Risk assessment for workers employed in aggregate shipment from Plymouth Jetty

Prepared by

The Montserrat Volcano Observatory

and

The Scientific Advisory Committee on Montserrat Volcanic Activity

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Risk assessment for workers employed in aggregate shipment from Plymouth Jetty[1]

Summary

The probability of a sudden-onset pyroclastic flow large enough to reach the Plymouth Jetty without warning in the next six months is estimated, in terms of odds, to be approximately 1-in-1,000 (this assumes that the current low level of volcanic activity, with no dome growth, continues). Such an event would be a lethal threat to workers in the vicinity of the jetty and along transport routes passing through Zone V.

Given projected working hours at the Plymouth jetty operation, the probability of one or more casualties due to a sudden, dangerous pyroclastic flow in the next six months is about 1-in-7,000. With uncertainties taken into account, the corresponding estimated occupational risks for workers at the jetty could fall anywhere in the range from 1-in-10,000 to 1-in-1000 (annualized exposure); these ratios are markedly higher than those for similar occupations in the UK (1-in-20,000).

A westerly-directed pyroclastic flow could reach the jetty area and trucking trail within as little as one to three minutes, allowing no time for workers to escape.

The methodological basis and information used in the assessment were reviewed and the main findings confirmed by the Scientific Advisory Committee (SAC) and the Montserrat Volcano Observatory (MVO) at their meeting in Montserrat, 14 – 16 November 2011[2].

[1] This report is advisory. It is offered, without prejudice, for the purpose of informing the party commissioning the study of the risks that might arise in the near future from volcanic activity in Montserrat, and has been prepared subject to constraints imposed on the performance of the work. While Committee members believe that they have acted honestly and in good faith, they accept no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG or GoM or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor can they accept any liability to any third party in any way whatsoever.

[2] The present report supersedes the Interim Report produced on 19 October 2011, in entirety.

Background

There is a current proposal to use the jetty at Plymouth for shipment of aggregate mined from the lower Belham Valley area during a 6-month period, starting immediately, while the main road north from the Belham Valley (to Little Bay) is being improved and the passage of large trucks is discouraged.

On 4 October 2011, a request was made to the Scientific Advisory Committee on Montserrat Volcanic Activity (SAC) and the Montserrat Volcano Observatory (MVO) from the Government of Montserrat National Disaster Preparedness and Advisory Committee (NDPRAC) for a quantitative assessment of volcanic risks to workers in such an operation. The last time such a risk assessment was carried out was in 2006, and the dome and the volcanic activity have changed considerably since then.

An initial assessment was undertaken using email and telephone, and an interim report delivered to NDPRAC on 19 October 2011. A reappraisal of those findings was undertaken when the SAC met at MVO, on 14-16 November 2011. This report brings together the findings of the preliminary analysis, together with some extended work to address the implications of uncertainties in the volcanological information that was the basis of the risk assessment.

The first response to the NDPRAC request was the preparation of a preliminary scientific discussion document, circulated amongst SAC/MVO scientists (Appendix 1). A set of hazard- and risk related questions were then drawn up, and the scientists' responses to these elicitation questions are recorded in Appendix 2. Appendix 3 contains some notes on further work that was done subsequently, considering the possible influence of scientific uncertainties on the risk findings; this additional work lends support to the main findings.

The risk assessment presented here is valid only for the present circumstances of low-level volcanic activity associated with a major pause in dome growth, and on the basis of the working hours arrangements indicated by NDPRAC and outlined below. In the event of a re-start in lava extrusion the hazards and worker risk exposures would need to be re-assessed since the likelihood of dome collapse and pyroclastic flow formation, and therefore the risk, would increase markedly.

An important assumption in this assessment is that if precursory signs of activity are recognized there will be a complete cessation of operations and immediate and speedy withdrawal of all personnel. But a dangerous eruptive event could start with effectively no warning, and such a scenario is the focus of this assessment.

Occupational Risk

Operations at Plymouth Jetty - assumptions

Total period = 6 months
Daily working = 8 hours (Monday-Friday) 1-3 days/week
Personnel: 1 each in 4 trucks; 2 in 1 barge, 4 in 1 tug; 2 in 1 police launch.

For the purposes of the risk assessment it is assumed that there is a threat for a worker at the jetty, and for truck drivers in transit from Lovers Lane to the Jetty and back. As a driver may have little or no view of the dome and valley (due to direction of travel or due to low cloud on the volcano), and may have no means of communication, he could be unaware of a sudden significant pyroclastic flow or surge coming in his direction.

With four trucks working, it is further assumed that at any one moment during working times there could be two trucks en route to or from the Jetty.

