

# Volcanic Islands and Seamounts

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**Abstract** Recent advances in seafloor imagery systems have enabled the extensive mapping of submarine volcanic areas, depicting with unprecedented detail a large spectrum of landforms. They can be grouped in two main types: volcanic and erosive-depositional landforms, reflecting the interplay between constructive and destructive forces that control the growth and morphological evolution of volcanic edifices. Volcanic landforms mainly include primary volcanic constructs (cones, lava flows and delta, undifferentiated bedrock outcrops), but also volcano-tectonic features, such as caldera collapses. Erosive-depositional landforms typically cover most part of the volcanic flanks and include features related to wave erosion and sea-level fluctuations (insular shelves and guyots), gravity-driven instability processes (landslide scars), and density gravity flows (gullies, canyons, fan-shaped features, sediment waves). However, despite the large number of marine studies realized until now, we are still far from having a complete mapping of these areas as well as reliable models for the correct interpretation of several landforms, mainly because of the paucity of direct observations. A systematic monitoring of active processes is essential to understand the genesis and evolution of such phenomena; repeated multibeam surveys are playing a key role in this regard. Also the comparison and parameterization of these landforms in different settings can provide insights on the main factors controlling their genesis. But it is necessary to set shared and standardized protocols for the interpretation and analysis of morpho-bathymetric data, also in consideration of the exponential increase in data availability from these areas, whose study is becoming crucial for several disciplines.

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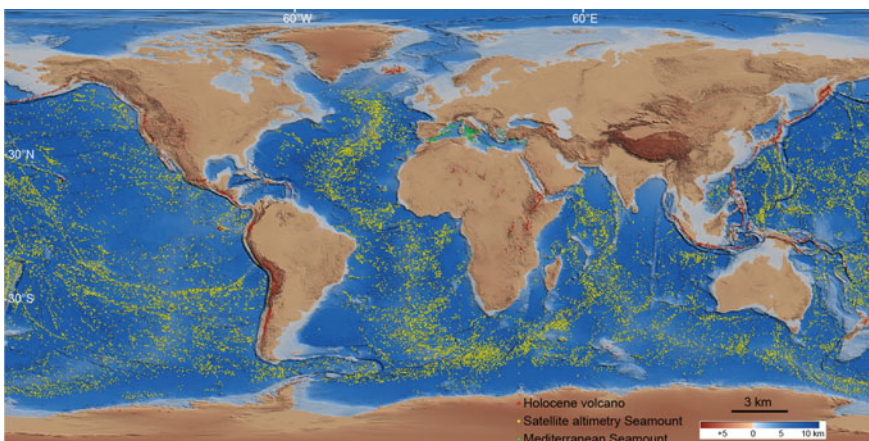
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## 1 Introduction

Few geological processes capture the popular imagination and boost scientist's question for knowledge about our planet more than active volcanism. Volcanoes have played a major role in the evolution of our planet, but also represent one of the main geohazards for human communities, being able to alter social evolution, as demonstrated by the Minoan eruption of Santorini that buried flourishing Bronze Age settlements (Friedrich 2000). It has been estimated that volcanic hazard caused more than 270,000 casualties in the last five centuries (Auker et al. 2013), most of them being the direct or indirect (tsunamis) result of sector collapses affecting the flanks of insular volcanoes. Although decades of subaerial geological mapping have contributed to the understanding of how volcanic islands evolve, they often represent only the tip of large edifices rising for thousands of meters above the sea-floor, as observed at Stromboli, where the 98% of the edifice lies underwater (Fig. 1). This implies that we are not able to reconstruct the thorough morpho-structural evolution of volcanic edifice without marine studies. These latter are essential for the study of seamounts, i.e. isolated underwater volcanic edifices that reach at least 1000 m in height (Menard 1964). Actually, modern studies identify seamounts as small as 50–100 m in height using high-resolution bathymetry (Smith and Cann 1990). Based on global satellite altimetry, Kim and Wessel (2011) recently identified ca. 25,000 potential seamounts with height >100 m (yellow points in Fig. 1).

