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Unusual sedimentary deposits on the SE side of Stromboli volcano, Italy: products of a tsunami caused by the ca. 5000 years BP Sciara del Fuoco collapse?

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Abstract

The role of sector collapse in the generation of catastrophic volcanigenic tsunami has become well understood only recently, in part because of the problems in the preservation and recognition of tsunami deposits. Tinti et al. [Tinti, S., Bortolucci, E., Romagnoli, C., 2000. Computer simulations of tsunamis due to sector collapse at Stromboli, Italy. J. Volcanol. Geotherm. Res. 96, 103–128] modeled a tsunami produced by the c. 5,000 years BP collapse of the Sciara del Fuoco on the island volcano Stromboli. Although deposits associated with this event are generally lacking on the island, volcaniclastic breccias on the SE side of the island extending to an elevation above 120 m a.s.l. may have been generated by this tsunami. Deposits above 100 m are dominated by coarse breccias comprising disorganized, poorly sorted, nonbedded, angular to subangular lava blocks in a matrix of finer pyroclastic debris. These breccias are interpreted as a water-induced mass flow, possibly a noncohesive debris flow, generated as colluvial material on steep slopes was remobilized by the return flow of the tsunami wave, the run-up of which reached an elevation exceeding 120 m a.s.l. Finer breccias of subrounded to rounded lava blocks cropping out at 15 m a.s.l. are similar to modern high-energy beach deposits and are interpreted as beach material redeposited by the advancing tsunami wave. The location of these deposits matches the predicted location of the maximum tsunami wave amplitude as calculated by modeling studies of Tinti et al. [Tinti, S., Bortolucci, E., Romagnoli, C., 2000. Computer simulations of tsunamis due to sector collapse at Stromboli, Italy. J. Volcanol. Geotherm. Res. 96, 103–128]. Whereas the identification and modeling of paleo-tsunami events is typically based on the observation of the sedimentary deposits of the tsunami run-up, return flow may be equally or more important in controlling patterns of sedimentation.

Keywords: tsunami; flank collapse; landslide; run-up; return flow; debris flow

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1. Introduction

The importance of tsunami generation by the collapse of volcanic edifices has been recognized only relatively recently. McGuire (1996) drew attention to the instability inherent in island and coastal volcanoes; the lack of buttressing on at least one flank of most such volcanoes results in seaward-directed stresses which may be released variously by aseismic creep, co-seismic downfaulting, or episodic sector collapse. Even in such an apparently simple stress regime, however, triggering mechanisms for flank collapse may be several, including: bulging from dome building or dike intrusion, oversteepening by rapid accumulation of eruptive products or other surface loading, and seismicity (McGuire, 1996). Keating and McGuire (2000) went farther and identified 23 causes of ocean–island instability, describing both endogenetic processes, such as those previously mentioned, as well as exogenetic mechanisms, including climatic effects, karstification, sea-level loading variations, and lithospheric flexure. Importantly, as noted by Moore et al. (1994), there is a significant difference between slumps and avalanches in terms of process, rate, and morphology. Whereas the former are segments of the edifice that are typically slowly displaced, the latter are rapidly displaced, high energy mass movements with long run-outs.

Therefore, it is the avalanches that create the specific hazard of tsunami generation, especially on island volcanoes and in cases where submarine landslides are involved in the collapse. Smith and Shepherd (1996) estimated that at least 20% of volcanigenic tsunami result from sudden volcanic edifice collapse. Even relatively small debris avalanches (<1 km^3) have been demonstrated as capable of causing destructive tsunami in historic times (Siebert et al., 1987; Satake and Kato, 2001). Tsunami generation often arises from the submarine collapse of large portions of the volcano, which may involve much greater volumes of rock than the subaerial portion (Satake and Kato, 2001). Krastel et al. (2001) documented giant submarine landslides, with volumes of 10 s to 1000 s km^3 and run-outs of over 20 km, on the flanks of the Canary Islands. These collapses occurred during the Pleistocene at a frequency estimated at one every 125 to 175 ka. The limestone-bearing Hulopoe Gravel, which crops out to an elevation of 326 m on the slopes of Lanai Island, was interpreted (albeit controversially) as the product of a giant tsunami event by Moore and Moore (1984, 1988). Although interpretation of the Hulopoe Gravel remains debated (Felton et al., 2000), recognition of the hazard potential and development of appropriate monitoring networks and forecasting capabilities in this and other collapse-prone settings is recognized as imperative for the safety of the millions who live in the vicinity of island and coastal volcanoes. For example: Smith and Shepherd (1996) conducted an assessment of the tsunami risk posed to the Caribbean region by the submarine volcano Kick 'em Jenny; Day et al. (1999) noted the potential for tsunami generation by flank collapse in the Cape Verde Islands; more recently, Ward and Day (2001) calculated the potential size of tsunami waves impacting the Atlantic coast of North America generated by flank collapse in the Canary Islands; and Tinti et al. (2003) have investigated the potential impact on the coastlines of Calabria and Sicily of a flank collapse at Stromboli volcano similar to the event of 5,000 years BP.