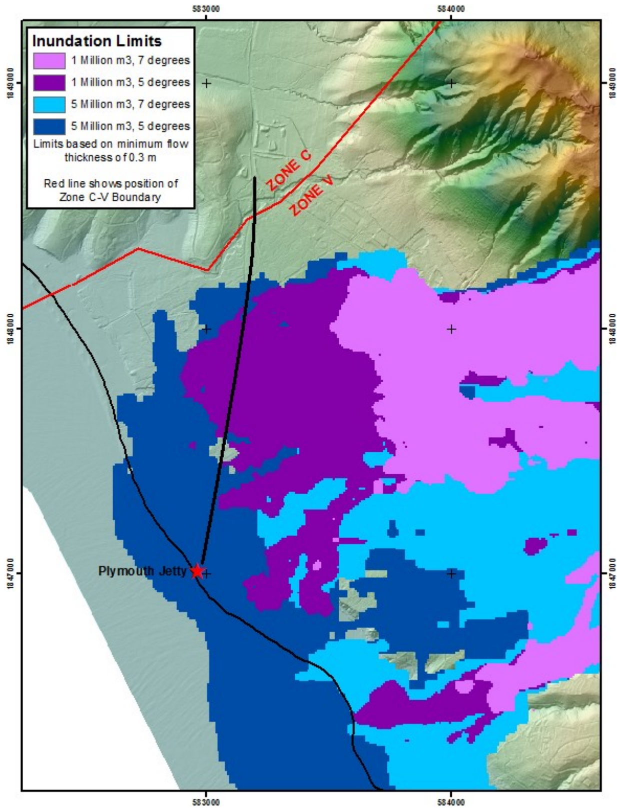

Fig.1 Approximate route of trucks (thick black line) travelling to and from Plymouth jetty via road from Cork Hill. The blue and purple areas represent areas expected to be covered by pyroclastic flows and surges (for explanation, see Appendix 2).

If an actual warning of incipient volcanic flow activity can be given, the evacuation method for truck drivers would be to drive north towards the Belham Valley and for the ship workers to evacuate via the police launch.

Flow occurrence probabilities

For characterizing pyroclastic flow hazard levels over the next six months we use the following key pieces of information:

From observations during the current pause period(s):

> The average rate of occurrence of flows to the west of any size greater than about 1,000 cubic metres since dome growth paused in February 2010 is about two per month. Thus it is very likely (i.e. a probability of close to one) of there being one or more flows of this size or greater in the next six months (see Appendix 1, Figure 1).

By elicitation (see Appendix 1 for background volcanological information, and Appendix 2 for elicitation details):

1. Based on observations of flows and flow modelling and the calculation shown in Appendix 1, the minimum volume of pyroclastic flow capable of reaching the jetty or trucking track is about 0.4 million cubic metres of material.

2a. The largest volume flow that could move towards Plymouth is assessed at:
about 9 million cubic metres of flow material.

2b. The probability of occurrence of this largest flow in the next six months is judged to be:
about 1-in-12,500

3. Given a continued pause in lava extrusion, we estimate by elicitation that just under half (40%) of future pyroclastic flows, originating from dome collapse, explosion or blast, would be sudden-onset without an effective warning.

Using best estimate central values to typify key factors, simple quantitative analysis indicates the probability of occurrence- without warning - of a pyroclastic flow that is big enough to reach the jetty area at any time in the next six months is about 1-in-1000 (actual result 1-in-900).

There are uncertainties associated with these elicitation-based estimates, and this important topic is considered below.

Occupational Risk Estimates

Based on information provided to the SAC by NDPRAC, operational working is assumed as 8 hours per day, 3 days per week, i.e. $1/7^{th}$ or 0.143 of total time. Therefore, the probability of workers being present and some becoming casualties if a pyroclastic flow occurs without warning is about 0.001 *x* 0.143 = 0.00014, or about 1-in-7,000 in the next six months.

> Given projected working hours at the Plymouth jetty operation, the probability of one or more casualties due to sudden, dangerous volcanic activity in the next six months is about 1-in-7,000.

For an individual worker at the jetty, this is equivalent to an annualized individual risk (i.e. Individual Risk Per Annum, or IRPA) of about 1-in-3,500, i.e. under the current condition of a volcanic pause and in the absence of an effective warning and time to escape.

For any one truck driver (of the four) this equates to an Individual Risk Per Annum (IRPA) of about 1-in-7,000, assuming that two drivers (in separate trucks) may be rotating through the danger area at any one time.

Uncertainties

Following on from the preliminary analysis report, the spreads on the pooled expert responses to the elicitation questions (see Appendix 2) have been used to quantify uncertainty on the estimated probability of occurrence, without warning, of a pyroclastic flow that could reach the jetty area at any time in the next six months. That uncertainty is expressed, in odds terms, by two values which span a plausible range either side of the central probability value:

1 in:
300 / **900** / 3000

In statistical terms, the outer two values (i.e. odds of 1-in-300, and 1-in-3000) determine an approximate 90% credible interval around the central median odds of 1-in-900 (to avoid spurious precision, this latter estimate was rounded to 1-in-1,000 in the preliminary report and above).

