Climate forcing of volcano lateral collapse: evidence from Mount Etna, Sicily

BY K. R. DEEMING1,2, B. MCGUIRE2,*, AND P. HARROP3

1School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, UK
2Aon Benfield UCL Hazard Research Centre, University College London, Gower Street, London WC1E 6BT, UK
3Tessella plc, 26 The Quadrant, Abingdon Science Park, Abingdon, Oxfordshire OX14 3YS, UK

In this study, we present evidence for early Holocene climatic conditions providing circumstances favourable to major lateral collapse at Mount Etna, Sicily. The volcano’s most notable topographic feature is the Valle del Bove, a 5 × 8 km cliff-bounded amphitheatre excavated from the eastern flank of the volcano. Its origin due to prehistoric lateral collapse is corroborated by stürtzstrom deposits adjacent to the amphitheatre’s downslope outlet, but the age, nature and cause of amphitheatre excavation remain matters for debate. Cosmogenic 3He exposure ages determined for eroded surfaces within an abandoned watershed flanking the Valle del Bove support channel abandonment ca 7.5 kaBP, as a consequence of its excavation in a catastrophic collapse event. Watershed development was largely dictated by pluvial conditions during the early Holocene, which are also implicated in slope failure. A viable trigger is magma emplacement into rift zones in the eastern flank of a water-saturated edifice, leading to the development of excess pore pressures, consequent reduction in sliding resistance, detachment and collapse. Such a mechanism is presented as one potential driver of future lateral collapse in volcanic landscapes forecast to experience increased precipitation or melting of ice cover as a consequence of anthropogenic warming.

Keywords: Mount Etna; lateral collapse; stürtzstrom; climate forcing; Holocene; cosmogenic exposure dating

1. Introduction

The start of the Holocene, 10 kaBP, marks a dramatic transformation in the Earth system and its component parts—the atmosphere, hydrosphere and geosphere (e.g. Roberts 1998; Walker & Bell 2004). Rapid planetary warming promoted a major reorganization of the global water budget as continental ice sheets melted to replenish the depleted ocean volumes. Contemporaneously,

*Author for correspondence (w.mcguire@ucl.ac.uk).

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atmospheric circulation patterns changed to accommodate broadly warmer, wetter conditions, leading to modification of major wind trends and a re-arrangement of climatic zones. A volcanic response to post-glacial environmental change is recognized (e.g. Zielinski et al. 1997), attributable to ice unloading in glaciated volcanic terrains (e.g. Jull & McKenzie 1996; Licciardi et al. 2007; Carrivick et al. 2009), to ocean loading associated with global sea-level rise (McGuire et al. 1997a) and to increased precipitation arising from warmer, wetter conditions (Capra 2006).

Here we present evidence, from Mount Etna in Sicily, for Holocene environmental change driving catastrophic failure of the volcano’s eastern flank. Catastrophic lateral collapse and ensuing stürztstrom (rapidly emplaced rock avalanche) formation is now recognized as marking a common, transitory stage in the life cycles of many long-lived volcanoes (Ui 1983; Siebert 1984; Holcomb & Searle 1991; McGuire 1996, 2006) ranging from strato-volcanoes to basaltic shields; in some cases such behaviour being displayed many times in the history of a single, long-lived volcano. Lateral collapse is a natural consequence of growing gravitational instability, as an edifice increases in mass and volume. Instability is often compounded by steep slopes, a mechanically weak structure and sometimes by high precipitation rates associated with a topographically elevated location. A destabilized edifice can be induced to collapse in one of a number of ways: notably increased ground accelerations associated with accompanying earthquakes, elevated mechanical stresses owing to gravitational loading or dyke injection, and pore-water pressurization, the latter two associated with the emplacement of fresh magma. Lateral collapse velocities typically exceed 40 m s\(^{-1}\), and may reach more than 100 m s\(^{-1}\) (Ward & Day 2001, 2003), with collapse volumes ranging from less than 1 km\(^3\) to more than 10 km\(^3\) at many continental and subduction zone volcanoes, and to 1000 km\(^3\) or more at the great basalt shields of Hawaii (McGuire 1996). Lateral collapse events are ubiquitous, with approaching 500 recognized at more than 300 volcanoes, and a time-averaged rate of close to 20 collapses a century over the last 500 years (R. Lowe 2007, unpublished data). In relation to the Holocene climate, the lateral failure of volcanoes may be promoted by increased availability of water as glaciated volcanoes lose their ice caps and precipitation levels rise as the world becomes warmer and wetter (Capra 2006), thereby favouring the development of increased pore-fluid pressures in edifices.

