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Emergency planning and mitigation at Vesuvius: A new evidence-based approach

P.J. Baxter [a,*], W.P. Aspinall [b], A. Neri [c], G. Zuccaro [d], R.J.S. Spence [e], R. Cioni [f], G. Woo [g]

[a] Institute of Public Health, University of Cambridge, Robinson Way, Cambridge CB2 2SR, UK
[b] Aspinall & Associates, 5 Woodside Close, Beaconsfield, Buckinghamshire HP9 1JQ, UK
[c] Istituto Nazionale di Geofisica e Vulcanologia Sezione di Pisa Via della Faggiola 32, I-56126 Pisa, Italy
[d] PLINIVS, LUPT Centre, University of Naples, Via Toledo 402, 80134, Naples, Italy
[e] Department of Architecture, 1-5 Scroope Terrace, University of Cambridge, Cambridge CB2 1PX, UK
[f] Dip. Scienza della Terra, Via Trentino 51, I-09127 Cagliari, Italy
[g] Risk Management Solutions, 30 Monument Street, London EC3R 8NB, UK

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ABSTRACT

Disasters from explosive volcanic eruptions are infrequent and experience in emergency planning and mitigation for such events remains limited. The need for urgently developing more robust methods for risk assessment and decision making in volcanic crises has become increasingly apparent as world populations continue to expand in areas of active explosive volcanism. Nowhere is this more challenging than at Vesuvius, Italy, with hundreds of thousands of people living on the flanks of one of the most dangerous volcanoes in the world. We describe how a new paradigm, evidence-based volcanology, has been applied in EXPLORIS to contribute to crisis planning and management for when the volcano enters its next state of unrest, as well as in long-term land-use planning. The analytical approach we adopted enumerates and quantifies all the processes and effects of the eruptive hazards of the volcano known to influence risk, a scientific challenge that combines field data on the vulnerability of the built environment and humans in past volcanic disasters with theoretical research on the state of the volcano, and including evidence from the field on previous eruptions as well as numerical simulation modelling of eruptive processes. Formal probabilistic reasoning under uncertainty and a decision analysis approach have provided the basis for the development of an event tree for a future range of eruption types with probability paths and hypothetical casualty outcomes for risk assessment. The most likely future eruption scenarios for emergency planning were derived from the event tree and elaborated upon from the geological and historical record. Modelling the impacts in these scenarios and quantifying the consequences for the circumvesuvian area provide realistic assessments for disaster planning and for showing the potential risk–benefit of mitigation measures, the main one being timely evacuation, but include for consideration protecting buildings against dilute, low dynamic pressure surges, and temporary roof supports in the most vulnerable buildings, as well as hardening infrastructure and lifelines. This innovative work suggests that risk-based methods could have an important role in crisis management at cities on volcanoes and small volcanic islands.

1. Introduction

EXPLORIS has developed methods for quantifying the risk in future explosive eruptions of Vesuvius to provide improved support for decision making in a future crisis, and some of their potential applications for emergency planning and mitigation will be described. In the wording of historians of science, this has been possible by adopting an evidence-science *paradigm*, a shift in thinking involving the novel application of formal probabilistic reasoning and statistical decision analysis which we refer to as *evidence-based volcanology*[1]. The need to find a robust approach to the mitigation of volcanic disasters is driven by the rapid increases of human populations in areas of active volcanism, especially at cities on volcanoes and on small islands. Although our main focus in this paper is Vesuvius, the methods were also found to be applicable for volcanic emergency management at the three island study volcanoes in EXPLORIS: Teide (Tenerife), Sete Cidades (San Miguel, Azores), and La Soufrière (Guadeloupe).

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[*] Corresponding author.
E-mail address: pjb21@medschl.cam.ac.uk (P.J. Baxter).

[1] A paradigm is an entire scientific outlook — a constellation of shared assumptions, beliefs and values that unite a scientific community and allow normal science to take place. The word is often used in the context of Thomas Kuhn's book *The structure of scientific revolutions (1963)*, the most influential work of the philosophy of science in the last 50 years (Okasha, 2002).

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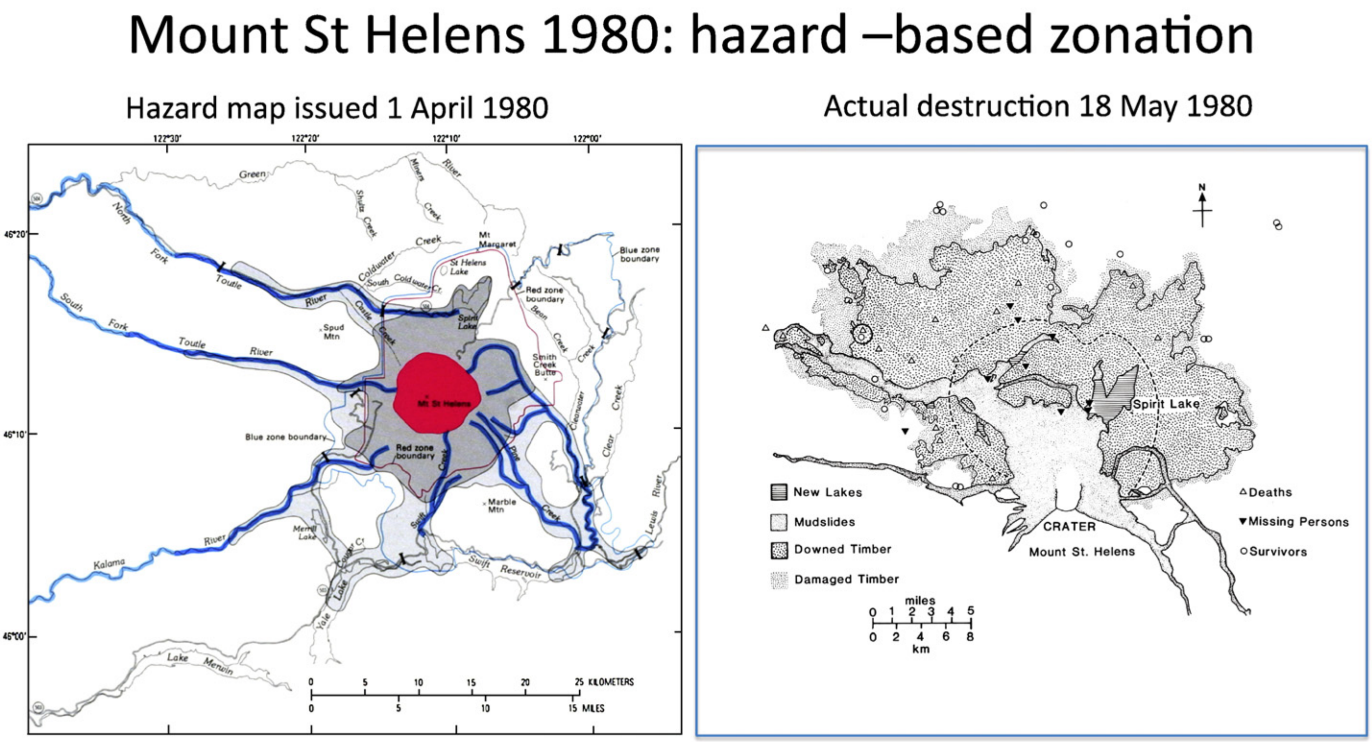

Fig. 1. Hazard map at the eruption of Mount St Helens, 1980 (left). The actual area of devastation caused by the main surge (right) was much larger than envisaged (Miller et al., 1981). Most people caught in the surge were killed (58 people), with survivors only at the periphery of the run-out (Baxter, 1990).

Forecasting explosive volcanic eruptions for disaster mitigation is a young science and the work of the relatively small number of scientists engaged on active volcanoes is slowly becoming more widely known through recent well publicised eruptions and volcanic crises (Scarpa and Tilling, 1996; Thompson, 2000).[2] The specific onset, style and duration of an eruption cannot be precisely determined by a volcano's precursory activity and so the accurate prediction of the outcome of a state of unrest at an explosive volcano, such as Vesuvius, is rarely possible. Nevertheless, valuable constraints can be placed upon the outcome if the past behaviour and eruptive history of the volcano is known, even if not well understood, for developing eruption scenarios and hazard maps that depict the areas of likely impact by eruptive phenomena around the volcano.

A precautionary approach to an impending eruption at an explosive volcano will defer to hazard mapping to define the "worst-case" hazard scenario. On working in this domain of low probability — high consequence incidents and uncertainty, Rosi (1996) advises: "when reliable evaluations are lacking, volcanic risk assessment must be necessarily conservative and consider events of large magnitude, *even if their probability of occurrence is remote* (our italics)." Rosi refers to such events as the *largest expected eruption*. Almost by definition, however, volcanic emergency management using this hazard-based approach will be without the benefit of rigorous decision-support tools and limited to a single eruption which dominates the risk scenario, leaving few options for emergency planners other than a precautionary evacuation if the activity during a renewed state of unrest becomes threatening.

2. Hazard and risk management at notable past eruptions

Surprisingly few advances in the understanding of the impacts of explosive volcanism, and the role of scientists in forecasting eruptions and devising mitigation measures, were made until the eruption of Mount St Helens in 1980. A study of the hazards of Mount St Helens, the most active volcano in the conterminous United States, had been completed by Crandell and Mullineaux (1978) only a short time before its renewal of activity with a magnitude 4.1 earthquake on March 20, 1980. The scientists of the US Geological Survey used the study to define the hazard zones to protect the public and forestry workers by limiting access to the wilderness area around the volcano (Miller et al., 1981). The Mount St Helens hazard-zonation map was issued on April 1 and was based on what was thought at the time to be the largest area likely to be impacted by pyroclastic flows and lahars (Fig. 1). This turned out to be an underestimate of the actual size of the May 18 eruption, with the directed blast covering an area about three times greater than the apparent extent of the largest such blast of the last 4000 years, and devastating an area 10–15 times larger (Miller et al., 1981). The size of the north-flank landslide and the lateral blast had not been forecast by the scientists and the volcano had given no warning.

At Mount Pinatubo, Philippines, in 1991 a hastily prepared hazard map, released on May 23, less than one month before the eruption, was all that was available to scientists due to the paucity of studies undertaken in the past (Fig. 2). The map incorporated the

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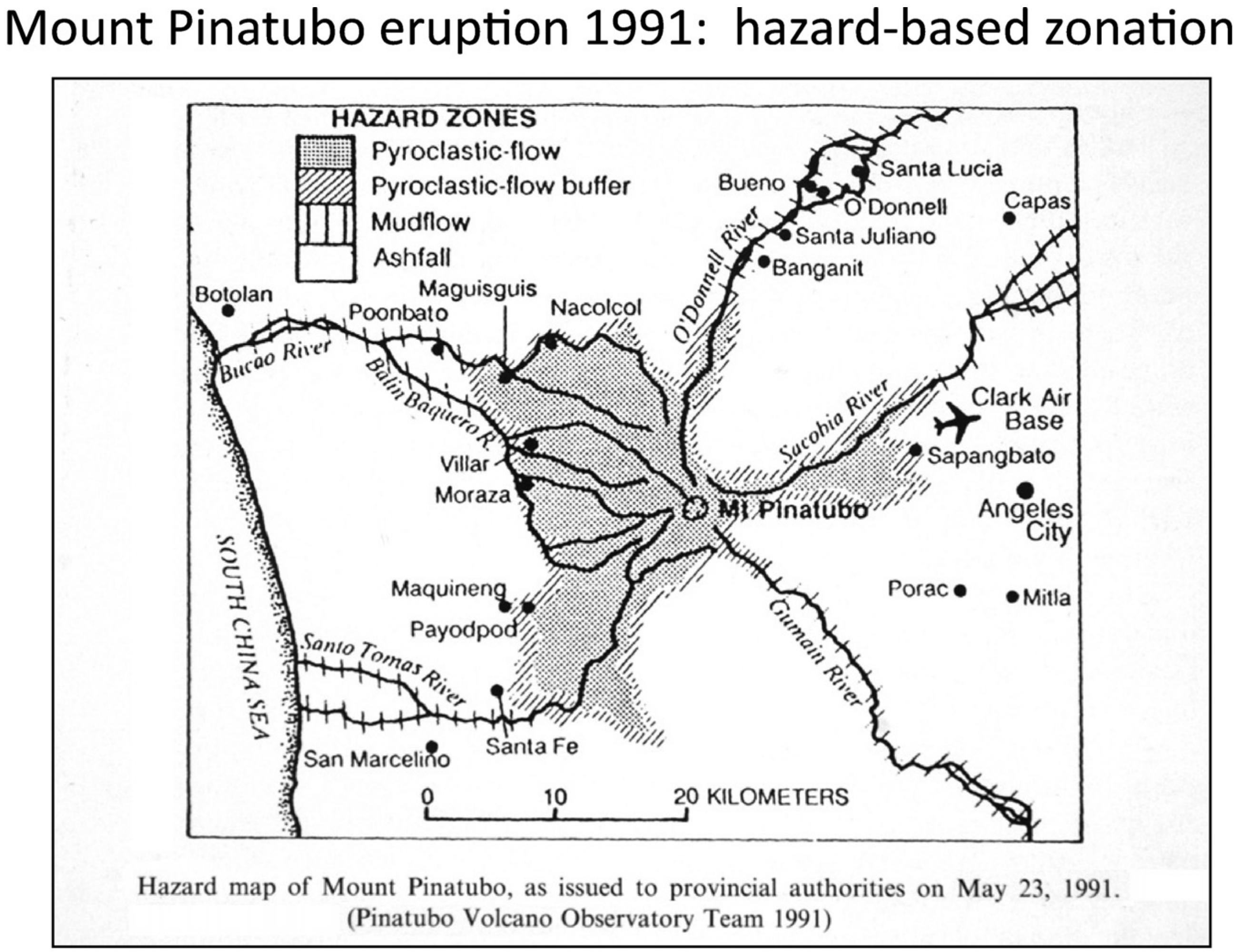
[2] Emergency planning and mitigation at explosive volcanoes is relatively new: major eruptions are too infrequent for scientists or emergency planners to build up a large individual experience and expertise. Almost invariably, every major eruption is a steep learning curve for those involved — scant reassurance to the public at risk. One leading volcanologist, Haroun Tazieff (1913–1998), was notable for providing a "flying doctor" service and offering his own personal experience by going from eruption to eruption. The main urgent need in a crisis is to set up modern volcano monitoring equipment in the hands of scientists experienced in interpreting the findings. The US Geological Survey (USGS) has a group available to do this to assist developing countries — VDAP (Volcano Disaster Assistance Program). At the next crisis of Vesuvius, scientists and equipment from EU countries will be involved in this task to assist their Italian colleagues. An overview of conventional volcanic crises management is well described by de la Cruz-Reyna et al. (2000) and in related papers in the Encyclopedia of Volcanoes.