Thus, taking uncertainties into account, and assuming the current low level of volcanic activity with no dome growth continues, the analysis suggests the odds of such an event in the next six months could be as high as about 1-in-300, while at the other extreme they could turn out to be about 1-in-3,000. However, our best estimate remains 1-in-900.

Corresponding uncertainties on individual occupational risk estimates for a jetty-based worker can be calculated directly: plausible IRPA risk values range from 1-in-10,000, to as high as 1-in-1000 (see Fig. 2).

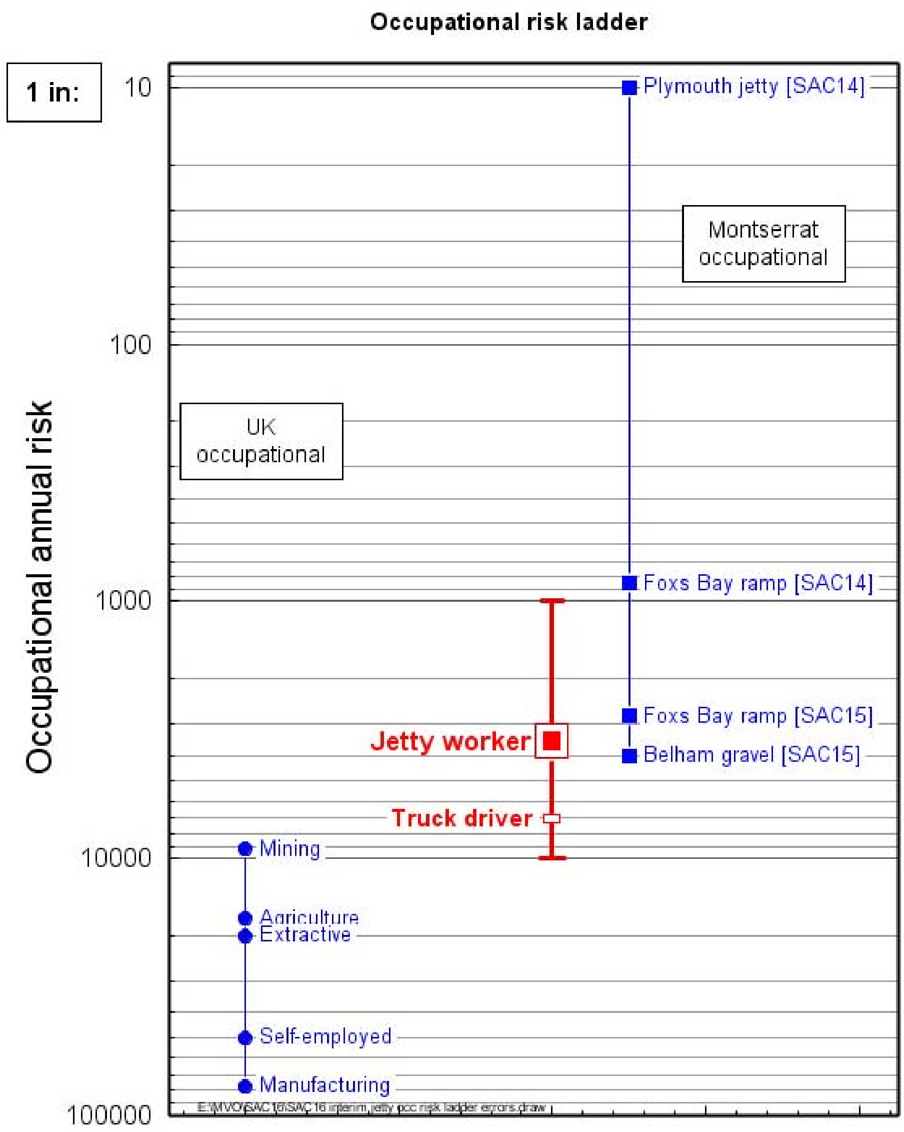

Fig. 2 Scale of occupational annual risk of death, specific for Montserrat, general for UK. Red markers in the centre of the chart show IRPAs for a worker at the jetty (larger marker) and for a truck driver (small marker); the uncertainty range on the jetty worker exposure estimate is shown by upper and lower horizontal cross-bars, denoting risk values spanning from 1-in-10,000 to 1-in-1000.

As shown in Fig. 2, in comparative numerical terms the IRPA values for a worker at the jetty and for a truck driver are significantly higher than occupational risk levels in the UK for extractive industry workers. The risk at the Plymouth jetty, due to volcanic hazards, could be (within uncertainty limits) at least 2 times greater, and conceivably up to 20 times greater, than the exposure of extractive industry workers in the UK to general operational risks; using the central value, the risk is about 6 times higher.