2. Volcano lateral collapse at Mount Etna

With a current height of 3340 m, and occupying an area of 1250 km\(^2\), Mount Etna is arguably the largest volcano located on continental crust. It has grown and developed over a period of 580 ka (Branca et al. 2004) on the east coast of Sicily, upon a seaward-dipping substrate of sediments and basement rocks. Etna is a polygenetic volcano constructed from several centres of activity that show a broad age progression (oldest to youngest) from east to west (figure 1). The earliest central-vent activity was concentrated in the vicinity of the Valle del Bove, leading to the formation of the Calanna centre, and later the Trifoglietto and associated centres further to the west. At around 80 ka BP (Gillot et al. 1994; Branca et al. 2004), activity switched to the northwest,
building the large central-vent strato-volcano known as the Ellittico. Following caldera collapse around 15 kaBP, activity became focused at the current centre of activity (Mongibello; see summit craters in figure 1), which is located within the Ellittico caldera. Historical activity is marked by eruptions from the summit vents and also by effusive eruptions lower down on the flanks that are fed by laterally propagating dykes. These follow preferential routes that define rift zones, the most important of which trend north and south from the summit (McGuire & Pullen 1989).

The volcano’s most notable topographic feature is the Valle del Bove (figure 1), a large (5 × 8 km) amphitheatre cut into the eastern flank, bounded by cliffs up to 1 km high and opening towards the Ionian Sea. More than 100 exposed dykes in the cliff walls mark the positions of east-northeast (ENE) and southeast (SE) trending defunct rift zones (McGuire & Pullen 1989), whose intersection is bisected by the long axis of the collapse amphitheatre (figure 1). While an origin owing to prehistoric lateral collapse is now corroborated by subaerial and offshore stürztstrom deposits adjacent to the amphitheatre’s open, downslope, outlet (e.g. Calvari et al. 1998; Del Negro & Napoli 2002; Pareschi et al. 2006), important aspects of the Valle del Bove have remained a matter of debate; most notably, the
nature and cause of its excavation, and its age. Models for its origin are diverse and include marine (Lyell 1849) or fluvial (Lyell 1858) erosion, glacial excavation (Vagliasindi 1949), gravity-driven progressive landsliding (Guest et al. 1984), edifice spreading (Borgia et al. 1992), eruption-triggered catastrophic failure (Kieffer 1977; McGuire 1982), and tectonically or magmatically driven failure following formation of the Ellittico caldera (Calvari et al. 2004).

Age estimates for the collapse are also disparate, ranging from ca 5 to 25 ka BP (Kieffer 1970; McGuire 1982; Guest et al. 1984; Chester et al. 1987; Calvari & Groppelli 1996). Accumulating evidence, however, increasingly supports a Holocene age for Valle del Bove formation. Calvari et al. (1998) allocate a 14C age of 8.4 ka BP (corresponding to an intercept of radiocarbon age with calibration curve at 6400 BC) to a palaeosol on top of a debris flow unit immediately above a stürztstrom component within a sequence of debris flows (the Milo Lahars; ML in figure 1) exposed immediately east of the Valle del Bove’s seaward outlet. The authors link the stürztstrom to an initial excavation phase of the Valle del Bove that they propose, on a petrological basis, involved the northern part of the Valle del Bove only and was linked to lateral collapse of the Ellittico eruptive centre. They recognize, however, that this interpretation may be erroneous; an alternative explanation being that stūrtzstrom debris derived from the southern flank of the Valle del Bove is not encountered within the exposed fraction of the Milo Lahar sequence. More recently, Calvari et al. (2004) reiterate the link with the Ellittico centre, proposing the formation of an initial Valle del Bove owing to lateral collapse ‘about 10 000 years ago’ of the prehistoric Ellittico eruptive centre, with subsequent enlargement occurring through episodes of minor collapse. A date of 5.340 ± 0.060 ka BP (Coltelli et al. 2000) for an overlying scoria layer provides an upper limit to the age of the Milo Lahar sequence, which is reasonably explained in terms of the downslope reworking of stūrtzstrom debris in the millennia immediately following Valle del Bove formation (Calvari et al. 2004).

Additional support for an early- to mid-Holocene collapse age comes from the Chiancone (Ch in figure 1), a ca 300 m thick (Ferrara 1975) fanglomerate sequence, the exposed units of which are primarily fluviatile, with secondary debris flow and pyroclastic units (Calvari & Groppelli 1996). The Chiancone crops out immediately east of the Milo Lahars and takes the form of a gently sloping topographic fan, with an area of 40 km², extending out into the Ionian Sea. The Chiancone, and its submarine extent, has a volume of at least 14 km³ (Del Negro & Napoli 2002) and is accepted (e.g. Rittmann 1973; McGuire 1982; Guest et al. 1984; Calvari & Groppelli 1996; Del Negro & Napoli 2002; Pareschi et al. 2006) as representing reworked volcanic products from the Valle del Bove in its upper portion and—in its deeper, unexposed levels—an earlier lateral collapse event, or events, for which the topographic evidence is now lost. Calvari & Groppelli (1996) report a 14C age of 7.590 ± 0.130 ka BP from a palaeosol about 1 m above a debris flow unit at the base of the exposed portion of the Chiancone. This they propose provides a minimum age for an ‘important eruptive event’ that may have been associated with the emplacement of the underlying debris flow unit. The age is comparable to that of the Milo Lahars and could plausibly reflect the timing of redeposition downslope of stūrtzstrom material derived from lateral collapse. The approximately 30 m of mainly fluviatile material deposited above this basal (to the exposed part of the Chiancone) debris flow unit is
ascribed by Calvari & Groppelli (1996) to post-formation enlargement of the Valle del Bove and continued downslope reworking in episodes of high-energy fluvial transport.

