 14 km. There is also evidence of a limited degree of phreatomagmatism in the Okmok tephra deposit (Wong and Larsen, 2010), which is also observed in the tephra sequences on Aluto (Ben Clarke, pers comm).

Off the flanks of both Aluto and Corbetti edifices are monogenetic cones which have produced scoria, PDCs and lava flows. The location of vents close to lakes has resulted in highly explosive phreatomagmatic eruptions producing widely-dispersed (>5 km) tephra (ash) fallout and PDCs with runout lengths of up to 6 km (Ben Clarke, pers. comm.). Although there are numerous documented phreatomagmatic complexes e.g. Table Rock Complex, Oregon (Brand and Clarke, 2009), Sinker Butte volcano in the Snake River Plain (Brand and White, 2007) and the Inyo Volcanic Chain, Long Valley (Miller, 1985), few have detailed studies on tephra dispersion, erupted volumes and eruption column heights. The Table Rock Complex is a mafic phreatomagmatic complex in the Fort Rock – Christmas Lake Valley Basin, South-Central Oregon, covering an area of 40 km^2 (Brand and Clarke, 2009, 2012). Brand and Clarke (2009, 2012) describe pyroclastic surge deposits formed from column collapse heights of up to 2.8 km above the vent. Their estimates are based on the runout lengths of the surge deposits, which are greater than 5 km, similar to observations of deposits from phreatomagmatic eruptions at Corbetti volcano (Ben Clarke, pers. comm).

Appendix 1 Stratigraphic sections for Corbetti volcano

The following stratigraphic sections are taken from published and unpublished literature.



Terrestrial stratigraphy of Corbetti volcano, Fontijn et al. (2018)

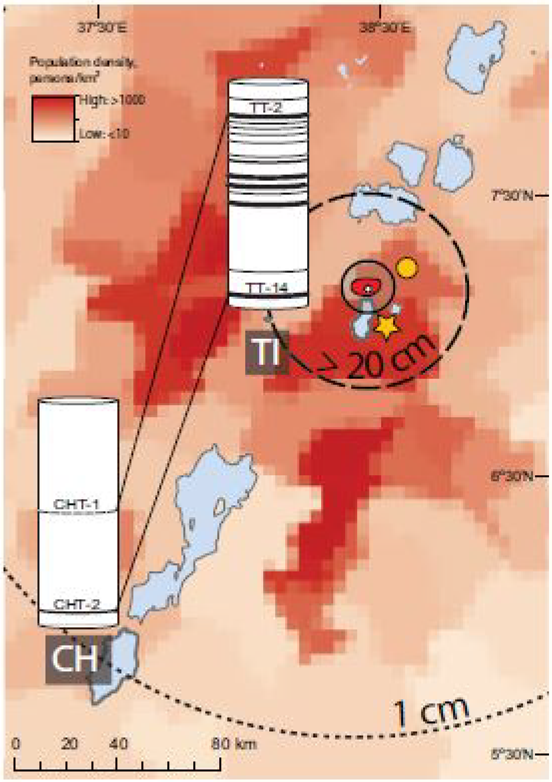
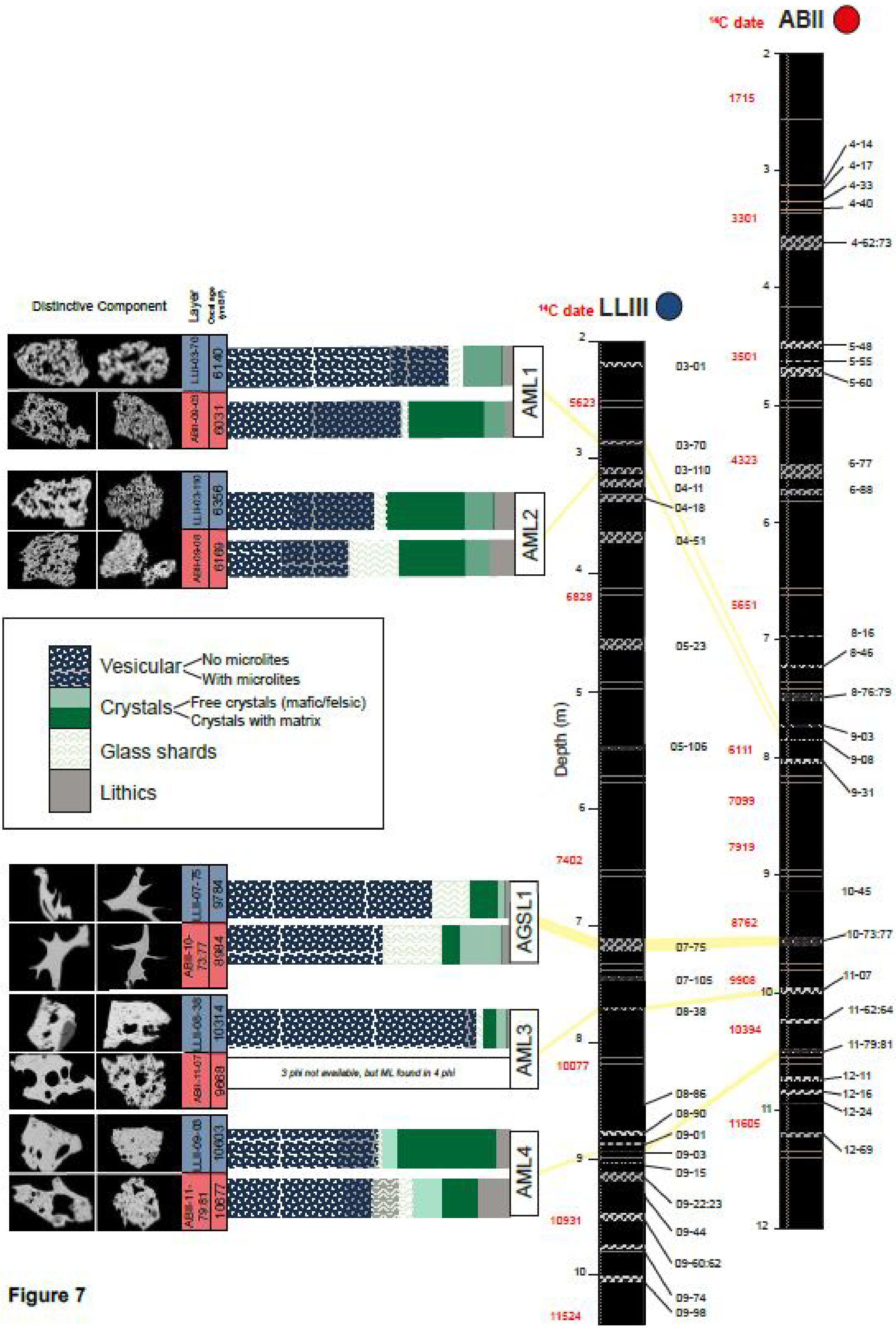