As a matter of record, other occupational risk levels from SAC14 and SAC15 reports are indicated on Fig. 2 (right-hand ladder). However, some key assumptions[3] in those assessments differed from the present risk model, and thus present as significantly higher occupational risk estimates for the Fox's Bay, Belham and Plymouth localities. Moreover, during the last nine months pyroclastic flow occurrences to the west and northwest have been much reduced in number compared with 1 – 2 years ago (Appendix 1 Fig. 1).

> If, in the next six months, there is resumption of lava extrusion then the present analysis no longer applies and the risk should be reassessed in the light of the new conditions.

Flow impact rapidity

We have also considered (question 4, Appendix 2) how quickly a sudden-onset pyroclastic flow could impact the jetty area and the track from there to Lovers Lane, if one were to occur without any clear and obvious precursory signals.

Elicited judgments on the shortest time that could elapse between the start of the event at the volcano and the flow reaching areas where workers are present could be as little as one-and-a-half minutes. In an extreme situation, for instance with a westerly-directed energetic pyroclastic flow, similar in violence to that of 11 February 2010, the interval could be one minute or even less.

Plausible reaction and escape times indicate that there would not be sufficient time for workers to escape from the area, before the arrival of such a fast-starting and fast-moving pyroclastic flow or surge from an event that happens without warning.

> The jetty area and trucking trail could come under lethal threat from a sudden-onset pyroclastic flow within as little as one to three minutes from the time the flow begins.

[3] e.g. in the SAC 14 assessment, the risk outlook included the possibility of continued jetty operations after dome growth restart; that scenario is not considered in the present analysis.

Appendix 1: Preliminary discussion document

Background

The lava dome at Soufriere Hills Volcano has sent material to the west down the Gages Valley toward Plymouth several times during the eruption. In particular, during August 1997 (when Plymouth was first inundated by pyroclastic flows), December 2001, December 2006, December 2008 and in January 2010. Access to Plymouth became much more hazardous after late 2006 when the dome grew to such a height that it overtopped the northern and western rims of English's Crater. On 10 September 2006 the Gages Wall vent developed on the rim of the crater and was, intermittently, the major source of gas release, ash venting and minor fountain collapse pyroclastic flows up to October 2008. By 28 December 2006 pyroclastic flows entered Gages valley as the crater rim was overtopped by the dome. Since late 2006 there has always been a large mass of dome lava above Gages Wall that we have considered a possible source of major dome collapse pyroclastic flows and lateral blast-derived flows (in the event of a structural failure of Gages Wall) that has been assessed routinely.

Since 2006, with the presence of the large dome above Gages, there have been numerous pyroclastic flows to the west of the volcano that have threatened Plymouth (~ 4.6 km from the dome) via Gages Valley. During extrusive Phases the largest such flows include:

Phase 3:
Several in late December 2006 – January 2007 reaching ~ 2 - 3 km, as far as Lee's Yard.

Phase 4:
28 July 2008 pumice flow (4 km, within 200m of sea).
25 August 2008 b&a flow (3 km, upper Plymouth/Lees Yard).
3 December 2008 b&a flow (4.6 km to sea at Plymouth)
5 December 2008 pf (3.4 km)
10 December 2008 pf (3 events of 4 – 4.3 km runout)
17 December 2008 pf (3.4 and 4.5 km nearly reaches sea)
24 December 2008 pf (4.6 km into sea?)
30 December 2008 pf (3.4 km)
3 January 2009 column collapse pumice pf (2 x 4.6 km into sea; 1 x 3.4 km)

Phase 5:
8 January 2010 vulcanian explosion flow (east edge of Plymouth ~ 3km)
20 January 2010 b&a flows (reach sea via Aymers Ghaut)
5 February 2010 vulcanian explosion flow (500m over sea via Aymers Ghaut).

During non-extrusive pauses throughout the eruption there have been fewer, smaller pyroclastic flows produced. Since the end of Phase 5 (11 Feb. 2010) there have been 41 small rockfalls and pyroclastic flows to the west. The maximum runout of these events is just over 2 km, though the majority are much less than that (Table 1). The minimum volume threshold of these recorded events is about 1000 m^3 and the largest is < 100,000 m^3. All of these have gone in the direction of Spring Ghaut and none toward Fort Ghaut.

Table 1: Runouts of PFs on the West flank since 12 February 2010

Runout (km)	Count
0-0.9	6
1-1.9	28
2.0-2.5	7

There has been one PF to the west since January 2011 (See Fig. 1). This event had a runout of less than 1 km.

