Bull Volcanol (2006) 68: 450–461
DOI 10.1007/s00445-005-0021-x

RESEARCH ARTICLE

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Observations of physical effects from tsunamis of December 30, 2002 at Stromboli volcano, southern Italy

Received: 3 May 2004 / Accepted: 22 August 2005 / Published online: 10 December 2005

Abstract On December 30, 2002, following an intense period of activity of Stromboli volcano (south Tyrrhenian Sea, Italy), complex mass failures occurred on the northwest slope of the mountain which also involved the underwater portion of the volcanic edifice for a total volume of about 2–3×10^7 m^3. Two main landslides occurred within a time separation of 7 min, and both set tsunami waves in motion that hit the coasts of Stromboli causing injuries to three people and severe damage to buildings and structures. The tsunamis also caused damage on the island of Panarea, some 20 km to the SSE from the source. They were observed all over the Aeolian archipelago, at the island of Ustica to the west, along the northern Sicily coasts to the south as well as along the Tyrrhenian coasts of Calabria to the east and in Campania to the north. This paper presents field observations that were made in the days and weeks immediately following the events. The results of the quantitative investigations undertaken in the most affected places, namely along the coasts of Stromboli and on the island of Panarea, are reported in order to highlight the dynamics of the attacking waves and their impact on the physical environment, on the coastal structures and on the coastal residential zone. In Stromboli, the tsunami waves were most violent along the northern and northeastern coastal belt between Punta Frontone and the village of Scari, with maximum runup heights of about 11 m measured on the beach of Spiaggia Longa. Measured runups were observed to decay rapidly with distance from the source, typical of tsunami waves generated by limited-area sources such as landslides.

Keywords Stromboli · Tsunami · Post-tsunami field-survey · Runup heights · Tsunami effects

Introduction

Stromboli is the northernmost island of the Aeolian archipelago in the southern Tyrrhenian Sea, Italy (Fig. 1). The volcano appears to have been in a state of continuous activity for the past 1,000–1,500 years (e.g. Rosi et al. 2000). In ancient times, it was given the name of "Lighthouse of the Mediterranean" because it emitted intermittent red flashes visible from great distances at night time. Presently, Stromboli is characterized by persistent activity with mild explosions and occasional explosive crises that usually last from minutes to days and which are characterized by ejection of old material, lava fountains and pyroclastic flows, etc. (Barberi et al. 1993; Rosi et al. 2000). Lava emissions also occur every 5–15 years producing flows which usually reach the sea.

The volcanic edifice extends steeply below the sea level to a depth of 1,200–1,500 m on the east and south flanks, and 1,700–2,200 m on the north and west flanks. The summit of the volcano reaches an elevation of 924 m. Its most characteristic feature is a deep scar located in the northwest sector of the cone called the Sciara del Fuoco (Fig. 2). This steep depression is the result of the most recent sector collapse, which occurred less than 5,000 years ago (Pasquarè et al. 1993) and was likely to be responsible for a tsunami whose effects, modelled through numerical techniques (Tinti et al. 2000, 2003), are speculated to have been disastrous in the entire southern Tyrrhenian basin. Stromboli's craters are located in the middle-upper part of the Sciara del Fuoco at a height of around 700 m. Most of the erupted material, including lava flows and pyroclastics, have been

Editorial responsibility: J. Gilbert

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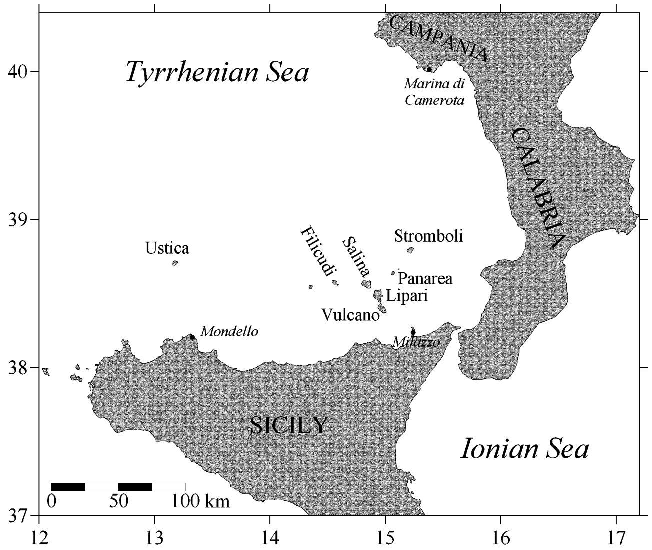

Fig. 1 Geographical sketch of the southern Tyrrhenian Sea, showing the position of Stromboli in the Aeolian archipelago and other coasts where the tsunami arrival was observed

accumulating onto the Sciara del Fuoco, progressively producing the present-day steep 40° slope (Barberi et al. 1993).

During the last part of 2002, Stromboli was dominated by intense explosive activity that lasted until December 28. On that day Stromboli started a new effusive phase that destabilized the flank of the Sciara del Fuoco, leading to the landslides of December 30. It has been ascertained that two major landslides occurred on that day (Bonaccorso et al. 2003; Pino et al. 2004). The first one at 13:15 (local time = GMT+1) was mainly submarine, whereas the second occurred 7–8 min later, creating a subaerial scar on the Sciara del Fuoco at a height of 500 m with a volume of about 7–8 × 10^6 m^3. The mass involved in the first landslide exceeded that of the second. Bathymetric and aerophotogrammetric surveys revealed that the total volume of the material transported by the two slides was about 2–3 × 10^7 m^3 (Baldi et al. 2003; Bosman et al. 2003; Chiocci et al. 2003).

