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Simultaneous magma and gas eruptions at three volcanoes in southern Italy: an earthquake trigger?

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ABSTRACT

In September 2002, a series of tectonic earthquakes occurred north of Sicily, Italy, followed by three events of volcanic unrest within 150 km. On October 28, 2002, Mt. Etna erupted; on November 3, 2002, submarine degassing occurred near Panarea Island; and on December 28, 2002, Stromboli Island erupted. All of these events were considered unusual: the Mt. Etna NE-rift eruption was the largest in 55 yr, the Panarea degassing was one of the strongest ever detected there, and the Stromboli eruption, which produced a landslide and tsunami, was the largest effusive eruption in 17 yr. Here, we investigate the synchronous occurrence of these clustered unrest events, and develop a possible explanatory model. We compute short-term earthquake-induced dynamic strain changes and compare them to long-term tectonic effects. Results suggest that the earthquake-induced strain changes exceeded annual tectonic strains by at least an order of magnitude. This agitation occurred in seconds, and may have induced fluid

and gas pressure migration within the already active hydrothermal and magmatic systems.

INTRODUCTION

Volcanoes interact with their environment on different scales, and with different modes and processes, ranging from climate and tidal relationships to tectonic interactions. Tectonic interactions, in particular, have received special attention in recent years. A correlation of earthquakes and eruptions was revealed by a statistical examination of global data catalogues and these relationships may occur over distances exceeding hundreds of kilometers (Linde and Sacks, 1998). A mechanical relationship between apparently interlinked processes is, however, still not understood, partly due to the limited number of studied cases. Recent papers suggest that dynamic strain, together with long-term tectonic extension (Hill, 2008) and/or short-term static extension associated with earthquakes (Walter and Amelung, 2007), may increase the number of volcanic eruptions. A series of volcanic unrests occurred in 2002 in southern Italy in the weeks following an earthquake, and may help to better understand such clustered events.

The Aeolian Arc is associated with the NW-ward subducting Ionian slab and currently hosts several active volcanoes. Tectonic deformation within the Arc is heterogeneous, being subject to extensional tectonics in the east (including the volcanoes of Stromboli and Panarea), dextral shear tectonics in the center (including Vulcano and Lipari), and compressional tectonics in the west (Alicudi and Filicudi, Figure 1; De Astis et al., 2003). The dextral shear of the central Aeolian Arc is associated with a NNW-SSE-trending structure constituting the northernmost part of the Maltese Escarpment. This is the surface expression of a tear separating the subducting oceanic lithosphere (to the east) from the colliding continental lithosphere (to the west). This tear allows the extension and the rise of asthenospheric material at Mt. Etna (Gvirtzman and Nur, 1999).

While there is a long-term interdependency between the southern Italy volcanism and tectonics (Neri et al., 1996; Lanzafame and Bousquet, 1997), in the short-term, the link is still debated. Historical records suggest that some particular events of volcanism at Mt. Etna have occurred in temporal proximity to large tectonic earthquakes (Feuillet et al., 2006). Synchronous activity at several volcanoes and their possible link to large tectonic earthquakes, however, has not been elaborated. In 2002, a significant earthquake took place west of the Aeolian Islands and was followed by a widespread aftershock sequence, and by major eruptions at Mt. Etna and Stromboli Island and anomalous degassing at Panarea. Through observation, seismic investigation and numerical modeling, this group of events is investigated here. Our study suggests that the volcanoes were further activated by dynamic pressure fluctuations associated with the earthquake, with implications that are important for understanding clustered activity and hazards in southern Italy and elsewhere.