In contrast to modern tsunami, for which eyewitness accounts and field measurements of both erosional and depositional effects are utilized in modeling studies (Synolakis et al., 1995), palaeotsunami recognition depends on the identification of ancient tsunami deposits (Bourgeois et al., 1988; Long et al., 1989; Smit et al., 1992; Bondevik et al., 1997). Tsunami deposition is most commonly characterized by the redeposition of coarse shallow marine or coastal sediments in a terrestrial environment, and recognition of these deposits is the primary field method of ex post facto measurement of tsunami run-up height, although patterns of erosion and deposition by both landward- and seaward-directed flow are complex (Moore and Moore, 1984; Synolakis et al., 1995; Bondevik et al., 1997; Dawson and Shi, 2000). Understandably, the nature of tsunami deposits varies greatly with coastal topography, the height of tsunami run-up, and with the nature of shoreline sedimentation in any coastal setting. Consequently, the possible variations in sedimentary processes and products during these complex events remain poorly understood (Bondevik et al., 1997). Sediment deposited during tsunami run-up is generally considered easy to recognize; shallow marine or beach sediments found in a stratigraphically narrow band in a landward environment is evidence of redeposition by wave run-up. Young and Bryant (1992) proposed, however, that the primary record of tsunami waves may be coastal abrasion. Only recently has the subsequent backwash, or return flow, been regarded as a process of significant geomorphic and sedimentologic consequence (Dawson, 1994; Maramai and Tinti, 1997; Dawson, 1999; Hindson and Andrade, 1999; Dawson and Shi, 2000).

In this paper, we describe sediment deposits on the southeastern flank of Stromboli that may be associated with a giant tsunami that resulted from a sector collapse on the volcanic island approximately 5,000 years BP. For purposes of comparison with this event, we also describe the deposits of several modern storm and tsunami waves of lesser magnitude. It is clearly important to assess the potential hazard for tsunami deposition on the island in view of possible recurrence of these and larger magnitude events in the future.

2. Setting

The volcanic island Stromboli is a part of the Aeolian Arc in the southeast Tyrrehenian Sea (Barberi et al., 1974). The subaerial cone of this active volcano reaches an elevation of 924 m a.s.l., but the exposed portion is only a part of the steep-sided edifice that rises from depths of 1500 m b.s.l. to 2200 m b.s.l. from the Sicilian–Calabrian continental slope (Gabbianelli et al., 1993). The subaerial cone has been built mostly within the last 100,000 years (Gillot and Keller, 1993), during which time the history of the volcano has been characterized by periods of edifice construction followed by sector collapse (Tibaldi, 2001). Instability of this edifice is promoted by a combination of factors, including: oversteepening during constructional phases; seaward-directed gravitational stress generated by the lack of buttressing of the northwestern flank; and dike intrusion along a northeast–southwest axial fault system (Tibaldi et al., 1994; Kokelaar and Romagnoli, 1995; Tibaldi, 2001). As noted by Satake and Kato (2001), Stromboli has a size and instability history rather similar to the Oshima-Oshima volcano. Events during the 1741 Oshima-Oshima eruption apparently were comparable to those that characterized the 2002 Stromboli eruption (Andronicco et al., 2003; Bonaccorso et al., 2003); both eruptions involved flank failure of subaerial and submarine portions of the volcanoes, generating tsunami waves with maximum run-up of 15 m in the case of Oshima-Oshima, and of 10 m in the recent example of Stromboli.

The most recent catastrophic collapse event of Stromboli, which occurred at most 5,000 years BP, created a deep indentation called the Sciara del Fuoco (SDF) on the northwest-facing flank of the volcano (Fig. 1; Gillot and Keller, 1993; Tibaldi, 2001). This horseshoe-shaped sector-collapse scar extends from an elevation of about 800 m a.s.l., for a lateral distance of about 3 km, to a depth of 700 m b.s.l., where it has a width of 2 km (Romagnoli et al., 1993). From analysis of the shape and extent of this depression, Kokelaar and Romagnoli (1995) estimated that the flank collapse responsible for the modern SDF produced an avalanche that displaced up to 1.8 km^3 of debris. The collapse products now comprise part of a 4 km^3 debris fan found at the base of the collapse scar, extending from a depth of 700 m b.s.l. to over 2500 m b.s.l. (Kokelaar and Romagnoli, 1995).