Figure 3. Corbetti caldera (C), Ethiopia, and correlations of tephras between Lakes Tilo and Chamo, overlain on a population density (persons/km²) map of the central Main Ethiopian Rift (MER) (2005 population count from the Socioeconomic Data and Applications Center; Center for International Earth Science Information Network, 2005) Star shows Awassa (A), and circle shows Shashamene (S). Isopachs for the Wendo Koshe Younger Pumice (WKYP) (dashed lines) are calculated using the exponential thinning relationship (Pyle, 1989; Fierstein and Nathenson, 1992), based on tephra thicknesses in Lakes Tilo and Chamo (this study) and at outcrops within the Corbetti caldera (Rapprich et al., 2016). Current distal data are limited to one dispersal axis; however, proximal data indicate a weak wind influence, thus simplified circular isopachs are inferred. We calculate that the Wendo Koshe eruption generated ~3 km³ of tephra (equivalent to ~1.5 km³ of silicic magma), blanketing the contemporary towns of Awassa and Shashamene with >20-cm-thick tephra deposits.

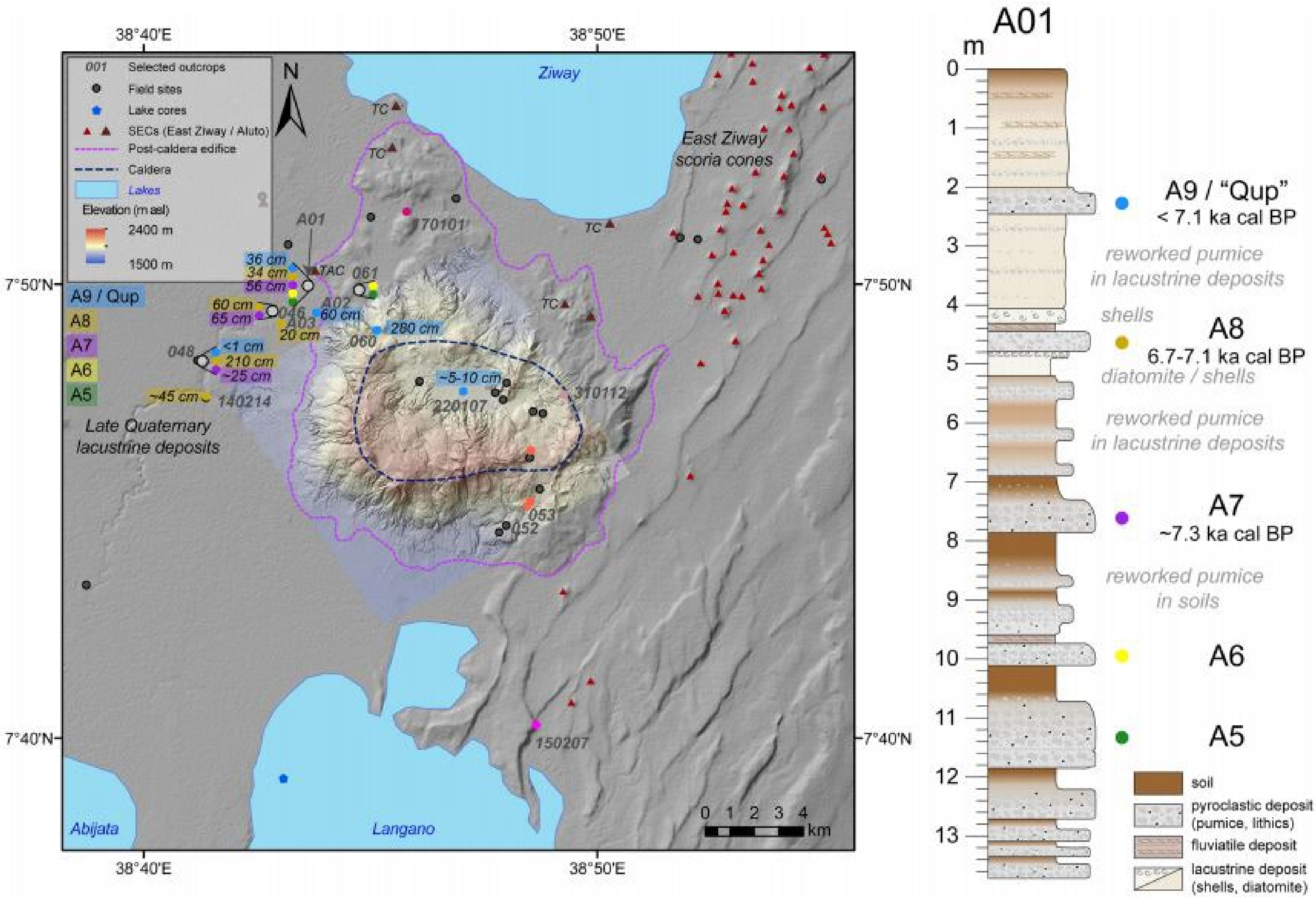
Correlation of Corbetti tephra from sediment cores from lakes Tilo and Chamo, Martin-Jones et al. (2017)