CHRONOLOGY OF THE EVENTS

The Palermo Earthquake

On September 6, 2002, at 01:21:27 UTC, an earthquake occurred ~40 km northeast of Palermo, Sicily (Rovelli et al., 2004), and 130–140 km west of the nearest continuously active volcanoes, Mt. Etna and Stromboli Island (Fig. 1). The earthquake was followed by more than 600 aftershocks $M > 1$, with hypocenters aligned in a north-eastern continuation along a ~100 km segment of a 050°-trending fault. The mainshock killed two people, damaged several buildings in the Palermo area, and was felt in eastern Sicily in the cities of Catania and Messina. In northern Sicily, the earthquake is thought to have triggered the Cerda landslide (Agnesi et al., 2005) and affected physical parameter recordings at thermal springs (Caracausi et al., 2002). Seismological characteristics were detailed in the International Seismic Catalogue (ISC), with the hypocenter located at 38.36 N 13.69 E at 12 km depth. The USGS NEIC and Harvard HRVD solutions provided a magnitude Mw = 5.9, with a focal mechanism nodal plane striking SW-NE (NEIC 242/60/145 or 351/60/35, and HRVD 26/50/40 or 267/60/133). As illustrated in Figure 2, the earthquake was soon followed by eruptions at Mt. Etna and Stromboli Island, and degassing close to the island of Panarea. At these 3 volcanic centers, the change and scale of activity were very unusual, as detailed below.

Mt. Etna eruption

Mt. Etna erupted in July-August 2001, as a consequence of the emplacement of an eccentric dike, an exceptional event in its recent history (Allard et al., 2006 and references therein). From October 27, 2002 to January 28, 2003, the volcano erupted again, now also associated with the opening of the NE rift. This was the first NE rift fissure eruption after 55 yr of quiescence (since 1947). Associated with this event, a major part of the east flank of the volcano was displaced eastward by up to several meters, with surface fracturing and hazardous earthquakes; these events have not been observed in recent decades (Neri et al., 2005).

Panarea degassing

Panarea lies in the eastern Aeolian Arc and had its main period of activity in the Holocene. A constructional phase occurred between 150 and 105 ka, followed by discrete explosive eruptions until 8 ka, associated with slight submergence (Lucchi et al., 2006). In historical times, only reports of degassing activity may be found. No dramatic increase or decrease in gas flux was ever instrumentally recorded before November 3, 2002 (Esposito et al., 2006). The anomalous period of increased degassing activity ended in January 2003. Observations showed that gas discharge occurred in at least three distinct areas ~3 km offshore of Panarea Island (Bulletin of the Global Volcanism Network, BGVN 27:10). Geochemical monitoring revealed a dynamic behavior changing in time, space and flux, with a component of the gases being directly associated with magmatic fluids (Capaccioni et al., 2007). The only other account of a similarly strong degassing episode refers back to the year 1865 (Billi and Funiciello, 2008).

Stromboli Island eruption

Stromboli Island, in the eastern Aeolian Arc, hosts one of the most active volcanoes with continuous archetypal strombolian eruptions. These are usually associated with gas bubble rise, coalescence and slug bursts, rather than juvenile effusion. Continuous radon gas measurements showed that summit degassing increased shortly after the 2002 Palermo earthquake (Cigolini et al., 2007). On December 28, 2002, Stromboli Island had its first dike-fed effusive eruption in 17 yr (since 1985), culminating two days thereafter in failure of part of the northern flank into the sea and the formation of a tsunami. The familiar strombolian activity resumed in mid-2003 (Ripepe et al., 2005).

STRESS AND STRAIN TRANSFER MODELING

Our calculations take the static and dynamic transfer of strain due to the September 6, 2002 Palermo earthquake into account. Strain changes were first calculated by producing synthetic seismograms at sites where we had actual seismic data available. We used seismic data from the Mediterranean Very Broadband

