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Unraveling Past Submarine Eruptions by Dating Lapilli Tuff-Encrusting Coralligenous (Actea Volcano, NW Sicilian Channel)

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The dating of young submarine volcanic eruptions, with their potential generation of tsunamigenic waves, is essential for a reliable hazard assessment. This is particularly relevant in highly populated coastal areas. The scarce knowledge of the underwater environment makes however, this reconstruction challenging. Our study is focused on the NW sector of the Sicilian Channel, where several small- and medium-size volcanic edifices are present. The only documented Surtseyan-type eruption occurred in A.D. 1831, forming the ephemeral Ferdinandea Island. Late Pleistocene to mid-Holocene eruptions have been up to now only hypothesized, and based solely on indirect data. Here we present the first radiocarbon dates of a coralligenous bioconstruction sampled at 34 m water depth from the summit of the Actea volcano, grown up progressively (up to nowadays) on a lapilli tuff deposit. Actea volcano is a recently discovered pyroclastic cone located at only four nautical miles off the SW coast of Sicily. The oldest age of the bioconstructions that started to encrustate the shallow water pyroclastics shortly after their emplacement (7,387 $\pm$ 175 cal years B.P.) represents a *terminus ante quem*, thus testifying a mid-Holocene submarine eruption in this sector of the Sicilian Channel. This method may be effectively used to bridge the gap between historical accounts and the geological record and thus may contribute to a better volcanic hazard assessment of submarine eruption and related phenomena such as tsunamis.

Keywords: Sicilian Channel, Actea volcano, past submarine eruptions, lapilli tuff, coralligenous, radiocarbon measurements, hazard assessment

INTRODUCTION

The reconstruction of past submarine volcanic eruptions and their frequency and intensity is of paramount importance to assess the hazard to which coastal areas may be exposed. Tsunamis associated to the activity of submarine volcanoes represent the major geo-hazard for the local communities living in their proximities and for coastal infrastructures. Tsunami waves may be produced by a series of events like volcano-tectonic earthquakes, volcano flank collapses and landslides, entrance of pyroclastic flows under the sea, underwater explosions and sudden ground movements at volcanoes (e.g., Paris, 2015). Although underwater explosions, including Surtseyan-type phreatomagmatic eruptions, typically generate short-term, large-dispersion waves compared to earthquakes, with a general limited far-field impact, wave run-up inland can be locally high, especially in narrow bays (Ulvrova et al., 2014). The hazard associated with these phenomena is quite unpredictable, and could in many cases be underestimated. However, the poor knowledge of the underwater environment, the limited monitoring activities and the expensive logistics represent the main obstacles to effectively evaluate volcanic hazard in coastal areas. Many underwater volcanoes still have unknown eruption histories, with the date of the last eruption often only hypothesized. Dating young volcanic eruptions is the essential ingredient to understand whether a volcano may be active and for a reliable volcanic hazard assessment, as well as for understanding evolution and magmatism in any geodynamic setting.

Recent submarine events occurred in Aeolian archipelago (southern Tyrrhenian Sea) have reaffirmed the importance of studying and monitoring these phenomena, which have implications for the hazard scenario. A landslide which affected Stromboli volcano on 30 December 2002 (Chiocci et al., 2008) has produced tsunami waves that caused significant damages around Stromboli Island and also reached Lipari and Vulcano Islands and the Sicily and Calabria coastlines. On the basis of geoarchaeological studies and investigation of tsunamigenic deposits in Stromboli Island, a medieval age tsunami in southern Tyrrhenian Sea, due to volcanic paroxysm eruption and landslides along the Sciara del Fuoco flank, was matched with historic documents describing destruction in Naples harbor, about 200 km from the volcano (Rosi et al., 2019). Recent studies are trying to evaluate the tsunamigenic potential of considerable submarine volcanic complexes, as the Marsili seamount (Tyrrhenian Sea), the largest active submarine volcano in the Mediterranean Sea (Gallotti et al., 2021), and the submerged part of Campi Flegrei caldera, located on the western part of the densely inhabited area of Naples (Paris et al., 2019).