Mount Pinatubo eruption 1991: hazard-based zonation

Hazard map of Mount Pinatubo, as issued to provincial authorities on May 23, 1991. (Pinatubo Volcano Observatory Team 1991)

Fig. 2. Hazard map at the Mount Pinatubo eruption, 1991 (Newhall and Punongbayan, 1996). The predicted area of devastation by pyroclastic flows and surges (PDCs) was based on the largest previous event known at the time and corresponded well to the actual event. Later, it became known that an even larger event had occurred at Mount Pinatubo.

extreme, worst case and this time it did correspond well with the distribution of the pyroclastic flows in the climactic eruption that followed on June 15. But Newhall and Punongbayan (1996) were to discover later that even bigger eruptions had occurred over 35,000 years ago and if the eruption had been of this order then tens of thousands of people would have died: “we and they were lucky”. Nevertheless, thousands owe their lives to the timely evacuation based on the published hazard map as the volcanic activity dramatically escalated.

Hazard-based approaches always have implicit risk assumptions, despite having the appearance of simplicity and being easily comprehensible. At Mount Pinatubo, the risk (uncalculated) was eventually judged to be elevated over an area as far as 25–30 km from the crater and from which people were advised to evacuate. A similar cautious judgement, had it been applied to the volcanic crisis on the small island of Montserrat, West Indies, would have led to its evacuation in 1997, when the escalating activity had reached a crisis point: only 17 km long and 9 km wide, the whole island appeared to come under threat as the explosive activity of the Soufrière Hills volcano grew following the onset of the eruption in July 1995. But recommending evacuation of the island would have ignored the totality of knowledge that had been accumulated by scientists since the eruption began and pre-empted their proposal to undertake a quantification of the risk and to use this to make a more proportionate response towards the mitigation of the volcanic hazard.

In December 1997, a meeting took place of a team of international scientists to undertake a formal, evidence-based analysis on the Montserrat eruption which included, for the first time in a volcanic crisis, a risk assessment which was based, not on one dominant, worst-case eruption, but eleven possible foreseeable eruption types and estimates of the casualties associated with these, ranging from the least to the most severe (lateral blast) events. This evidence-based approach incorporated all that was known about the volcano, including its geological history, the protective features of the topography of the island, numerical modelling of the pyroclastic flow and tephra fallout, and estimates of the vulnerability of the island's buildings to tephra fallout. An event tree was devised and conditional probabilities were assigned to its branches, the values obtained by elicitation using a mathematical technique that weighted the individual scientist's expert judgements. The method also incorporated the model and statistical uncertainties involved. The outputs shown here in the form of a risk map (Fig. 3) show the zones of societal risk for a hypothetically distributed population of suffering five or more severe casualties in the following 6 months, decreasing to the northern part of the island and farthest from the volcano, where the risk fell to background levels. The map and supporting data underlay the judgment of the volcanologists that the whole island did not need to be evacuated as a precaution; instead, part of the population closest to the volcano at the time needed to move further north to reduce the most immediate risks.

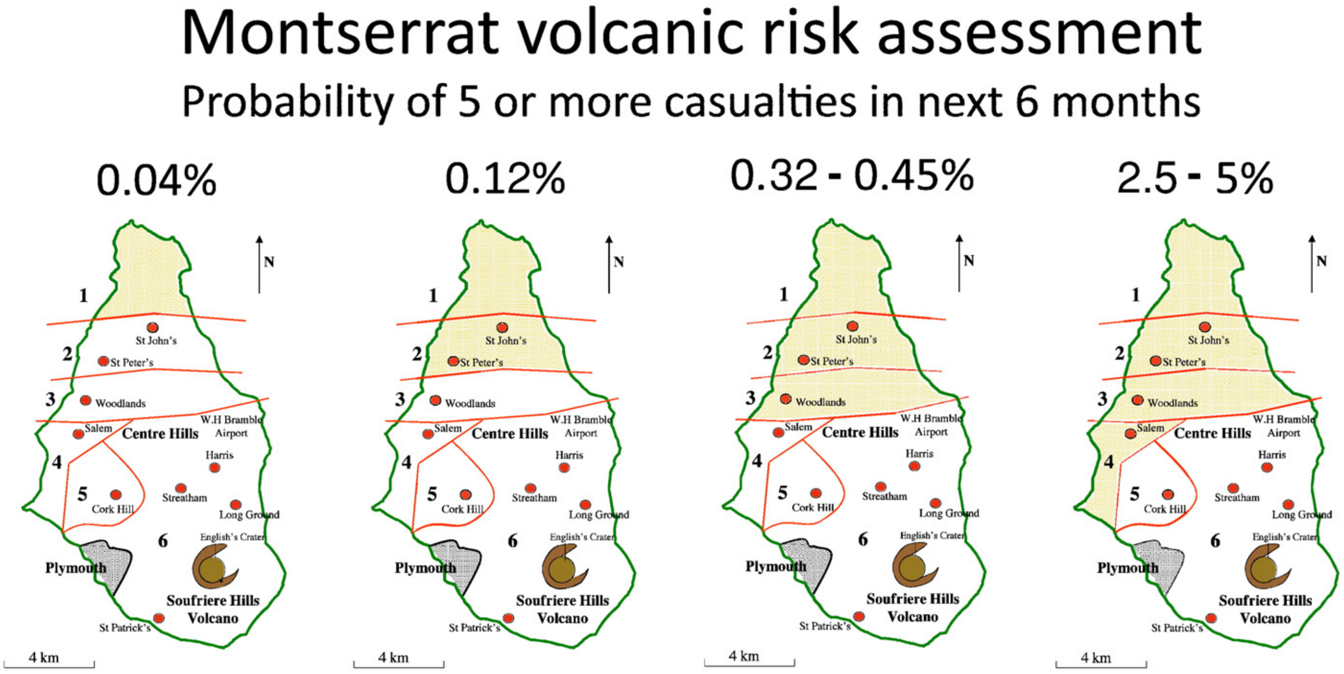


Fig. 3. Example of a risk map produced during the volcanic crisis in 1997 on Montserrat, West Indies (see Aspinall et al., 2002). The outputs are in the form of area-specific societal risk (the probability of 5 or more severe casualties in the 6 months following the risk assessment, expressed as a percentage) which is of most use to decision makers, but individual risk was also considered. Societal risk, unlike individual risk, incorporates the scale aversion factor of multiple fatalities or large numbers of seriously injured arising in a single incident. The societal risk increases the closer the location of the actual population (in the shaded area) to the crater, the northern part of the island was at a background risk for the Caribbean (area 1 = 0.04%), with the risk increasing from area 2 (0.12%) to area 3 (0.32–0.45%) and area 4 (2.5–5%). The last two figures were judged as presenting an unacceptable societal risk.

This judgement was accepted by the authorities and a full-scale evacuation was avoided.[3]

At both Mount St Helens and Mount Pinatubo, the state of unrest lasted only about two months between the beginning of premonitory signs of renewed activity and the cataclysmic eruptions, a period long enough for volcanologists to collate their available knowledge on the past eruptive activity of each volcano and to provide a forecast of a "worst-case" eruption for hazard zonation and evacuation planning, whilst being short enough to maintain their credibility with the authorities and the public (Newhall and Punongbayan, 1996). This is an important point: the hazard-based evacuation should not be seen as a sensible reaction to the uncertainty and as a fail-safe measure, because a disgruntled population will eventually force the authorities to allow them to return if no eruption actually occurs and there is no visible evidence of growing activity, when they could nevertheless be at the same, or even greater, risk from an eruption (Simkin et al., 2001)[4].

Indeed, at certain other explosive volcanoes, including Popocatepetl, Mexico; Tungurahua and Guagua Pichincha, Ecuador; and Galeras, Colombia, the state of unrest has not always been followed by a major eruption, highlighting the uncertainty amongst scientists in making forecasts. In each of these crises, a precautionary and lengthy evacuation would have had severe political and socio-economic consequences, even if such a step would have been feasible in the face of strong opposition from an unconvinced populace. On a small island like Montserrat, where the eruptive activity continued for years, a hazard-based approach could not eventually be sustained, as people responded to the volcanologists' uncertainty over worst-case scenarios by refusing to evacuate from their homes in the absence of demonstrably threatening activity. In other words, sections of the population had begun to adopt their own form of risk-based judgement, as indeed some people did when they returned to the exclusion zone against all scientific and official

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[3] The scientific argument for a wide hazard zone is the inherent unpredictability of explosive eruptions and the limitations of scientific knowledge. This unpredictability can be termed *chaotic behaviour*. Chaotic does not mean *random*: ordinary chaotic systems are completely deterministic and computational even if they seem to behave as though they are not deterministic at all. This is because the accuracy according to which the initial state of the volcanic system needs to be known for a deterministic prediction of future behaviour can be totally beyond anything that is conceivably measurable. Moreover, due to the strongly non-linear nature of their governing dynamics, small changes in the initial conditions can have large influences on the eruptive outcome, yet they are beyond our ascertainment. Thus, even if the full dynamical state of the volcano were known, an eruption is apparently governed by feed-back mechanisms which control and stabilise its dynamics, so that small and unpredictable changes in conduit or vent size during the eruption, for example, would be enough to initiate transitions in the eruptive phenomena. Behaviour that manifests critical sensitivity to very small changes either in initial conditions, or as a result of feedback, is present everywhere in nature. But although chaos imposes a fundamental limit to prediction (this is *epistemic* uncertainty — see Footnote 9), scientific models can be robust enough in the best hands to constrain the range of expected eruptive phenomena and make forecasts when based on data from all available sources, including the all-important monitoring of activity with modern equipment. See Woo (1999). A meeting held in London in December 1997 by the Chief Scientist to the UK government and his advisors concluded that the methodology used by the scientists at the Soufrière Hills volcano was sound and he based his advice to ministers on the strength of the scientific risk assessment.

[4] The numbers of people killed in volcanic eruptions over last centuries is surprisingly small — less than 300, 000 people — despite averaging 2 to 4 fatal eruptions per year in recent decades. An analysis of the fatalities showed that many occurred in the first 24 h when the element of surprise was greatest, but nearly two thirds of deaths and half the fatal events took place over one month after the eruption started, with fatal events occurring even years after the onset. The message is clear, that volcanic eruptions can present risks for months or even years after their beginning and should not be regarded in the same category as floods, hurricanes and earthquakes. Their onset may be sudden like these other natural disasters, but they contrast with these in that the danger does not necessarily decline rapidly with time and may actually increase because of the unpredictability of the eruptive behaviour and the desire of a willing population to believe that the danger has passed and they can resume normal living. See Simkin et al., 2001.

advice, and with fatal consequences for nineteen people, on June 25, 1997 (Loughlin et al., 2002).

3. Evidence-based volcanology

The risk methodology used on Montserrat in 1997 has since been called "evidence-based volcanology," a form of probabilistic reasoning that resembles evidence-based medicine and which has now become widely accepted by medical professionals (Aspinall et al., 2003). The methodology is used in diagnosis and decision making in patient management and treatment, and for deriving guidelines in clinical practice (Hunink and Glasziou, 2001; Sackett et al., 2000). In evidence-based sciences all aspects of evidential reasoning are treated by formal probabilistic procedures. Frequentist results from conventional statistical analyses are incorporated, where they are available, as is uncertain evidence and the weight accorded to it (degree of belief, subjective probability). All available theoretical and observational information is used. The application of probability theory adopts the precepts of Bayesian statistics. Psychologists have clarified the cognitive processes involved in clinical reasoning in medicine in the light of two influential approaches: decision making and problem solving (Elstein and Schwarz, 2002). Psychological decision research also has applicability in volcanic risk management because, like medicine, it is influenced by statistical models of reasoning under uncertainty. The hallmarks of decision making are that it is open to revision with even partial, or imperfect information, and it is evidence-based. The use of decision trees (or event trees, their volcanological equivalent in EXPLORIS) is an important way of displaying information and formalising judgement.[5] The aim is to arrive at a "rational consensus." Problem solving, in contrast, is intuitive, and relies on individuals defining a hypothesis, often by pattern-recognition or categorisation based on individual past experience, and then seeking the specific evidence to support it. The danger is that it becomes closed to data that contradicts the hypothesis; instead of being evidence-based, it can become "eminence-based" (Taleb, 2007).

The evidence-based strategy in decision making is bottom-up, open to opinion-revision, sceptical and *empirical*, whilst problem solving is more top-down, formulaic and *authoritarian*.[6] The most instructive example in the history of volcanology of problem solving and its pitfalls was the public policy fiasco at Guadeloupe in 1976, when two factions of volcanologists argued over their separate hypotheses on whether La Soufrière volcano would erupt or not by selecting data which supported their view and ignoring data which did not (Fiske, 1984; Newhall and Punongbayan, 1996; Zelinsky and Kosinski, 1991). The authorities were not prepared to accept any loss of life from volcanic activity, but their precautionary approach was criticised when the volcanic activity eventually declined without a major eruption. Seventy thousand people were evacuated from Basse Terre for nine months, a decision that led to bitter recrimination amongst the scientists involved (Barberi and Gasparini, 1979). In our view, the authorities made the right decision, given the inadequate information available to the volcanologists, the uncertainty involved and the potential consequences to the large number of people at risk, especially as EXPLORIS scientists consider it to be a form of failed eruption — much more serious than a "phreatic, non-magmatic, non-event," as some scientists viewed it at the time (Komorowski et al., 2005).

The analytic approach to risk assessment employed in EXPLORIS attempts to enumerate and quantify all the process and effects of the eruptive hazards of a volcano that influence risk, a scientific challenge that combines field data from eruptions with theoretical research on volcanic processes. Alfred Lacroix (1904) pioneered the way in the ruins of St Pierre, and major advances were to follow from 1980 onwards, most notably at the eruptions of Mount St Helens, Mount Pinatubo, and the Soufrière Hills volcano, Montserrat.[7] A growing number of studies now constitute the evidence-base for decision analysis and decision making in volcanic crises. We summarise some of the main sources of information on which the analytical evidence for each volcanic hazard is based later in this paper.