Seismographic Network (MedNet http://mednet.rm.ingv.it) at a station in Antillo (AIO, 37.9712°N, 15.2330°E, H = 751 m), recorded by a STS2-station at 20 Hz, and from another station maintained by INGV Catania in Tortorici (TORT, 38.040°N, 14.810°E, H = 540 m), recorded at 200 Hz by an accelerometer station (details are provided in the electronic supplement). These stations are located 142 and 104 km from the Palermo earthquake epicenter, respectively, and span the distance range of the investigated volcanoes (Mt. Etna - 134 km, Panarea - 124 km, Stromboli Island - 141 km). Upon successful reproduction of the amplitudes of these seismograms in computer models, we were able to simulate strain changes at any other location, namely at Mt. Etna (37.734°N, 15.004°E), at Panarea (38.63°N, 15.07°E), and at Stromboli Island (38.789°N, 15.213°E). Since we were interested in how the earthquake caused transient changes at depth, we first simulated the seismic wave fields and then calculated the associated pressure fluctuation at depth (electronic supplement S1-3). This provided a quantitative estimate of the scale of transient pressure changes under each of the volcanic centers, i.e., 2 km below sea level at Mt. Etna, Panarea and Stromboli Island. We assume that this is a reasonable depth that may host hydrothermal as well as shallow magmatic reservoirs.

The Palermo earthquake synthetic wave propagation essentially depends upon the earthquake source and strength considered (model fault data is provided in the electronic supplement S1). This plane is discretized by 100 point sources, which are triggered by the rupture front propagating circularly from the hypocenter at a constant velocity of 2 km/s. The seismic moment of each point source is released via a set of Brune’s sub-events (Brune, 1970). We did not attempt to perfectly match the waveforms, but rather the three component amplitudes that yield information about the magnitude of induced dynamic strain changes. The characteristic duration of each point source is comparable to the rise-time of the earthquake, which is related empirically to the magnitude and stress drop (Boore, 1983). Using the semi-analytical code by (Wang, 1999) to calculate synthetic seismograms, we produced the Green's functions for the standard seismic reference model IASPEI91. Synthetic seismograms of the earthquake are obtained by convolution between the Green's functions and the source functions described above. The results are shown in Figure 3 and further explained below.

The calculations show a large fluctuation of the three components at 2 km depth. As shown in Figure 3, the east and north components, as well as the vertical components of all synthetic waveforms, display 15 to ~18 seconds of time lag between p- and s-wave arrivals, which is consistent with the distance of 125–140 km between the earthquake hypocenter and the volcano locations. Amplitudes at all sites are similar to the true recordings at Antillo and Tortorici. At the Mt. Etna site, the vertical component is larger, while at the Panarea and Stromboli sites the N-S component is larger, which is related to the moment tensor solution applied in the initial rupture model and considered to be realistic. From these three components, we infer that the pressure changes are fluctuating for ~25–30 seconds at ± 10 kPa at Mt. Etna, and ± 8 kPa at Panarea and Stromboli Island. Thus, the dynamic pressure fluctuations reach ~20 kPa and then fall back to near zero after the seismic waves pass. A small offset from the zero line is found due to static offset related to the permanent dislocation induced by the earthquake model. The static offsets are negligible (< 1 kPa) and are thus an implausible eruption trigger, while the dynamic fluctuations (~20 kPa) exceed values known to have induced seismicity or volcanic activity elsewhere, as discussed below.

DISCUSSION AND CONCLUSIONS

The observed degassing activity at Panarea and the types and scales of the eruptions at Mt. Etna and Stromboli Island were each considered peculiar within the context of their recent decades of activity. Even more remarkable is the synchronous occasion of these events. Large eruptions and degassing events have been observed at the three volcanic centers in the past, although never in such a close temporal proximity as in the period from October-December 2002. In this article, we investigated the influence of a possible external trigger that set off all three volcanoes. As shown, the preceding Palermo earthquake induced transient changes at the magmatic and hydrothermal systems of these volcanoes.

Alternatively, one may speculate whether the 2002 synchronous activity was an expression of a general geodynamic reorganization affecting the southern Tyrrhenian area. A geodynamic reorganization can cause static stress changes and thus act as a regional tectonic trigger, and may have locally led to both the Palermo earthquake and the simultaneous volcanic activity. However, regional seismicity does not suggest major plate movement (electronic supplement S2). As recently suggested (Cigolini et al., 2007), and as quantitatively tested in this work, the possibility that the volcanic activity increased due to dynamic stress changes directly associated with the earthquake mainshock alone appears to be reasonable. Although the models presented herein are simplified, ignore complex heterogeneities and time dependent rheology, they may help to understand the simultaneous 2002 volcanic activity in Italy.