However, we are still far from having real number of seamounts distribution, mainly due to lack of a full coverage of oceans by using swath bathymetry. Seafloor



**Fig. 1** Shaded relief map of the world (data from Ryan et al. 2009), with the distribution of Holocene volcanoes (data from the website [volcano.si.edu/ge/GVPWorldVolcanoes.kml](http://volcano.si.edu/ge/GVPWorldVolcanoes.kml)), seamounts derived from global satellite altimetry (Kim and Wessel 2011) and from the Atlas of the Mediterranean seamounts (Wurthz and Rovere 2015)

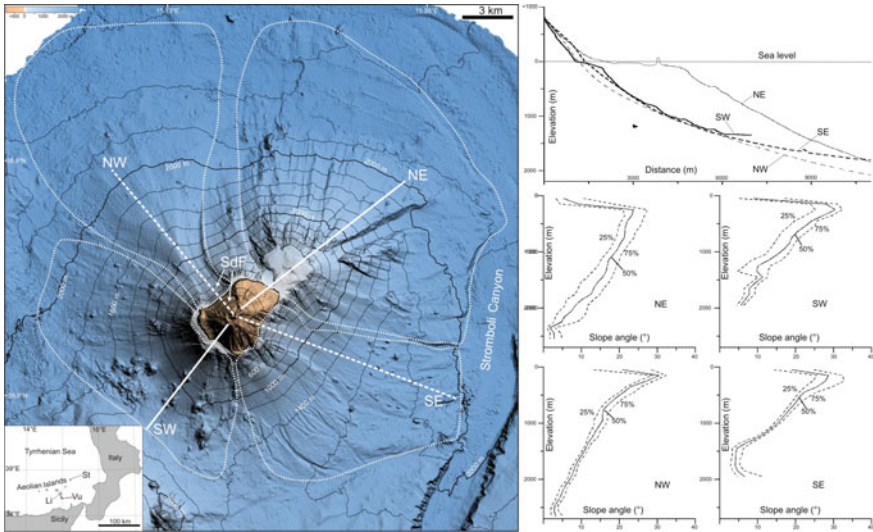
imagery systems are, in fact, playing a key role in the exploration of the oceans, changing our vision on the extent, distribution and variability of landforms. Moreover, the growing availability of detailed Digital Elevation Models is leading to the systematic parametrization of the volcanic edifices and associated landforms, providing insights on the complex interplay between volcanic, tectonic, erosive-depositional and eustatic processes controlling their genesis (e.g., Mitchell 2001; Ramalho et al. 2013; Grosse et al. 2014). In this regard, the present chapter would represent an outgrowth of the expanding interest in the geomorphology of submarine flanks of volcanic islands and seamounts. The study of these areas is becoming crucial for several disciplines, because of (a) the strong interaction between seamounts and geostrophic currents, (b) their role as hotspots of biodiversity, (c) the future harvesting of mineral resources, and (d) the geohazard related to volcanic activity and slope failures affecting volcanic edifices.

## 2 Submarine Geomorphology of Volcanic Islands and Seamounts

Morpho-bathymetric data collected in submarine volcanic areas has revealed a large suite of geomorphic features referable to two main types: volcanic and erosive-depositional landforms (Sect. 3). The growth and morphological evolution of volcanoes are, in fact, the result of interaction between constructive and destructive forces. The constructional processes prevail during the relatively short periods of eruptive activity, whereas destructive forces become dominant during the longer inter-eruption periods or when volcanic activity has ended. In order to evidence differences between “constructional” and “failed” flanks (i.e., dominated by mass-wasting processes), bathymetric cross-sections and graphs of cumulative surface gradients can be useful (Fig. 2, Mitchell et al. 2002). In the case of Stromboli edifice, characterized by a quasi-bilateral symmetry of the flanks with respect to its SW-NE rift axis (Romagnoli et al. 2009a), the NE and SW flanks show a large variability of slope gradients, reflecting the uneven morphology of constructional slopes. In contrast, the failed SE and NW flanks show a narrower distribution of slope values that linearly decrease with depth (Fig. 2).