According to a reconstruction based on eyewitness accounts (Tinti et al. 2005a), both landslides produced a tsunami. The first event was triggered by the submarine landslide and was characterized first by a negative sea movement, while the subaerial landslide was responsible for the second tsunami whose first polarity cannot be deduced from the available accounts. At the foot of the Sciara, the submarine slide caused a sea-level depression of about 10–15 m, immediately propagating in both directions northward towards the village of Piscità and southward towards Ginostra. A destructive tsunami, starting with an initial slow withdrawal, hit the northern coasts of the island with three to four big waves. After 3 min the water invaded the beach of Ficogrande, and 1 min later the tsunami attacked the areas of Punta Lena and Scari, producing severe damage. At about 13:20 local time, the waves arrived at the island of Panarea (Figs. 1 and 3) with an initial sea withdrawal followed by two to three strong sea swellings causing damage to the harbour of San Pietro. The second tsunami was generated around 13:22 local time by a subaerial mass failure. Only a few people were able to distinguish the arrival of the second tsunami, while most considered it as the continuation of the first.

The tsunami waves reached all the other Aeolian Islands in about 20 minutes. According to Maramai et al. (2005a), abnormal sea perturbations were noticed at Milazzo on the northern Sicilian coast, some 60 km south of Stromboli (Fig. 1). The sea waves propagated also in the direction of the island of Ustica, about 170 km west of Stromboli, where they are reported to have impacted around 14:00 local time. Finally, tsunami effects were observed along the southern coasts of the Campanian region at about 13:55 local time (Fig. 1) (Nappi et al. 2003). Available far-field observations are summarized in section "Tsunami effects in the other Aeolian Islands and in the far field" of the present study.

In this paper, we present measurements of the maximum tsunami runup and inundation collected during three post-event field surveys that were carried out at Stromboli and at Panarea in the weeks following the December 30, 2002 events. These data are useful to draw a general picture of the tsunami characteristics, and further to serve as a basis both for the reconstruction of the events through numerical simulations (Tinti et al. 2005b) and for the validation of the numerical model itself. It must be stressed that these experimental data can only describe the cumulative effects of the two distinct tsunamis that occurred on December 30, 2002. It is not possible to numerically distinguish the effects of the two phenomena.

Tsunami field survey at Stromboli

Surveys and methods

Measurements and observations were collected during three different surveys conducted in cooperation between two Italian groups, one from the University of Bologna and the other from INGV in Rome. The first two surveys were performed in January 2003 (namely from the 11–13th and from the 21st–23rd of January), while the third was undertaken in mid March 2003. The primary goal of the surveys was to identify the coastal areas affected by the tsunamis and to assess the main characteristics of the tsunami wave effects from a physical point of view. Eyewitness accounts were important and enabled us not only to obtain information for various sites, in particular for those where no particular signs of the tsunami could be recognized, but also to understand the dynamics and the timing of the wave phenomena, and hence to reconstruct the sequence of the events.

The surveys concentrated on the northern and northeastern sectors of the island, running approximately from Punta Frontone on the northwest to La Petrazza on the southeast (Fig. 2), for a total length of about 4 km. In the lower panel of Fig. 2, the surveyed area has been separated into three distinct boxes labelled A, B and C. Zoomed views