Our model calculations suggest that pressure fluctuations occurred surrounding the magmatic and hydrothermal reservoirs of the volcanoes on the order of 20 kPa. These values may appear small considering absolute pressures at magma stagnation levels (GPa), or magmatic overpressures required for magma chamber wall rupture and dike propagation (MPa). However, values on the order of tens of kPa appear large in comparison to long-term plate tectonic forcing and to short-term extrinsic forcings, including various types of tidal and earthquake triggers. Long-term tectonic strain rates in the Aeolian Arc and at Mt. Etna are generally less than 100 nanostrain yr^{-1} (D' Agostino and Selvaggi, 2004), which is about one order of magnitude smaller than values estimated from the Palermo earthquake model presented in this paper. Short-term forcings, in turn, related to dynamic triggering elsewhere suggest that stress changes below those calculated in this work might be significant. For instance, seismicity increases at the Long Valley caldera associated with regional and teleseismic tectonic earthquakes were found to be triggered if the 5 kPa threshold was reached (Brodsky and Prejean, 2005). Such small changes may lead to a chain of adjustments within a magma-hydrothermal system already in a critical state and may explain the delay between the earthquake and observed volcanic activity. The chain of adjustments may begin with the excitation and ascent of gas bubbles, and associated pressure and density changes within a magmatic reservoir and other fluid-filled structures (Manga and Brodsky, 2006), that may even lead to rupture and magma intrusion (Walter and Amelung, 2007).

Considering the distance to the earthquake, other time dependent quasistatic (viscoelastic) effects are probably of minor influence (see also Hill et al., 2002). Similar dynamic interaction may have occurred already before, as in 1865, when strong degassing was observed at Panarea and eruptions occurred at Stromboli and Mount Etna following strong earthquakes. The pressure fluctuations detected in this work might thus be indirectly significant, and a relationship with a long-term tectonic effect as illustrated in the conceptual model of Figure 4 must be considered. Long-term and steady strain increase is abruptly exceeded manifold during the passage of seismic strain.

We note that the volcanoes located within the eastern Aeolian Arc became active, while other volcanoes located on the central and western Arc did not show any significant changes. The structural tectonic configuration reveals that the eastern Aeolian Arc is subject to extensional tectonic strain, being transtensional in the central and compressional in the western Arc (De Astis et al., 2003). Regions near Mt. Etna are in part also subject to extensional tectonic strain (D'Agostino and Selvaggi, 2004) and to a complex local volcano-tectonic deformation additionally related to intrusions and gravitational spreading (Feuillet et al. 2006). In a simplistic view, this work may imply that volcanoes located in extensional tectonic environments are more prone to being activated by dynamic effects, providing a possible explanation of why the volcanoes closer to the Palermo earthquake did not show any response related to remote triggering. Although in the present scenario volcanoes located closer to the earthquake source are generally less active, such an interpretation is consistent with recent findings regarding the triggering of earthquakes (Hill, 2008), which suggested that extensional tectonic regimes are more vulnerable to dynamic triggering than compressional regimes. The fact that the synchronously excited volcanoes have already been in a near critical state, both in terms of their magmatic system (eruptions at Stromboli Island and Mt. Etna) and hydrothermal system (Panarea) may be of additional importance, as the local pore pressures may have been already elevated when the remote trigger occurred. Once these conditions are met, dynamic stresses focus the activity of the volcanoes, inducing synchronous unrest.