## 3 Volcanic and Erosive-Depositional Landforms

Volcanic landforms include primary constructional and volcano-tectonic features, often representing the end-members of a continuum process. The most common volcanic landforms are cones (Sect. 3.1), lava flows and delta (Sect. 3.2), caldera collapses (Sect. 3.3) and undifferentiated bedrock outcrops. These latter are coherent and linear ridges, often oriented in a radial direction from the island.



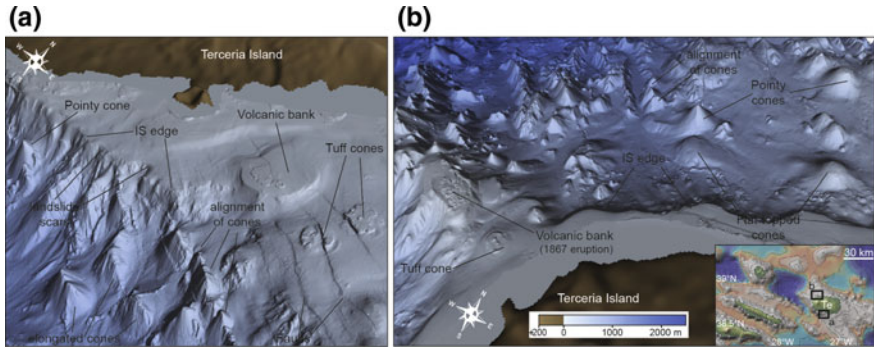
**Fig. 2** On the *left*, shaded relief map of Stromboli edifice, with the location of the bathymetric cross-sections (*white lines*) shown in the *upper right*; *SdF* Sciara del Fuoco. *Dotted white lines* delimit the areas where slope graphs, shown in the *lower right*, were computed (modified from Casalbone et al. 2010). Slope graphs were realized by sorting slope gradients within each flank for prefixed depth intervals, and a slope cumulative distribution is computed for each depth interval. Location of Aeolian Islands is shown in the *inset*; *St* Stromboli Island; *Li* Lipari Island, *Vu* Vulcano Island

Because of their degraded morphology, they are commonly interpreted as old remnants of bedrock outcrops carved by marine erosive activity.

Erosive-depositional landforms may cover instead most part of the submarine extent of a volcanic edifice, leading to its progressive enlargement and formation of a large volcanoclastic apron (Carey 2000). These landforms show a large variability in size and morphology, being the result of a large spectrum of sedimentary processes acting at different magnitudes and time scales. Based on the dominant processes involved in their formation, we can distinguish landforms associated to (a) wave erosion and sea-level fluctuations (Sect. 3.4), (b) gravity-driven instability processes (Sect. 3.5), (c) confined and unconfined gravity flows (Sect. 3.6).

### 3.1 Volcanic Cones

Volcanic cones may have conical or sub-conical shapes, be elongated along preferential directions or show a more complex shape. Moreover, they can be isolated, aligned along the main regional tectonic trend, or occur in clusters. The different distribution and shape of the cones provide insights into the interaction between magmatism and tectonics. Volcanic features radially oriented to the flank of the



**Fig. 3** 3-D view (vertical exaggeration  $\times 2.5$ ) of the SE (a) and NW (b) offshore of Terceira Island; see Sect. 3.1 for details

volcanic edifices, suggest that they are mainly the result of local magmatic stress (e.g., Tibaldi and Lagmay 2006). In contrast, elongated or aligned features indicate a main role played by regional tectonic lineaments. These latter are typically observed in tectonically-controlled setting, where they formed through systems of volcanic and tectonic fissures, which provide a preferential pathway for the ascent of magmas through the crust (e.g., Gudmundsson 1986; Searle et al. 2010). An example of these features is reported from Terceira offshore in the Azores (Fig. 3, Casalbone et al. 2015).

Based on their morphology, volcanic cones can be further divided into two main sub-types: pointy and flat-topped.