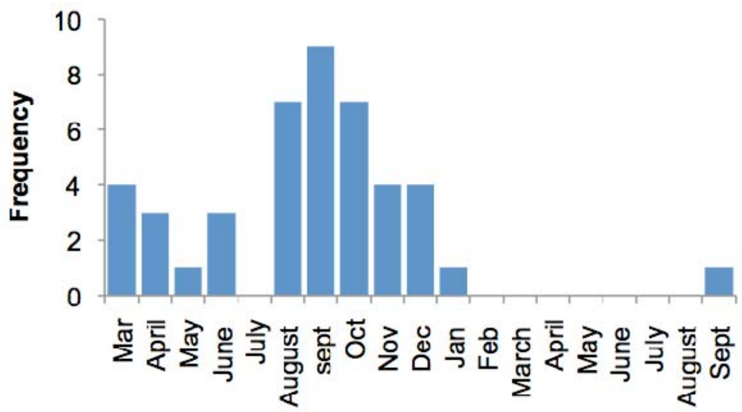

Fig 1 Documented pyroclastic flows to the west, since Feb 2010

The source for all of the PFs and rockfalls on the West flank has been an area of overhanging dome rock at an elevation of about 900 m. Each rockfall/PF progressively removed various parts of this overhang. Volumes for these events have been on the order of 10^4 - 10^5 m^3.

There is some evidence that there is a greater propensity for pyroclastic flow generation during pauses during the “wet season”. However, the low number of events over the last 20 months is despite considerable rainfall and numerous lahars, particularly in the last 3 months. In addition, none of the last 5 PFs travelled more than 1.5 km.

Hazards

1. Pyroclastic flow/surge reaching jetty/ship/truck during
   - (i) Gravitational collapse of part of dome generating pf.
   - (ii) Vulcanian explosion with fountain collapse pf.
   - (iii) Partial dome collapse and lateral blast.
2. Pyroclastic fall during Vulcanian explosion.
3. Lahars involving trucks in Belham Valley or on Plymouth fan.
4. Gas exposure.

Here we only concern ourselves with hazards in 1, above.

Real and Simulated Pyroclastic Flows

We know from the field measured volumes of flows in Phases 4 and 5 that reached the sea or near to it at Plymouth that individual collapse volumes of ~1-2 M m^3 are required. Pumice flows and block and ash flows of this size have taken between 100 and 270 seconds to reach the coast. The time available to respond (by a worker) can also be effectively reduced by cloud obscuring the advancing flow and the isolation of an individual truck driver from outside events.

The source of any such collapses is the western side of the dome which is one of the largest experienced in the whole eruption, with a summit elevation of 1083 m asl. (Fig.2). It is limited to the east by the collapse crater formed on 11 February 2010 ~ 250 m to the east of the western side, by the N-S length of Gages Wall (~ 350 m) and by the height above the base level of the Gages Wall at ~ 800 m asl (~280 m). A collapse volume of 1 M m^3 (e.g. cube equivalent of ~100x100x100 m) can readily be sourced from this potential collapse mass.

The issue of a maximum collapse volume that could be channelled into the Gage's Valley is less easy to determine. For larger/higher collapse masses material will also descend Tyer's and Spring Ghauts and perhaps also collapse to the north, as well as entering Gages Valley. Although there is a potential collapse source volume of the order of 10 M m^3, a more likely maximum realisable volume is thought to be ~ 5 M m^3. Even a source volume of 5 M m^3 (cube equivalent of ~170x 170 x170 m) could extend a large fraction into the remaining mass between the 11 February 2010 collapse scar and the western face, depending on the actual geometry, and will also expose higher pressure rocks capable of greater mobility.

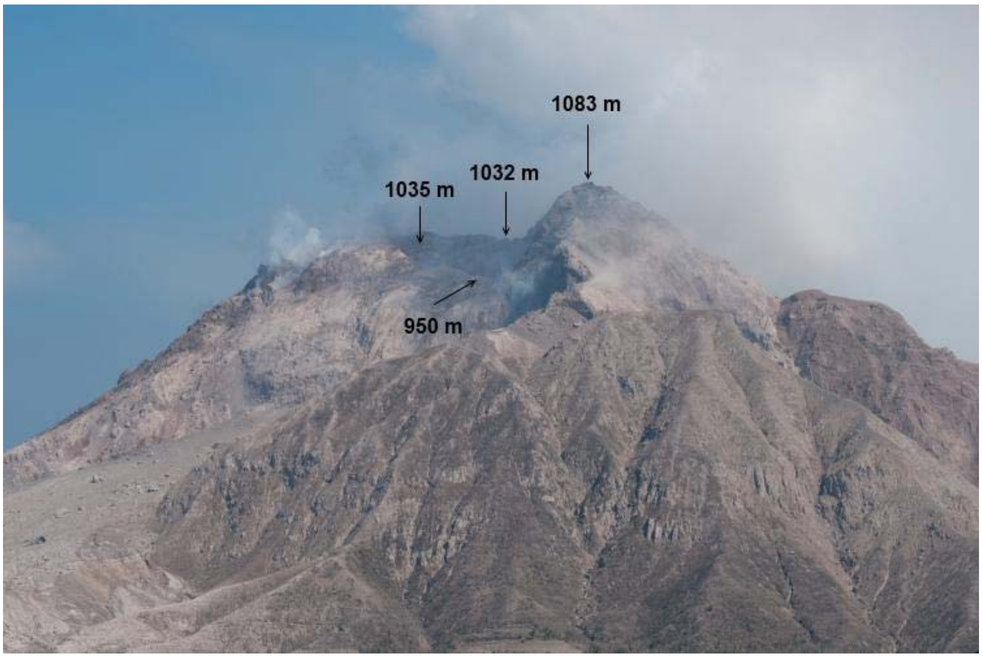

Fig.2 Potential collapse source into Gages Valley (to the right), seen from MVO.