Appendix 2 Stratigraphic sections for Aluto volcano

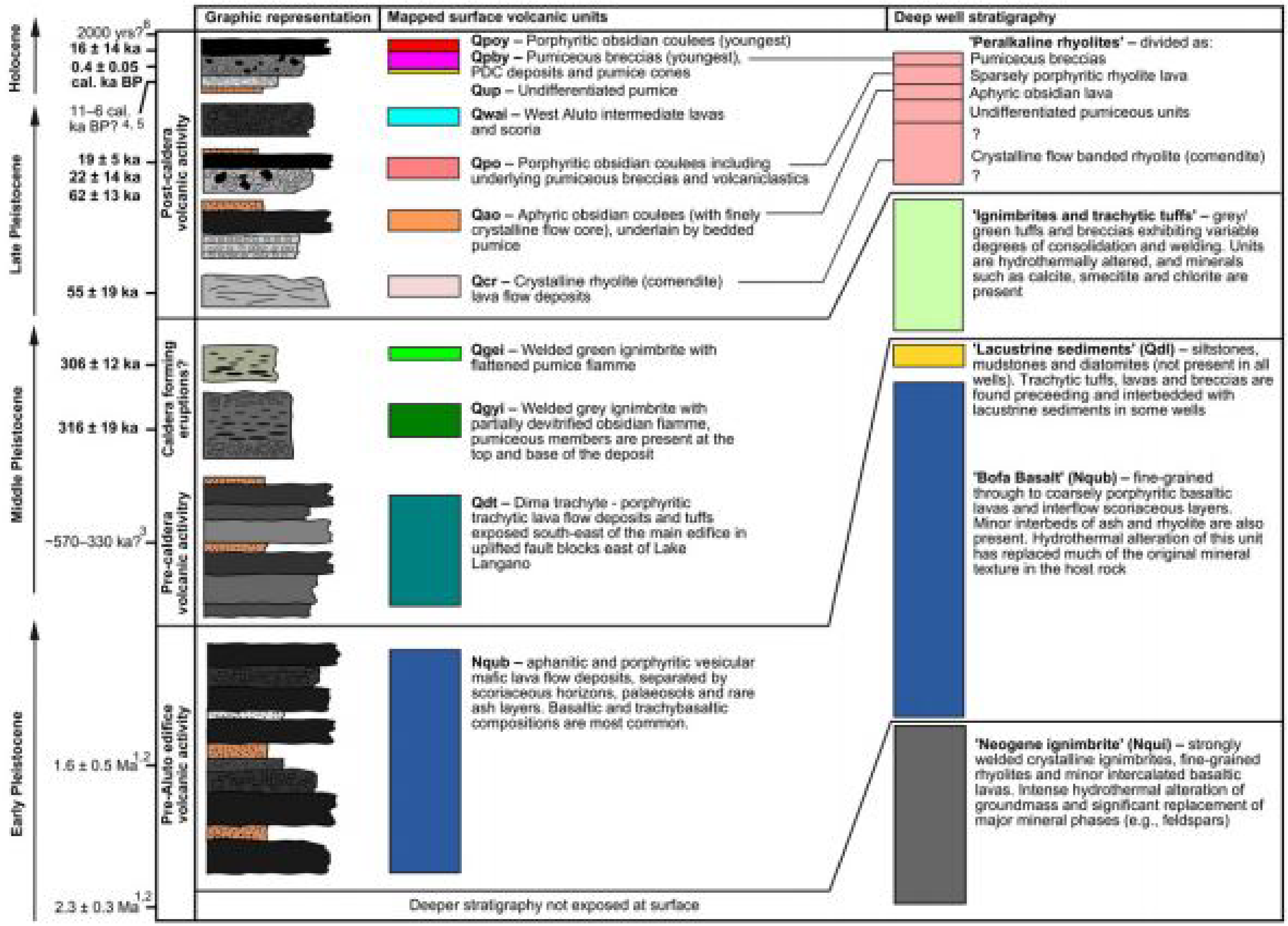
The following stratigraphic sections are taken from published and unpublished literature.