This study focuses in the central-western sector of the Sicilian Channel, where the only volcanic event documented in historical times is the Ferdinandea Island generated by a Surtseyan-type eruption in A.D. 1831 (Colantoni et al., 1975), and quickly dismantled after a few months. Another eruption took place in A.D. 1891 in the SW Sicilian Channel, a few nautical miles west of Pantelleria Island (Conte et al., 2014). It seems that other eruptive volcanic episodes have occurred in historical time, but there are no reliable reports describing them. While the main evidence for past subaerial volcanic eruptions' size and intensity comes from the interpretation of their effusive and pyroclastic deposits, the occurrences of past underwater eruptive events is more challenging. Pre-historic volcanic episodes in the Sicilian Channel have been inferred by various authors through: (i) the analysis of specific morphologies of the volcanic cones and depositional terraces of their flanks, linked to the post-Last Glacial Maximum (LGM) phases of sea-level rise (Cavallaro and Coltelli, 2019), (ii) the geometric arrangement and stratigraphic correlation of shallow seismic reflectors related to marine transgressive markers (Zecchin et al., 2015; Lodolo et al., 2019a), and (iii) the presence and dating of the considerable accumulations of fossil red coral deposits found at the base of some submarine cones (Lodolo et al., 2017). However, none of these analyses were addressed to direct or indirect datings, making the reconstruction of Quaternary volcanic activity in the NW Sicilian Channel speculative in many aspects.

This sector of the Sicilian Channel is characterized by a widespread and scattered anorogenic volcanism which occurred mainly during Quaternary, with the build up of the islands of Pantelleria and Linosa, and the formation of a series of submarine edifices located in eastern Adventure Plateau, within Graham Bank and the nearby Terrible Bank and, as recently discovered, a few nautical miles off the SW coast of Sicily (**Figure 1**; Calanchi et al., 1989; Rotolo et al., 2006; Civile et al., 2015; Coltelli et al., 2016; Cavallaro and Coltelli, 2019; Lodolo et al., 2019a). Part of this volcanism is related to the Pliocene rifting process that produced the grabens of Malta, Linosa, and Pantelleria (Boccaletti et al., 1987; Ben-Avraham et al., 2006; Civile et al., 2010, 2014, 2021; Lodolo et al., 2012; among others), and part is linked to the presence of a NNE-trending, lithospheric transfer zone named Capo Granitola-Sciacca Fault Zone, which traverses the central sector of the Sicilian Channel (Calò and Parisi, 2014; Fedorik et al., 2017; Civile et al., 2018; Ferranti et al., 2019; Palano et al., 2020). High-resolution bathymetric data have shown that most of the volcanic centers in the Graham Bank, lying at 150–250 m water depths, are monogenetic tephra cones (Cavallaro and Coltelli, 2019) aligned with the Capo Granitola Fault System (CGFS). In the Terrible Bank the volcanic edifices, associated to the Sciacca Fault System (SFS), are smaller in size with respect to those of the Graham Bank (Coltelli et al., 2016) and may represent relict volcanic necks fed by a relatively shallow magma chamber (Lodolo et al., 2019b). The six edifices recently discovered a few nautical miles from the SW Sicily coast (Lodolo et al., 2019a) show variable morphologies, from truncated cones to very low relief with horseshoe-shaped structures, as documented by high-resolution swath bathymetry. The closest volcano to the coast, named Actea, lying on the northern part of the CGFS at water depths between 62 and 70 m, with its top at 34 m below sea level, has a complex morphology, where a crater-like structure is not recognizable. The most relevant feature of Actea is a W-trending, large lava flow (∼4 km long and 1.5 km wide) originating from the W flank of the pyroclastic cone, without any significant sedimentary cover, as highlighted by the high-resolution seismic profile (**Figure 2**).

Here we present for the first time a radiocarbon dating study performed on a fragment of coralligenous encrusting on a lapilli tuff sample recovered in the summit of the Actea volcano, which testifies the occurrence of a mid-Holocene eruption.

METHODOLOGY

Coralligenous Bioconstruction Analysis

The coralligenous accretions sampled at the Actea volcano summit cone were firstly analyzed to evaluate the main