Displacement of the sea by the entering avalanche deposit and the submarine collapse may have generated tsunami waves of significant size. Wave heights of tens of metres have been documented for tsunami generated by the historical collapse at Ritter Island (Papua, New Guinea) in 1888, an event of similar magnitude to the SDF collapse (Ward and Day, 2003). Based on a conservative estimate of 0.97 km^3 for the volume of the most recent collapse of the SDF, Tinti et al. (2000) modeled the formation and propagation of the landslide, and of a subsequent tsunami wave that reached a shallow-water height of tens of metres. According to the model, the island bathymetry caused refraction of the wave around the island, thereby impacting the entire island perimeter, with maximum wave height potentially exceeding 50 m on the southeast side of the island. In this paper we describe a deposit on the southeastern sector of Stromboli, the opposite side of the island from the SDF, that may validate this model.

3. Field observations

The slopes of the subaerial cone of Stromboli are steep, between 40° and 50° over much of the island

(Fig. 1). Consequently, much of the surface of the island is geomorphologically unstable; those areas not presently mantled by contemporary pyroclastic products are undergoing erosion, exposing products of Neostrombolian and greater age. Few locations on the island offer relatively complete exposures of the stratigraphy developed over the last 5,000 to 6,000 years. Lower elevations on the island in the vicinity of the SDF (the northern and western sides) are well-covered by Neostrombolian and more recent lavas and pyroclastic products, a consequence of the northwestward migration of the eruptive vent over the last 15,000 years (Pasquaré et al., 1993). By contrast, reworked epiclastic products are better exposed on the southern and eastern slopes (Hornig-Kjarsgaard et al., 1993).

The deposit we correlate with the ca. 5000 years BP SDF collapse is exposed on the southeast side of the island, about 100 m north of the coastal point named Malpassedu (Fig. 1). Exposures occur above the beach in a steep valley called Le Schicciole that has a slope of 35° to 45°. The valley is surrounded by walls of lava, attributed to the Vancori eruptive cycle, which rise 20 to 30 m (Fig. 2; Hornig-Kjarsgaard et al., 1993). The deposit we describe is exposed in surficial outcrops only above an elevation of 100 m, but is exposed sporadically in ravines incised through a mantle of volcanic ash, which fills the valley, down to an elevation of 15 m a.s.l. In the ravines, the breccia is typically overlain by 1 to 4 m of volcanic ash and scattered colluvial lava blocks.

Surficial exposures of the deposit at the upper elevations (above 100 m a.s.l.) are widely scattered, but correlative, over a broad area, suggesting a sheet-like geometry within the valley. The outcrops between 100 and 120 m a.s.l. comprise a poorly sorted, clast-supported breccia of disorganized subangular to angular lava blocks (Figs. 3 and 4). The maximum exposed thickness of the deposit in the upper reaches of Le Schicciole is 2 m, as seen in small ravines incised into the deposit, but the base of the breccia bed at this elevation is not visible. The blocks are a heterogeneous assemblage of lavas coloured red, gray, and black, representing a mixture of basaltic to trachytic lavas of the Vancori eruptive cycles (Hornig-Kjarsgaard et al., 1993). The surfaces of some blocks display evidence of oxidation. Individual clasts are up to 70 cm in length (a-axis), and the mean clast size is 15 cm, but the range of grain sizes displays a continuum from ash to blocks. Approximately 50% of the breccia consists of grains >2 cm in diameter. No grading or stratification is discernible within the deposit. The larger blocks are in point contact, resulting in a clast-supported fabric. Spaces between the blocks are filled by a gray-coloured matrix of ash- to lapilli-sized lava fragments. The