Lake sediment stratigraphy, McNamara et al. (2018)



Map of Aluto and composite terrestrial stratigraphy, Fontijn et al. (2018)



Stratigraphic summary of mapped units at the surface on Aluto, Hutchison et al. 2016

Appendix 3 Background information on the MER central volcanoes

The following is a summary of the eruptive histories of the other central MER volcanoes that are included in the RiftVolc project area. These have been included for reference.

Shala

Shala caldera lies to the north of Corbetti caldera, and contains a 250 m deep lake (Fig. 2) (Di Paola, 1972). Ignimbrites associated with the caldera formation are dated at 240 ± 30 ka (Mohr et al., 1980). Post-caldera activity is from the Tullu Fike pumice dome complex on the northern caldera rim (Fig. 2) (Fontijn et al., 2018). The volume of the Tullu Fike complex is estimated at 3 km^3 DRE, an order of magnitude less than the cumulative post-caldera volumes of Corbetti or Aluto (Hutchison et al., 2016b; Fontijn et al., 2018). The age of the post-caldera activity is unknown.

Isolated, possible post-caldera forming, basaltic scoria cones lie to the north and south of Shala caldera. Again, the ages of these are unknown.

Bora-Baricha

The Bora-Baricha complex (Fig. 9) comprises low-relief pumice domes and ridges, which are poorly accessible and therefore the least studied of the MER volcanoes (Fontijn et al., 2018). The Bora edifice is highly dissected, whereas Baricha comprises abundant obsidian lava flows and domes with limited soil cover. There is evidence of persistent hydrothermal activity in the area. Ages of the domes and flows are unknown; however, faulted ignimbrites SE of the complex have reported ages of 115 ka to 1.8 Ma (Bigazzi et al., 1993). There is no evidence of a caldera in the area therefore it is assumed that the younger eruptive products of Bora-Baricha and Tullu Moye, to the east, have concealed remnants of caldera walls (Fontijn et al., 2018).

Fontijn et al. (2018) describe abundant silicic pyroclastic tephra fall and PDC deposits on the western and eastern sides of the complex. To the northeast of Baricha is a section with at least seven pumice lapilli breccia deposits interbedded with poorly developed palaeosols (Fig. 9, outcrop 147). A nearby gully exposes at least six more pyroclastic deposits underneath (Fontijn et al., 2018). The ages of these fall deposits are unknown due to a lack of dateable material; however, the fresh appearance of the pumice together with the limited soil covers suggests a Late Quaternary age (Fontijn et al., 2018).

To the south-southeast of Bora-Baricha is a road-cut which reveals at least 5 metres-thick pyroclastic fall and PDC deposits, interbedded with poorly-developed soils and reworked yellow ash horizons (Fontijn et al., 2018). Fontijn et al., (2018) attribute the source of these deposits to the low-relief ridges and domes to the east of Bora.

Tullu Moye

Tullu Moye is a complex of low-relief pumice domes and obsidian lava flows, situated approximately 15-20 km east-southeast of Bora-Baricha (Fig. 9). The Tullu Moye cone itself comprises pumice and ash and has a crater about 700 m in diameter (Di Paola, 1972). Pyroclastic deposits near Tullu Moye are typically poorly-sorted pumice lapilli and breccia deposits (Fontijn et al., 2018). Obsidian lava flows occur along fissures with a NNE-SSW strike, the same strike as faults dissecting basaltic scoria cones to the south and north. The youngest of these obsidian lava flows occurred about 5 km to the north-northeast of Tullu Moye (Di Paola, 1972), as recently as 1900 AD (Bizouard and Di Paola, 1978; Gouin, 1979). Based on vegetation cover and historical accounts, Fontijn et al., (2018), suggested two recent eruptions occurred in the Tullu Moye area in recent times.