4. Formalising judgement in EXPLORIS

More detailed accounts of the EXPLORIS methods can be found in the accompanying papers in this volume and so we present here just an overview of the formal probabilistic reasoning and statistical decision analysis tools that we used.

In brief, our EXPLORIS team of expert scientists began by evaluating the available evidence on the past and present activity of Vesuvius (including historic accounts and old chronicles) and the published literature on eruptions from analogous volcanoes and their environmental and human impacts. This accompanied the construction of a graphical display of all future types of eruptive activity (for a given future time period, in this study ten years) in the form of an event tree, which starts with Vesuvius moving from a state of repose into a state of unrest and the different eruptive sequences unfolding along the branches, or paths, of the tree.[8] The branches were next populated with conditional probabilities using an expert elicitation method with the expert scientific group which allows for wide divergences of individual opinion. The probabilities were based on historical and geological data from Vesuvius and theoretical models of magmatic and eruptive processes. Mathematical techniques were used in formalising the expert judgement elicitation and to capture

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[5] Evidence-based medicine is the most recent and the most successful initiative to date to apply statistical decision theory in clinical medicine. Decision analysis was founded on the work of von Neumann and Morgenstern (1947). Decisions are laid out in decision trees, which are tools for an explicit and systematic approach to decision making based on the premise of rationality (Elwyn et al., 2001). The uptake of decision trees is limited in routine clinical medicine because of an insurmountable time barrier to their use (Sackett et al., 2000). Medicine and volcanology differ in one important respect, namely that the former is data-rich and statistical evidence is relatively easy to obtain, whilst volcanology is hampered by the rarity of eruptions to study. We do not think that this detracts from applying decision making to volcanology — to the contrary, it strengthens the case, as we cannot identify any other way of dealing with the uncertainty associated with this particular domain of science.

[6] The American pragmatist philosopher CS Pierce (1839–1914) is credited with first questioning the certainty in which science was held and viewing science as "opinion-revision" In fact, it was a Scot, David Hume (1711–1776) during the Enlightenment who first disconcerted thinkers over the fallibility of science, though his ideas were not taken up until over a century later. Hume tackled the problems of pseudo-science and belief in mysterious transcendental entities (both of these problems can surface in the charged atmosphere of volcanic crises), when he argued we need look no further than at ordinary experience, or if beyond that, in the refined experience of science. He said: "a wise man proportions his belief to the evidence" (Magee, 1987). Some might argue that an evidence-based approach is just another science-construct and reductionism, as inappropriate for dealing with the dilemma of Vesuvius as appealing to San Gennaro (the patron saint of Naples), when it is fundamentally a politico-social problem requiring a political, not a scientific, solution. We would argue that dealing with a future volcanic crisis without robust science-based decision- and risk-based tools is equivalent to a ship leaving port without charts and navigation instruments.

[7] Alfred Lacroix (1863–1948) was the first scientist to undertake a systematic field study of the impacts of an explosive eruption (at St Pierre) to in order to explain an eruptive phenomenon which he was also the first to photograph (at Mont Pelée): pyroclastic density currents (PDCs). His observations in the ruins of St Pierre were recorded in his classic monograph (Lacroix, 1904) and were remarkably consistent with those made a century later on the impacts of PDCs in Montserrat (Baxter et al., 2005). A PDC has not struck a modern city and Lacroix's work remains a unique reference and inspiration for analytical risk studies.

[8] It has been recent practice of scientists in the USGS Cascades Observatory to draw up event trees at volcanic crises and they have been found valuable in defining the range of potential eruption types based on the known past behaviour of a volcano, according to Dan Miller at the Naples final meeting of EXPLORIS. Newhall and Hoblitt (2002) described the construction of a generic event tree at a hypothetical explosive volcano, and derived branch probabilities from a range of global data sources and references for estimating the individual risk to a hypothetical person living in a hypothetical town.

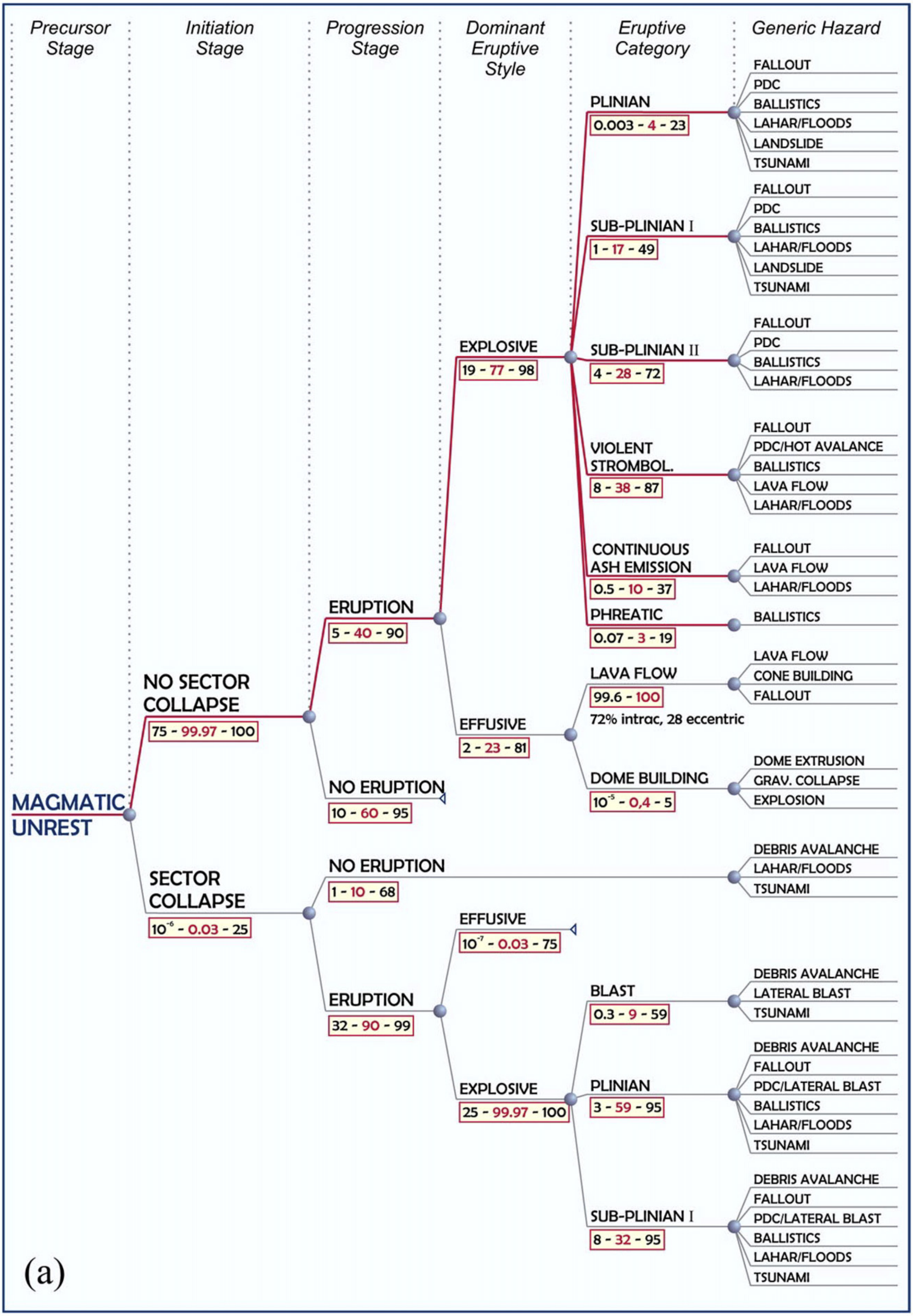

Fig. 4. The EXPLORIS event tree for Vesuvius (Neri et al., 2008-this issue). The whole tree is shown, but the paper focuses on the branches for the main five explosive eruptions. The hypothetical branch probabilities (and 5% and 95% credible intervals) were those obtained from the expert elicitation with EXPLORIS researchers (see text).

Table 1
Emergency planning scenarios: the elicited key explosive eruptions and their probabilities (5% and 90% credible intervals) and impacts (deaths) for emergency planning and risk assessment. The numbers of deaths are hypothetical meaning that they are the numbers that would occur if no evacuation or other mitigation measures were instituted. The numbers are derived using the expert elicitation method (see text for explanation)

Eruption type	Probability (%) (5% and 95% credible intervals)	Hypothetical no. of deaths (approximate scale)
A. Plinian	4% (0.003–23%)	10,000's
B. Sub-Plinian (1)	17% (1–49%)	1000's
C. Violent Strombolian	37% (8–87%)	100's

epistemic and stochastic uncertainty.[9] The event tree, with slight modification, becomes an eruption scenario tree for emergency planning purposes by adding the estimated or modelled losses (buildings, lives) for each eruptive outcome. From this, three or more main emergency scenarios and their probabilities were defined for emergency planning purposes: these scenarios were developed in more detail and refined by performing numerical modelling of eruptive impacts for risk assessment and mitigation.

4.1. Constructing the event tree for Vesuvius

The event tree is essentially a timeline which starts with the state of unrest and follows the different potential paths to eruption with chance nodes at each step where the volcano can move to one of at least two possible states of increasing or declining activity (Fig. 4). The construction of the whole event tree for Vesuvius took many meetings of EXPLORIS participants and represents a milestone in the scientific understanding of the volcano (Neri et al., 2008-this issue). In dealing with expected volcanic scenarios, the guide to the future behaviour of a volcano lies in its past activity, assuming that the system approximates to a state of equilibrium (Rosi, 1996), or steady state ("stable boundary conditions"), over this long period. In EXPLORIS, we drew on the current knowledge of Vesuvius and its behaviour in the last twenty thousand years (Cioni et al., 2008-this issue). We regarded this period as the most applicable for forecasting the volcano's behaviour on the current state of knowledge if a state of unrest began in the next ten years.

The branches of the tree are populated with conditional probabilities and these are obtained from the group of scientists by a formal elicitation method (Neri et al., 2008-this issue), which enables multiple opinions to be combined using an elegant mathematical weighting technique which gives greatest weight to experts who are the highest scorers for "informativeness" (in effect, the *precision* of their estimates) and for being "calibrated" (the *validity* of the estimates). The event tree probabilities presented here and in Neri et al. (2008-this issue) are the first outputs of our research which exploited the wide range of expertise of EXPLORIS scientists and their shared knowledge of the EXPLORIS research findings.

The tree can then be completed by incorporating losses at the end of the paths; in EXPLORIS we have used deaths or severe casualties as our end-points. These figures can be rough estimates in the first instance (Table 1), or refined by pyroclastic flow and tephra fallout modelling, as outlined below.

The tree displays five main types of explosive eruptions: the Plinian, the sub-Plinian types 1 and 2, violent Strombolian and the continuous ash emission (i.e. we neglect the possibility of phreatic explosions). The last Plinian eruption was in AD 79 and was witnessed by Pliny the Elder. The largest eruption of the last millennium at Vesuvius was a sub-Plinian type 1 in 1631 and was also documented in chronicles at the time. The last sub-Plinian type 2 was in AD 512, but we only have the stratigraphic record for this. The two largest eruptions in the 20th century, in 1906 and 1944, were violent Strombolian and were well recorded at the time. Our knowledge of the continuous ash emission type is based on stratigraphic and compositional evidence only.

4.2. Choosing the key eruptions for emergency planning and displaying uncertainty

The event tree provides invaluable information on the main types of explosive eruptions that can follow the state of unrest, but there are no clear rules on how the eruptive types should best be ranked according to their probabilities and consequences.[10] All the eruptive outcomes in the event tree have to be considered in emergency planning and no realistic outcome should be discounted, but the most serious or the most probable eruptions need to be given priority and these are shown in Table 1, together with their provisional probabilities and scale of impacts. It is the case that overall the larger eruptions are much less frequent than the smaller ones[11] and the latter will have more manageable impacts for targeted mitigation measures. A full evaluation of the eruption scenarios is needed before Table 1 can be completed with the involvement of emergency planners (see below).

The worst scenario is a Plinian eruption, followed by the sub-Plinian 1 (1631-type) eruption, which is currently the reference eruption on which the National Plan for Vesuvius is based (Dipartimento della Protezione Civile, 1995), and then the most likely but less severe event, the violent Strombolian. For the sake of simplicity here we neglect the sub-Plinian 2 scenario that is intermediate, in terms of scale and probability, between the sub-Plinian 1 and the violent Strombolian. The violent Strombolian is not associated with major pyroclastic flow formation and so its consequences are relatively smaller than the other types and the mitigation measures are different.

Table 1 shows that the probability of an explosive eruption being on the scale of the 1631 reference eruption is considered to be four times more likely, and the violent Strombolian nearly ten times more likely, than the worst scenario eruption (the Plinian). However, the

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[9] For a full treatment of epistemic and stochastic uncertainty, and subjective probability, see Woo (1999). Uncertainty that can be ascribed to lack of knowledge is *epistemic*, and that associated with randomness is stochastic or *aleatory*: the two forms of uncertainty reflect the underlying duality of probability. Another way of expressing epistemic uncertainty is by the "*known unknowns*" and the "*unknown unknowns*". We can try to reduce epistemic uncertainty by more research, for example, into the known unknowns, but there will always be limits to our knowledge, as in the unknown unknowns. In evidence-based science, probability can tell us how strong the evidence is for some effect taking into account all the evidence at hand, not only the evidence of one data set. *Conditional probability* expresses the probability of some event conditional on the occurrence of some other event — that is, *given* that this other event has occurred (the probability that event E occurs given that event F is known to occur). *Single-event probabilities* — in statements like "the probability that an eruption will happen in the next six months is X percent" — is a Bayesian use of probability as logical reasoning (inference) in evidence-based science.

[10] Risk ranking. Ranking eruptions using a single number derived by multiplying the hazard probability by the number of casualties is tempting, but will lead to confusion because of the inability of this method to distinguish between high frequency, low consequence events and low frequency, high consequence events. Ranking emergency scenarios should inevitably incorporate the judgement of the emergency planners.

[11] Many phenomena follow an inverse relationship between their frequency and magnitude known as a *power law*. The best example in earth sciences is the Gutenberg–Richter relation for earthquakes. Globally, volcanic eruptions appear to follow a similar distribution. The power law distribution gives more frequent large eruptions than a bell (normal distribution) curve and produces a pattern characterised by lots of small eruptions broken episodically by large eruptions. This does not help in forecasting the next eruption at a volcano like Vesuvius, as we do not know its underlying state at any given moment (see Footnote 3). Nor does it mean that forecasting should err on the side of small eruptions and that an optimistic forecaster of small events will on average do better than a pessimistic one. For example, the last two eruptions at Rabaul volcano (Mount Tavurvur), Papua New Guinea (1937 and 1994), have both been moderately large.