Pointy cones are found in all water depths and geodynamic settings, so that their shape is not indicative of specific environmental conditions and/or eruptive mechanisms. However, since high hydrostatic pressure reduces gas exsolution from magma and favors effusive eruptions, the deeper pointy cones should be presumably dominated by effusive activity with respect to shallow-waters cones, where the pyroclastic component increase. This latter becomes dominant in the case of tuff cones formed during surtseyan eruptions, i.e., phreatomagmatic eruptions characterized by violent explosions caused by rising magma coming into contact with sea-water. Tuff cones are commonly found in shallow-water sectors and are characterized by a flat summit, sub-concentric furrows and ridges, and other small circular features, that likely arose from episodic eruptions into shallow-water and subsequent wave erosion (Fig. 3). Wave erosion is a very efficient process in destroying volcanic cones made of poorly consolidated materials, as reported at Surtla and surrounding satellite vents during the 1963–1966 eruption (Romagnoli and Jakobsson 2015). More in general, submarine flat-topped cones are found at depths  $< -200$  m as a consequence of wave reworking during sea-level fluctuations (Sect. 3.4). When the flat summit is much larger than their height, flat-topped cones are also named volcanic banks (Fig. 3).

Differently, flat-topped cones with larger basal diameters (1–5 km) and height of few hundreds of meters, were reported at depths  $> 700$  m along the submarine flanks

of Hawaiian Islands and Puna Ridge (Clague et al. 2000). These features appear to be monogenetic and they are probably formed during prolonged low to moderate effusion of magma, with low viscosities and volatile content on gentle slopes.

From a morphometric point of view, one of the main parameters used for the characterization of volcanic cones is the ratio between cone height and average basal diameter, providing insights both on the degree of erosion of the cones and on the geodynamic setting where they form (Fornaciai et al. 2012). It is noteworthy the most significant advances in our understanding of the formation and morphological evolution of volcanic cones come from repeated bathymetric surveys, as reported from the Monowai Seamount (Watts et al. 2012) or offshore El Hierro Island (Rivera et al. 2013).

### 3.2 *Lava Flows and Lava-Fed Deltas*

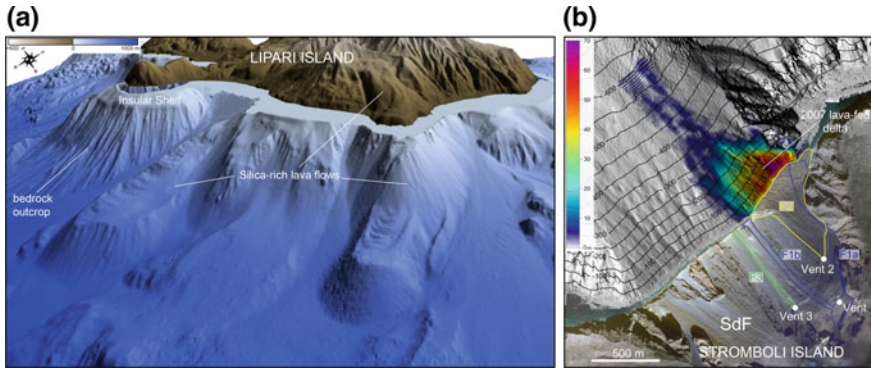
Submarine lava flows are generally characterized by distinctive lobate outlines, high acoustic reflectivity, low relief, and a rugged surface texture. In some cases, submarine effusive activity can form complex lava fields, where it is difficult to recognize the single lava flows.

Because of the paucity of direct observations of active submarine eruptions, lava flow morphology can provide insights on eruptive processes. Most of the studies on submarine lava flows were realized along the Mid-Oceanic Ridges, where ship-based bathymetry allowed to depict only the gross morphology of lava flows, so their emplacement mechanisms were mainly reconstructed through visual inspections. Only a few, recent studies are trying to merge visual observations with ultra-high resolution multibeam bathymetry collected using AUV to map the variability of morpho-facies and structures of the submarine lava flows at metric or sub-metric scale (Caress et al. 2012; McClinton and White 2015).