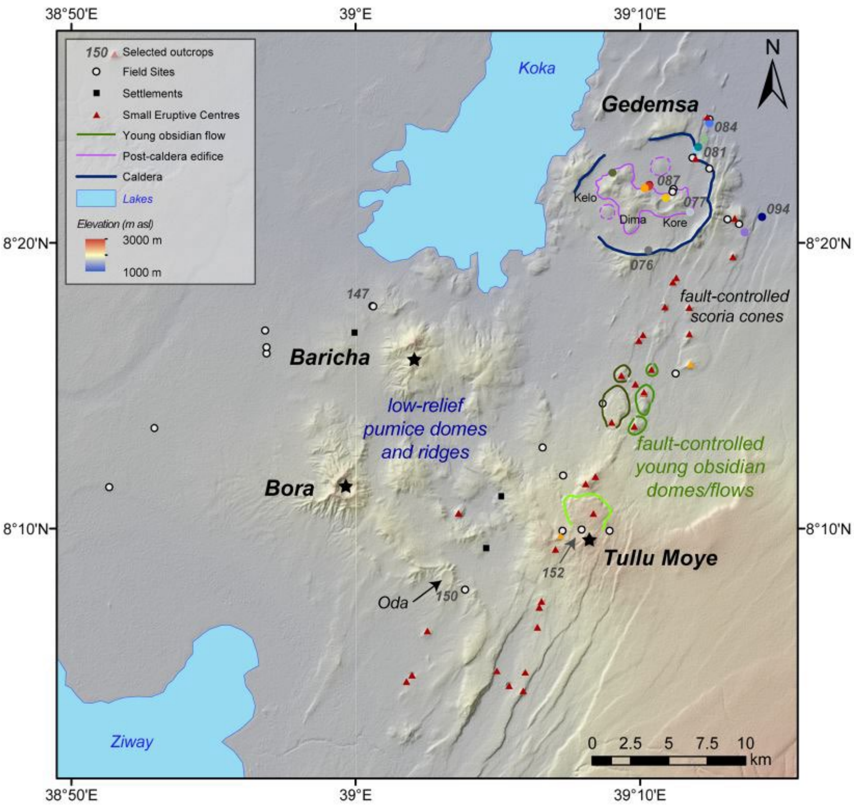


Figure 9 Location map of the Boar-Baricha and Tullu Moye complexes, from Fontijn et al. (2018).

Gedemsa

Gedemsa caldera is approximately 8 km in diameter, and lies just 20 km to the northeast of Baricha (Fig. 9). The caldera formation has been constrained to between 265 ± 0.02 and 319 ± 0.02 ka based on dating of pre- and post-caldera deposits (Peccerillo et al., 2003). Pre-caldera deposits comprise rhyolitic lava flows and domes and pumice fall deposits. Within the caldera are three domes: Kelo, Dima and Kore (Fig. 9). They are largely comprised of poorly-sorted pumice lapilli and bomb breccias, which are interpreted as proximal fall deposits from the domes (Fontijn et al., 2018). Interbedded with the fall deposits are locally welded facies and obsidian lavas. Fontijn et al. (2018) have identified at least six pumice fall deposits that are geochemically distinct from the caldera-forming deposits. Three were sampled from the proximal deposits on the edifices of Kelo, Dima and Kore. The source vents of the other three deposits has not been constrained; however, they are geochemically distinct, and are assumed to represent additional post-caldera activity.

Dilute PDC deposits are described near the northeast caldera rim, with clasts of scoria, basaltic lava and obsidian (Peccerillo et al., 2003; Fontijn et al., 2018). These deposits lie stratigraphically above the post-caldera pumice fall deposits, and have been interpreted as phreatomagmatic, related to volcanism along the Wonji Fault Belt (Peccerillo et al., 2003). Basaltic scoria cones lie to the northeast, east and southeast of the caldera, aligned with the regional NNE-SSW Wonji Fault Belt. Other lava domes and pumice deposits are described to the northwest and southwest of the caldera (Thrall, 1973), the ages of which are unknown (Fontijn et al., 2018).

Boset-Bericha

The Boset volcanic complex comprises two adjoining stratovolcanoes, Boset-Gudda and Boset-Bericha, which are aligned along a NNE-SSW trending lineament parallel to the Wonji Fault Belt (Fig. 10). They comprise thick trachytic and peralkaline rhyolite lava flows with associated pyroclastic deposits. The flows have run-out distances of up to 11 km and are often sourced from breached cones (Siegburg et al., 2017). The Gudda edifice has a series of northeast-southwest aligned craters up to 300 m in diameter (blue stars, Fig. 9). Some of these have associated obsidian lava flows of Holocene age (3.3 ± 2.4 ka; Siegburg et al., 2017). An arcuate ridge on the north-western slope of Boset-Gudda has been interpreted as a remnant caldera wall, which formed after 119.8 ± 6.1 ka (Siegburg et al., 2017).

Fontijn et al. (2018) describe up to six individual pyroclastic fall deposits exposed in road and dry river gully sections on the western lower flank of Boset-Gudda. The most recent is the Boset Pumice, a well-sorted pumice lapilli fall deposit, with thicknesses of over 3 m in the most proximal outcrops. Based on the method of Pyle (1989), Fontijn et al. (2018) calculated a minimum volume of 0.5 km^3, with a dispersal pattern to the west, and an estimated primary deposit thickness of 20 cm in the city of Adama (Fig. 10). The source vent is thought to be located on the flanks of Gudda, and may correspond to one of the late Holocene craters identified by Siegburg et al. (2017) (Fontijn et al., 2018). Stratigraphically below the Boset Pumice is a thin scoria fall deposit that is traceable over 10 km. This has been geochemically linked to basaltic trachyandesitic lava flows dated at 4.2 ± 3.2 ka.