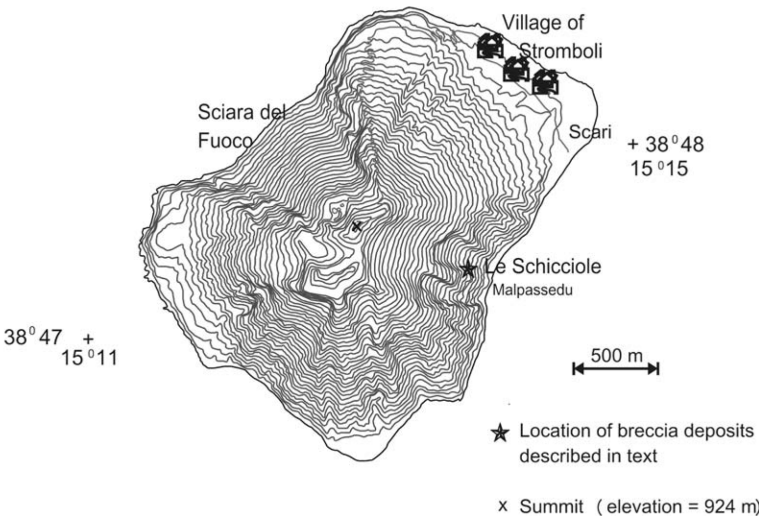

Fig. 1. Topographic map of Stromboli with the locations of Sciara del Fuoco, Scari, Le Schicciole, and Stromboli village indicated. Contour interval equals 20 m.

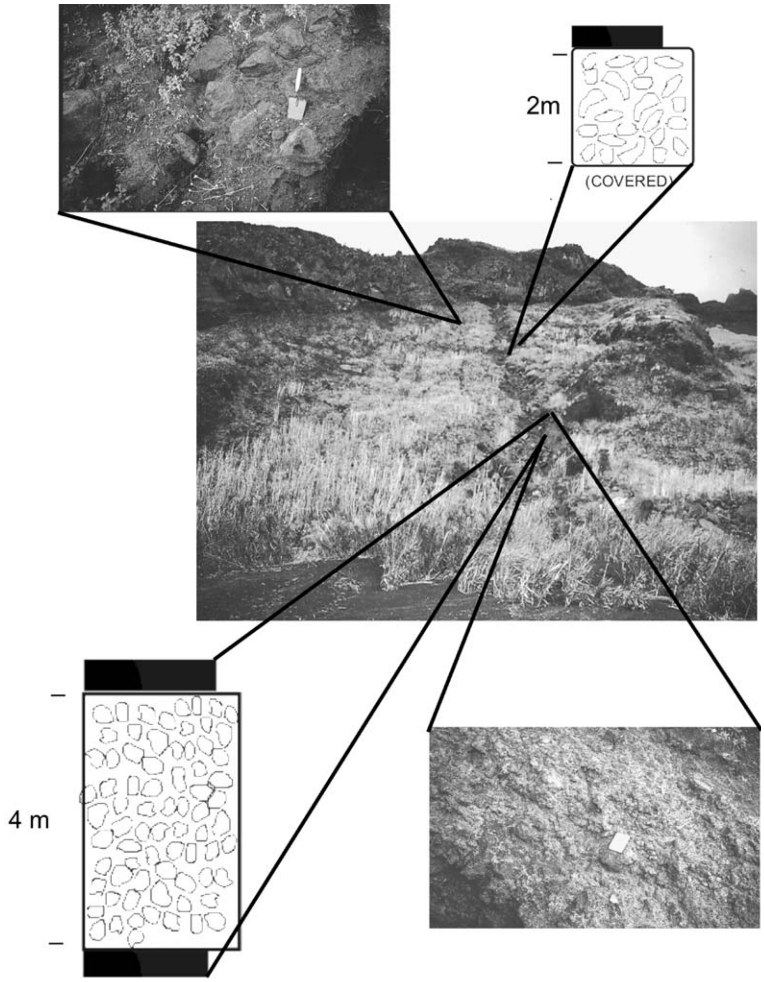

Fig. 2. View from beach of the southern rim of Le Scicciole. The lava ridge to the right joins the left wall at an elevation of about 200 m a.s.l. A coarse lava block breccia is exposed at the surface (upper left insert) at elevations above 100 m and in the ravine in the center of the photograph, where it is covered by ash (upper right measured section). The finer breccia (lower insert photograph and section) is exposed in the walls of the ravine at an elevation of 15 m. The trowel in the upper left insert is 30 cm. The field book in the lower right insert is 19 cm.

orientation of a–b plane of blocks with bladed or discoidal shapes, as defined by Zingg shape analysis, was measured in outcrop; the orientation of these blocks is highly variable, ranging from subhorizontal to nearly vertical, with no preferential orientation observed (Fig. 5). The grain size and fabric of this breccia contrasts with overlying pyroclastic and colluvial material consisting predominantly of volcanic ash and widely separated lava blocks. At elevations below 100 m a.s.l., the deposit is poorly exposed at the surface, but is exposed sporadically beneath 1 to 4 m of ash and colluvial blocks in the walls of an erosional gully that extends from 100 m down to 15 m a.s.l. The lighter colour of the breccia matrix contrasts strongly with the overlying dark volcanic ash layer, rendering the deposit easily visible.