It is even more surprisingly that very few studies were realized on submarine lava flows in shallow-water setting and more in general on the behavior of subaerial lava flows penetrating into the water. In general, this behavior seems to be mostly controlled by the lava flow type: pāhoehoe and ‘a’ā. The latter flows show a more coherent behavior under water with respect to pāhoehoe flows, which are often completely disintegrated to form breccias. This is likely due to the lower thickness and greater vesicularity, permeability, and joint density characterizing pāhoehoe lava flows with respect to the ‘a’ā type (Stevenson et al. 2012 and reference therein). Moreover, it is noteworthy that ‘a’ā and more generally silica-rich flows are able to form a thick carapace that would favor the thermal insulation of lava flows from the sea water, and thus their movement on the seafloor in a caterpillar-like fashion. An impressive example of submarine extent of silica-rich flows is recognizable in the NE part of Lipari, where they move down −900 m for a length of ca. 3 km (Fig. 4a, Casalbore et al. 2016).

Prolonged lava flows penetrating into the sea are also able to form lava-fed delta along the coastline. Also in this case, the emergent part of these landforms has been



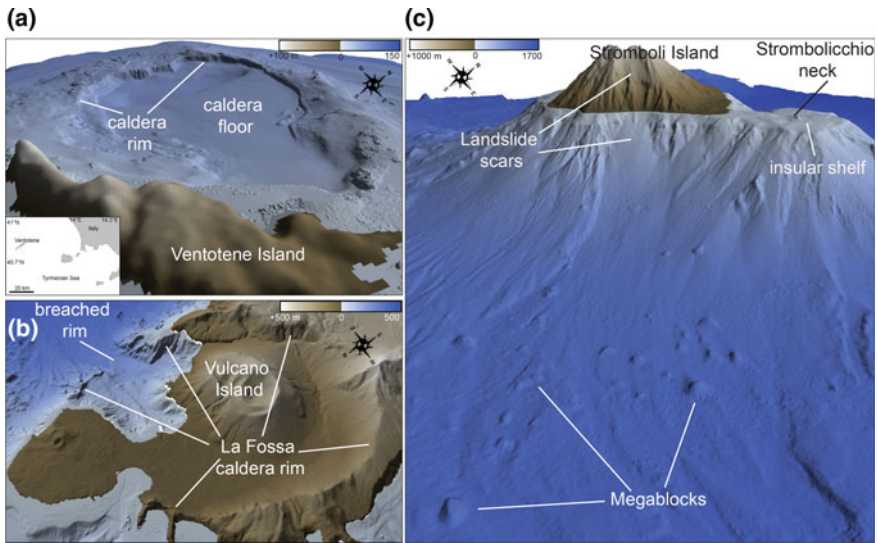


**Fig. 4** 3-D view of the NE flank of Lipari, where two lava flows are recognizable, representing the offshore extent of subaerial silica-rich coulee. On the *right*, aerial photo of Sciara del Fuoco (*SdF* location in Fig. 2) and bathymetric residual map between the pre- and post-2007 eruption surveys draped over post-2007 eruption bathymetry (modified from Bosman et al. 2014). The values in the *scale bar* indicate the thickness in meters of sea floor accretion due to the emplacement of the delta fed by subaerial lava flows emitted during the 2007 eruption, whose limits are indicated by the *green, blue and yellow lines*

studied and monitored in detail, whereas little is known about their subaqueous counterpart (Mitchell et al. 2008). The only example of bathymetric monitoring of an active lava-fed deltas was realized during the 2007 eruption at Stromboli Volcano (Fig. 4b, Bosman et al. 2014), allowing to constraint the main processes responsible for its emplacement and growth. In detail, this study have shown that (a) the position and rate of delta accretion are strongly dependent on feeding points and effusion rates; (b) the slope gradients and morphology of the basal surface control the overall delta architecture and the amount of volcanoclastic debris, (c) sudden collapse of portions of the submarine delta may occur simultaneously with volcanic accretion, with implication on the correct estimation of the emplaced volume and effusion rates.