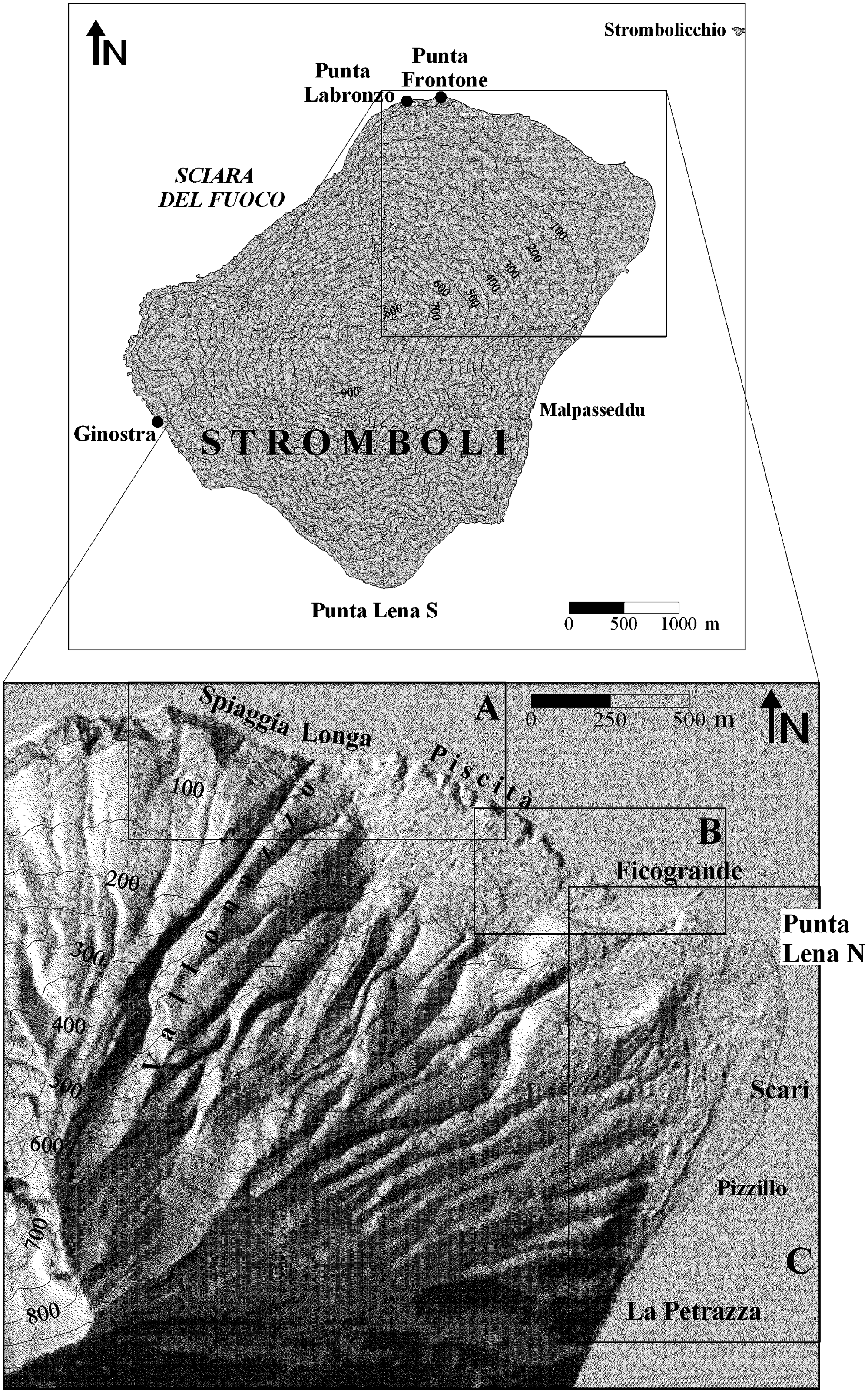

Fig. 2 *Upper panel*: basic toponymy and topographic map of Stromboli, kindly provided by Professor P. Baldi, University of Bologna (GNV Project no. 13: Sviluppo e Applicazione di Tecniche di Telerilevamento per il Monitoraggio dei Vulcani Attivi Italiani). See also Baldi et al. (2003). *Lower panel*: zoomed view of the portion of the island surveyed during the post-event campaigns described in this paper. The three boxes *A*, *B* and *C* are detailed in Figs. 4–6, respectively

of the boxes are provided in Figs. 4–6, respectively. A circumnavigation by boat allowed us to inspect the remaining coastline from the sea. During the circumnavigation, it was possible to land on the Punta Lena beach on the southeastern end of the island. To avoid misunderstandings, we note that there are two localities in Stromboli sharing the same name "Punta Lena": the northeastern and southeastern corners of the island (see Fig. 2). In this work we will use the name Punta Lena to indicate "northern Punta Lena".

The field procedures we adopted reflect those employed by the international tsunami community in several post-tsunami field surveys around the world (see for instance Baptista et al. 1993; Synolakis et al. 1995) and codified by IOC/UNESCO (1998). At each site, after the identification of the maximum runup marks, the typical measuring operations for each observation consisted of recording the time and geographic position and in measuring the vertical and horizontal distances between the mark and the local sea level. Depending on the position of the runup mark, we often had to establish one or more intermediate positions between the local sea level and the mark itself. In some cases, these allowed us to build a topographic transect along the selected profile.

All the runup values reported here are relative to the instantaneous sea level and are not corrected for the tide at the time of the tsunami arrival. As can be deduced from the record of the tide-gauge installed in the port of Panarea, jointly operated by INGV-CNT (Rome) and by ISMAR-CNR (Bologna), the tsunami occurred during low tide, which implies that the runup measurements we collected

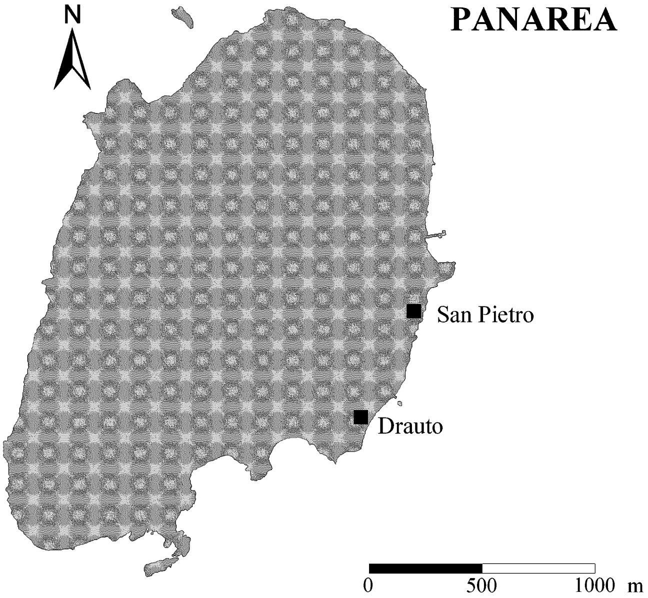

Fig. 3 Coastline of the island of Panarea and position of the villages cited in the text