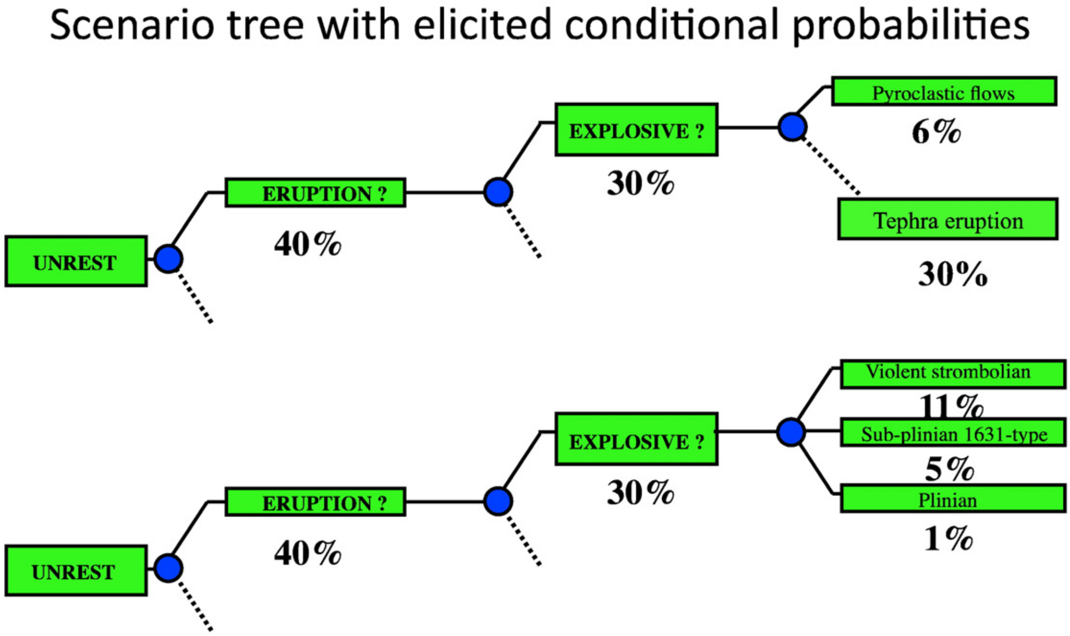

Fig. 5. A branch of the event tree reproduced from Fig. 4 can also represent a scenario tree with elicited conditional probabilities shown on the separate branches. The numbers are derived from the trial elicitation of EXPLORIS researchers as in Fig. 4.

uncertainty of the scientists over these probabilities is demonstrated by the broad credible intervals; this shows that there is a need to revisit the knowledge base and repeat the elicitation to see if the ranges can be reduced and to identify the reasons for the wide discrepancies of opinion shown here. If the intervals turned out to be irreducible, it would indicate the large epistemic uncertainty in the scientific knowledge and reflect the limits of our current knowledge. Marzocchi et al. (2004) adopted a statistical approach using an event tree for quantifying probabilities of volcanic events and found a non-negligible (1–20%) chance that the next eruption could be larger than the Emergency Plan reference eruption, which is consistent with our findings (Neri et al., 2008-this issue).

The same information is presented in the form of a branch of the event tree and this time taking into account the conditional probabilities (Fig. 5). Multiplying the probabilities along the path provides a new perspective, with a surprisingly low probability of the state of unrest ending with one of the key eruptions. This way of presenting the data shows that the most likely outcome of the state of unrest is for the volcano to return to repose, rather than erupt. If, instead, the course is towards an eruption then, according to the event tree, it is about three times more likely to be an explosive rather than an effusive event. For presentational purposes, it is best to use frequencies rather than probabilities[12]. In other words, one in a hundred states of unrest would culminate in a Plinian eruption, and five in a hundred with a sub-Plinian 1. Only one in ten states of unrest will end in a violent Strombolian eruption, even though this is the most likely explosive eruption. Overall, only six out of a hundred states of unrest will end with an eruption accompanied by pyroclastic flows, whereas one in three states of unrest will end with an eruption accompanied by tephra fallout (all of the explosive eruptions are accompanied by tephra fall).

As displayed in Table 2, the development of pyroclastic density currents (PDCs) could, according to our experts, take place around 47 days into the crisis and this phase could last about 5 h, and the tephra fallout begin after 46 days, but both of these values (50% percentiles) have wide credible intervals reflecting the uncertainty of the experts' estimates. The duration of the eruption (54 days from the onset of unrest) is short, but is also surrounded by large uncertainty.

If further work confirms these preliminary estimates, decision makers would have plenty to think about. For example, as there is a reasonable likelihood that the state of unrest might not end in an eruption at all according to Table 1, how soon should the area around the volcano (the Red Zone) containing 500,000 people be evacuated, especially if the probability of a pyroclastic flow eruption is as low as stated? Should the area of the Red Zone be based on the National Plan's reference sub-Plinian eruption or the larger, but less likely, Plinian event, which would impact on an even larger population? In Table 2, the limits of the credibility intervals are notional 5% percentile values, which can be interpreted as a 95% chance that the fallout phase will start after 4 days or longer into the state of unrest and the PDC phase after almost the same time. But this means that there is a small chance that Vesuvius could be in full eruption within under a week of the announcement of the state of unrest, which might be before the evacuation of the area is complete and have disastrous consequences. If so, how far should the emergency plans extend and should they include search and rescue planning for casualties? The mid-duration of the PDC phase is expected to last 5 h — short enough for it to be feasible to be followed by an effective search and rescue operation for casualties and trapped individuals caught in the PDC and the fallout phases. Finally, if an early and full precautionary evacuation was undertaken the officials involved in the decision would need to be aware of the small chance that the eruption might not occur until over a year into the state of unrest — in

Table 2
Elicited median lead times and 5% and 95% credible intervals from the start of the state of unrest to the given hazard event, showing duration of the PDC phase and the whole eruption. The numbers are derived from the same expert elicitation as in Table 1

Tephra fall on towns	4.3–46–435 days
PDCs impacting towns	4.33–47–444 days
Whole duration of eruption	7.5–54–515 days
Mean duration of PDC phase	0.2–5.0–86 h

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[12] Minds are adapted to talk about frequencies of important events, not their probabilities or percentages. Few people walk about with probabilities in their heads, for forecasting the weather or even gambling (*odds* are preferred by punters). Natural frequencies can be shown to facilitate inferences made on the basis of numerical information (Gigerenzer, 2002).

Fig. 6. Map of circumvesuvian area showing the Vesuvius crater and Mount Somma, with the towns affected by the 1906 and 1944 eruptions.

practice, dangerously long for a population of this size to be held in evacuation in the absence of threatening activity[4,13].

Answers to these and other important planning questions are not straightforward and would need to be based on an understanding of the eruption scenarios (see below) and not just on these elicited "estimated occurrence probability" values.

5. Descriptions of the explosive eruption scenarios

A large body of historical evidence exists on the eruptions of Vesuvius since the sub-Plinian eruption in 1631.[14] Cioni et al. (2008-this issue) describes the eruptive history of the volcano over the last 20,000 years and the scenarios for emergency planning are based on their paper (including Cioni et al., 2003), as well as selected reports.

5.1. Plinian and sub-Plinian eruptions

The largest, most recent Plinian eruption of Vesuvius (the Avellino) occurred in the Bronze Age (3500 BP), but the best studied by volcanologists is the famous AD 79 event, on which this summary is based. In a future eruption the opening phase marked by vulcanian-type explosions and ash-charged convection columns could be expected to last no more than a few hours, and the impacts would be confined to the vent and upper slopes (although ash could produce significant problems even at larger distances). The main phase with a stratospheric eruption column could last several hours (20 h in AD 79, according to Pliny the Younger's account). Fallout in the proximal and medial sectors would be up to several meters and contain coarse grained pumice, leading to roof collapses; damage from ash fallout would extend to hundreds of kilometres downwind. Two types of PDCs can occur in the late stages of this phase, as what occurred in the AD 79 eruption: low volume, dilute flows from partial column collapse with run-outs up to 9 km, e.g., as far as Pompeii, and denser and hotter flows, with similar run-out distances, at the end of the phase arising from column collapse. After the climax, phreato-magmatic explosions continued for days, but the main event generated was caldera collapse associated with strong seismic activity and the most energetic PDCs extending for 20 km or more destroying the area around the volcano. Lighter, phreato-magmatic activity accompanied the waning of the eruption, which took weeks.

The sub-Plinian 1 eruption has the same phases as the Plinian, but with lower magnitude and intensity; the duration is shorter and the area impacted smaller. The hazards and emergency management issues are the same. The last two sub-Plinian 1 events were in AD 472 (Pollena) and 1631 (reference eruption), the latter being well documented in contemporary chronicles. In AD 1631, the opening phase lasted only 2 h and was not accompanied by PDCs. The main eruption column (height 20–21 km) was sustained for 8 h. Thick (1–2 m), coarse grained pumice and scoria (coarse lapilli) deposits were emplaced downwind in the proximal sectors, with ash fallout causing problems for hundreds of kilometres. Enhanced ash sedimentation

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[13] The uncertainty over forecasting eruptive events for practical decision making is in parallel with the problem of medical diagnosis, in that both are subject to false alarms and false reassurances, with the potential for making costly or deadly mistakes. One application of evidence-based medicine at the bedside is to use Bayesian statistical methods for determining the probability that patient has a specific disease when the clinician is faced with a positive test result, or set of results, a task not fundamentally very different from volcanologists interpreting eruptive precursors in a crisis, a comparison which is found scattered about the volcanological literature. In the days before scientific medicine, with its statistical methods and the availability of medical treatment that we have today, the reputation of the doctor depended upon making an accurate diagnosis, which was fraught with uncertainty, and forecasting the patient's outcome in terms of life and death as a balance of probabilities: the teachings of a celebrated physician of that era, Sir William Osler (1849–1919), who would have embraced evidence-based medicine, invoked young doctors to be humble in their ability to do this with the reminder that "medicine is a science of uncertainty and an art of probability." (Silverman et al., 2008). An urgent challenge for volcanology is to develop probabilistic methods for volcanic forecasting in a domain that is "data-poor" compared to modern medicine and deals with relatively rare events — a fundamental difference between the two disciplines.

[14] Most famous of all observers of the volcano was the English diplomat Sir William Hamilton, whose stay in the Bourbon capital of Naples as Royal Envoy from 1764 to 1798 was at a time when Vesuvius was in a state of semi-persistent activity and its dramatic sights inspired artists, thinkers and the scientists of the day. As the first scientist to recognise that explanations for volcanic activity should be sought by interpreting the evidence from extensive observations in the field and not, as he said, from the comfort of a chair, he was the first empirical volcanologist. He became aware of the negative consequences of volcanism when he was present at the three notable lava flow eruptions in 1771, 1774 and the worst, in 1794, which destroyed Torre del Greco. After 1631, and until 1906, Vesuvius displayed frequent explosive activity in two main styles: periods of effusive Strombolian activity and violent Strombolian eruptions, with periods of inactivity not exceeding seven years. During the past two centuries of activity, the 1822 and 1906 eruptions were both violent Strombolian and were the greatest eruptions of the 19th and 20th centuries, respectively. Since the 1944 eruption, the conduit has remained sealed and the volcano has been in a state of repose.

over proximal areas was caused by syn-eruption rain showers. Naples also received ash fall and was reportedly in darkness for two days. Contemporary authors emphasised that many roof collapses were triggered by the wet ashes, which within about 10 km of the crater attained a primary thickness of around 20–40 cm.

In the collapsing, or fountaining, stage that follows the main phase, the generation of very hot (>300 °C), dense, topographically controlled PDCs that extended to the sea from Portici to Torre del Annunziata, continued for 2 h in 1631 in association with the collapse of the summit portion of the volcano. Seven main "rivers of fire" or PDC lobes flowed in a south-west direction along valleys, probably because of the barrier-effect of Monte Somma deflecting the PDCs away from the north-east side. About 4000 people are said to have died in the eruption, mainly from the actions of the PDCs, but Guidoboni (this volume) quotes a lower figure of under one thousand; it is certain that many thousands did evacuate to safety. The final phreato-magmatic phase can be accompanied by heavy ash fall as far as 40 km downwind (AD 472). Heavy rainstorms triggered by the eruption (due to ash acting as nuclei for raindrop formation, or the condensation of steam released from the crater during the phreato-magmatic phase) caused floods and warm lahars that coursed down the volcano in many directions and were amongst the most destructive phenomena (Rosi et al., 1993); these secondary hazards are outside the scope of EXPLORIS. In 1631 the secondary hazards of lahars and floods affected the plain at the northern foot of the volcano and the valleys of the Apennines (40–60 km downwind) for days.

Several sub-Plinian 2 eruptions have occurred in the last 3900 years, the last in AD 512. Here, we shall regard it as a smaller version of the sub-Plinian eruption and without major pyroclastic flow activity. As the thickness of the fallout deposit can be greater than 10 cm at least as far as 15–25 km away from the event, roof collapse would be the primary hazard. But even small volume, dilute PDC dispersed close to the vent can be hazardous due to the very dense urbanisation of the volcanoes slopes.

The density of the tephra can range from 500–1500 kg/m^2, being less dense in the Plinian fallout. The rate of accumulation of the tephra deposit is relevant to the hazard. For the same three eruption types the accumulation rates are given by Cioni as 10–20, 5–15 and 5–15 cm/h, respectively. Such rates are so high as to make escape impossible once the fallout has started, due to low visibility. The 1631 fallout also contained numerous clasts large enough to cause direct injury as far as 8–9 km from the vent; walking outside would be highly dangerous without head protection. The occurrence of rain at the same time would lead to mud-like fallout which could not be tolerated for long outside, either.

To summarise, in these highly devastating eruptions mitigation for a repeat event would need to be directed at accurate risk zoning to define evacuation limits to protect against PDCs, and measures to protect against direct risks to life from tephra fallout in sectors extending at least 10 km from the summit vent, with the direction of the main fallout depending upon the state of the tropospheric winds at the time of the eruption.