### 3.3 Caldera Collapses

Calderas are circular depressions observed on many volcanoes, with diameters ranging from few up to tens of kms. They occur in all geodynamic setting and their formation has been commonly related to vertical collapse of the roof of a magma chamber during large eruptions. Because of their hazard potential, but also their link to ore deposits and geothermal energy resources, a worldwide database of calderas has been recently realized (Geyer and Marty 2008). In submarine setting, most studies on submarine calderas focused on basaltic volcanoes associated with mid-ocean ridges or intraplate hotspot volcanism. In these cases, caldera formation is thought to represent the result of syn- or post-eruption collapse following magma



**Fig. 5** On the left, 3-D view (vertical exaggeration  $\times 2$ ) of the caldera depressions recognized off Ventotene (**a** location in the *inset*) and Vulcano (**b** location in the *inset* of Fig. 2) Islands; see Sect. 3.3 for further details. On the *right*, 3-D view of the eastern, failed (Sect. 3.5) flank of Stromboli island; note also the presence of a wide insular shelf around Strombolicchio neck (Sect. 3.4)

withdrawal, from a central magmatic conduit to supply flank eruptions (e.g., Fornari et al. 1984). Calderas are also frequently observed at submarine arc volcanoes, where they have been associated to large explosive eruptions (e.g., Wright and Gamble 1999).

A caldera collapse typically displays a flat floor bounded by high and steep scarp forming the caldera rim, as shown in Fig. 5a off Ventotene Island (Casalbore et al. 2014a). This caldera is  $4 \times 2.5$  km in size and its formation has been related to a large explosive eruption occurred at between 0.15–0.3 Ma. In other cases, caldera depressions can be the result of multiple coalescing collapses, as for instance observed at La Fossa Caldera (Vulcano Island, Fig. 5b; Romagnoli et al. 2012 and reference therein). The NE part of the caldera lies under water and its rim was partially breached by marine retrogressive erosion, leading to the successive dismantling of the submarine caldera infilling.

### 3.4 Landforms Associated to Wave Erosion and Sea-Level Fluctuations

These landforms typically display a planar summit surface and are found at depths  $< 200$  m, exception made for areas affected by long-term subsidence. In the Sect. 3.1,



we have already seen as shallow-water flat-topped cones can be interpreted as the result of wave erosion cutting the summit of pointy cones. Wave erosion is, in fact, responsible for the development around volcanic islands of shore platforms that initiate as soon as volcanism wanes during stable relative sea levels (Trenhaile 2000). These features progressively evolve into reefless insular shelves as surf migrates landward and seaward with changing sea levels (Quartau et al. 2010). At Stromboli, for instance, a wide shelf formed around the Strombolicchio neck (Fig. 5c), representing the remnant of an older eroded volcano dated at ca. 200 ka (Gillot and Keller 1993) whose conical summit has been completely dismantled by erosion. The shelf edge is located at ca. -130 m, just corresponding to the lowest level reached by the sea during the Last Glacial Maximum about 20 ka ago.

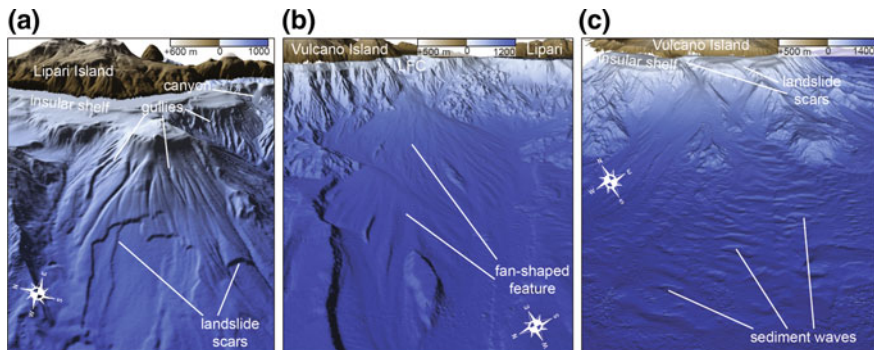
Once these shelves are formed, their size and morphology is mainly controlled by the competition between wave erosion that enlarges them and volcanic progradation that reduces their size. Shelf width generally tends to increase with exposure to wave action through time and a direct relationship between shelf age and shelf width is often observed (Quartau et al. 2014 and reference therein).