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FIGURE CAPTIONS

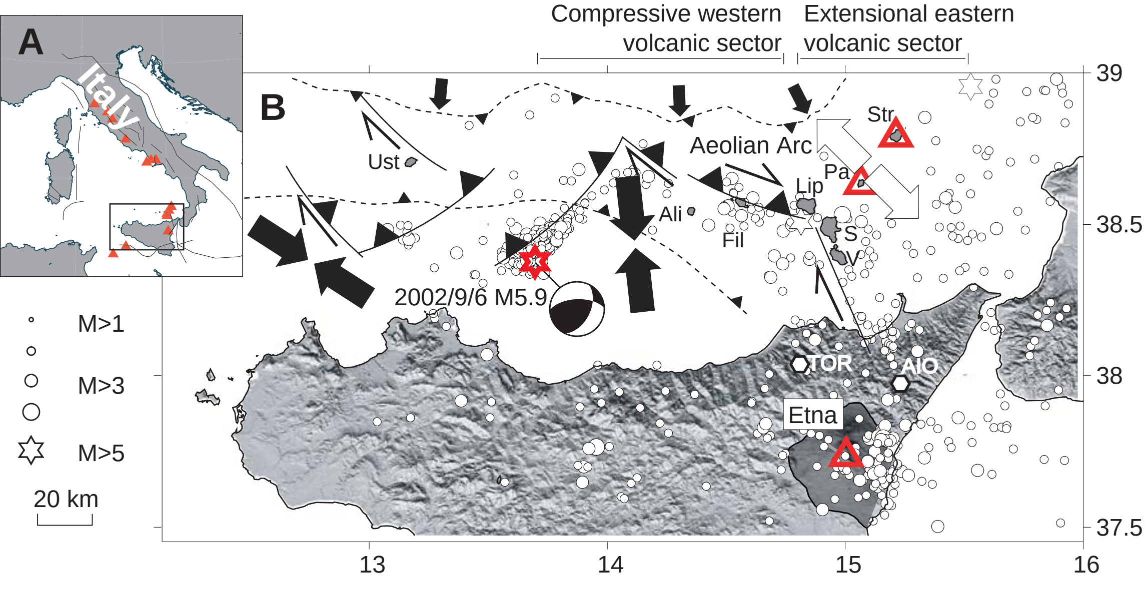
Figure 1. Shaded relief map of Sicily and the Aeolian Islands. Tectonic strain orientation, black arrows show compression in the western volcanic Aeolian Arc, white arrows show extension in the eastern Aeolian Arc (after Billi et al., 2007). Circles are earthquake M > 1 epicenters from the ANSS earthquake catalogue 2000–2005, stars are

mainshocks M > 5, Harvard CMT solution is provided for Palermo M = 5.9 event. Note that four M > 5 earthquakes occurred during the observation period, but two had depths > 200 km (2001/5/17 (M = 5.2) and 2004/5/5 (M = 5.5)), while the September 2002 earthquake and its aftershocks were shallow (< 30 km). Earthquake mainshocks and remotely triggered volcanoes investigated herein are shown with red symbols. Tectonic lines from Billi et al. (2007).

Figure 2. Volcanic activity (red lines) shortly after the largest earthquake and its aftershocks in September 2002. Earthquakes with magnitude > 5 are indicated by stars. Earthquakes from ANSS catalogue 2000–2005.

Figure 3. Synthetic seismograms showing east-west (E), north-south (N) and vertical components (Z). From these three components, we determined the pressure change (P, shown in red) as a function of time. Pressure fluctuations reached ± 10 kPa for Mt. Etna and ± 8 kPa for the Panarea and Stromboli Island volcanoes.

Figure 4. Conceptual model of the time-strain changes in the Panarea-Stromboli-Etna systems. Extensional tectonic strain built up in the long-term, locally causing elevated pore pressure at hydrothermal and magmatic centers. Earthquakes induced short-term fluctuations exceeded the long-term signals by an order of magnitude. In the case of the 2002 events, strain changes are similar to 10–20 yr of tectonic strain, but occurred within seconds.