At the lowest elevation, a well-exposed, 4-m-thick section that is texturally distinct from the upper breccia crops out below a dark, ash-rich soil cover; the base of this deposit rests visibly over a dark ashy layer similar to that overlying the deposit. Locally, outsized lava blocks (up to 1 m long) occur at the base of the deposit. Similar to the breccia at higher elevation, the lower deposit also comprises a non-

Fig. 3. Surficial exposure of the breccia at about 100 m a.s.l. Lava blocks up to 50 cm long are heterolithic and tightly packed (clast-support fabric). Folded rule (upper left) is 21 cm.

graded, clast-supported breccia, but in contrast to the upper exposures, this lower deposit displays crude stratification parallel to the slope. The clasts of this lower breccia are smaller, with a maximum clast size of 20 cm (*a*-axis length) and mean size of 8 cm (Fig. 6). The clasts have a subspherical to discoidal shape, and are more homogeneous in composition than in the upper deposit, comprising mostly black lavas. The clasts are mostly in point contact with the interclast space filled by a matrix of ash- to lapilli-sized particles. The matrix (clasts<2 cm) comprises approximately 40% of the deposit. The limited extant of the outcrop does not expose a sufficient number of clasts for statistically meaningful analysis, but visual inspection indicates that clasts with a discoidal shape are generally oriented parallel to, or at a low angle to the depositional slope (Fig. 6). This is in contrast to the fabric of the coarser breccia at higher elevations. The precise nature of the transition from the breccia at higher elevations to this finer-grained deposit is unknown due to incomplete exposure in the gully, but the transition appears to be abrupt over an elevation change less than 10 m. The breccia deposit is not exposed below 15 m a.s.l.

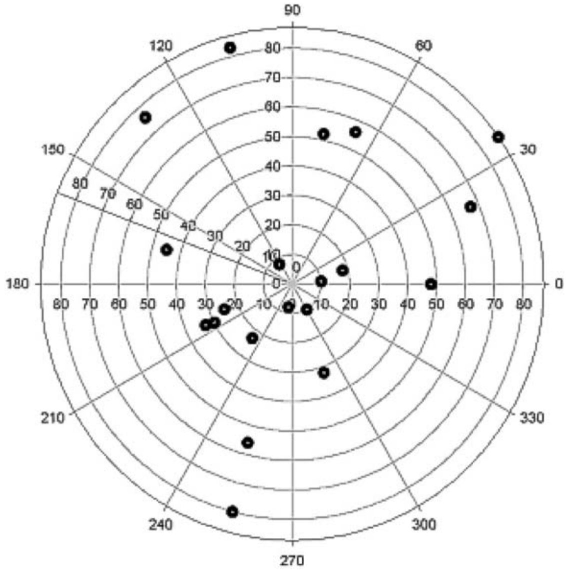

Fig. 5. Plot of poles to a–b planes of 20 discoidal clasts in upper breccia outcrops reveals high variability of clast orientation with a subequal distribution of a–b plane dips between high angle (>45°) and low angle (<45°).

Fig. 4. Exposure of breccia in ravine at about 120 m a.s.l. reveals wide range of clast sizes and varying clast orientations including near-vertical. Field book (lower right) is 19 cm for scale.

Fig. 6. Detail of lower breccia at about 15 m a.s.l. located in lower part of ravine in shown Fig. 2. Dark, ash-rich soil layer overlies deposit at upper right. The arrow indicates a discoidal clast that is oriented approximately parallel to depositional slope. The field book (for scale) is 19 cm long.

4. Interpretation

The breccia deposit exposed above 100 m is texturally distinct from the overlying colluvium and from pyroclastic and epiclastic deposits described elsewhere on the island by previous authors. Unlike the lahars of Secche di Lazzaro, for example, (Bertagnini and Landi, 1996), the upper breccia has a disorganized, clast-supported fabric and the matrix is nonindurated, lacks accretionary lapilli, glassy shards, or palagonitic colouration (Hornig-Kjarsgaard et al., 1993). Other evidences for emplacement as a pyroclastic flow, such as juvenile material, bombs, or blocks with radial cooling joints, are also absent (Duncan et al., 1996). Additionally, the accumulation of colluvium tends to form gravitationally sorted deposits with a slope-parallel mean clast orientation (Tanner and Hubert, 1991). Although the oxidation of the surface of some lava blocks in the deposit suggests that the material first resided as colluvium, the extreme poor sorting, the concentration of lava blocks in a clast-supported fabric, and the random orientation of these blocks, rather than parallel to the slope, argue for redeposition as a mass flow. Sustained seismic shaking during a collapse or regional earthquakes might cause mass movement, but tectonic earthquakes on Stromboli are rare (Falsaperla and Spampinato, 1999), and the resulting process would more likely be an avalanche that would produce a deposit with a distinctly recognizable texture. However, features suggestive of a debris–avalanche origin, such as jig-saw fracturing and the preservation of original stratification (Smith and Lowe, 1991), are absent from the deposit. Additionally, seismicity would have triggered more extensive mass-flow deposition than we observe; the absence of deposits with the characteristics we observe at Le Schicciole in a similar stratigraphic position at other locations on the island, at either higher or lower elevation, suggests that the conditions for formation of this deposit were unique to this part of the island.