Another typical landform associated to wave erosion is guyot, i.e. seamount having a smooth and flat top. Its formation is similarly related to wave cut of a volcanic island, but it also undergo coral reef or atoll formation and lagoonal infilling, and then subside through the bank stage (at depths <200 m) to become a guyot.

### ***3.5 Landforms Related to Gravity-Driven Instability Processes***

Because of their rapid growth, volcanoes may become unstable and experience failure at any spatial from minor rock falls up to catastrophic collapses involving volumes up to thousands of cubic kilometers. The predisposing factors for volcano instability are manifold, encompassing internal and external causes (Mcguire 2006). The triggering of the collapse is typically associated to a short-live dynamic event, such as an earthquake or dyke intrusion.

A collapsed flank is morphologically characterized by horseshoe-shaped scars in source area, and by fan-shaped features with hummocky terrains and megablocks (i.e. debris avalanche deposits) in depositional area, as observed along the E flank of Stromboli (Fig. 5c). Multiple collapses are observed in many volcanoes, such as in the NW Stromboli affected by 4 coaxial collapses in the last 13 ka (Tibaldi 2001), forming a large fan-shaped bulge at the base of the Sciara del Fuoco (SdF in Fig. 2; Romagnoli et al. 2009b). This is likely due to the fact that a failed flank becomes a weakness zone within the edifice and can lead to a depressurization of the underlying magma chamber, focusing subsequent volcanic activity within and along the collapsed area (Tibaldi et al. 2009 and reference therein). Likewise, the occurrence of large-scale collapses perpendicular to the main axial rift zone (Fig. 2)



**Fig. 6** 3-D view (vertical exaggeration  $\times 2$ ) of the W flank of Lipari Island (a), NE (b) and SW (c) flanks of Vulcano Island, where several erosive-depositional landforms were identified (see Sects. 3.4, 3.5 and 3.6 for further details). Location of the islands is shown in the inset of Fig. 2

is a common feature observed for volcanic edifices lying in extensional regimes. It can be explained by the outward flank displacement due to the dykes intrusion along the rift zone (Voight and Elsworth 1997).

Smaller landslides are also widespread along the flanks of volcanic edifices, commonly occurring at higher frequency with respect to the large events. In the active NW flank of Stromboli, a tsunamigenic submarine landslide occurred on the 30th December 2002, with a maximum observed run-up of 10 m. The extent and geometry of the failure were reconstructed through the comparison of pre- and post-slide bathymetries, allowing to compute a mobilized volume of ca.  $10 \times 10^6 \text{ m}^3$  (Chiocci et al. 2008). The same authors interpreted the high gradients and the presence of volcanoclastic layers within the slope as the main predisposing factors for the slope failure. Volcanoclastic layers, in fact, may act as weakness levels due to their particular shear behavior (low grain resistance) if sudden strain/stress increments occur.

Slide scars at hundred-meters scale are often recognized at the edge of the insular shelf or along the older volcanic flanks draped by a relevant sedimentary cover (Fig. 6a). Deposits related to these scars are often not recognizable on the bathymetry, likely due to the fact that landslide mass either lost cohesion during failure or failed as a cohesive mass and disintegrated downslope.

### 3.6 *Landforms Related to Confined/Unconfined Density Gravity Flows*

Landforms typically related to confined density gravity flows are mainly gullies and canyons. Gullies are narrow channelized features at hundred-meter length, commonly having a V-shape section. They are mostly located in the upper part of the

submarine slope, mainly carving the volcanic bedrock. However, gullies can also radially affect the sedimentary blanket covering the flanks of old volcanic cones (Fig. 6a).