From a hazard elicitation perspective we use a flow volume of 1 M m^3 as a threshold value for an event that could threaten the workers at the jetty. We will assess the risks posed by other magnitude events in our fuller study at SAC16.

Titan2D simulation results

Fig.3 shows two sets of simulated pf deposits with 1 and 5 M m^3 volumes, with 7 and 5 degrees of basal friction, and 25 degrees of internal friction (equivalent to the block and ash flow component and surge component results respectively presented at SAC15) thresholded at a minimum thickness of 0.3 m. The 5 M m^3 surge component indundates the Plymouth coastline whilst the 1 M m^3 reaches to within a few hundred metres of the jetty.

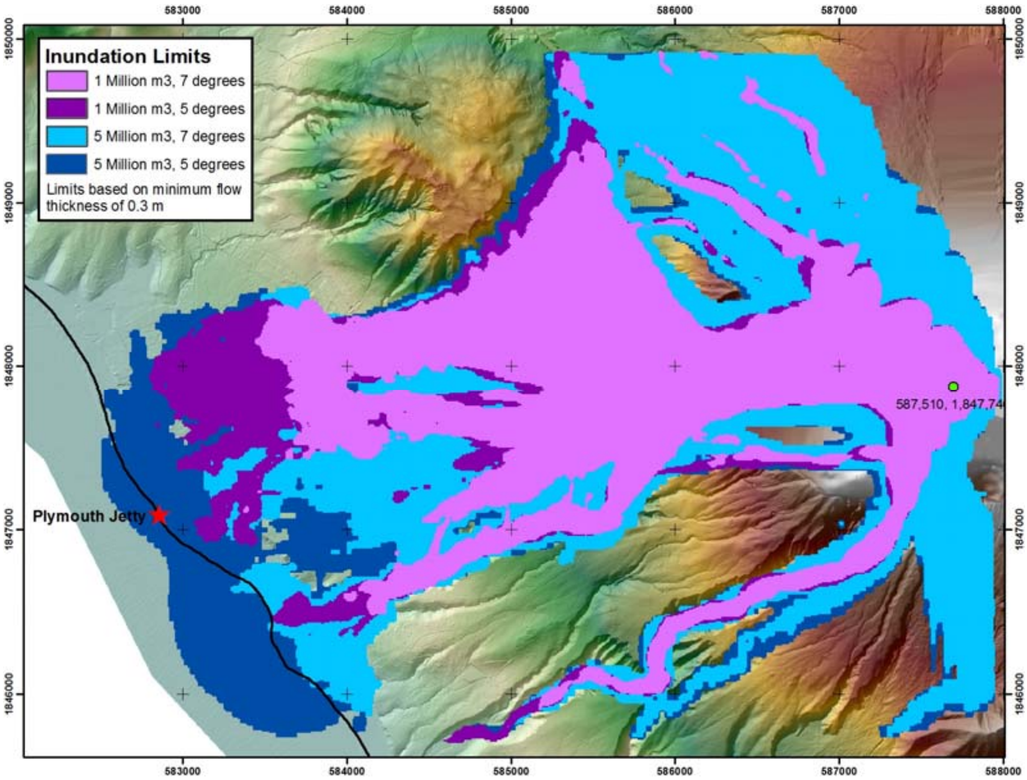

Fig.3 Titan-2D simulations of pyroclastic flows towards Plymouth jetty.

Working Scenario
Total period = 6 months
Daily working = 8 hours (Monday-Friday) 1-3 days/week
Personnel: 1 each in 4 trucks; 2 in 1 barge, 4 in 1 tug; 2 in 1 police launch.

Given suitable warning (at least 15 minutes) the evacuation method for truck drivers would be to drive north towards the Belham Valley and for the ship workers to evacuate via the police launch.

Hazard Scenarios
The main factor influencing hazard is whether the volcano is extruding lava or not. In the 5 years since October 2006 (when the current state of perceived threat to Plymouth reached its current high level) the volcano has been extruding lava for a total of about 12 months and not extruding lava for about 48 months. During those 12 extrusive months there were a total of about 17 events that generated pyroclastic flows with runouts greater than about 3 km towards the west.