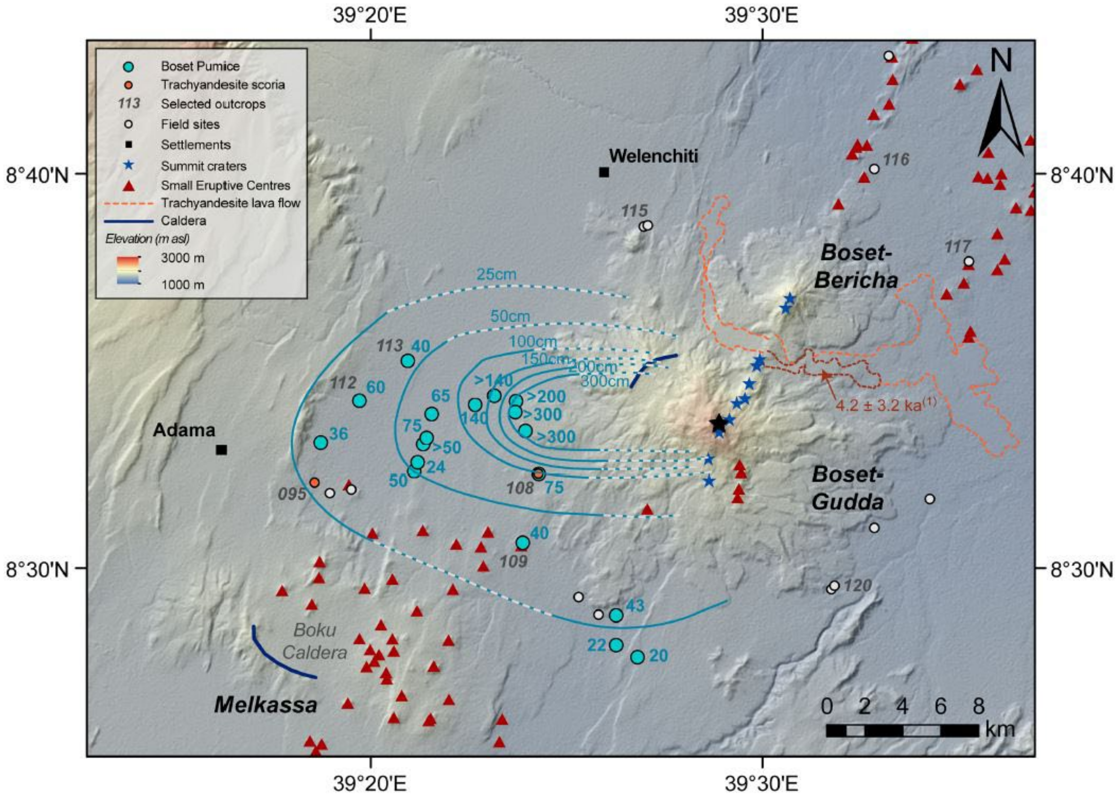


Figure 10 Location map of the Boset volcanic complex, with the isopachs for the Boset Pumice. Figure has been taken from Fontijn et al. (2018).

Kone

The Kone volcanic complex comprises at least three nested calderas (Fig. 11). Pre-caldera activity comprises trachyte and rhyolite lava flows and domes, which are exposed in the caldera walls. The caldera-forming eruptions emplaced several metres of unwelded pumice fall deposits interbedded with welded ignimbrites (Rampey et al., 2010; Fontijn et al., 2018). The age and stratigraphy of pyroclastic deposits at Kone is poorly constrained. Rampey et al., (2010) identified a number of post-caldera silicic lava flows and domes along the southern and northern Kone caldera rims; however, the age of these is unconstrained. During their field visit, Fontijn et al. (2018) did not find any evidence of fresh-looking post-caldera pyroclastic deposits.

Basaltic lava flows fill the Korke and Kone calderas. The most recent may have occurred historically with reports of an eruption in 1810-1830 AD (Harris, 1844).

Fentale

Fentale caldera lies at the northern end of the MER, at the junction with the Afar depression. The caldera forming eruption has been dated at 168 ± 38 ka. Post-caldera obsidian and rhyolite lava flows erupted from vents and fissures within the caldera, as well as on the northeast, east, southeast and west flanks of the volcano. Fresh superficial pumice lapilli scattered around the lower slopes of Fentale suggest that some post-caldera eruptions of effusive lava flows also had an explosive component. However, Fontijn et al. (2018) could not find any evidence of significant post-caldera silicic explosive volcanism.