Classic debris flows are sediment gravity flows in which well-known features, such as a rigid plug and rafted boulders, result from the support strength provided from a cohesive matrix (Nemec and Steel, 1984; Smith and Lowe, 1991). Noncohesive debris flows lack clay-sized material in the matrix, but still may display typical debris-flow features, such as inverse grading, caused by grain interactions during flow (Nemec and Steel, 1984). We interpret the coarse-grained, disorganized breccia exposed at higher elevations in the Le Schicciole valley as a water-generated mass-flow deposit, possibly as a noncohesive debris flow. This interpretation is based on the lack of bedding in the deposit, the random clast orientation, the extremely poor sorting, and the heterogeneous nature of the clasts, all considered typical characteristics of debris flows generated by sudden remobilization of loose material (Nemec and Steel, 1984; Tanner and Hubert, 1991). The weathered surfaces of many of the blocks in the breccia suggest that the material in the breccia accumulated as colluvium on the slopes of the volcano prior to redeposition.

Torrential rainfalls are considered a primary trigger for many debris flows in terrestrial environments (Johnson and Rodine, 1984). Although intense precipitation events capable of moving blocks by traction flow might be possible, debris flows are unlikely to be generated by rainfall in this setting. This is because precicipation easily infiltrates the porous, ash-rich colluvial material and fails to create sufficient pore pressure for initiation of mass flow (Blair, 1999). By contrast, the sudden and intense nature of the return flow created by a tsunami wave would simultaneously inundate pore spaces, causing high pore pressures and weakening grain–grain contacts, and create high velocity traction flow that would be quite capable of mobilizing material of all sizes on steep slopes. Therefore, we suggest that at high elevations on the steep coastal slopes, where excessive run-up heights are possible, backwash may be an effective agent in sediment mobilization. The rapid loss of momentum of a tsunami wave as it climbs the slope quickly decreases the transport competence, resulting in the confinement of deposition by the advancing flow to lower elevations. Given a steep gradient, the subsequent return flow easily attains high velocity, and assuming sheet-flow conditions, an upper-flow-regime state. Such rapid surface flow is considered capable of remobilizing colluvial material accumulated on steep slopes to create debris and hyper-concentrated flows (Smith and Lowe, 1991).

Because the base of the upper deposit is inaccessible, only the upper contact with the overlying soil materials has been sampled for radiocarbon dating;

analyses have yielded only recent ages for carbonized plant material in this soil. We note, however, that modern plant roots penetrate the entire thickness of the soil layer, potentially contaminating ancient organic material through exchange with the modern atmosphere during decay. Although the age of this deposit is as yet poorly constrained, we argue that the stratigraphic position, clearly postdating Vancori eruptions and probably younger than Neostromboli pyroclastic products, but overlain by recent volcanic products and well-formed soil, suggests an age correlative with the main SDF collapse, about 5000 years BP.

We offer a contrasting interpretation for the process that deposited the breccia bed at the lower elevation (15 m a.s.l.), which displays a stratigraphic equivalence to the breccia at higher elevation. This we interpret as the deposit of a tsunami wave during run-up. The smaller, more rounded clasts that comprise this bed may have originated as reworked volcaniclastics, possibly beach debris, suggesting that this material was carried landward by the translatory motion of the advancing wave. In this regard, the lower breccia constitutes an "atypical" tsunami deposit (Dawson and Shi, 2000). We propose that the apparent limitation of clasts of this size and shape to this lower elevation indicates that the advancing wave rapidly lost momentum during advance, causing most primary (landward) deposition at elevations well below the maximum run-up. Scattered large blocks at the base of the breccia contrast with the breccia in their greater size and angularity. We note that blocks of this size are generally absent from the beach, but occur at the base of the slope. Therefore, we interpret these blocks in the breccia as colluvium that was present at the base of the slope prior to the advance of the tsunami. During run-up, these blocks were transported a minimal distance up slope and buried by finer-grained debris derived from the beach. Although this deposit lacks bioclastic marine sediments, we note below that this type of material is rare on the coast of Stromboli. Poor exposure of the lower deposit prevents identification of the maximum height of deposition by wave run-up. However, the limited exposure of the deposit formed by wave run-up is not surprising given the potential for reworking and erosion by the return flow, or for burial by mass-flow deposition triggered by the return flow. As the transition between the two distinct breccias is not exposed, one possibility (among several) is that the run-up deposits were originally buried by return flow deposits that were subsequently eroded. Finally, we suggest that on coastlines with steep slopes, which may favor particularly strong return flow, it may not be possible to distinguish entirely between deposition by advancing flow and by intense return flow.