3. Lateral collapse and watershed abandonment at Mount Etna

While effusive activity from the youngest, major eruptive centres (Ellittico 80–15 ka and Mongibello 15 ka to present day; Branca et al. 2004) has extensively remoulded and resurfaced the topography of much of the volcano, the outer flanks of the Valle del Bove preserve prominent, deeply incised valleys (figures 2 and 3) reminiscent of the parasol drainage pattern distinctive of volcanoes in tropical environments with high rainfall and surface runoff. The valleys are the downslope remnants (figure 3a) of a more vertically extensive channel system that originally drained elevated topography in that part of the volcano now occupied by the Valle del Bove, but which is now truncated by its enclosing cliff wall. The channel system, which is inactive today, may have been initiated by meltwater associated with the disintegration of late Pleistocene snow and ice fields that capped the Ellittico eruptive centre at the time of the Last Glacial Maximum (Neri 2002). The watershed will have been reduced in size following caldera collapse of the Ellittico caldera ca 15 ka BP, although it may have benefited from snow melt and runoff associated with a caldera lake or lakes (Del Carlo et al. 2004). Its current form, however, is interpreted primarily as a reflection of erosive drainage events associated with the anomalously (for Etna) warmer and wetter conditions that prevailed in Sicily during the early Holocene (Frisia et al. 2006). Evidence for highly energetic fluvial flow is provided by the presence of palaeo-waterfalls up to 75 m high (figure 3b), large (>1 m) rounded and polished in-channel boulders and erosive scour features at elevations of up to 3 m above current channel floors.

Here, we seek to better constrain the timing and nature of the Valle del Bove lateral collapse using cosmogenic 3He exposure dating to determine maximum fluvial erosion-surface ages within the drainage channels. These we interpret as providing a best-estimate, minimum age for channel system abandonment owing to destruction of its watershed by the excavation of the Valle del Bove; the assumption being that this event effectively removed the channel catchments resulting in a cessation of erosive fluvial episodes.

4. Cosmogenic 3He exposure dating of channel abandonment at Mount Etna

Through determining the duration of surface exposure to extraterrestrial cosmic rays, cosmogenic exposure dating (Kurz 1986) allows the ages to be established of processes that expose, exhume or extrude rock. High-energy cosmic rays bombard the Earth and, after attenuation by the geomagnetic field and atmosphere, and shielding by topography, generate cosmogenic nuclides in surface-exposed rocks. One of the more common cosmogenic nuclides generated in situ by this bombardment is 3He. This is a stable isotope that is retained in the crystal lattices of the minerals garnet, hornblende, olivine and clinopyroxene, the latter...
two of which are common constituents of Etnean volcanic products. As $^3$He is a particularly rare, naturally occurring isotope on the Earth, small amounts produced by cosmic ray bombardment of the Earth’s surface leave a strong signature in surface-exposed minerals.

Cosmogenic exposure dating, based upon in situ-generated nuclides, is an established tool used for providing quantitative estimates of the timing and rate of a range of geomorphological and geological processes including uplift, resurfacing, burial, faulting, fluvial erosion, marine action, glacial retreat and rapid mass movement (see Cockburn & Summerfield 2004 and references therein for a comprehensive review of geomorphological applications). On volcanoes, the method is increasingly widely used to date lava flows and cinder cones, to build and constrain eruptive chronologies and to shed light on processes and mechanisms such as rift-zone reorganization (e.g. Kurz et al. 1990; Poreda & Cerling 1992; Cerling & Craig 1994; Foeken et al. 2009). Cosmogenic exposure dating has also been successfully used to constrain the timing of lateral collapses.

Figure 2. Digital elevation model of the Valle del Bove (Tarquini et al. 2007) showing the prominent, deeply incised, truncated valleys on the outer northern and southern flanks of the Valle del Bove. AR, Acqua Rocca; AT, Acqua del Turco. Locations of samples from which cosmogenic $^3$He exposure dates were obtained are also shown (see table 1 for additional information including altitude, longitude, latitude and nature of the sampled exposed surface). Samples other than those indicated were all obtained from Acqua Rocca. The location of the baseline test sample (ET00KD1) at Due Monti (latitude 37.47.04.80; longitude 15.03.06.02) is not shown. Scale bar, 1 km.
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Figure 3. The truncated Valle degli Zappini incised into the outer southern flank of the Valle del Bove. (a) The Acqua Rocca palaeo-waterfall is obvious in the centre of the image. (b) Close-up view of the 75 m high Acqua Rocca palaeo-waterfall.

at Piton de la Fournaise (Réunion Island; Staudacher & Allègre 1993), Tenerife (Harrop 1996) and Fogo (Cape Verde Islands; Foeken et al. 2009), through dating of appropriate lava flows and faults that indirectly bracket the timing of the collapse.