5.2. The violent Strombolian eruption

The two main eruptions of Vesuvius in the 20th century, in 1906 and 1944, were violent Strombolian, the latter being the last eruption before the present repose period. Four other eruptions of similar type and magnitude as the 1906 event had occurred since 1631, though the impact in 1906 was the most severe in its lethality and effect on the population. The main paroxysmal phase is often preceded by effusive activity (from the crater or lateral fissures) and followed by a phreato-magmatic phase ending in a period of long-lasting (days to months) ash emission. Lava fountains rising up several kilometres characterise the main phase, which can last hours to days. The duration of the lava fountains can be tens of minutes to hours and they leave thick deposits of lapilli or scoria along a narrow sector of the dispersion axis. Episodes of inclined lava fountains can also occur, inducing unexpectedly fast fallout deposition and showers of rocks (blocks) over restricted areas.

The eruption in 1906 is of particular interest as it may be regarded as an example of a "worst" scenario for a violent Strombolian eruption with the implications for modern-day living in a future eruption capable of being drawn from the contemporary accounts[15]. It began on 4 April after years of summit activity at Vesuvius and started with lava emissions from the summit and the southern flank accompanied by frequent explosions and ash emission. The main lava flow travelled 3.5 km to Boscotrecase (Fig. 6). In the evening of 7 April, the explosions became very loud and could be heard in Naples; volcanogenic earthquakes were experienced throughout the Vesuvius region and caused panic in Naples. Lava fountaining began late at night and was directed towards Ottaviano, with a storm of lapilli and clasts hitting and breaking the windows, many facing away from the volcano (Perret, 1924). People started taking to the roads and most eventually escaped the town, despite the complete obscurity, protecting their heads with various objects such as baskets, boards or chairs; those unable to walk took cover in barns (Cimmino, 2001). By 0300 on 8 April the houses started to cave in under the weight of fallout, which began to cease around 0600. The town received about 80 cm of fallout, but this accumulated to depths up to 2 m near buildings, probably because of it falling off the pitch-roofs. Piles of lapilli were sometimes seen on the level of the first floors of the houses due to this effect. Hundreds of houses were totally destroyed under the weight of tephra, with hardly any left intact, and three churches collapsed (no

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[15] The most graphic account is by the volcanologist Frank Perret (1924), who makes all the other reports look staid in comparison. He spent most of the eruption at the Royal Vesuvian Observatory (Osservatorio Vesuviano), only 2.5 km from the summit crater and his account is essential reading to learn (and feel) the violence of the eruption, in which he and his fearless colleagues came close to death, on one occasion when the Observatory was enveloped in a gas cloud (one young man in a group of locals sheltering in the building died from its effects). Other reports include: Cimmino (2001); Hobbs (1906); Lacroix (1906); Johnston-Lavis (1909). For more on Frank Perret and the 1906 eruption see T. Gidwitz (2005): http://www.vesuvius.tomgidwitz.com/html/10__the_eruption_-_phase_iii.html. This report in the London Times on April 11 1906 graphically summarises the "distressing scenes" around Vesuvius: *Last night was a quiet one in Naples. On Sunday night there was a notable diminution in the activity of the volcano, which is now still further decreasing. The intermittent explosions and continuous rumble below are only to be heard at comparatively close quarters: the change of wind carries the dense cloud of ashes out to sea, stretching a thick vale between Naples itself and the coast line of Castellammare and Sorrento: and, what is more important, the slow course of the lava streams is stayed at Torre Annunziata and Torre del Greco, though there was still a discernible movement this morning in the stream which branched off near Torre Annunziata towards Pompeii. Professor Mattucci, who has regained his post of observation, reports a decided amelioration in the symptoms and has expressed his belief that the worst is over. Naples has today resumed its normal life, though very far from its normal aspect. Though the ashes have ceased for the moment to fall on the town, they lie inches deep in all the streets, rising in clouds of fine impalpable dust and thickly coating both houses and wayfarers. It appears a grey city inhabited by grey ghosts, which is at least an improvement upon Saturday and Sunday nights, when the threatening thunder of the volcano, a thick pall of darkness torn by distant flashes of volcanic explosions and a suffocating atmosphere made it resemble an ante-chamber of hell. The Neapolitans too, have taken courage again, and the pitiful little processions bearing a body image or picture, sometimes composed of only a dozen or so of half-distraught peasant women, have now deserted the streets, though even last night they were still to be seen here and there. If the appearance of Naples is not fraught enough, that of the threatened towns is most wretched. Torre Annunziata seems utterly abandoned save by a few carabinieri and troops, who mount guard in its empty streets. Torre del Greco is in little better ease. Resina and Portici suffered less in the general panic, but were deserted temporarily by a good many of the inhabitants, who are now returning to their homes. Bosco-Trecase is destroyed. The villages on the north-east of Vesuvius–Ottajano, San Giuseppe, and Terzigno — I have not yet been able to see, but from all accounts their condition is sufficiently deplorable. From San Giuseppe is reported the only loss of life. The roof of the old church, long known to be unsafe, succumbed, it is supposed, to the added weight of ashes and volcanic debris and fell in, burying in its ruins a great number of women and old people who were gathered in prayer to avert the destruction of their town. According to the last accounts 37 dead bodies have been extricated, besides a number of injured. A report of a similar disaster at Terzigno is now denied, though that town has also suffered severely from the hail of redhot stones and debris.*

one was killed in the churches as they were kept closed). Roofs and floors were burst in and walls burst-out (Chester and Duncan, 2007). In nearby San Giuseppe and San Gennaro, the lapilli shower had begun in the middle of the night and went on for some 4 h in absolute darkness. About 1 m of lapilli accumulated overnight on the roof of San Guiseppe church; at 0915 on April 8 the roof caved in killing 105 people and severely injuring 90 more, who were sheltering there; a hundred others escaped. There were a further 106 deaths in Ottaviano and San Giuseppe, most as a result of the collapse of flat and tiled roofs of stucco houses, and a few due to people being struck by bombs and falling clasts. About 60 people were seriously injured. Overall about 300 people died and a similar number were seriously injured. Rescuers managed to dig out several people alive (Chester and Duncan, 2007).

Tephra also affected a wide area to the west of the volcano and up to 15 cm ash fell in Naples (the discrepancies in some reports, which suggest only 2 cm thickness, is probably due to accumulations of ash from roofs against buildings, etc., being included in the estimates), causing the collapse of the roofs of the Monte Oliveto market and a few poorly constructed houses; ten people died. Swirling winds kept Naples and the western and northern circumvesuvian area shrouded in ash for most of the eruption. In Naples the people had to protect their eyes from the ash with glasses, celluloid plates or other devices, with the better off carrying opened umbrellas (Hobbs, 1906). At Torre del Greco, Resina and Portici, the ash depth was reported as 15 cm (Hobbs, 1906), or as much as 45 cm, according to Delmé-Radcliffe (Chester and Duncan, 2007). Fear drove 100,000 people to self-evacuate from Naples on April 8 and 3000 people left Portici on ships sent by the navy, with thousands of others making their own way to Naples to escape the violent rain of ash and lapilli which lasted 30 h at Torre del Greco. A lava flow destroyed parts of the communes of Boscotrecase and Boscoreale. The whole eruption lasted from 4th to 20th April, with further ashfalls, but lahars and floods continued to disrupt the impacted areas for several years afterwards and caused a few more deaths.

The 1906 eruption had a much greater impact on the local population than the one in 1944, but then the fallout was much more plentiful in the earlier event. In 1944 the fallout was mainly directed by low-level winds towards Salerno, with the heaviest deposit at Terzigno and Pompeii along the dispersion axis marked by the 35 cm isopach. The 10 cm isopach was located at 20 km from the crater. At Terzigno, many aircraft at an Allied Air Force base were damaged by the rain of ash and lapilli. Chester et al. (2007) have made the most detailed summary yet of the eruption from available sources. The eruption began with the crater filling with lava and then it spilled over the rim and headed towards San Sebasiano at 1630 on 18 March. Another flow went as far as 3 km towards Torre del Greco. The lava reached San Sebasiano at 0300 on 21 March and eventually destroyed the town. The lava moved at 50 to 100 m/h, at which speeds people learned not to panic. At 1700 on 21 March a lava fountain began and there were about 8 episodes of fire fountaining overall with durations of between 18 and 40 min, ending on 0730 on 22 March. More sustained explosive activity with ash falls began on 22 March, when there was a large eruptive column accompanied by an electrical storm and frequent seismic activity. All the 21 deaths in this eruption resulted from tephra-induced roof collapse in the Pagani/Nocera area (within the 35 cm isopach), where the buildings were typically mud/adobe, and one person was killed in Terzigno by a falling rock.

These two events show how in a future violent Strombolian eruption a single sector can be most impacted by directed lapilli fallout from lava fountains, depending upon the eruption dynamics and the direction of low-level winds at the time. Nevertheless, ash fallout could produce major impact even at the regional level depending on eruption duration and wind directions. No major pyroclastic flow activity occurs and mitigation in the main is about protecting houses and people against localised, very heavy lapilli and clast fallout and volcanic ash. Lava flows emitted from low-level vents, whose location cannot be predicted, can move quite rapidly, but no one died from the main flows in 1906 and 1944. Great explosions and a period of earthquakes led to panic in Naples and many towns in the circumvesuvian area, leading to spontaneous mass population movements, in 1906. Important questions are: what would be the impact of a 1906 or 1944 event today, given the denser population present and more modern housing and infrastructure, and how large is the scope for mitigation in such an eruption? To what extent would modern life (health, transport, lifelines, businesses, etc.) in the Naples megalopolis be disrupted? One aspect addressed below under risk modelling is the resistance of the roofs of buildings to the fallout and the risk to their hypothetical occupants.

5.3. Continuous ash emissions in the final eruptive phases

The ash emissions in the final phase of the Plinian, sub-Plinian and violent Strombolian events could last for months and cause disruption over wide areas. The prolonged ash falls that followed the last phases of the AD 79 and 1631 eruptions gave layers impervious to rain water that added to the risk of flooding and lahar generation. Other events characterised by prolonged ash emission have recurred at Vesuvius since the 3,900 BP eruption of the Avellino pumice. Many of these events are recorded in the products of the activity in the Middle Ages, with thicknesses ranging from a few centimetres to decimetres in the currently inhabited area at the base of Vesuvius. The eruptive processes involved are not fully understood, but they could also be associated with effusive activity close to the vent.

The fallout of low-level ash plumes emitted over periods of several months of phreato-magmatic activity would comprise dense ash (1300–2400 kg/m^3) and might well have corrosive properties from adsorbed acids. The effects on infrastructure and transport in future events could have widespread temporary economic and social consequences, and the fine fallout could cause widespread acute respiratory disorders amongst the population.

5.4. The next eruption of Vesuvius

In summary, it is not known when the present repose period of Vesuvius that began following the last eruption in 1944 will end, but the onset of signs of renewed activity will constitute a new state of unrest if the activity appears to be escalating towards an eruption. If an explosive eruption eventually occurs, the Plinian and sub-Plinian eruptions would have similar opening phases lasting at least a few hours and marked by Vulcanian explosions and tephra fallout confined to the upper areas of the volcano. Earthquakes are likely given that the conduit is now sealed and explosive energy will be needed to clear a vent. The eruption centre is likely to be in the present crater area, but it could form elsewhere. The main phases of Plinian or sub-Plinian 1 eruptions would be devastating within the Red Zone, with extensive impacts due to fallout and pyroclastic flows, and the secondary hazards of floods and lahars. Recovery from the eruption in the circumvesuvian area would take many years.

The most probable case is the violent Strombolian eruption, which is likely to begin with earthquakes and effusive activity (in the crater or, less commonly, from a lateral vent and a fast-moving lava flow extending into populated areas) and moderate ash emissions, accompanied by loud shocks and explosions, but the main hazard to life is from the lapilli and ash fallout from paroxysms of lava fountaining which are mostly directed along a narrow dispersion axis. The last phase contains strong ash emissions subject to low-level winds, the fallout from which could cause major disruption and respiratory health problems in the affected areas for at least many days, if not months, over areas considerably more extensive than the current Red Zone. In contrast to Plinian or sub-Plinian 1 eruptions, the recovery phase would likely be over months, rather than years.

All explosive eruptions can be associated with episodes of continuous ash emission, but solitary ash emission eruptions can also probably last for months, whilst the main eruption phase is quite short-lived.

5.5. Evacuation decision making

The eruption of Mount Pinatubo involved the hasty evacuation of tens of thousands of people who would have been killed in the numerous and large pyroclastic flows if they had delayed beyond a few more hours. This rapid flight of so many people is in contrast to the advanced warning anticipated at the closely monitored Vesuvius[16]. The decision on when to evacuate is a fraught one which has to be taken by emergency officials and agreed by politicians, based on the advice of a technical committee of volcanologists who are interpreting the monitoring data being collected on the state of the volcano. The uncertainties already described should be at the forefront of the decision-making process. Few experts (or politicians) have experience of evacuating large populations, which is an important reason why risk tools to support such decision making are needed.

A major explosive eruption with a high probability of occurrence should, all things being equal, have a greater influence on the decision to evacuate the population at risk than a low probability. A procedure of progressive updating of the probability outputs of the event tree during the state of unrest would lend itself to being incorporated into an evacuation decision model of some kind, but the rules for doing this are still not established (Woo, 2008). A lengthy state of unrest would undoubtedly lead to a shift in the behaviour of the population and a disruption of economic activity whilst a threat of an eruption lasts, and these and other unknown influences still mean that an evacuation decision has to be a political judgement based on the best scientific evidence from the monitoring of the volcano and robust risk assessment tools.

Emergency planning in advance of a crisis should employ numerical modelling of the consequences of the above scenarios based on the past eruptions and apply them to the modern urban environment and its lifelines. This would refine the eruption scenarios on which the evacuation decision would be based, to show just how extensive the consequences of inaction could be, as well as defining the areas around the volcano at most risk.

6. Vulnerability and numerical consequence modelling at Vesuvius

One of the main aims of the EXPLORIS project was to develop examples of how the impacts of the primary eruptive hazards in the main emergency planning scenarios, based as they are on past eruptions, could be numerically modelled for modern-day conditions in the circumvesuvian area. The purpose of these models is for risk assessment and for refining the consequences to be expected in a future eruption in a form that can be plotted on geographical information system (GIS) maps. This required the development in EXPLORIS of innovative PDC and tephra modelling, combined with vulnerability functions for the actual buildings and their occupants in the hazard areas around the volcano. Previous published studies have mostly used generic methodologies for hazard assessment and mapping only, and without quantifying vulnerability.[17] This section will not repeat the modelling methods described in the accompanying papers in this volume (Esposti Ongaro et al., this volume; Macedonio et al., 2008-this issue), but will focus on the inputs of relevance to mitigation.