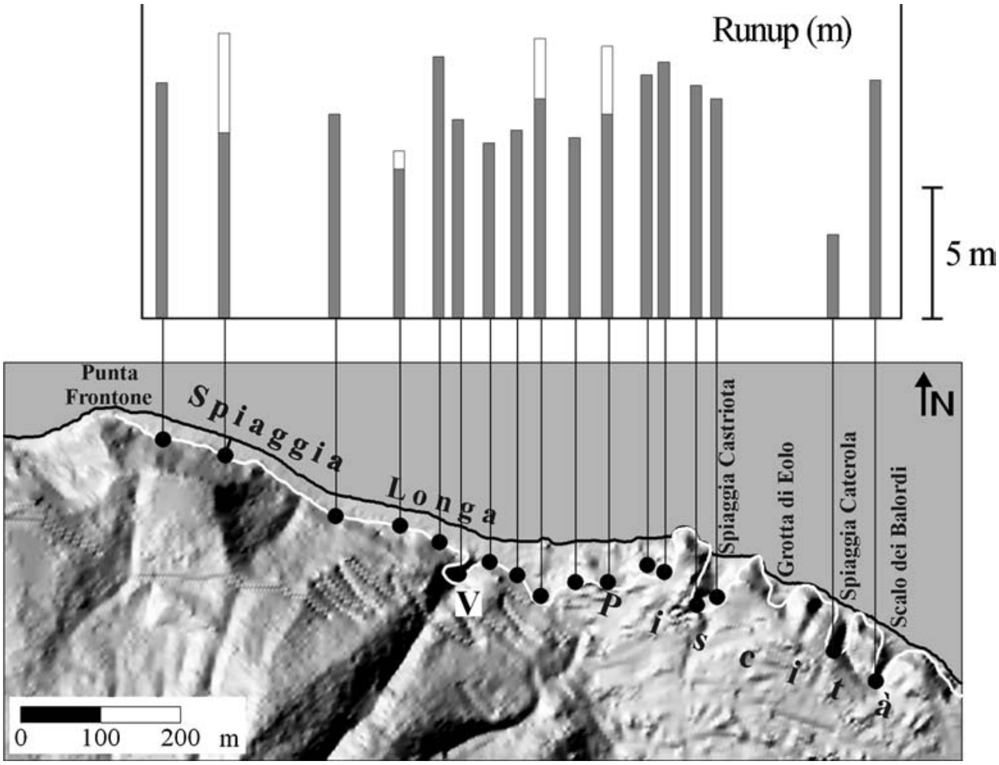

Fig. 4 Detailed view of sector A of Fig. 2, showing the sites where runup measurements were collected, and the histogram of the measured maximum runup elevations. Some of the sketched locations are representative of more than one measurement. In the histogram, the *grey bars* indicate the smallest runup recorded at each site and the *white bars* indicate the largest. When only one measurement is available, the corresponding value is represented with a *grey bar*. The *white line* marks the maximum inland penetration of the tsunami. The *black segment* connecting the shoreline and the second measured point from the northwest indicates the path of the transect detailed in Fig. 7. Site *V* is the portion of the narrow "Vallonazzo" valley where channelling of water occurred

generally represent an underestimate of the values at the time of the tsunami impact. The same record reveals that the tidal excursion varies approximately between 20 and 50 cm, which can be interpreted as the maximum error affecting our runup measures.

Site-by-site field observations

Spiaggia Longa

The uninhabited beach called Spiaggia Longa extends approximately for 500 m from Punta Frontone to the westernmost houses of the village of Piscità (see Figs. 2 and 4). Starting from Punta Frontone and for a length of about 300 m, the beach is quite narrow (width ranging approximately between 15 and 25 m), is covered with boulders and blocks and is delimited by a variably steep backshore escarpment. Further on the beach widens, and the boulders are gradually replaced by sand and pebbles near the shoreline. The identification of the signatures of the tsunami was difficult here. In some points the violent impact of the water waves was revealed by small landslides and/or by uprooted or flattened vegetation. Along the narrow portion of Spiaggia Longa, corresponding with the crown of a small fresh rockslide almost certainly triggered by the tsunami wave impact, we measured the highest value of runup (10.9 m) of the entire survey. Figure 7 shows a schematic view of the topographic details along the corresponding measured transect (whose path is sketched in Fig. 4 as a black solid segment connecting the coastline and the second measured point from the northwest), which exhibits a horizontal extension of about 21 m. Figure 4 summarizes the locations of the other measured sites and the corresponding runup values, varying in the range 6.7–10.9 m. An interesting site is represented by the sea-facing portion of the narrow valley known as “Vallonazzo” (Fig. 2), indicated in Fig. 4 with the letter V. The flattened vegetation observed here was a clear signature of sea-water channelling which occurred along the valley itself. At this site, we measured a maximum runup height of 7.6 m and a horizontal water ingression of about 45 m.

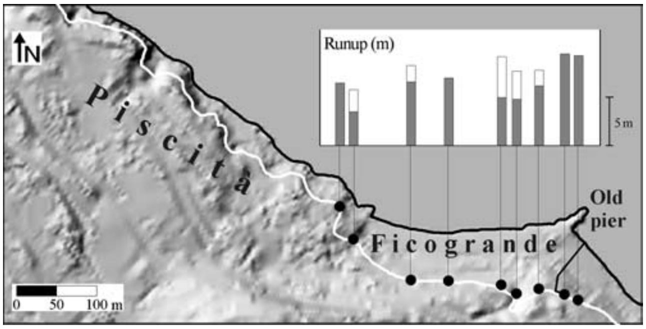

Fig. 5 Same as Fig. 4, but corresponds to sector B of Fig. 2. The *black solid line* in the *lower-right part* of the map indicates the path of the transect shown in Fig. 10