Each of these flows would be considered a threat to anyone at the jetty. Hence working at the jetty when the dome is actively extruding lava is far too hazardous and will not be considered further here. However, this rate of 1.4/month (17/12) for jetty-threatening events if magma is involved does give an indicative likelihood in the event of a re-start of extrusion.

During the current, non-extruding state, the dome has produced no pyroclastic flows to the west that have exceeded half the distance to the jetty over a period four times as long as it has extruding. This suggests that the dome morphology without eruptive forcing is resistant to moderate and large volume (> 0.1 Mm^3) gravitational collapses. But there must be a small probability of a larger collapse of this kind.

There have been large collapses, mostly unheralded, of the dome during pauses in extrusion (e.g. 3 July, 5 November, 12 November 1998, 20 July 1999 and 3 March 2004), but these have involved material moving harmlessly to the east down Tar River Valley. We have the evidence of the 41 westerly collapse events (Table 1) since February 2010 ranging in volume from ~1000 to ~100,000 m^3. We need to assess the likelihood of a ~ 0.1 – 1 M m^3 event capable of reaching the jetty using these observations together with an estimate of the probability of the largest possible collapse.

Given that the current state is paused, under what conditions would a re-start of lava extrusion/magma rise initiate a pyroclastic flow-generating event with no precursory signals to enable MVO to alert the workers and for them to evacuate in time? The likelihood of precursory seismicity lasting a few hours for an initial Vulcanian explosion is high.

In the event of a re-start in lava extrusion we would re-assess the hazards.

SAC/MVO
13 Oct. 2011

Appendix 2: Elicitation questions and responses

Following circulation of the discussion document (Appendix 1), twelve hazard- and risk related questions were put to SAC members and MVO staff in a structured elicitation. Responses were obtained from seven scientists, and processed using the EXCALIBUR package, providing the following outcomes.

1. What minimum (DRE) volume of a pyroclastic flow/surge should be used as a low-end anchor for calculating risk levels due to flows, i.e. the size that is capable of reaching to within a few hundred metres of the Plymouth jetty?

5%ile	50%ile	95%ile
0.01 Mm^3	0.4 Mm^3	1.9 Mm^3

2a. What is the (DRE) volume of the largest pyroclastic flow that could be sent to the west in the next six months,

5%ile	50%ile	95%ile
0.4 Mm^3	8.8 Mm^3	18 Mm^3

2b. and what is its probability (%) of occurrence in next six months?

5%ile	50%ile	95%ile
0.0001	0.008	2.1

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3. Given a continued pause in lava extrusion, what are the relative probabilities of a pyroclastic flow reaching at least as far as within a few hundred metres of the jetty within the next 6 months in each of the following scenarios (with probabilities expressed as percentages)[4]:

a. Collapse of a portion of the lava dome occurring WITHOUT sufficient precursors to effect a warning?

5%ile	50%ile	95%ile
0.001	0.1	4.2

c. A Vulcanian explosion occurring WITHOUT sufficient precursors to effect a warning?

5%ile	50%ile	95%ile
0.0001	0.002	2.2

[4] n.b. Questions 3b, 3d and 3f concerned certain warning circumstances, but are not used in the risk assessment.

e. Collapse of a portion of the existing dome with a lateral blast WITHOUT sufficient precursors to effect a warning?

5%ile	50%ile	95%ile
0.00001	0.002	0.08

4. Given a significant pyroclastic flow that travels to the coast in the vicinity of Plymouth jetty, what is your estimate of the **minimum** elapsed time (minutes) from onset at the volcano to reaching the coast, in each of the following scenarios:

a. In a collapse of a portion of the lava dome that occurs WITHOUT sufficient precursors to effect a warning?

5%ile	50%ile	95%ile
1.4	2.1	3.7

b. In a Vulcanian explosion occurring WITHOUT sufficient precursors to effect a warning?

5%ile	50%ile	95%ile
1.2	2.4	4.1

c. From a collapse of a portion of the existing dome with a lateral blast WITHOUT sufficient precursors to effect a warning?

5%ile	50%ile	95%ile
0.6	1.5	2.7

Appendix 3 Empirical model for flow occurrence rates

The jetty worker risk exposure findings, presented in the main part of this report, are based on expert elicitation of relevant parameters about patterns of flow occurrences, guided by observational data from the volcano (Appendix 2). The elicitation approach allows the experts to take into account such experience data from the past, but to vary its characterization in line with expectations for possible future patterns.

This appendix explores, as a form of consistency check, what those observational data suggest when used as the primary basis for indicating future risk levels. Where relevant in this analysis, flow volumes and corresponding frequencies of occurrence are defined as ranges by reference to relevant uncertainties in the elicitation findings. Thus three plausible maximal flow volumes and their associated probability of occurrence are taken from Appendix 2 elicitation findings, and interpolated to the exceedance base-rate for flows of any size above minimal (0.01 million cubic metres).