5. Modern high energy shoreline deposits on Stromboli

Eruptions of Stromboli during 1930, 1944 and 1954 are reported to have generated tsunami of modest size (Rittmann, 1931; Barberi et al., 1993). To investigate if there exists a sedimentary record of these events, we trenched the beach at Scari (Fig. 1) to expose a stratigraphic section (Fig. 7). The site chosen is characterized by active shoreline deposition, rather

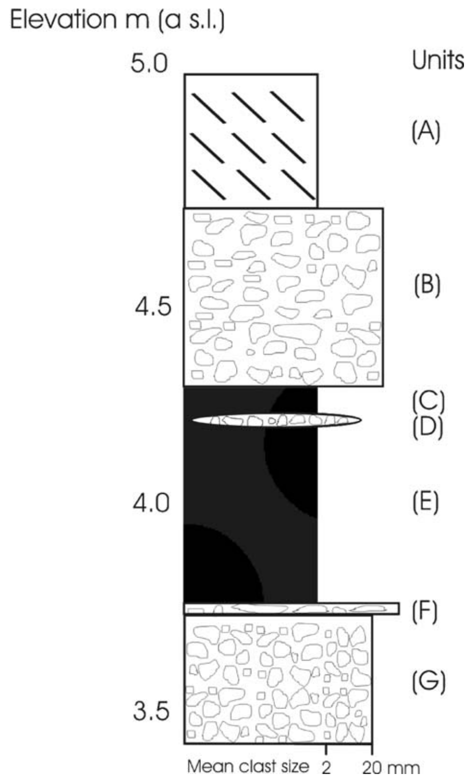

Fig. 7. Stratigraphic section exposed by trenching the backshore of the beach at Scari; stratigraphic units are described (as labeled) in the text. Elevation is relative to sea level.

than erosion, as indicated by active dune-building in the backshore. The resulting stratigraphic section was 1.4 m thick and has an upper elevation of 5 m a.s.l.. The section comprises, from the top down: (a) a 30-cm upper layer of well-sorted, cross-bedded ash; (b) a 40-cm layer of poorly sorted, coarsely bedded, matrix-supported pebbly gravel with most clasts ranging from 0.5 to 4 cm in diameter, and sparse outsize clasts up to 10 cm. This bed is ungraded and has a matrix of well-sorted ash. It overlies (c) a 6-cm layer of well-sorted black ash, and (d) a 4-cm-thick, laterally discontinuous lens of moderately sorted pebbles from 1 to 2 cm wide. Below this is (e) a 40-cm layer of well-sorted and ungraded black ash. At a depth of 1.2 m there occurs (f) a 4-cm layer of coarse gravel, with most clasts between 4 and 8 cm long and outsize clasts up to 16 cm in length. The clasts, which have heterogeneous lithologies, display well-rounded, discoidal shapes, and an imbricated fabric. The lowermost layer exposed in the trench (g) comprises more than 30 cm of clast-supported pebble gravel with ash matrix. The pebbles are from 1 to 3 cm in diameter, well-rounded, well-sorted, and of heterogeneous composition. The matrix consists of well-sorted black ash.

The uppermost layer in the section (a) is clearly a part of the modern eolian depositional regime in the present backshore environment. The lowest layer (g) is similar to the modern shoreline gravel in terms of clast size and fabric. Therefore, we interpret this layer as a previous shoreline built at an elevation about 4 m higher than the present shoreline. Thus, all coarse layers between (a) and (g) represent sediment accumulation in the backshore during events of higher than average energy conditions. Layer (f), for example, contrasts with layers (a) through (e) in the size, discoidal shape, and imbrication of the clasts, suggesting emplacement by a large wave or series of waves; possibly this layer is a sedimentary record of one of the tsunami that occurred during eruptive episodes of the volcano during the twentieth century. Imbricated fabric and coarse block size have been considered as recognizable features of tsunami deposits (Bryant and Nott, 2001). Interestingly, layer (f), among all of the layers exposed by trenching, bears the closest resemblance to the lower breccia deposit in regard to clast size and fabric. This suggests that a common process is responsible for their deposition. Notably, marine bioclastic debris is completely lacking in the stratigraphic section or on the modern shore. Presumably, the shallow ocean bottom surrounding the island is only sparcely inhabited by shelly organisms.