A
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Compressive western volcanic sector
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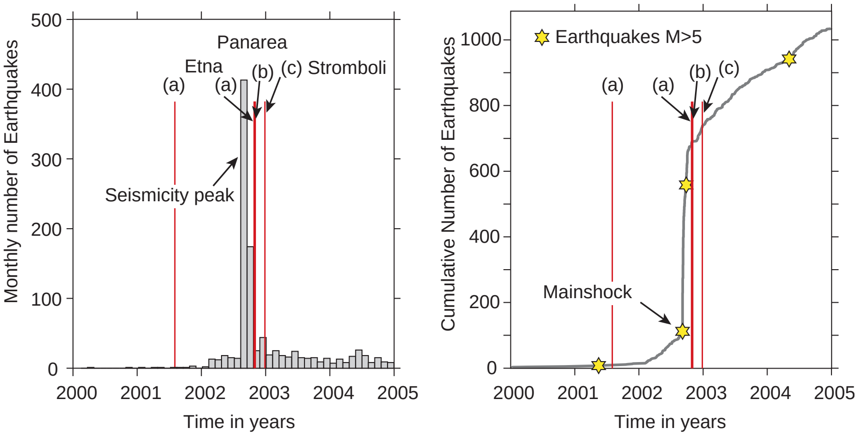
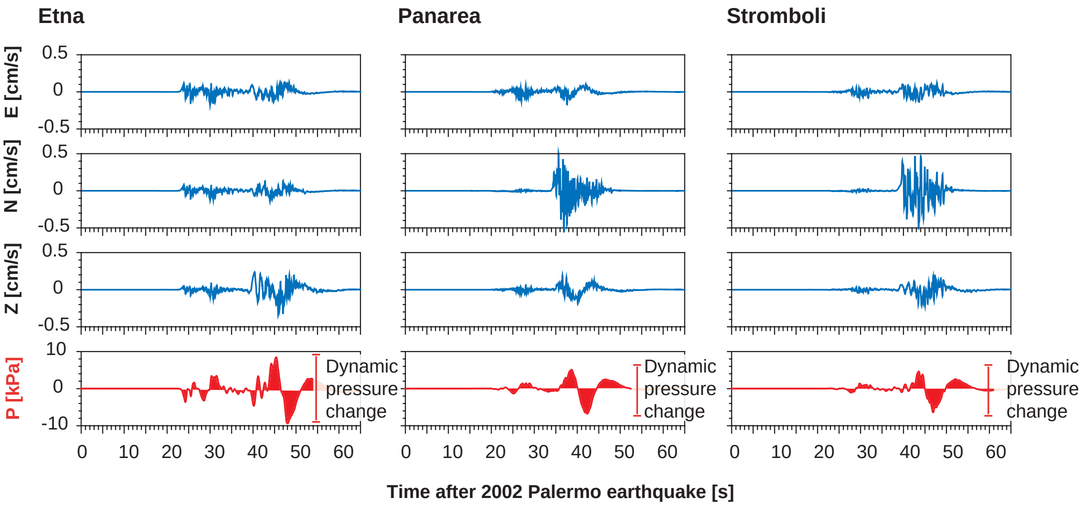

Monthly number of Earthquakes
500
400
300
200
100
0
Panarea
Etna
(a)
(a)
(b)
(c) Stromboli
Seismicity peak
2000
2001
2002
2003
2004
2005
Time in years
Cumulative Number of Earthquakes
1000
800
600
400
200
0
Earthquakes M>5
(a)
(a)
(b)
(c)
Mainshock
2000
2001
2002
2003
2004
2005
Time in years


Etna
Panarea
Stromboli
E [cm/s]
N [cm/s]
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Dynamic pressure change
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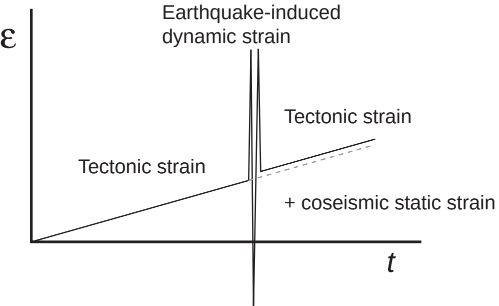
Time after 2002 Palermo earthquake [s]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