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Palaeo-fluvial features have also been targeted in cosmogenic exposure dating campaigns (e.g. Cerling 1990; Cerling et al. 1994), and examples of the application of the technique to dating bedrock in fluvial channels can be found in Pratt et al. (2002) and Schaller et al. (2005). Most relevant to this study, Seidl et al. (1997) conducted a cosmogenic exposure dating campaign along the length of a river valley on Kauai island (Hawaii), sampling bedrock, boulders, channel sides and a waterfall lip for multiple cosmogenic nuclide analysis, with the aim of elucidating valley evolution.

In this study at Mount Etna, sample sites (figure 2) were selected according to the availability of exposed rock containing a high percentage of clinopyroxene phenocrysts, and at elevated locations above channel floors to minimize the chances of (i) previous burial by tephra fall, reworked tephra or sediment and (ii) erosive influences from any post-truncation flow associated with localized heavy rainfall. Samples for analysis were collected from three truncated channels that showed good preservation of bedrock and other exposed surfaces and were least affected by rock falls (table 1): the Acqua Rocca and Acqua del Turco valleys on the southern flank of the Valle del Bove, and an unnamed truncated valley on its northern flank in the vicinity of the Serra delle Concazze.

In total, 28 samples were collected for the purposes of cosmic ray exposure dating yielding 16 ages (table 1; figure 2). The remaining 12 samples were excluded from the analysis because of insufficient, suitable, phenocrysts material.

In the Acqua Rocca, a 75 m high palaeo-waterfall located in the Vallone Acqua Rocca degli Zappini, 18 samples were taken from a variety of sites, including in-channel boulders and bedrock surfaces, 11 of which yielded cosmogenic $^3$He ages. Exposure in the neighbouring Acqua del Turco channel and tributaries, immediately to the east, was significantly poorer. As a result, four samples were collected, one from an in-channel boulder and the others from exposed bedrock. Just two of the samples provided ages. Three exposed bedrock samples were taken in the unnamed north flank valley, two in the vicinity of a palaeo-waterfall, both of which yielded an age. In order to validate the method, three samples (two from in-channel boulders and one from exposed bedrock) were also collected from the actively eroding Due Monti valley on the north flank, which is known to act still as a conduit for rainfall runoff and snow-melt and would consequently be expected to yield a zero age. Only one sample provided an age.

Cosmogenic $^3$He was extracted from clinopyroxene crystals liberated from bulk rock samples. Crushing of samples released phenocrysts of clinopyroxene from the matrix, which were concentrated and separated using a combination of magnetic and heavy liquid separation techniques, then thoroughly cleaned. Gas extracted from the separated phenocrysts was purified before analysis in a MAP 215 90° sector noble gas mass spectrometer. Comparison with a well characterized calibration gas (air enriched with artificially mixed helium) yielded accurate helium isotope ratios and abundances required for exposure age calculation. For individual samples, the exposure age ($t$) is determined on the basis of the cosmogenic $^3$He abundance ($N$) and a given production rate ($P$) of stable cosmogenic nuclides, calculated from $t = N/P$. The production rate is sensitive to variation in altitude, latitude, sample depth, past geomagnetic field variations and topographic shielding, for all of which subsequent corrections are applied. Deeming (2002) provides a detailed discussion of sampling strategies, preparation methods, analytical techniques, the correction process and age determination.
Table 1. Surface exposure ages determined from abandoned drainage channels on the northern and southern flanks of the Valle del Bove. Ages designated as ‘zero’ are shown together with the actual determined dates (in parentheses). All errors are to 1 s.d. Interpretations of younger ages are tentative and based upon local (to sample) conditions.