This produces three relationships between flow size and probability of exceedance. The upper curve is selected here, being more precautionary for hazard estimation. Intercepts on this line - for three values that represent a plausible range for the jetty-impacting "threshold flow" volume - show the corresponding probability of exceedance as a function of volume.

The median and upper bound volume values for the threshold flow are taken directly from the elicitation findings (Appendix 2); the lower bound volume is chosen by reference to model results rather than the elicitation outcome, which is judged to have produced an unrealistically small lower-bound volume for reaching the jetty. In this way additional empirical control is applied to the model – such small volume flows are more frequent and if used uncritically as the threshold could inflate the hazard estimate.

The consequence of applying these empirical constraints in an alternative risk model ("power-law") provides the following ranges for the probability of a flow to jetty vicinity (at or above threshold volume), and can be compared with those produced by the expert elicitation approach:

	No warning event odds 1 in:	Any event odds 1 in:
Elicited	300 / 900 / 3000	125 / 415 / 1300
Power-law	220 / 1750 / 12500	140 / 655 / 2500

where, in all four cases, the outer two values define an approximate 90% credible interval for uncertainty about the central median value.

Thus, the empirical model, based on recent patterns of flow activity and an assumed size-frequency relationship, suggests a slightly lower level of risk exposure for jetty workers. This additional analysis of pertinent volcanological information lends support to the view that the findings provided by the expert elicitation are reasonably appropriate for the current low-level volcanic conditions and assumed working circumstances.

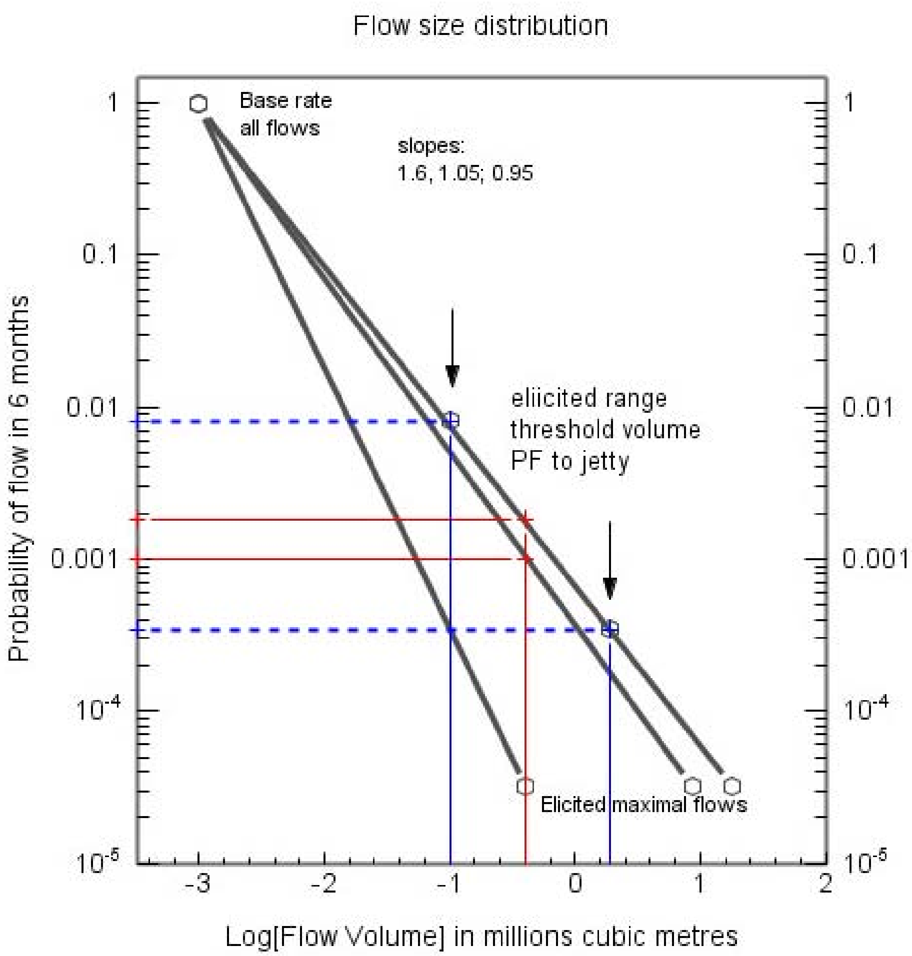

Fig. A3.1 Plot showing the method of estimating the probability of the threshold volume for a pyroclastic flow that has no effective precursory warning reaching the jetty in the next 6 months. For a consistency analysis, the range of probabilities for three indicative minimum flow volumes that could represent thresholds for reaching the jetty (i.e. 0.1; 0.4; and 9 million cubic metres) are estimated by interpolation on the upper power-law relation (thick black line) between corresponding probabilities for the two end-member flow sizes (i.e. ~18 million maximum, and 1,000 cubic metres as base rate).