Uniquely, EXPLORIS developed a risk-based approach by using a detailed inventory of the building typologies in the circumvesuvian area, including the vulnerability of their key elements to PDCs, tephra fall and earthquakes. Descriptions of the building stock and population of the circumvesuvian area, and their vulnerabilities to PDCs and tephra fall, have already been published (Spence et al., 2004a,b, 2005a,b). It is noteworthy here that around 70% of people live in apartment blocks, mostly constructed in the post-war period. These are of reinforced frame construction, with reinforced concrete slab roofs and floors. Buildings built before the 20th century, inhabited by 16% of the population, are traditionally more vulnerable and nowadays have pitched tile roofs of timber construction, flat terrace roofs of steel joists covered in concrete, or modern reinforced concrete slabs. Those built in the early 20th century may have had vaulted roofs originally, like the older buildings, which are now replaced by reinforced concrete roofs or tile roofs supported by steel trusses.

The general principle of incorporating building and human vulnerability in risk estimation in EXPLORIS is as follows. A mathematical vulnerability function combining *physical vulnerability* parameters (that define the impact on the building of certain peak intensity values of the hazard parameter) with human vulnerability parameters (that define the probability of human casualties for different levels of physical damage) was developed for use at all the EXPLORIS volcanoes. Different vulnerability curves apply to different types of construction. The vulnerability methodologies for buildings and human occupants in PDCs (Spence et al., 2005a; Zuccaro et al., 2008-this issue) and in tephra falls (Spence et al., 2005b; Zuccaro et al., 2008-this issue) have been described.

6.1. Vulnerability in pyroclastic flows

Pyroclastic flows and surges (PDCs) are high temperature clouds of erupted particles and gases capable of flowing down the slopes of volcanoes at high speeds. They are the most destructive forces in explosive eruptions and have caused the most deaths. At Vesuvius they have ranged from dilute surges (single or repeated pulses lasting only a few minutes) to dense pyroclastic flows lasting over an hour or more and leaving thick deposits. They are formed by partial or total collapse of the eruption column, as in the AD 79 event, and by “boiling over” the crater rim, as in the sub-Plinian 1 eruption of AD 1631. Numerous dilute and transitional surge-pyroclastic flow types of PDC of varying intensity occurred in the AD 79 eruption. The temperatures of the PDCs inferred from their deposits at 5–6 km from the crater have ranged from 250 °C to well over 350 °C, which is above the combustion temperature of most flammable materials. As well as their

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[16] The rapid movement in the face of an impending eruption is summed up by the commemorative plaque the Viceroy of Naples ordered should be attached to the Granatello in Portici after the 1631 eruption as a warning to future generations. The advice ended: *So if you have any sense pay attention to the eloquent advice on this tablet — don't concern yourself with your house or with packing bags — put out to sea*. In the devastating eruption of Rabaul, 1994, in Papua New Guinea, the population of Rabaul (about 15,000 people) rapidly evacuated itself with only a few hours to spare and without waiting for the authorities to declare an evacuation, as the continuous felt earthquakes and ground uplift were reminiscent of the last major eruption in 1937.

[17] Vulnerability. A general definition of vulnerability in natural disasters is the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (Wisner et al., 2004). The literature on volcanic risk management has developed over the years a specific terminology since Fournier d'Albe's paper (1979) first introduced the now well known risk equation:

$$\text{Risk} = \text{hazard}*\text{value}*\text{vulnerability}.$$

In EXPLORIS we use these terms as follows. *Hazard* is the probability of a particular area being affected by the damaging volcanic event (or a specific hazardous action) within a given time period; value is the population of buildings or individuals in the hazard area; and vulnerability is the proportion of the value that is most susceptible, or most likely to be lost, to the hazard. For example, mitigation, or risk reduction, measures could include lowering value in the equation through the timely evacuation of potentially hazardous areas, or by reducing vulnerability by strengthening lifelines, roads and buildings against damage from volcanogenic earthquakes or ash falls.

intense heat, their force against structures in their paths depends upon their density and speed.

EXPLORIS has mostly focused on one type of PDC, namely the dilute, violent PDC of small volume (covering areas less than 10 km^2 with small-thickness deposits), such as the surge that destroyed St Pierre in 1902, and the lateral blast at Mount St Helens, 1980, which are the PDCs most likely to be encountered by emergency planners (Baxter et al., 2005). The more dilute PDCs in the AD 79 eruption would likely be this type as well, such as the first surge to hit Herculaneum, whose intense heat killed instantly hundreds of people sheltering in the caves by the beach, but caused little damage to structures (Mastrolorenzo et al., 2001). Three of these “prototype” PDCs were erupted on three separate occasions from the Soufrière Hills volcano, Montserrat, in 1997, and detailed studies of their impacts on buildings have provided important clues to the vulnerability of urban areas to PDCs in explosive eruptions, as well as updating the classical work by Lacroix at St Pierre[7] (Baxter et al., 2005).

The defining features of the dilute PDC, at least by the time its run-out reaches inhabited areas, are comparatively low dynamic pressure (1–5 kPa), moderate temperatures (250 °C or less), low to moderate density (5–15 kg/m^3) and relatively low velocity (<100 km/h). In this type of PDC total destruction of a built-up area is not inevitable throughout its entire run-out, and developing methods for defining which areas are most at risk and what types of mitigation measures which could be feasible to adopt was a goal of EXPLORIS. Previous PDC modelling of the sub-Plinian reference eruption was two-dimensional and indicated that the PDCs in this eruption were like the prototype when their run-out reached the main conurbations along the coast at 5–7 km from the crater (Dobran et al., 1994; Todesco et al., 2002; Esposti Ongaro et al., 2002). EXPLORIS developed the first three-dimensional model of a PDC at Vesuvius (Neri et al., 2007; Esposti Ongaro et al., this volume) and the first simulations confirmed these findings and also showed how the Mt Somma deflected the PDCs in the sub-Plinian 1 reference eruption over a wide area across the flanks towards the sea. In the actual eruption in 1631, the pyroclastic flows were channelled in valleys and would have been much more destructive than the dilute PDC, as their valley-filling lobes showed thicknesses of 4–5 m along the main flow axis and appear to have been deposited as a single flow unit.

There are three impact states of importance as the dynamic pressure against a building increases: first the glazed openings fail, then the shuttered openings and solid doors, and finally the wall panels (Spence et al., 2007). Temperature and entrained missiles will also add to the risk of glazing failure. Failure of the openings allows the incursion of the hot PDC which will kill or seriously injure the occupants, and ignite fires when the ash comes into contact with furnishings. Multiple failures of openings will also allow more air in to fan the flames. Where the buildings are sheltered, or the windows are protected, the rate of infiltration of the hot gas–particle mixture into the intact envelope of the building will depend upon how normally it is well sealed against the weather (the infiltration rate through the normal ventilation process is specific to the style of building and climate), but the temperature and hot particle concentration will keep rising inside rooms depending upon the duration of the flow of the PDC outside the building and the frequency of arrival of any further pulses of the PDC. Gradually lethal levels of temperature (hyperthermia and burns) and particle concentrations (asphyxia) will be attained with prolonged PDC activity. The temperature flux incorporates the external temperature of the PDC and its duration, combined with the ventilation rate of the building, as the best parameters for predicting casualties in hypothetical occupants in an eruption (Spence et al., 2007; Spence et al., 2008-this issue).

Human casualties will arise amongst those caught outside in the heat and irrespirable atmosphere of the moving current, with any survivors suffering from severe burns to the skin and the respiratory tract (Baxter, 1990). The dynamic force of the PDC could be greater than a strong wind and the blast will knock people over or thrust them against walls; dirt and missiles from the ground become entrained in the current to add to its density and violent impact. Survival outside in a dilute PDC at Vesuvius should be regarded as impossible, unless the individual is in a well-sheltered position at the distal end of the run-out.

For the first time, a human survival curve was used as a vulnerability function for exposure to convective heat from the direct heat of a PDC or the rising temperature as the PDC infiltrates its way into houses which have remained intact against the impacts of the dynamic pressure and any missiles entrained in its flow. In addition to those killed by the incursion of the PDC through one or more openings, the numbers of hypothetical occupants who survive with burns can be estimated, as well as those who die or are injured by heat due to the infiltrating hot gas–particle mixture into the houses that remain intact, depending upon the duration of the flow. The escape times from high-rise buildings on fire can also be modelled to estimate numbers of fire victims.[18]

Boarding and sealing windows against the incursion of a PDC would constitute a mitigation strategy. Hurricane boards placed to cover windows were found to be an unintentionally effective device in the largest PDC event on Montserrat, where evacuated houses avoided fire damage (Baxter et al., 2005). In the Red Zone simple measures such as strong window shutters or plywood boards capable of withstanding 5–10 kPa lateral loading could protect the interior of the house against a dilute PDC and prevent the whole house catching fire. People could also survive in those circumstances inside a building if the duration of the PDC was short (less than 10–20 min) and later make their escape, but this could not be proposed as a safe alternative to evacuation. Multiple fires in unprotected buildings would break out in the area impacted by a PDC and the potential for the spread of these needs to be considered. In some areas, like Portici, high-rise buildings have been erected very close to one another and even ordinary fires have a real potential to trigger new fires in adjacent buildings through thermal radiation and flying embers.[19] This same proximity of buildings could, however, have very important sheltering effects in protecting buildings against a PDC, especially on the sides of those buildings facing away from the crater.

6.2. Vulnerability in tephra falls

Sudden and catastrophic roof collapse is one of the deadliest impacts of large explosive eruptions, as in the AD79 and 1631 events at Vesuvius, the two largest eruptions of the volcano in the last two thousand years. The two severest eruptions in the last two hundred years (1822 and 1906) were both violent Strombolian, and the fallout containing lapilli from lava fountaining in 1906 destroyed roofs and caused buildings to collapse throughout the town of Ottaviano, as described above. Substantial advances have been made on the vulnerability of buildings and their occupants in tephra falls by the EXPLORIS group (Spence et al., 2005b). The mass loading of tephra

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[18] Injury from the effects of convective heat is an almost uniquely volcanic problem which is encountered in PDCs. There are good data on burns caused by fires or the direct contact of the skin with hot objects, as well as the effects of radiant heat, but data are sparse on heat injury and skin burns from contact with intensely hot atmospheres. Examples include the effects in people in air raid shelters in the mass bombing raids of cities in the Second World War and in passengers escaping from burning aircraft on the ground. New survival curves were prepared for EXPLORIS by D. Purser.

[19] Fire spread and super-fires (firestorms and conflagrations) are unlikely to occur unless there is considerable structural damage to reinforced concrete buildings in these densely populated areas accompanied by numerous large individual fires. Further work is needed to model the conditions that can lead to fire-spread in the circumvesuvian area.

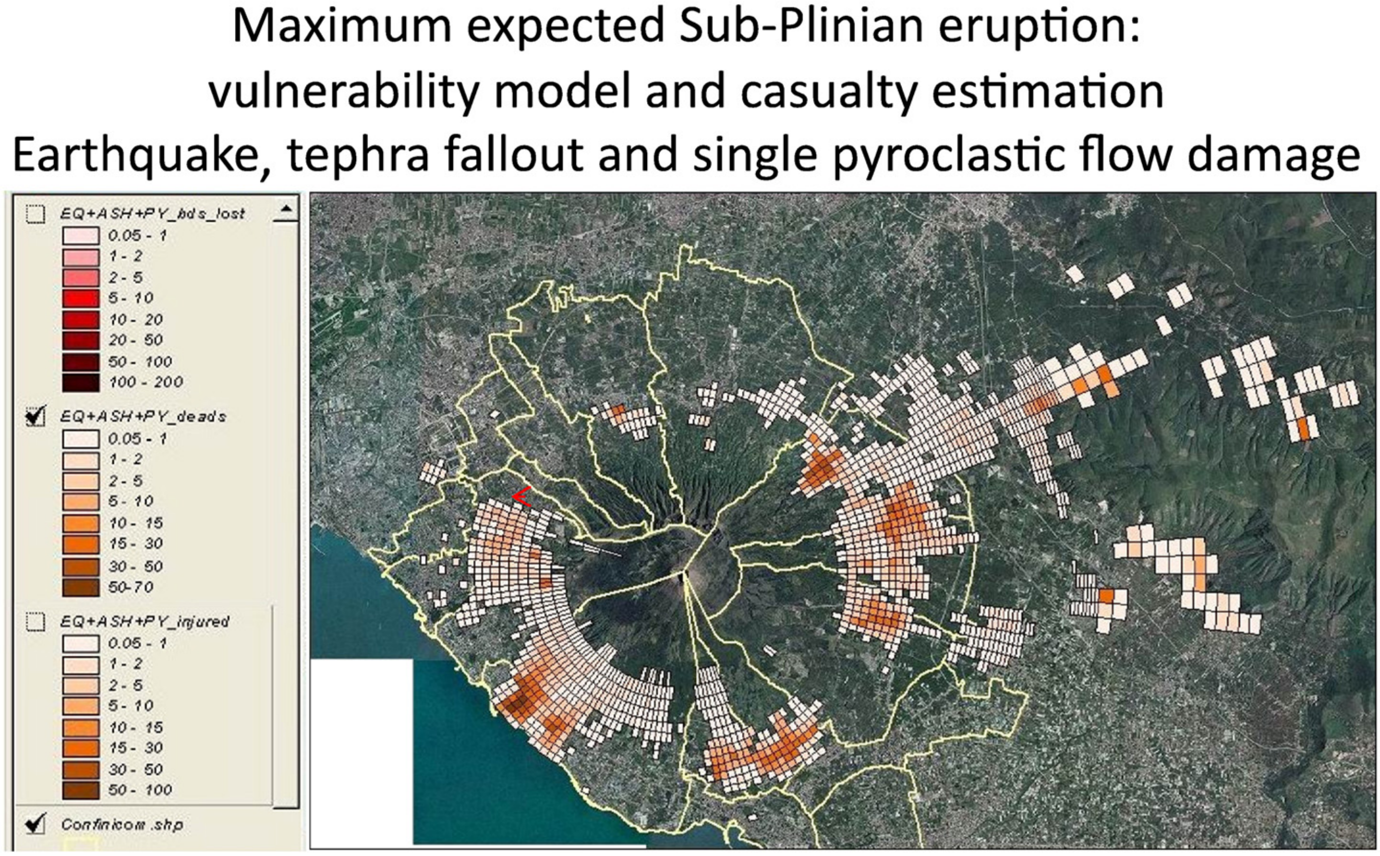

Fig. 7. Simulation of a future sub-Plinian 1 (reference) eruption and the hypothetical consequences to buildings and occupants. The damage is the cumulative result of a sequence of hazard impacts: earthquake, tephra fallout and a single pyroclastic flow. The Red Zone area demarcated by the outermost comuni boundaries is also shown, and it is evident that lethal impacts can potentially occur beyond the Red Zone, an important consideration for mitigation planning (Zuccaro et al., 2008-this issue).

deposits on roofs is crucial in defining the hazard and can be obtained by multiplying the thickness of ash by the bulk density of the deposit. A soaking of ash by heavy rain can slightly increase the bulk density by compacting the mixture. Zuccaro et al. (2008-this issue) have shown that reinforced concrete roofs in the circumvesuvian area are quite resistant to collapse, needing at least 500 kg/m^2 loading to affect the weaker types. But the roofs of some houses with poorer quality roofs, such as tiles on timber, will collapse at loads between 100 and 200 kg/m^2.