<table>
<thead>
<tr>
<th>sample</th>
<th>location</th>
<th>latitude</th>
<th>longitude</th>
<th>altitude (m)</th>
<th>exposed surface</th>
<th>exposure age (yr BP) ±</th>
<th>interpretation of age yielded</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET00KD2021</td>
<td>Acqua Rocca</td>
<td>37/42/25.75</td>
<td>12/02/49.49</td>
<td>1500</td>
<td>bedrock; waterfall top</td>
<td>25 966 ± 6149</td>
<td>analytical error</td>
</tr>
<tr>
<td>ET00KD22</td>
<td>unnamed valley: north flank</td>
<td>37/45/36.38</td>
<td>15/03/05.96</td>
<td>1925</td>
<td>bedrock; waterfall base</td>
<td>7419 ± 1256</td>
<td>minimum channel abandonment age for northern flank valley</td>
</tr>
<tr>
<td>ET00KD7</td>
<td>Acqua Rocca</td>
<td>37/42/25.75</td>
<td>15/02/49.49</td>
<td>1400</td>
<td>bedrock; waterfall base</td>
<td>7222 ± 949</td>
<td>minimum channel abandonment age for Acqua Rocca</td>
</tr>
<tr>
<td>ET00KD15</td>
<td>Acqua Turco</td>
<td>37/42/32.23</td>
<td>15/03/16.05</td>
<td>1475</td>
<td>elevated chute</td>
<td>5858 ± 1031</td>
<td>post-abandonment burial and re-exposure</td>
</tr>
<tr>
<td>ET99KD21</td>
<td>Acqua Rocca</td>
<td>37/42/25.75</td>
<td>15/02/49.49</td>
<td>1400</td>
<td>bedrock; waterfall base</td>
<td>4426 ± 636</td>
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</tr>
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<td>37/42/25.75</td>
<td>15/02/49.49</td>
<td>1500</td>
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<td>3787 ± 881</td>
<td>general weathering</td>
</tr>
<tr>
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<td>37/42/25.75</td>
<td>15/02/49.49</td>
<td>1500</td>
<td>in-channel boulder</td>
<td>3061 ± 411</td>
<td>boulder disturbance</td>
</tr>
<tr>
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<td>15/02/49.49</td>
<td>1500</td>
<td>bedrock; pothole</td>
<td>3038 ± 407</td>
<td>post-abandonment burial and re-exposure</td>
</tr>
<tr>
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<td>37/42/25.75</td>
<td>15/02/49.49</td>
<td>1500</td>
<td>in-channel boulder</td>
<td>2014 ± 315</td>
<td>boulder disturbance</td>
</tr>
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<td>ET99KD15</td>
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<td>1985 ± 489</td>
<td>post-abandonment erosion</td>
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<td>post-abandonment erosion</td>
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<tr>
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<td>37/42/25.75</td>
<td>15/02/49.49</td>
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<td>post-abandonment burial and re-exposure</td>
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<tr>
<td>ET99KD12</td>
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<td>15/03/20.14</td>
<td>1575</td>
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<td>recent rock-fall</td>
</tr>
<tr>
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<td>37/42/25.75</td>
<td>15/02/49.49</td>
<td>1500</td>
<td>bedrock; scour</td>
<td>0 (−3217) ± 412</td>
<td>unknown</td>
</tr>
<tr>
<td>ET00KD1</td>
<td>Due Monti</td>
<td>37/47/04.80</td>
<td>15/03/06.02</td>
<td>1675</td>
<td>in-channel boulder</td>
<td>0 (−39) ± 75</td>
<td>baseline test sample: actively eroding channel</td>
</tr>
</tbody>
</table>

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5. Results and interpretations

Cosmogenic exposure dating of eroded surfaces within abandoned drainage channels on an active volcano is not straightforward. This is a consequence of the potential of a suite of past and contemporary processes that could operate to deliver cosmogenic exposure ages that post-date the abandonment event. These include periodic tephra accumulation, rare erosive (and limited) streamflow associated with highly localized extreme precipitation and boulder saltation or movement owing to earthquake-related ground shaking, together capable of shielding original surfaces or exposing new ones. Tephra shielding is considered as the most likely source of younger exposure ages from channel samples; the prevailing northwesterly wind direction typically transporting ash and scoriaceous fall material to the southeast of the Mongibello (active since 15 ka BP) summit vents and across the sample sites. During historic times, individual explosive events are likely to have deposited significant thicknesses of tephra in the vicinity of the sample sites. A caldera-forming event in 122 BC, for example, deposited 0.25 m in the City of Catania, 25 km south-southeast of the Valle del Bove’s southern flank, with estimated thicknesses of 0.5 m in the vicinity of the Acqua Rocca and 0.10–0.25 m across the northern flank of the Valle del Bove (Coltelli et al. 1998). Accumulations of several centimetres of tephra in the sample areas have also been observed by one of the authors (McGuire) on a number of occasions over the last 30 years, associated with moderate explosive events at the summit vents. While individual tephra burial events may be temporary (months to decades), such is the level of tephra production at the summit vents that cumulative shielding arising from repeated burial over thousands of years would be sufficient to reduce exposure ages significantly.

As a consequence of post-abandonment processes, the expected product of a cosmogenic exposure dating campaign targeting surfaces within such a channel system is an array of ages, the oldest of which will provide a best-estimate, minimum age for channel abandonment. For Etna, the campaign returned an array of 16 ages (table 1), 15 of these ranging from 0 to 7.419 ± 1.256 ka BP, together with a single outlier (sample ET00KD2021) of 25.966 ± 6.149 ka BP determined from exposed bedrock near the lip of the waterfall in the Acqua Rocca valley. We propose that the outlier is an artefact of the analytical process and address this issue in more detail later.