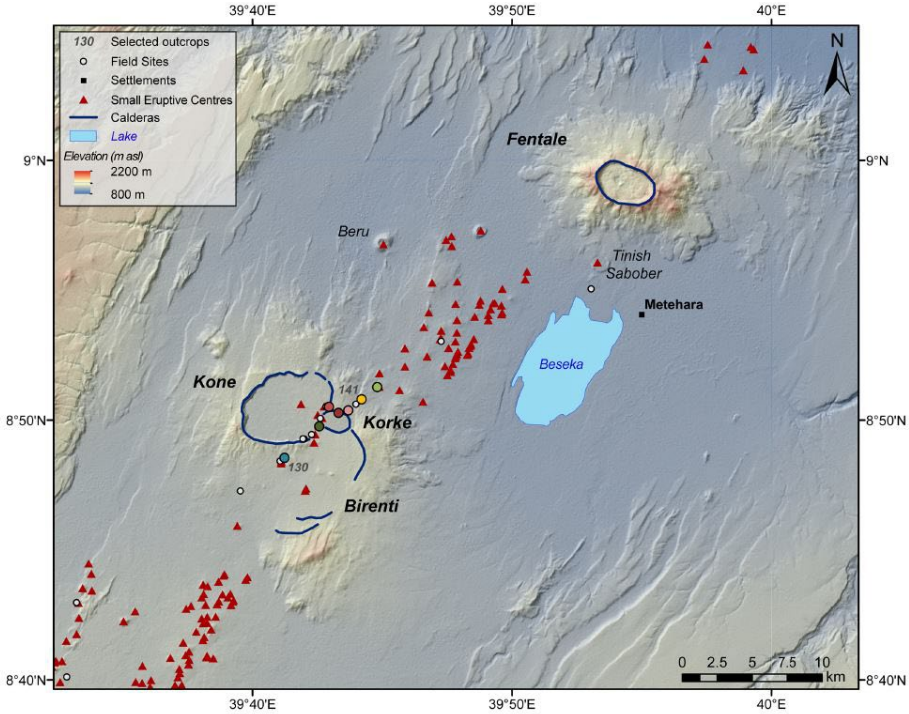


Figure 11 Location map of Kone and Fentale volcanic centres, from Fontijn et al. (2018).

South of Fentale caldera is a basaltic tuff cone, which pre-dates the caldera-forming eruption. However, more recent basaltic lava flows have erupted in the same region. Reports by Harris (1844) suggests that the area was active during the late 1700s AD (Fontijn et al., 2018).

Bishoftu and Butajira volcanic fields

The main eruptive centres described above lie on the main axis of the MER; however, off-axis volcanism occurs as numerous small eruptive centres forming the volcanic fields of Bishoftu and Butajira on the western rift shoulder (Fig. 1). These fields are assumed Late Quaternary in age because of their morphologically young appearance, but no dating has been carried out.

Appendix 4 Elicitation briefing document

What we want to achieve and how we propose to do it.

Knowledge of historical activity at volcanoes in the central Main Ethiopian Rift (Corbetti, Aluto, East Zway, Butajira, Fentale, Kone, Boset, Beru) is limited, and while there have been focused efforts on improving knowledge of Holocene eruptions (frequency and magnitude), there are still substantial knowledge gaps. Eruption magnitudes and frequencies are difficult to calculate due to limited exposure of deposits and lack of material for dating. In order to model the spatial footprint of likely future volcanic hazards, we need to be able to express the uncertainty about certain key variables in terms of statistical distributions. Given the limited amount of data available, we are looking to elicit the judgement of a small group of experts (using the SHeffield ELicitation Framework: SHELF). The elicitation will produce statistical probability distributions that describe the uncertainty around frequency-magnitude relationships. This document provides details on the elicitation method.

Elicitation is based on the premise that an expert has a mental model of uncertain quantities, reflecting their understanding and experience. This model is probably not explicit, still less might it be written down in statistical terms. In the terminology of SHELF, this model is referred to as an expert's subjective belief distribution. The expert, through his or her experience, has an intuitive sense of the likely distribution of variable quantities in their field of expertise. Elicitation is a method to extract and quantitatively capture this tacit model.

Elicitation methods have been developed through research by statisticians and psychologists, and are now widely used. For example, they have been applied in medicine to establish diagnostic rules, for risk assessment in the nuclear industry, in meteorology and in finance. In this exercise we shall use the SHELF elicitation framework and software developed by the University of Sheffield.

The SHELF elicitation framework does not use weightings of experts through an algorithm, but aims, after an elicitation of individual opinions, to form a group aggregate view through discussion. The experts are not necessarily expected to change their beliefs to agree with a single model. Instead, the group aggregate model represents the model that a rational independent observer might form having witnessed the discussions and accounted for the views of all of the experts.

As with all elicitation procedures we aim to avoid some common problems that can arise when people think about uncertain quantities. One such problem is "anchoring" by which an individual or group, when reflecting on an uncertain quantity, tend not to adjust any initial values "first thought of" sufficiently in response to the factors that they take into account.

Our uncertainty model, probability and random quantities.

In this exercise we are interested in the number of eruptions over a specified period of time, and the number of eruptions of specified magnitude, that will occur in 10,000 eruptions for the volcano. This quantity is unknown, so we treat it as a random variable, which can be characterised by a statistical model that specifies the probability that it occurs within specified intervals.

Consider a trial in which we toss a fair coin 51 times, and count the number of heads. The number of heads is a random quantity, but we can specify the probability of different outcomes within the range of possible values. This range is [0,51], but note that the probability of an outcome anywhere near either extreme is very small. The figure below shows the probability function for this case. Note that this shows probabilities, because the number of heads is a count, but we could approximate this distribution by a normal.

This probability function allows us to quantify uncertain outcomes. For example, we can say that the number of heads for a trial will fall within the interval [20,30] with probability 0.87, and that the probability of getting fewer than 10 heads is slightly over one in a million.