Deaths and injuries are caused by direct trauma from being struck by falling structural beams, tiles, etc., and also from entrapment and asphyxiation caused by burial under the infilling ash. Simplified estimates of fatalities and surviving casualties in roof collapses were first based in part on building collapse data in earthquakes and from a photographic survey of building damage in the Pinatubo eruption in 1991, and were applied in an earlier study of volcanic risk for the single story, vernacular housing at Furnas volcano, Azores (Pomonis et al., 1999). Subsequently, the estimates were widened in EXPLORIS to include multi-storey buildings, but field survey data on which to refine further these estimates remains insufficient.

Tephra fall deposits in the larger eruptions of Vesuvius typically comprise highly vesicular pumice and have low bulk density compared to the deposits of wet, dense, phreato-magmatic ash which are common in the fallout sequences of many eruptions (Cioni et al., 2003). It is misleading to think of tephra fall only in terms of ash in a future sub-Plinian 1 eruption: in the 1631 event it contained angular and subangular lapilli, bombs, lithics and scoria clasts, with the largest lithics and clasts being capable of causing head injury and smashing windows, as far as 8 km from the volcano. The main fallout from the 1631 plume was along a narrow east axis with a 10 cm isopach at 30 km from the crater, but a much more extensive area of settled ash occurred which in an eruption today would have serious consequences for transport and lifelines. The extent of the fallout depends upon the prevailing winds at different heights in the troposphere. An even larger area, extending hundreds or thousands of kilometres, could be affected by airborne ash, causing disruption to human activity and transportation.

Buildings with weak roofs could be “hardened” to bring them up a resistance of 5 kPa (500 kg/m^2) by the use of temporary propping using wooden or metal props placed beneath the purlins of tiled roofs. An alternative strategy would be to tell people in vulnerable housing to move to more robust buildings (which would need to be identified in advance) at the start of an eruption.

6.3. Vulnerability in earthquakes

The effects of earthquakes on buildings can be reasonably well estimated using macro-seismic intensity scales. There is some uncertainty, however, about the seismic intensities and their importance in volcanogenic earthquakes, as the literature on the subject is sparse and the contemporary chronicles on the 1631 eruption make little reference to the effects on buildings of the earthquakes during the escalation of activity towards eruption or during the eruption itself. EXPLORIS developed the concept of cumulative damage to buildings from the state of unrest onwards, even though single earthquakes would not be of sufficient intensity to do much damage (Zuccaro et al., 2008-this issue). However, localised building collapses occurring during the state of unrest could impede evacuation by blocking roads, and the modelling of such seismic impacts was shown to provide valuable information to

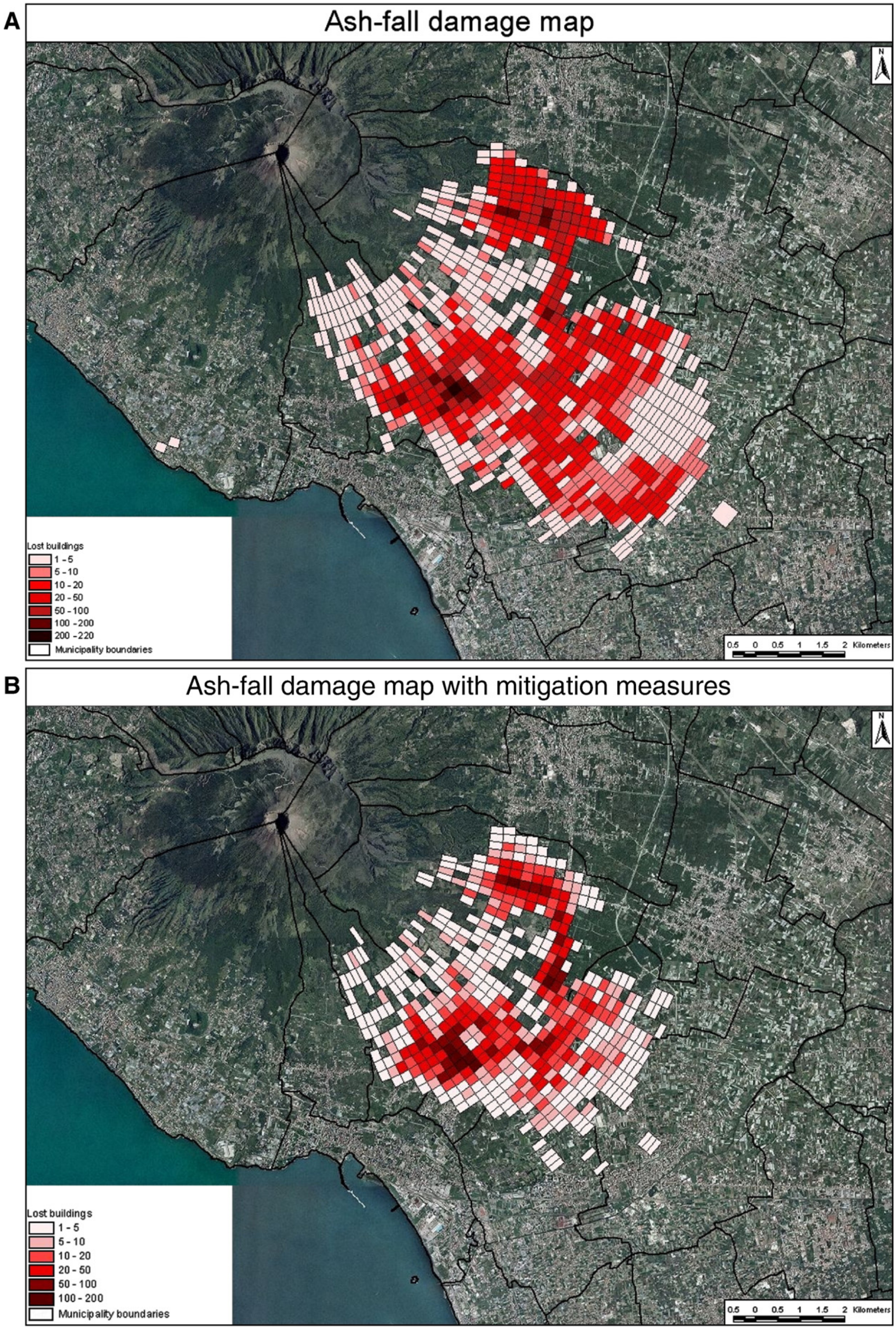

Fig. 8. A and B. First simulation of a violent Strombolian eruption on the scale of 1944 event: without mitigation measures (A) and with mitigation measures (B). See text for explanation and Macedonio et al. (2008-this issue).

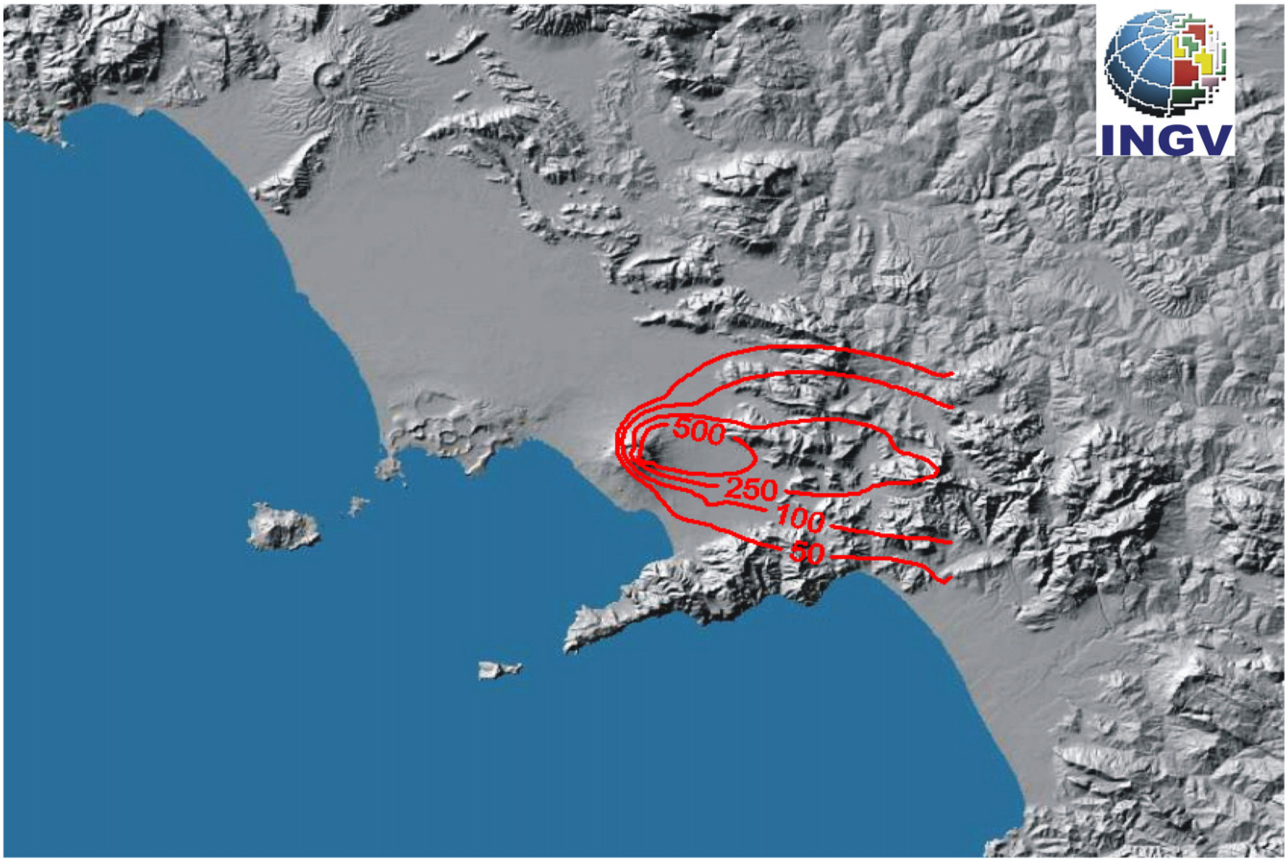

Fig. 9. MESIMEX fallout map (isopachs kg/m^2) used in evacuation planning during the state of unrest: forecasting the area of tephra fallout from a threatened sub-Plinian eruption to direct the evacuation routes taken next day away from this area (Macedonio et al., 2006).

the Civil Protection in the Mesimex exercise in October 2006, which simulated a week of escalating unrest that culminated in an eruption.

6.4. Modelling the impact of a sequence of volcanic hazards

Any actual eruption sequence may subject an individual building close enough to the volcano to a series of events potentially causing damage: one or more earthquakes, continuous tephra fall and a series of PDCs. The state of the building at any point in time during and after the eruption, and the hypothetical effects on its inhabitants, depends not only on the vulnerability of the building and its inhabitants to each separate hazard, but also to the lasting effects of those which have preceded it. A simplistic approach is to ignore these interactions and treat vulnerability as if it is not affected by the preceding hazards. Of course, buildings which have been destroyed cannot be destroyed (or occupants killed) a second time, but a simple joint probability approach that estimates survival after multiple events as the product of the probabilities of survival of each separate event will avoid such double counting. However, there is little doubt that, for example, a succession of moderate earthquakes will reduce the resistance of many buildings to a PDC.

Thus Zuccaro et al. (2008-this issue) have developed for Vesuvius a dynamic cumulative damage model for the resistance of buildings impacted by the sequential forces of the three phenomena combined; this appears to us to lead to the most realistic conservative scenario in a future sub-Plinian 1 eruption. Up to a certain limit of tephra deposit on a roof, the resistance of many buildings to lateral pressure from the PDC is increased, whilst the seismic resistance is lowered. Most vulnerable to the effect of ash loading and a strong earthquake are the top storeys of reinforced concrete buildings with large roofs, but tall reinforced concrete and masonry buildings with rigid floors are more resistant to the combination of the three hazards.

7. Modelling impacts and risk assessment: the scope for mitigation measures

At the start of EXPLORIS, Vesuvius was unique amongst the four main study volcanoes in having a national emergency plan. The plan, first issued in 1995 and undergoing revision as EXPLORIS was ending, is hazard based. The Red Zone area around Vesuvius is based on the run-out limits of PDCs (based on the 1631 PDCs extension and later modified to take into account the Comuni boundaries); the Yellow Zone for tephra fallout; and the Blue Zone where flooding and lahar formation might be expected. Evacuation from the Red Zone, the most dangerous area, would safeguard the lives of 500,000 people. Numerical simulation modelling, as advanced in EXPLORIS, should help to further delineate these zones for the different scenarios and those for violent Strombolian eruptions in the future.[20]

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[20] We do not regard a given numerical simulation model as a close depiction of a future eruptive event, but the basis for understanding a potential range of behaviour, which needs to be revised as knowledge and computer power grows. Models have both epistemic and stochastic uncertainties. In the MESIMEX exercise an ensemble of four different fallout models, namely HAZMAP, Macedonio et al. (2005), FALL3D (Costa et al., 2006), VOL-CALPUFF (Barsotti et al., 2008) and TEPHRA (Bonadonna et al., 2005) — was used, a technique also applied in weather forecasting (Macedonio et al., 2006). For a full treatment of models as hypotheses, see Oreskes et al. (1994).