Discounting this age leaves comparable (within error) maximum ages for each of the abandoned channels sampled: 7.419 ± 1.256 ka BP (ET00KD22) for the un-named northern flank valley; 7.222 ± 0.949 ka BP (ET00KD7) for the Acqua Rocca; and 5.858 ± 1.031 ka BP (ET00KD15) for the Acqua Turco. We accept the first two ages as approximating to the best-estimate minimum ages for abandonment of, respectively, the unnamed north flank valley and the Acqua Rocca on the southern flank. Similarity of the ages supports abandonment that was effectively simultaneous on both flanks and occurred ca 7.5 ka BP. The somewhat younger maximum age for the Acqua Turco may be an artefact of burial and re-exposure. It is notable that the oldest ages were both delivered by samples taken at elevated positions (2 m for ET00KD7 and 5 m from ET00KD22) above the valley floors and at the bases of palaeo-waterfalls. Such waterfalls are unlikely to have been used following destruction of the channel watersheds, thus minimizing post-abandonment erosion, while elevation of sample sites would
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minimize the potential for tephra burial. In contrast, the Acqua Turco location was only 0.5 m above the floor and therefore more likely to have undergone burial by tephra for significant periods of time. While it is possible that a larger sample of dates might deliver an older age, we have confidence that the above dates are close to the true age of channel abandonment. While some later expansion of the Valle del Bove must be expected owing to gravitational instabilities, we argue that the main event was catastrophic, thereby truncating the channels and decapitating the watershed for both flanks simultaneously.

Younger ages in the array are interpreted as representing different exposure histories of the samples (table 1). Based upon local (to sample) conditions, these are most likely to be a consequence of boulder disturbance, perhaps owing to rare high-energy, fluvial action or earthquake-related ground shaking (samples ET99KD17; ET99KD15); variable burial (by tephra, debris, rock falls) and (re-) exposure (ET99KD21; ET00KD19; ET00KD18); post-abandonment fluvial erosion (ET99KD20; ET00KD23); or unknown cause (ET99KD18; ET99KD19). A $3.787 \pm 0.881$ kaBP age obtained for sample ET99KD16, taken from an elevated tor within the Acqua Rocca is likely a consequence of general weathering, while the zero age (actually $−1.253 \pm (−0.812)$ kaBP) delivered by sample ET00KD12 seems to reflect doubts in the field about the nature of the sample site, and is probably derived from a block in a recent rock fall. ET00KD1 is a control sample collected from an in-channel boulder within the Due Monti active drainage channel on the north flank of the Valle del Bove. This actively eroding sample was expected to provide a zero exposure age. The determined zero age (actually $−39 \pm 75$ yr BP) obtained validates use of the method on Etna and supports its utility in constraining timing of the cessation of high-energy fluvial flow along the sampled abandoned channels. All zero ages determined during the campaign demonstrate that insufficient time had elapsed to accumulate significant abundances of cosmogenic $^{3}$He$_{c}$ (less than approx. 300 years) and are recorded as negative values. These negative ages are the product of insufficient $^{3}$He release from the fusion step to account for all the inherited $^{3}$He. This may be the result of the crush $^{3}$He/$^{4}$He ratio being different from the inherited $^{3}$He/$^{4}$He ratio of the trapped He in the fusion step contrary to the assumption in equation (5.1) below that these values are the same. Such variations may be caused by radiogenic He or sample shielding, for example,

$$^{3}$He$_{c} = ^{3}$He$_{f} - ^{4}$He$_{f} \left( \frac{^{3}$He}{^{4}$He} \right)_{i},$$

whereby the cosmogenic $^{3}$He component (c denotes cosmogenic) can be derived using the inherited component $^{3}$He/$^{4}$He ratio from the crushing (i denotes the inherited component) to correct the $^{3}$He$_{f}$ (f denotes release by fusion) for any remaining $^{3}$He$_{i}$. The crush-released Ne was used to correct the $^{4}$He$_{i}$ for atmospheric contamination assuming that all the Ne was atmospheric.

The single outlier (sample ET00KD2021) age of $25.966 \pm 6.149$ kaBP may be explained in one of three ways. First, the anomalously high age could represent the true timing of abandonment of the waterfall and the channel system as a whole. Should this be an accurate exposure age, the campaign would have delivered more ages in the 7–26 kaBP range.
Assuming that the data from the mass spectrometric analyses are correct, a second possibility is that this sample could have had a long period(s) of exposure prior to channel abandonment or could have formed by low-energy water flow slowly cutting through the bedrock a few centimetres in total for a large amount of time (ca 18000 years). In this scenario, when water flow subsequently ceased approximately 7 ka BP, 18000 years of pre-exposure had already accumulated producing an anomalously high exposure age. The low steady-state erosion rate of 0.03 m ka⁻¹ required to generate the ‘extra’ 18000 years of exposure prior to the Valle del Bove collapse, assuming a maximum eruption age for the Trifoglietto lava substrate of 65 ka and an erosion depth of 0.54 m, is not, however, compatible with the high energy flows expected to be associated, first, with melting of summit snow and ice fields, and second, with the pluvial conditions of the early Holocene. Such conditions are attested to by the form of the truncated valleys themselves and by fluvial scour features to a height of 3 m above the present channel floor, indicative of deep, energetic, high volume flows. Further support comes from the Due Monti sample (ET00KD1) detailed below, taken from a currently but ephemerally active valley to the north of the Valle del Bove. This ‘baseline test’ sample produced a zero exposure age indicating periodic, high-energy flows affecting these valleys. This demonstrates that while such valleys are active cosmogenic nuclide build-up in the surface is negligible.