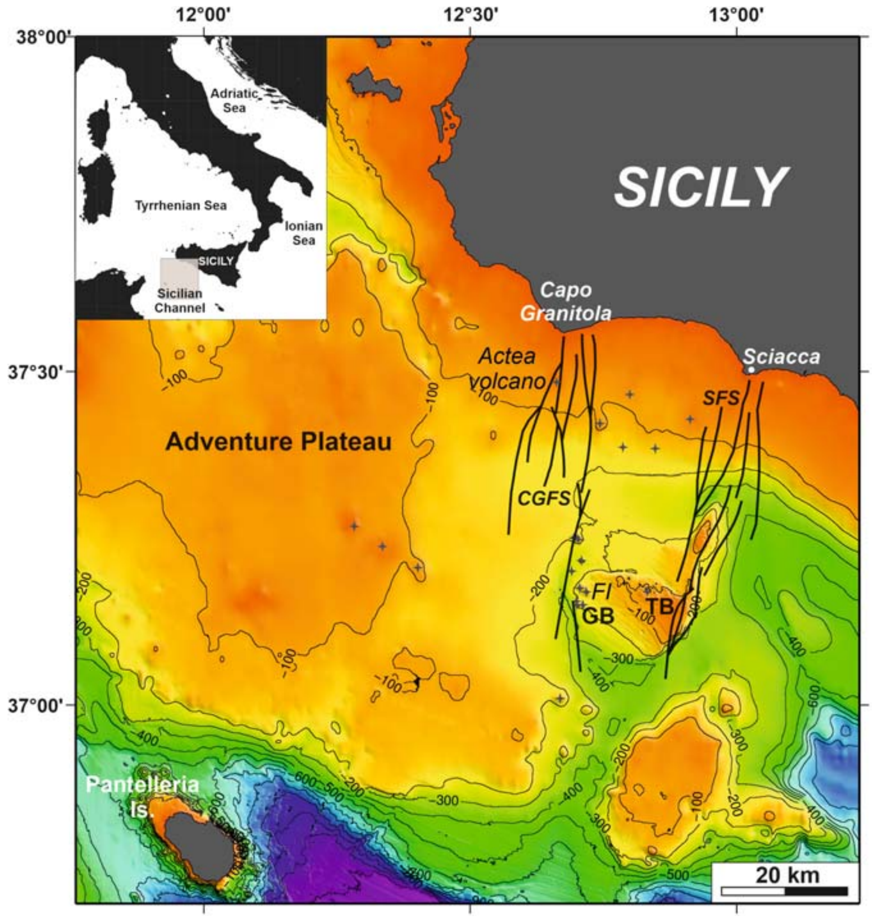

FIGURE 1 | Bathymetric map of the NW sector of the Sicilian Channel (data taken from the EMODnet portal, https://portal.emodnet-bathymetry.eu/). Contours every 100 m. Brown stars indicate the location of the volcanic edifices. TB, Terrible Bank; GB, Graham Bank; FI, Ferdinandea island; CGFS, Capo Granitola Fault System; SFS, Sciacca Fault System. Box in the upper left corner indicates the location of the study area.

taxa characterizing the bioconstruction. Taking into account the typical layers of organisms usually growing on healthy coralligenous bioconstructions (Valisano et al., 2019) we found mainly encrusting organisms and a general composition that resembles that reported for coralligenous growing on granitic lithology (Canessa et al., 2020) even if bryozoans in the present coralligenous accretions show a higher diversity. The coralligenous structure was compact and only one species of boring organism was found, the sponge *Spiroxya heteroclita* Topsent, 1896, highlighting a regular stratification of the algal thalli.

Radiocarbon Measurements

Four coralligenous fragments were separated from the lapilli tuff part of the sample taken at the top of the Actea volcano at 34 m water depth. The samples indicated in **Table 1** were subjected to dating with the radiocarbon method using the technique of high-resolution accelerator mass spectrometry (AMS) at the CEDAD center of the University of Salento (Calcagnile et al., 2019). The macro-contaminants present in the samples were identified by observation under an optical microscope and mechanically removed; afterward the samples were treated with H_2O_2 in order to remove the most external layer. The extracted material was then subsequently converted into carbon dioxide by acid hydrolysis with H_3PO_4, and then reduced to graphite by reduction. H_2 was used as a reducing element and iron powder as a catalyst. The amount of graphite extracted from the samples (>1 mg) was sufficient for an accurate experimental age determination. The radiocarbon concentration was determined by comparing the measured values of the ^{12}C and ^{13}C ion beam currents, and the ^{14}C counts with the values obtained from standard Sucrose C6 samples supplied by the IAEA (International Atomic Energy Agency). Conventional radiocarbon ages were corrected for isotope fractionation effects and for machine and processing background. In order to correct the measured ages for isotopic fractionation the measured ages, the $\delta^{13}C$ term was obtained from the beam currents measured with the AMS system, while the formulas reported in Stuiver and Polach (1977) were used. Correction for background was carried out by analyzing ^{14}C-free IAEA C1 standard (Carrara Marble) chemically processed in the same way as the samples. For the determination of the experimental error in the radiocarbon