Canyons are larger and longer channelized features, often draining the entire submarine flanks. The most active canyons strongly indent the insular shelf, arriving up to few hundreds of meters far from the coast (Fig. 6a). Small and crescent-shaped seafloor waveforms within their thalweg are considered as a proxy of active sedimentary dynamics (e.g., Babonneau et al. 2013).

The most common landforms associated to unconfined gravity flows are fan-shaped deposits, often found at the base of the channelized features, where a marked decrease of slope gradients occur. These landforms can range in width from some hundreds of meters up to thousands of kms (Cilaos fan off La Reunion Island, Sisavath et al. 2011). Their size mainly depends on the availability of sediments from the source area (the drainage basin of a river, climate conditions, abundance of loose volcanoclastic material) as well as by the morphological link between sub-aerial and submarine slope. An example of large fan-shaped feature is shown at the base of La Fossa Caldera (Fig. 6b), covering an area of 20 km<sup>2</sup> between -350 and -1150 m. This feature is characterized both by a swale and ridge morphology and the lacking of hummocky terrains, indicating that its formation is likely the result of the gradual stacking of gravity flows, fed by the dismantling of the La Fossa caldera infill (Sect. 3.3).

Large sediment waves, with wavelength of several hundreds of meters and wave height up to tens of meters are another common landform associated to unconfined gravity flows along the flank of volcanic islands (Fig. 6c; Wynn et al. 2000; Leat et al. 2010; Sisavath et al. 2011; Casalbore et al. 2014b).

## 4 Gaps in Present-Day Knowledge and Perspectives for the Future

The previous sections have shown how the submarine flanks of volcanic islands and seamounts are characterized by several volcanic and erosive-depositional landforms. Of course, the presented landforms do not exhaust the list of the landforms recognisable in these areas, but they are likely the most common features. For the sake of clarity, only landforms whose formation can be attributed to well-defined processes have been presented, but the interpretation of submarine volcanic landforms is often more problematic. This is intrinsically due to the fact that a landform can be the result of different processes or a complex interplay of multiple processes operating at different temporal scale. In addition, reliable models for the genesis of several landforms in the submarine environment are often lacking, mainly in relation to the paucity of direct observations. Their interpretation is often based on the results of laboratory studies and/or the comparison with similar phenomena observed onland, where their formation can be more easily monitored. However,

some landforms and associated processes are exclusive of the marine environment and their study requires in situ monitoring. In this regard, repeated bathymetric surveys are a fundamental tool for monitoring the evolution of a landform and link it with own genetic process, especially if integrated by direct observations.

The comparison and systematic parameterisation of submarine volcanic landforms in different settings can represent a further and low-cost step to better constraints the factors controlling their formation and development. In contrast to terrestrial applications, the use of such techniques in the marine environment is still in its infancy (Lecours et al. 2016). In order to exploit the full potential of such analysis, methods and interpretations need to be standardized, particularly in view of issues specific to the marine environment. This means that a great effort has to be realized by geoscientist working in submarine and subaerial volcanic areas to set shared protocols for the interpretation and analysis of submarine volcanic landforms, taking into account the lessons learned from terrestrial volcanic geomorphology (Thouret 1999). In the next years, it is predictable an exponential increase in data availability from submarine volcanic areas, considering (a) the recent advances in quality and cost-effectiveness of available technologies, (b) the growing interest for the functioning of deep-sea systems and (c) the large areas that have not been surveyed, yet.

As volcanic island is concerned, another main gap remains the link between their subaerial and submarine morphology. Indeed, although the evolution of volcanic islands is continuous above and below sea level, scientists are not always able to reconcile the onshore and offshore data in a consistent way (Quartau et al. 2014). This is due to the fact that bathymetric surveys in shallow-water are very time-consuming, but also to the paucity of multidisciplinary studies involving field volcanologists and marine geologists. However, it is fundamental to improve our ability to integrate these data, because submarine information provides complementary evidence not visible above sea level and vice versa, mainly in consideration that coastal volcanic processes can directly impact the life of local communities.

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