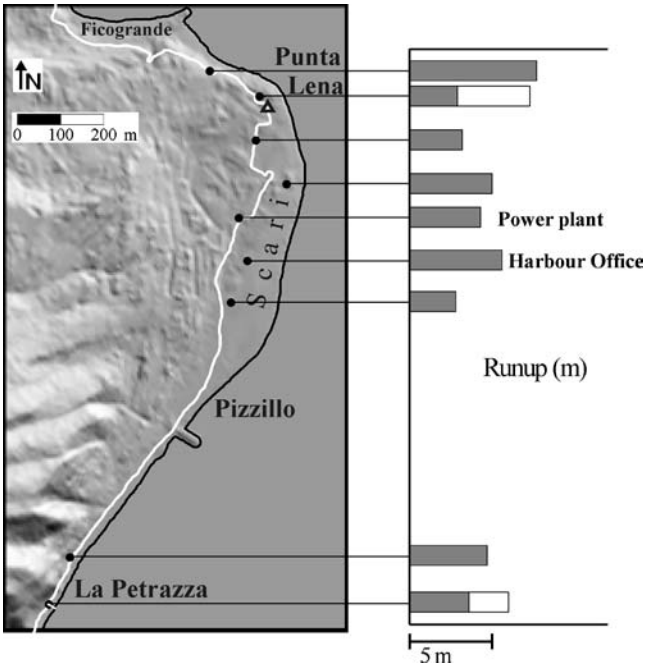

Fig. 6 Same as Fig. 4, but corresponds to sector C of Fig. 2. The *white solid line* at La Petrazza indicates the path of the transect in Fig. 13. The *black open triangle* denotes the site where the lowest runup for Punta Lena was measured (2.9 m)

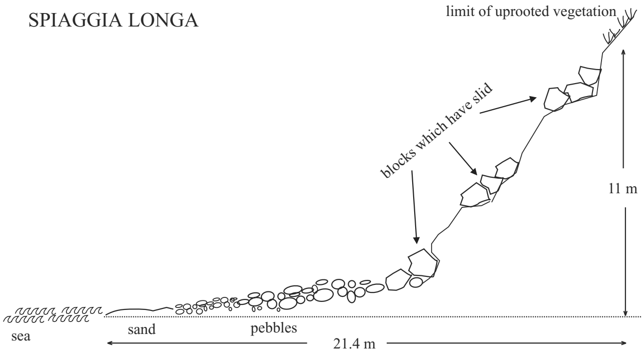

Fig. 7 Topographic transect measured at Spiaggia Longa corresponding to the site where the highest runup value (10.9 m) of the entire survey was recorded. The path covered by the transect is sketched in Fig. 4 as a *black solid segment* connecting the coastline and the second measured point from the northwest

Piscità

At the southeastern end of Spiaggia Longa, the first houses of the hamlet of Piscità are found. Here the coastline is characterized by a sequence of pocket beaches and inlets separated by rocky promontories, as can be seen in Figs. 4 and 5. The impact of the tsunami waves was severe. The buildings directly facing the beach and standing below 11–12 m above sea level were seriously damaged, even at distances of some 50–60 m from the shoreline, while those placed approximately 12 m above sea level remained untouched or were only marginally affected. Typical effects of the tsunami impact were low brick walls and balustrades knocked down, door and window frames

Fig. 8 Flattened vegetation, small boats carried inland, and small walls toppled down as observed in one of the houses at the northwestern end of Piscità. The picture was taken during the first of three surveys (11–13 January 2003)

unhinged, windowpanes broken, sand deposited inside the houses and along the inner narrow streets, shrubs flattened, and small boats and other objects moved inshore (Fig. 8). In some houses, the water impact was so violent that furniture underwent a sort of "centrifugal effect" and was heaped untidily in the rooms.

In the northwestern sector of Piscità, at the end of Spiaggia Longa, maximum runups lie in the range 6.9–10.7 m. In the small inlets near Ficogrande, runup measurements are variable. For example, we measured an 8.9-m maximum runup at the small beach called "Spiaggia Castriota" (Fig. 4). Some 100 m along, in the inlet called "Spiaggia Caterola", maximum runup was estimated at only 3.2 m, while in the following pocket beach, called "Scalo dei Balordi", the value for the measured runup was again up to 9.1 m. In terms of the horizontal wave penetration in the three above-mentioned sites, we measured 41, 45 and 57 m, respectively.

Ficogrande

The border between Piscità and Ficogrande is indicated by the sloped street that connects Piscità and the port of Pizzillo. The village is separated from the sea by an approximately 40 m-wide by 230 m-long beach, delimited by two piers and characterized by sand and pebbles (Fig. 5). Ficogrande is mainly a summer resort, with several hotels and holiday houses directly facing onto the beach. Fortunately, due to the winter season, the beaches and the village buildings were almost completely uninhabited. Thus the impact of the water waves, which were particularly violent here, caused no fatalities. The damage produced by the tsunami was severe. Some small buildings were completely flattened, many walls were knocked down, including an inner wall in a house located about 5 m above sea level. A substantial amount of sand and pebbles was deposited in courtyards, terraces and inside the houses. Moreover, the tsunami moved every object it found along its path, including volcanic blocks, boats and scooters, and heaped everything in courtyards or along narrow streets and stepped paths (Fig. 9).