On 30 December 2002, two landslides on the SDF generated tsunami waves with heights up to 10 m a.s.l. that penetrated up to 120 m from the shoreline (Andronicco et al., 2003; Bonaccorso et al., 2003; Bertagnini et al., 2003; Maramai et al., 2003). Although the volume of the two landslides was about three orders of magnitude smaller than the main SDF collapse, the tsunami waves that formed during this event still caused significant damage inland on the east coast of the island (Bertagnini et al., 2003; Maramai et al., 2003) and reached the town of Milazzo, 50 km distant on the Sicilian coast (Andronicco et al., 2003). Following inland penetration of the waves, the surface of the beach along the eastern side of the island was littered with clasts up 40 cm long and incised by rills from the return flow. Notably, the return flow of one tsunami wave carried concrete blocks exceeding 3 m^3 in volume in a seaward direction for up to 20 m at Punta Lena. Unfortunately, no surveys have been made on the south coast of the island to examine the sedimentologic effects at Malpassedu.

6. Discussion

Recognition and classification of deposits associated with the ca. 5000 years BP tsunami previously modeled by Tinti et al. (2000) represent an advance in our understanding of tsunami generation and propagation. Using the shallow-water approximation of the Navier–Stokes equations of fluid mechanics, a method which is shown to be applicable to wave generation by sliding masses along underwater inclines (Villeneuve and Savage, 1993), Tinti et al. (2000) modeled wave formation; the wave size and travel times were then calculated using the finite element method. The model predicted the formation of a small leading wave front, trailed by a higher amplitude trough, followed by a very high amplitude wave crest. Bathymetric effects resulted in the arrival of multiple crests at some locations, and, most significantly, convergence of the refracted wave fronts on the southeast side of the island at Malpassedu. Constructive interference of these convergent fronts resulted in a predicted shallow-water wave elevation of over 50 m. A similar wave convergence on the side of an island was observed during the 1994 East Java tsunami (Synolakis et al., 1995).

Whereas the maximum height of tsunami run-up can be estimated qualitatively, given sufficient bathymetric data (Synolakis et al., 1995), absolute quantitative modeling remains difficult to attain (Satake, 1994); calculated run-up may be as dependent on wave form as on slope, bed roughness, and wave height (Geist, 1999). An empirical factor of 2 to 3 times deep-water wave amplitude has been used successfully, although a variation of run-up height of from 1 to 20 times has been demonstrated (Geist, 1999). At Malpassedu, a maximum run-up of slightly more than twice the predicted wave amplitude, based on the most conservative estimate of the initial collapse volume, would inundate the slopes on which the mass-flow deposit is observed. If the wave effects were recalculated given detailed topographical data and a more robust estimate of the slide volume and consequent increase in slide energy, penetration of the tsunami to much greater elevation, perhaps over 200 m a.s.l., is feasible.

7. Conclusion

The ca. 5000-years BP tsunami generated by the sector collapse that formed the modern Sciara del Fuoco likely affected the entire perimeter of the Stromboli coastline at lower elevations, but the deposits of this event are mostly buried by more recent volcanic products or have been eroded from the steep slopes that characterize the island topography. A sedimentary record of this tsunami is recognized only near Malpassedu, the location of the calculated maximum wave height. A breccia of subrounded to rounded lava clasts that crops out at 15 m a.s.l. at this location comprises beach material, similar to that observable on the modern beach, that was redeposited by the advancing wave during run-up. Disorganized, nongraded, clast-supported breccias of subangular to angular lava blocks cropping out above 100 m a.s.l. near Malpassedu are interpreted as a mass-flow deposit, possibly a noncohesive debris flow, generated when intense return flow of the tsunami wave remobilized colluvial material covering the steep slopes. The location of these deposits matches the model calculation for the location of maximum wave amplitude by Tinti et al. (2000). Convergence of the wave fronts refracted around the island in both directions produced a wave with a shallow-water amplitude of at least 50 m, based on a conservative estimate of the volume of the triggering landslide. This work demonstrates the value of theoretical modeling of catastrophic events, and the importance of their comparison with the geologic record. Identification of the landslide potential of island and coastal volcanoes can lead to the calculation of the associated tsunami risk and therefore should become a priority of the scientific community and civil protection agencies.

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