A third possibility for the outlier age relates to the analytical process. In the case of ET00KD2021, the fusion-released \(^{4}\text{He}\) was unusually low when compared with the fusion-released \(^{3}\text{He}\), with very little \(^{4}\text{He}\) surviving the crushing process in this sample compared with the others. We suspect that, as a consequence, the mass spectrometer was unable to locate the \(^{4}\text{He}\) peak during the analysis routine. In such circumstances, the routine reverts to a stored mass position that appears not to have been accurate in this case. The measurement could not be repeated because of a paucity of sample material. The anomalously large age could therefore be because of analytical error. Additionally, very little \(^{4}\text{He}\) survived the crushing process in sample ET00KD2021 when compared with the rest of the samples. Thus, given that ET00KD2021 is not a gas-poor sample, more fusion-released \(^{4}\text{He}\) should have been expected from this sample. The problem is not with a low abundance of fusion-released \(^{4}\text{He}\) being detectable, as sample ET98KD6 released half the amount of \(^{4}\text{He}\) released by ET00KD2021 and was clearly detected. In light of the above discussion, we conclude that the exposure age outlier is most probably because of incorrect reading of the peak position.

6. Implications of exposure ages for the formation of the Valle del Bove

The ca 7.5 ka BP age of collapse is broadly consistent with those dates obtained from the Milo Lahar and Chiancone sequences, and discussed earlier. While the 8.4 ka \(^{14}\text{C}\) age of Calvari et al. (1998) is approximately 1000 years older than our age for channel abandonment, it is within error of the 7.419 ± 1.256 ka BP age from the northern flank and close to within error of the Acqua Rocca age of 7.222 ± 0.949 ka BP and is highly likely to mark the same event.

Importantly, it is worth noting that the single \(^{14}\text{C}\) age of Calvari et al. (1998) may not be entirely reliable. Radio-carbon ages determined at active volcanoes are known to be notoriously susceptible to contamination by magmatic CO₂,
which has the outcome of reducing the $^{14}$C content of plants, thereby increasing the apparent age of sampled material; an effect recognized as being particularly significant in carbon dating of material less than 10,000 years old (Sulerzhizky 1971). Notably, Sulerzhizky demonstrated, for the Kamchatka and Kurile volcanic regions, that contamination with magmatically derived carbon could result in recent plant remains yielding $^{14}$C ages as old as 6 ka BP. The carbon contamination problem has previously been recognized at Etna, and has been proposed by Guest et al. (1984) to explain a suite of wide-ranging $^{14}$C ages on the upper tephra ashes, exposed in a number of valleys truncated by the southern rim of the Valle del Bove. Consequently, it may be that the age of emplacement of the stürtzstrom material within the Milo Lahars is somewhat younger than that proposed by the single 8.4 ka $^{14}$C age of Calvari et al. (1998).

In linking channel abandonment with the excavation of the Valle del Bove we assume that the sampled valleys were actively eroding up to the time of watershed decapitation. This is supported by the fact that the early Holocene northern Sicilian climate remained warm and wet at the time indicated by the maximum exposure ages, prior to the onset of much drier conditions around 6000 years ago (Frisia et al. 2006). Making the assumption that the channel system was initiated ca 16 ka BP when melting of ice fields capping the Ellittico volcanic centre commenced (Neri 2002), maximum erosion rates over the period from initiation to abandonment can be determined. For the Acqua Rocca waterfall on the southern flank and at the north flank location of sample site ET00KD22, which yielded the $7.419 \pm 1.256$ ka BP exposure age, these erosion rates are very similar (0.44 and 0.38 m ka$^{-1}$, respectively) and comparable with incision rates from fluvially driven channel erosion in comparable volcanic terrains, such as at Kauai (Hawaii; Seidl et al. 1997).

7. Nature of the collapse mechanism

We propose a collapse model predicated upon the onset of early Holocene pluvial conditions in northern Sicily (figure 4), with a sustained wet climate modifying the hydrology of Mount Etna so as to ensure significant elevation of the water table and saturation of the upper part of the edifice. Such conditions are consistent with frequent, high-energy, surface run-off and the formation of the deeply incised drainage system now truncated by the Valle del Bove rim. The character of the Milo Lahar and Chiancone sequences, dominated by fluviatile and debris flow lithologies, also supports conditions significantly wetter than those prevailing over the last 6000 years, and it is perhaps noteworthy that ages from the top of both sequences coincide with the prevalence of more arid conditions (figure 4). The character of tephra units also attests to water playing a significant role in eruptive activity during the early Holocene. Del Carlo et al. (2004) (figure 4), for example, report the occurrence of a sequence of phreatomagmatic ashes, ranging in age from 7.5 to 12 ka BP. These they interpret as having been erupted by a series of sub-Plinian eruptions taking place within a lake- or snow-filled Ellittico caldera, suggesting an elevated water table and saturated edifice at which rising magma and water were able to interact easily. Guest et al. (1984) also speculate that the water table could have been higher at this time, and that the summit caldera could have acted as a trap for snow and meltwater. Although phreatomagmatic
eruptions have occurred more recently, most notably at $3.150 \pm 0.060 \text{ ka BP}$ (Del Carlo et al. 2004), such activity does not seem to have been as common during the drier late Holocene.