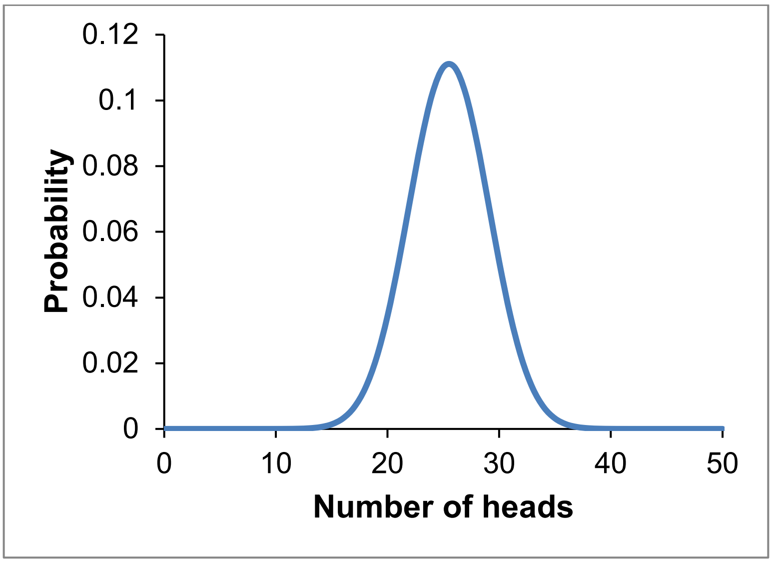


Figure 1. Probability function as an expression of uncertainty.

We can also define the *median* value of the variable such that the probability that the value at the random site is less than the median is 0.5. This is a central value of the distribution, 25.5 in this case. However, in general the median does not necessarily equal the mean, sum variables may have an asymmetric probability function, with a long upper tail, in which case the mean is larger than the median. Note that if we ran 1000 trials we would expect 500 to fall below the median value and 500 to be above.

We can divide the range of values of the unknown variable more finely. For example, the *first quartile* of the distribution divides the range between the lower bound and the median such that the probability that the unknown value falls between the lower bound and the first quartile is equal to the probability that it lies between the first quartile and the median (0.25 in each case. That is equivalent to saying that we would expect the result to be below the first quartile in 250 trials out of 1000, and between the first quartile and the median in another 250 cases. The first quartile of the distribution above is about 22.5. The third quartile (which divides the range between the median and the upper bound into two intervals of equal probability) is about 28.5. Note that these quartiles are quite tight about the median relative to the full range of the random variable.

Within the SHELF framework we encourage you to think of a particular case (e.g. a particular volcano) in terms of some large number of possible instances of cases identical with it in all respects (structure, geological setting etc) but independent of each other. You might picture these in "parallel universes". The aim of this is to encourage you to consider the range of possible behaviours, given the (limited) evidence you have available. So, for example, in a notional set of 1000 cases, most might have very few eruptions, but a few may have a rather larger number, giving an "upper tail" to the probability distribution.

The elicitation procedure

In order to elicit your mental model of the uncertainty of the quantities that we are interested in, you are asked to consider a series of questions. In the elicitation framework we use you are asked to give individual answers to these questions, but the final answers should be a group consensus after discussion. We will be asking about the numbers of eruptions of some volcano perhaps of a certain magnitude, expected over a specified time period. In order to address the question you should imagine a set of 1000 volcanoes of identical setting to the one of interest, but independent of each other. The questions that we ask you to consider are as follows:

1. What is the plausible range of the quantity of interest (e.g. the number of events over a particular time period)? These are the minimum and maximum values that you consider reasonably possible. They are not necessarily the maximum and minimum possible values but you would be very surprised if these values were exceeded.

2. What is the median value of the quantity? You are considering 1000 instances of the specified volcano over the time period. What is the number such that 500 of these can be expected to have fewer eruptions and 500 more? Note that the median is not necessarily half-way between the lower and upper bounds. It could be, for example, that you might expect most of the cases to have rather few eruptions, with an upper "tail" of cases with more, in which case the median may be closer to the lower bound than to the upper.

3. What is the first quartile of the quantity (Q1)? You are considering 1000 instances of the specified volcano over the time period. What is the number such that 250 of these can be expected to have fewer eruptions and 750 will have more, with 250 falling between the first quartile and the median?

4. What is the third quartile of the quantity (Q3)? You are considering 1000 instances of the specified volcano over the time period. What is the number such that 250 of these can be expected to have more eruptions and 750 will have fewer, with 250 falling between the median and the third quartile? Note that Q1 and Q3 need not be symmetrical about the median.

In the SHELF elicitation framework we form a group consensus on the minimum and maximum values. Each expert then writes down a median value and quartiles, and these are used to fit distribution functions. The different distribution functions are then discussed in the group and the reasons for any differences in opinions are highlighted. Finally, the group are asked to step in the shoes of a rational independent observer and agree upon the median and quartile values would best reflect the beliefs that this observer would have formed having witnessed the discussion. A final distribution function is then fitted with these values.

After you have had an opportunity to study this briefing document there will be a briefing session. The aim of this will be to discuss and clarify any issues in this document and the elicitation exercise more generally.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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