The results of numerical simulation modelling of two eruptive scenarios and their impacts in the built-up Vesuvian area will be briefly outlined here as examples of the EXPLORIS tools and as a demonstration of the implications of the vulnerability of buildings and their occupants in influencing the estimated numbers of hypothetical casualties for risk assessment and mitigation purposes. The interested reader is referred to Zuccaro et al. (2008-this issue), for a full description of the methods and outputs. It is important to appreciate that the deaths and injuries are first computed for risk analysis on a hypothetical population which remains in place during the course of an eruption and does not evacuate or adopt any risk reduction measures: we emphasise that this is not what is likely or intended to happen and the numbers are not the expected casualties except in a statistical risk sense. Work on the modelling and mitigation of the consequences of an eruption can proceed even if we do not know how likely it is the event will occur. But constraining the likelihood of each type of eruption can help to prioritise the mitigation measures for emergency planners, and statistically combining probabilities from the event tree with casualty outputs from the models will eventually permit the drawing of risk maps for Vesuvius based on individual and societal risk, as was done for Montserrat (Fig. 3).

7.1. Scenario 1: eruption on the scale of 1631 reference event (Fig. 7)

A scenario chosen for a 1631 reference eruption is one of volcanogenic earthquakes affecting the area during the state of unrest, followed by tephra fallout to the west of the volcano and then a single PDC towards the coast in the main phase (Zuccaro et al., 2008-this issue). The cumulative impact of the seismic energy leads to some building collapses and weakening of the roofs of other buildings in the fallout area, as estimated using a macro-seismic intensity scale. The EXPLORIS three-dimensional PDC model has been used for estimating the direction of the flow and its dynamic pressure and temperature in the built-up area. The tephra load on roofs across the fallout area is derived from the FALL-3D model output (Macedonio et al., 2008-this issue). The consequences of these phenomena in the impacted areas are shown, with the impacted buildings in various states of damage severity in Fig. 7.

The estimated number of dead was 4412 in the Red Zone without any measures to protect the buildings against the incursion of the PDC or collapse of roofs under the weight of tephra (a board to cover the window and a temporary roof support, respectively), compared to 1843 hypothetical deaths if such measures were in place (a reduction of about 60% hypothetical deaths in total). The feasibility of using such measures to protect houses and other buildings needs further evaluation, but the scope for reducing the impacts is clearly substantial.

7.2. Scenario 2: eruption on scale of the 1944 event (Fig. 8A and B)

A scenario for a violent Strombolian eruption according to the 1944 event was modelled using the FALL3D code (Macedonio et al., 2008-this issue) and was based on a 1944-size eruption, using grain-sized data from the 1906 eruption and the available meteorological (wind) data. The map of the damaged buildings is shown (Fig. 8A) for a tephra loading of >100 kg/m^2 and an estimated 2990 deaths was calculated using the vulnerability modelling. This is a much higher death toll than in 1944 (21 deaths) which can be attributed to the much increased density of population around Vesuvius since then, but these numbers can be reduced to 1892 (Fig. 8B) by a temporary strengthening of the weaker roofs, e.g., by the use of portable props. The same risk reduction would be achieved by simply advising the people in the most vulnerable houses to move to designated buildings with stronger roofs when the eruption starts. These measures clearly provide a major and worthwhile reduction of the potential impact.

7.3. Scenario 3: evacuation called and real time, worst-case modelling (based on 1631 reference eruption) used to forecast sector of main tephra fallout (Fig. 9)

The MESIMEX exercise in October 2006 followed soon after the final meeting of the EXPLORIS project in Naples in May of that year. It was gratifying for the EXPLORIS team to see the modelling tools developed in EXPLORIS being applied, with the outputs of four different fallout models being combined and run in real time using the prevailing meteorological data[20] to guide the Civil Protection in their evacuation exercise of the Red and Yellow Zones (Macedonio et al., 2006). The forecast for the plume-track was for the next day, when the eruption appeared likely, and it showed the importance of evacuating in a direction away from the east-south-east sector where the heaviest fallout was expected (Fig. 9).

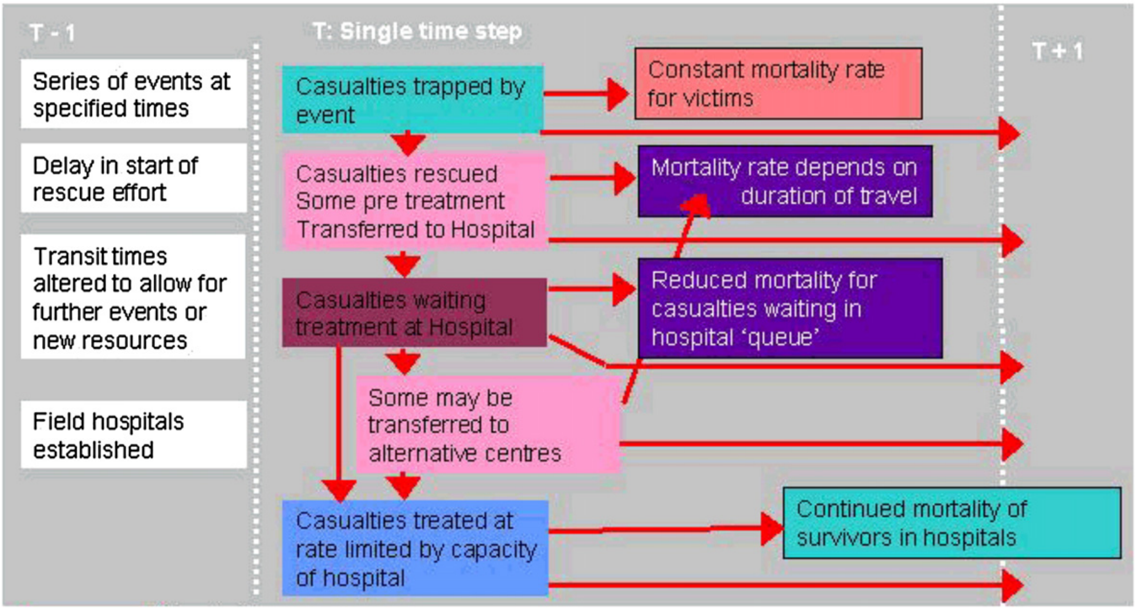

Fig. 10. Schematic outline of the casualty time-step model (Spence et al., this issue). The outline shows the main factors incorporated in the model and are capable of being analysed for their contribution to mortality in people injured in a pyroclastic flow; it is a test of search and rescue capability, pre-hospital casualty management and hospital inpatient care (see text).

For this type of model forecasting to become a practical tool for emergency planning and mitigation the outputs in terms of damaged and destroyed houses, and hypothetical deaths (or injuries), must eventually be presented in ranges and probabilities. A single number of deaths, for example, for a given scenario is an inadequate guide to the impacts of an expected eruption, where there is uncertainly over its magnitude, power and duration, and a whole range of hypothetical casualties that might arise. As well as ranges and distributions for inputs to models, stochastic uncertainty can be incorporated by techniques like the widely used Monte Carlo simulation to provide outputs, such as the estimated numbers of deaths or injuries, in the form of probability distributions (Woo, 1999). The full range of impacts of the expected scenarios and their probabilities is a requirement of a risk-based approach which prevents a false expectation of large numbers and doomsday scenarios, when what might actually happen is on a much smaller scale, for example, and is readily capable of being planned for.

8. Other mitigation measures

8.1. Search and rescue planning

Hazard-based planning for an eruption will be reliant on early evacuation, in theory, as a precautionary measure, and an assumption of this approach is that the population will be willing and able to move when directed. This work has already shown that such an approach is not without its own risks and uncertainties, and is not a panacea to the problems of decision making, as we have described above. There are unfortunately well-founded reasons for planning for a disaster in which people are in place when an eruption begins. For example, the activity might escalate so fast that there is not enough time to evacuate everybody in an organised and timely fashion; people may resist evacuation, as in Tungurahua, Ecuador; or people will return to their homes in danger zones despite official warnings during protracted periods of evacuation (e.g., Montserrat; Loughlin et al., 2002). How relevant these examples are to Vesuvius is not known. Search and rescue plans would need to be considered for large numbers of burns casualties, and for people trapped under roof collapses, as described above. Such planning would be entirely novel to the emergency services, but the knowledge is now available to support the development of such plans.

A casualty search and rescue simulation model was devised in EXPLORIS and used to study the main determining factors that governed the survival of burns victims in a mass rescue after a hypothetical eruption of Soufrière, Guadeloupe[21] (Spence et al., 2008-this issue). The casualty model could also be applied to Vesuvius. Fawcett and Oliveira (2000) originally described the principles of the model for an earthquake scenario, but the method is readily applicable to emergency planning at volcanoes. The main inputs are summarised in Fig. 10 and include the numbers of casualties, survival times with and without treatment, the accessibility and capacity to triage and treat at the available medical centres, and the mode and availability of land, sea and air rescue. The model can be run on most personal computers and is a time stepping (updated every 2 h), zone-based programme on the movement and treatment of casualties, with casualties and treatment facilities located in each zone connected to other zones by defined travel times. These inputs can be varied in the model to study the main influences that govern survival, such as the availability and emergency capacity of standing and field hospitals, access to tertiary referral centres, numbers of rescue teams and transport, e.g., helicopters, and the optimum time for rescue to begin.[22]

8.2. Land use planning

We have explored in this paper the use of an evidence-based approach towards advancing mitigation at Vesuvius and provided preliminary examples of its application to forecasts and warnings, disaster preparedness, engineering measures for reducing building vulnerability and real-time eruption modelling to guide decision making as the crisis unfolds. One of the main innovations in EXPLORIS is the use of probabilistic reasoning in crisis management to measure and analyse information for decision making. On a different time-scale than an emergency is land-use planning and the fundamental vulnerability presented by over-development around Vesuvius in the areas of greatest volcanic hazard. Orsi et al. (2003) have summarised this problem, that historically mankind's plans have not taken into consideration that the catastrophic events at Vesuvius have a longer recurrence time than a human life. Every day pressures on development and economic activity tend to push such hazards out of sight when the common perception is that there is a low probability of a reawakening of the “sleeping giant” in an individual's lifetime (Barberi et al., 2008). This is a general problem at all explosive volcanoes, even when reliable hazard maps showing the extent of the areas at potential risk are available.[22] In this realm and with its intractable uncertainty, it is the burden of prudence and not the burden of evidence (proof) that should guide authorities (a form of the precautionary principle), instead of the use of probabilities.[23]

9. Conclusions

Vesuvius has a unique status amongst the earth's volcanoes as its frequent explosive and effusive activity over the centuries has attracted more scientific interest and studies than any other. The present state of repose since 1944 has allowed a massive growth of population around its flanks, which now presents scientists and decision makers with a major challenge, as the size or timing of the next eruption cannot be forecast from the precursors once a new state of unrest begins.

An evidence-based and multi-disciplinary approach to decision making in a future crisis has been described as the basis for the development of mitigation strategies. It adopts formal probabilistic reasoning and statistical decision analysis in an analytic approach which enumerates and quantifies all the processes and effects of the eruptive hazards of the volcano that determine risk, whilst influenced by statistical models of reasoning under uncertainty.

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[21] The treatment and management of burns injuries is a specialised area of medicine and is beyond the scope of this paper. Evidence on survival times of burns victims in pyroclastic flows is sparse. Limited information is available from eruptions at Unzen (1991) and Merapi (1994). Severe, full thickness burns affecting over 40% total body surface area (TBSA) should be regarded as not survivable in a mass casualty event, especially as the victim is likely to have suffered airway burns and severe lung injury from the inhalation of hot ash as well. Treatment is most likely to be life-saving in victims with TBSA 20–40%. The health sector would need to plan at a national level for a future eruption of Vesuvius, as even a modest number of survivors with burns would be beyond the capacity of local hospitals to treat in their intensive care facilities.

[22] The production of hazard maps at volcanoes is a growth industry amongst scientists. Although volcanologists are very aware of the vital importance of their work, the response of authorities, even in technologically advanced countries, is still quite variable. The global picture is far from encouraging. We regard hazard mapping as a key step in the development of risk maps, which then can serve to show the consequences of inaction in greater relief. The subject is too young to yet know if risk modelling will have a greater impact on land-use planning decisions.

[23] An example of a cross-generation hazard of this type is the worst natural disaster risk faced by the United Kingdom — a major North Sea surge and coastal flood along the east coast of England, which occurs around once every hundred years or more. The last one in 1953 was the worst natural disaster to strike Britain in the last century and left 300 dead (over 1500 died as the surge swept across the English Channel into Holland). In 1968, the eminent physicist and cosmologist, Sir Hermann Bondi (1919–2005) was asked to advise the government on the construction of a great barrier across the River Thames to protect London against future flood risk, which he convincingly justified on the basis of the precautionary principle rather than on any risk-benefit analysis based on probabilities. His justification hinged on the grounds of the enormity of the potential disaster and the availability of reasonable measures to prevent it (Baxter, 2005). The Thames Barrier was opened in 1982.

EXPLORIS has incorporated several key advances that are unique to Vesuvius for resolving the spatio-temporal impacts of a future explosive eruption and which can be integrated in risk assessment, mitigation and emergency planning. These are the detailed studies on its past eruptions and their products, an event tree and its emergency scenarios, advanced deterministic and probabilistic numerical modelling of PDCs and tephra fallout, a comprehensive vulnerability database on the built environment in the circumvesuvian area, and the mapping of modelled impacts on the buildings and infrastructure, with their consequent hypothetical casualties. The model outputs can be also provided in real time to assist decision making in an actual crisis.

This pioneering work has shown the feasibility and uses of developing a risk-based mitigation strategy at Vesuvius and the need for multi-disciplinary methods that incorporate model and stochastic uncertainty. Operating guidelines and rigorous substantiation tools need to be an integral part of its future application at Vesuvius. A large amount of work will be needed to refine these models and their probabilistic inputs and outputs, including risk maps, but it is evident from the examples of our research how the tools can be used for mitigation and emergency planning purposes. The advances over hazard maps, or previous risk maps, include the incorporation of the totality of knowledge of Vesuvius and its inhabitants, and the most recent information on the inner state of the volcano.

To be able to incorporate all of these spatio-temporal factors into a probabilistic framework, which incorporates scientific uncertainty in a way that can inform decision making, represents a major advance on present methods of volcanic disaster management and provides a logically consistent foundation for the development of emergency planning and mitigation at Vesuvius.

Acknowledgements

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