Water has long been recognized as playing a critical role in destabilizing slopes and triggering landslides, both in non-volcanic and volcanic terrains (e.g. Day 1996; Voight & Elsworth 1997). In the latter, the pressurization of pore water in saturated rock by rising magma has been proposed as an effective trigger for lateral collapse (e.g. Elsworth & Voight 1996; Iverson 1996; Elsworth & Day 1999). When magma is emplaced into a saturated, porous material, it mechanically strains the surrounding medium, resulting in pressurization of the pore fluid. Magmatic heat will also act to increase pore pressures through thermal expansion of the fluid and by driving groundwater flow capable of spreading excess pore pressures further afield. In concert, the resulting pressurization can lead to a reduction in the sliding resistance sufficient to initiate lateral collapse. On Etna, opportunity for high-level magma–water interaction, leading to edifice destabilization and spontaneous collapse, was optimal at the time of maximum utilization of the drainage channels, when water tables were highest and surface run-off at a level far greater than that observed today.

Lateral collapse under these conditions may have been triggered at Etna through forced dyke emplacement from the central conduit system into intravolcanic rift zones in the volcano’s water-saturated eastern flank—perhaps,
already seriously weakened by hydrothermal alteration within an elevated water table. Elsworth & Day (1999) show that dykes of the order of 1 m wide and more than around 1 km long are capable of generating mechanical and thermal fluid pressures along a basal décollement and magmastatic pressures at the dyke surface that, together, can trigger failure and lateral collapse. Significantly, deformation monitoring of contemporary dyke intrusion events at Etna reveals a metre or more of horizontal displacement associated with each rifting episode (McGuire et al. 1990). Owing to growth of Etna on an uplifting and eastward-tilting basement, high-level magma emplacement at this time occurred preferentially in the form of dykes concentrated along the eastern (ENE and SE) rift zones, the intersection of which is bisected by the long axis of the Valle del Bove, and that today are well exposed in the back-wall of the amphitheatre (McGuire et al. 1997b). A contribution to pre-collapse instability may also have been provided by progressive lateral mechanical displacement of the eastern flank associated with repeated dyke emplacement. Whether or not the Valle del Bove lateral collapse triggered a violent explosive eruption as a consequence of the exposure and decompression of magma stored at high levels in the edifice is not known. No particularly distinctive or widespread tephra unit has an age corresponding to the timing of collapse, which may have occurred without significant accompanying eruptive activity. It is also possible that there was no magma involvement at all. If the eastern flank, or a part thereof, was already sliding under its own weight on the tilted basement, then elevated pore pressures alone, or water-driven slow cracking—held to be a contributory factor in the formation of non-volcanic stürzstroms (e.g. Kilburn & Petley 2003)—may have been sufficient to trigger failure and collapse.

8. Conclusion

There is strong evidence for lateral collapse at Mount Etna ca 7.5 ka BP, coinciding with early Holocene pluvial conditions in northern Sicily, and for elevated water tables and a saturated edifice being instrumental in promoting instability and initiating collapse. A robust cause-and-effect link remains to be determined, however, justifying both further study of Etna’s Valle del Bove and its associated deposits, and potential climate connections with volcano instability and lateral collapse in general. A link between volcano lateral collapse and increased water availability has been tentatively proposed previously. Day et al. (1999, 2000) have argued in favour of a role for elevated pore-fluid pressures in triggering lateral collapses at ocean island volcanoes during warm, wet, interglacial periods. Capra (2006) has also proposed that more humid post-glacial conditions may have promoted failure of unstable volcanic edifices and suggested that future warming may play a similar role. To date, however, ages of collapse events are neither sufficiently numerous, nor well enough constrained, to be able to make a categorical causal link with wetter conditions or other climate parameters (Keating & McGuire 2004). Notwithstanding this, anthropogenic planetary warming may lead to greater water availability in many volcanic landscapes and may reasonably present increased opportunity for high-level water–magma interaction, together providing greater potential for future lateral collapse. Notably, conditions for elevated water tables may be promoted
through increased meltwater production at ice-capped volcanoes, for example in Kamchatka, Alaska, the Andes and Iceland, and forecast precipitation increases across volcanic terrains such as Indonesia and Papua New Guinea and at high latitudes (IPCC 2007).

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