In the northwestern part of Ficogrande, mainly corresponding to a restaurant called "La Tartana", measured runups lie in the interval of 3.5–6.5 m. The water waves here were able to climb up the main street coming from Piscità for several tens of meters. Moving eastward along the beach, the maximum runups tend to increase. Based on tips from eyewitnesses, we selected a watermark along the stepped path that separates the hotels "La Sirenetta" and "Miramare". The measured runup and horizontal penetration were 8.3 m and approximately 65 m, respectively. Because the direction of impact of the tsunami waves was almost perpendicular to the beach and to the houses in this part of the hamlet, the highest runups occurred in the eastern part of Ficogrande, in the sector facing the old eastern pier that is no longer used. The pier did not provide any protection, as is shown by the 9.3-m runup measured at a point beyond the pier itself. The transect corresponding to the highest runup value in Ficogrande (9.5 m) is

Fig. 9 Photo showing small boats, broken walls and debris carried by the tsunami waves and channelled along one of the narrow streets of Ficogrande. The picture was taken during the second of the three surveys (21–23 January 2003)

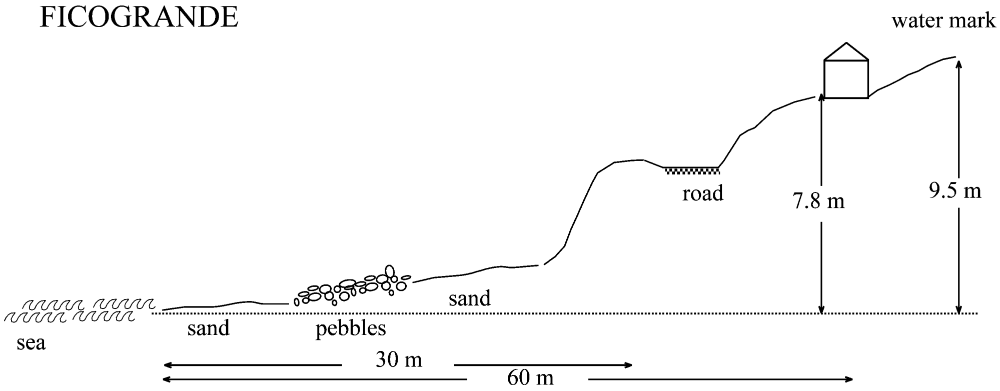

Fig. 10 Detailed transect corresponding to the last houses at the eastern termination of Ficogrande

represented by a solid black line in Fig. 5 and is sketched in Fig. 10. The water waves climbed up the beach, overtopped the street, entered the terrace of a house where fresh sand deposits and damaged doors were observed (local runup equal to 7.8 m), then travelled through the backdoor of the house and continued to climb up the narrow street in the back to a height of 9.5 m above sea level. The horizontal extent of the transect was approximately 60 m.

Punta Lena

Punta Lena is the northeastern corner of the island of Stromboli (see Figs. 2 and 6). In recent years, several holiday houses and small villas have been built very close to the shoreline. The local dynamics of this stretch of coast is characterized by beach erosion, which is reported by local inhabitants to have increased after the construction of the eastern pier of Ficogrande in the 1970s (named "Old pier" in Fig. 5). This problem led to an attempt to protect the shore through the emplacement of concrete blocks along the shore itself in the early 1980s. These reinforcements did not attenuate the effects of the tsunami impact on the houses of Punta Lena, which suffered very severe damage. Boundary walls, gates, doors and windows were knocked down or destroyed (Fig. 11a). Railings and iron fences were bent, and were excellent indicators of the direction of the impacting waves. Pebbles thrown shoreward by the waves remained stuck inside the slots of several windows. Small pebbles were also found over the roof of

Fig. 11 **a** Typical damage observed to holiday houses in Punta Lena which were built very close to the shoreline. The picture was taken during the second of the three surveys (21–23 January 2003). **b** Another typical view of damage produced by the 30 December 2002 tsunamis. Furniture is heaped inside and outside a house in Punta Lena. The picture was taken during the second of the three surveys (21–23 January 2003)

a building at the height of about 7 m. Water rushed in the narrow passages between the houses and into the internal courtyards dragging gas cylinders, household appliances, vegetation and small boats with it. Furniture inside several houses was heaped or ejected outside due to strong whirlpools (Fig. 11b).

Maximum runups at Punta Lena vary between 2.9 and 7.7 m; Fig. 6 summarizes locations and values of the measurements. The highest value (7.7 m) was found at the western end of the hamlet, close to the restaurant called "Punta Lena". Here the watermark was a lava block brought inshore as far as the main street. The corresponding horizontal penetration of the tsunami was estimated here at 40 m. The lowest runup (2.9 m) was measured inside a courtyard corresponding to a collapsed small wall. At this site, indicated as an open black triangle in Fig. 6, the ingression was about 60 m.

Scari

At the southeastern termination of Punta Lena, the main street makes a right turn and starts to run almost parallel to the coast. Here the village of Scari begins. The residents usually refer to Scari as a zone that extends to the south to include the area where the main pier of the island is found. The correct map toponymy of this location should be Pizzillo. In this paper, we will adopt the place name of Scari both for Scari itself and for Pizzillo. Scari is characterized by a wide beach, mainly composed of pebbles and sand, with a very gentle slope assisting water to penetrate deep inland. This is the locality where the maximum horizontal inundation was measured. In recent years in the northern section, several private holiday houses have been built directly on the beach a few tens of meters from the shoreline. More buildings stand landwards on the opposite side of the main street. They are mainly warehouses, boat depots and small huts. The most important building is the electric power plant that provides energy for all of Stromboli Island, except for the village of Ginostra. Due to the beach width and the increasing distance from the tsunami source region, the tsunami impact in Scari was less disastrous than in the other hamlets. Damage occurred to the aforementioned houses built on the northern sector of the beach. Here we observed similar kinds of damage seen at Piscità, Ficogrande and Punta Lena. Particularly impressive were the erosion produced by the tsunami on the house foundations and the possible formation of erosional scarps (Fig. 12a); in this second case, however, eyewitnesses did not agree on the existence and/or the possible height of the scarps prior to the tsunami occurrence.

We measured a horizontal sea penetration of about 146 m corresponding to the football field placed at the border between Scari and Punta Lena. Here the water waves attacked the beach, overtopped the street, bent the fence (Fig. 12b; from the direction of bending we estimated a medium direction of 261°W for the incoming waves), invaded the football field and, according to an eyewitness, reached the base of the stairs of a private house. The runup at this house was 3.2 m. Another interesting site is represented by the electric power plant. The water waves flooded the power plant area, which is found at a distance of about 134 m from the shoreline. The runup here was estimated at 4.3 m. The maximum value for the runup (5.6 m) was measured at the Harbour Office, which is built on the beach and is about 80 m from the sea. The mark was the height of the wall of the office facing the sea, which was reported to have been overtopped by the tsunami. This is thus a minimum value.

La Petrazza

Along the stretch of coast south of the Scari pier, traces of the tsunami impact were not obvious. Very likely, the tsunami here was responsible for erosive phenomena associated with small landslides of the steep near-shore escarpments. In some places, watermarks were represented by uprooted vegetation or by huge blocks detached from the scarps. The measured runup values range from 1.5 to 6 m, with maximum ingression of about 22 m. The short white segment connecting the shoreline with the southernmost measured point in Fig. 6 represents the path of the transect corresponding to the highest runup elevation (6 m). Figure 13 illustrates some details of the transect itself.

The southern and southwestern coasts

These sections of the Stromboli coast running clockwise approximately from Malpasseddu to Punta Frontone is almost inaccessible from land (Fig. 2). The effects of the tsunami on this long coastal belt were estimated qualitatively during a boat trip around the island. The only place where it was possible to land during the trip was southern Punta Lena. Here, the stone-covered beach is uninhabited and characterized by vegetation close the shoreline. At the time of the survey (January 2003), the vegetation was untouched, which indicates that the tsunami produced no effect in southern Punta Lena.

We also collected some clues from eyewitnesses at Ginostra, located in the southwestern part of the island. The village itself stands at about 50 m above sea level, so no tsunami effect was observed there, but its small harbour was affected by strong sea agitation, causing a couple of small boats to be carried onto dry land.

Tsunami effects in the other Aeolian Islands and in the far field

A detailed description of the field surveys carried out in the Aeolian Islands and in the far field is provided in Maramai et al. (2005a) and for the coasts of Campania in Nappi et al. (2003). Here we briefly summarize their main findings, particularly those related to the observed tsunami's first polarity and duration.

Within 20 min from the generation of the tsunami, waves reached all the Aeolian Islands from Panarea to Vulcano. The time of impact of the first tsunami on the northern sector of Panarea (13:20 local time) and the time taken by the sea waves to reach the southern coasts of the island (about 2 min later) are well documented by the records of the three-component broadband seismometer stations installed at the island (La Rocca et al. 2004). In terms of tsunami

Fig. 12 **a** Erosion effects observed along the Scari beach during the first survey (11–13 January 2003). **b** Fence bent by the tsunami along the portion of the main road running between Scari and Punta Lena. Picture taken during the first survey (11–13 January 2003)

effects, Panarea is the only island that suffered significant damage. Measurements have been carried out in San Pietro harbour (Fig. 3) where the wave effects were more evident. In this locality, the sea first receded for about 100 m and then attacked the coast, causing damage to structures on the beach (kiosks, tables, etc.) and carrying small boats inland. Three withdrawals and subsequent inundations were observed. The maximum measured runup value was 2.3 m with an ingression of 36.5 m. At Drauto, a considerable sea retreat of about 20 m was observed, with the sea then

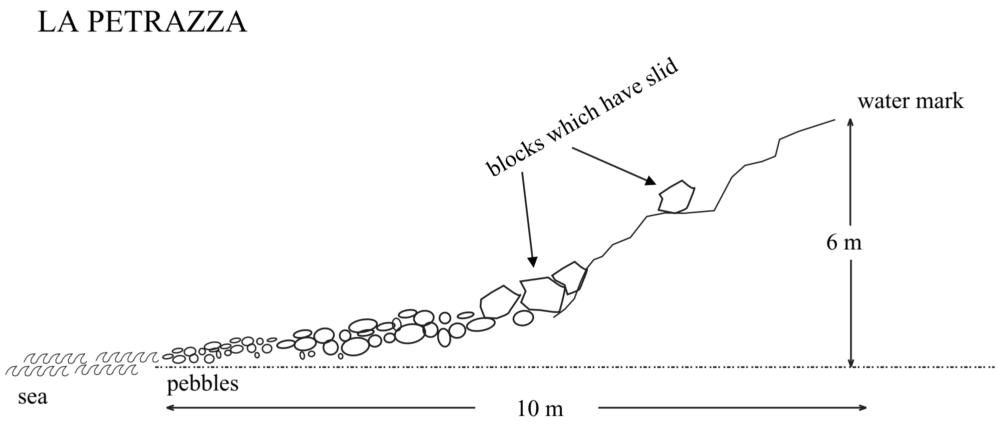

Fig. 13 Details of the transect surveyed at La Petrazza corresponding to the largest local runup measurement (6 m)

flooding the beach slightly further than the usual limit, without any damage.

In all the other islands of the archipelago (Fig. 1), tsunami effects were observed, but without causing any damage. Eyewitnesses report anomalous sea behaviour typically manifested as extraordinary tides or whirlpools. At Salina, the tsunami arrival time, from eyewitness accounts, ranges between 13:20–13:40 local time, depending on the location of the observers. Along the northern and southwestern coasts of the island, available accounts report an initial withdrawal of the sea, while a rise was the first movement observed along the eastern sector of the coastline where the tsunami was manifested as a sequence of 3–4 waves. At Lipari, the first tsunami wave was observed between 13:25–13:35 local time. On the northern side of the island a withdrawal was seen first; two waves were reported, and the entire phenomenon lasted 15–20 min. The first tsunami polarity and the number of waves along the eastern coasts are more controversial. A sea retreat between 13:30–13:40 was the first tsunami manifestation reported along the coasts of Vulcano; the sea movement consisted of 2–3 waves. Similar observations are attributed to Filicudi, where the tsunami was seen around 14:00 local time.

The tsunami propagated into the entire southern Tyrrhenian Sea, with energy very likely focussing especially towards the south and southwest in the direction of northern Sicily, west towards the island of Ustica and northeast towards northern Calabria to southern Campania. In Milazzo (northern Sicily), a single powerful wave attacked the oil refinery where a tanker involved in discharge operations made leeway for about 10 m. The tsunami was also observed at Mondello, ca. 10 km north of Palermo, as a series of sea swells starting around 14:00 and lasting for about 20 min. Regarding Ustica, located 170 km west of Stromboli, the tsunami started around 13:45 with a low withdrawal along the eastern coasts of the island, followed by an inundation. The sea agitation lasted for about 2 h. Finally, the tsunami waves attacked the southern Campania coasts at about 13:55. In particular, in the village called Marina di Camerota eyewitnesses saw the sea first recede and then attack the little harbour like a fast tidal movement.

Conclusions

This paper is a short report of the observations made in a number of surveys carried out in the weeks following the Stromboli tsunamis. The zone most affected was found to be the northern and the northeastern coasts of Stromboli, where most of the houses built along low beaches were destroyed or severely damaged. The toll of the tsunamis did not involve human fatalities because of two main reasons. Firstly, there were no people living in most of the affected houses at the time of the tsunamis, since private houses and hotels are used as holiday facilities during most of the year, except in late autumn and winter when they are vacant. Secondly, local residents and the very few tourists present were alerted by the noise produced by the arriving tsunamis and had time to run to safer places.

The zone of the highest damage was only a few kilometres long, and therefore it was possible to perform a very detailed survey. In the field, we were not able to find any means to discriminate between the two tsunamis since their arrivals were separated by a very short time interval. Only interviews with some eyewitnesses allowed us to partly clarify the different characteristics of the two episodes; we concluded that probably both were violent enough to be destructive (Tinti et al. 2005a). Runup heights were seen to decay as one moved from the source area in the Sciara del Fuoco towards the hamlet of Scari. No measurements could be taken near the source, since it was believed to be too dangerous to work there immediately after the tsunami events. Also, the traces of tsunami impact were very likely obliterated by the subsequent episodes of lava flows and slope failure. The surveyed coastal segment next to the source was Spiaggia Longa (Fig. 1) where the highest runup value of 10.9 m was found. Here the waves impacted a steep cliff beyond a narrow stony beach and produced a clear mark on the vegetation at the head of a fresh rockfall, probably caused by the tsunami itself. The observed rapid decay is typical of limited-area tsunami sources such as landslides, and is much larger than the tsunami decay usually associated with seismic sources (Okal and Synolakis 2003). This provides evidence that the tsunamis could not have been caused by a tectonic dislocation.

The tsunamis were also violent at the beach of Scari on the eastern coast of Stromboli almost opposite to the source region, demonstrating that tsunami waves are able to travel around islands and affect areas that are in the shadow of typical short-wavelength wind waves. This is well known and is both experimentally and theoretically verified (see Tinti and Vannini 1995).

These events were the first damaging tsunamis to hit the coasts of Italy in the last 50 years (see the Italian tsunami catalogue by Tinti et al. 2004). The impact on the local population and on public opinion in general in Italy was thus quite strong. The occurrence of these tsunamis caused by complex mass failures on the flank of Stromboli helps explain the cause of other tsunamis known to have taken place during previous eruptive crises of the volcano. A recent re-analysis of historical tsunamis which have occurred in the Aeolian Islands since the beginning of the last century reveals that (1) at least two more cases of a double tsunami occurred at Stromboli (1930 and 1944), (2) the second tsunami in 1930 was characterized by certain features (violent attack of Punta Lena, negative first arrival followed by flooding, etc.) which resemble the first tsunami of 2002, pointing to a submarine failure in the Sciara del Fuoco area as the cause of the waves (Maramai et al. 2005b). Mass failures along the slopes of Stromboli during eruptive paroxysms of the volcano can be the genesis of local tsunami episodes, which may have occurred six times since 1916 (Maramai et al. 2005b). This frequency of occurrence outlines the importance of carefully describing the features of the recent 2002 tsunamis, since this information can contribute to prevent and protect from the effects of future events.

Acknowledgements The research was funded by INGV-GNV. The authors wish to acknowledge the support received from the Italian Civil Protection authorities who provided authorization to access the sites during the emergency period and indispensable logistics.

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