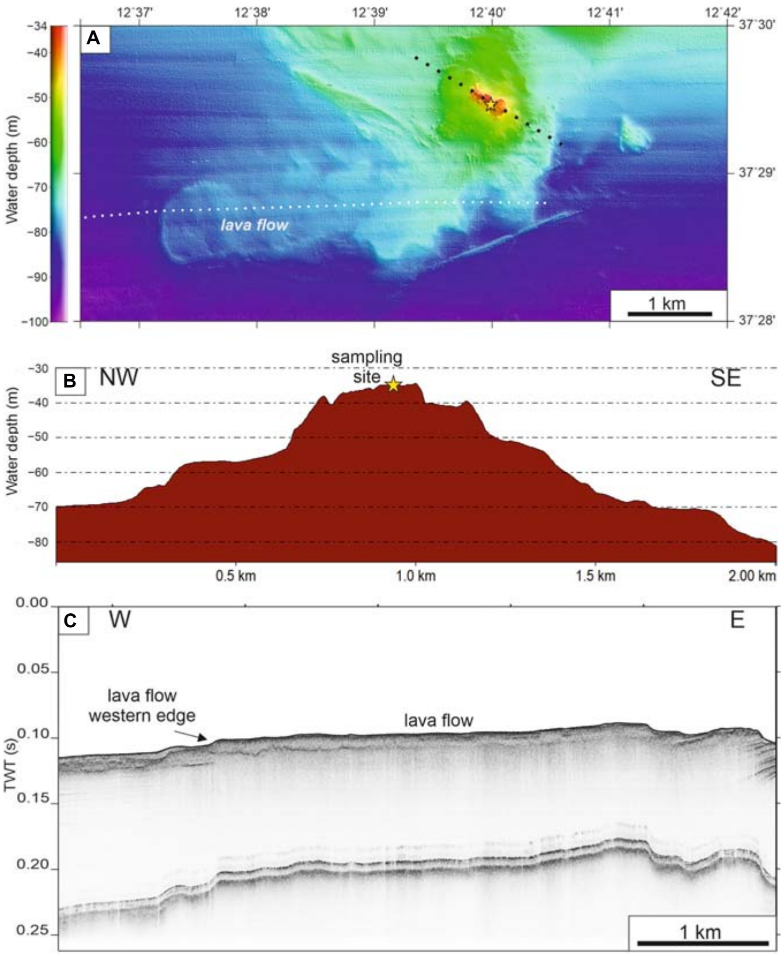

FIGURE 2 | (A) Shaded-relief of the high-resolution swath bathymetry of the Actea volcano. Black dashed segment indicates the location of the bathymetric profile in panel **(B)**, with the location of the sampling site (yellow star); white dashed segment indicates the location of the high-resolution seismic profile displayed in panel **(C)**, which crosses W-E the large lava flow, where no sediment cover is found. These geophysical data have been acquired on February 2018 by the R/V *OGS Explora*. Details on instruments and acquisition parameters, and on data processing can be found in Lodolo et al. (2019a).

date, both the scattering of the data around the average value and the statistical error resulting from the ^{14}C count were taken into account. The resulting conventional radiocarbon ages were converted into calendar ages (see **Table 1**) by using the OxCal version 4.2 software, and the last internationally accepted calibration curve for marine data (MARINE2020) (Heaton et al., 2020). A local ΔR value of -88 ± 50 was used as measured by Siani et al. (2000), referred to the recently established calibration curve and available in the online database (http://calib.org/marine/) for a location close to the sampling area.

TABLE 1 | Radiocarbon measurements performed on the lapilli tuff-encrusting coralligenous (Actea volcano).

Sample ID	Lab code	Radiocarbon age (B.P.*) or ^{14}C content (pMC*)	Calibrated age (Probability 95.4%)
CG1	LTL20311A	5,280 ± 45 years B.P.	5,530 ± 205 cal years B.P.
CG2	LTL20312A	832 ± 40 years B.P.	362 ± 167 cal years B.P.
CG3	LTL20313A	6,990 ± 45 years B.P.	7,387 ± 175 cal years B.P.
CG4	LTL20314A	104.08 ± 0.54 pMC	After 1955 A.D.

**B.P., before present; pMC, percent modern carbon.*

RESULTS

A small lithified pyroclastic sample was collected by divers near the top of the Actea volcanic edifice at 34 m below sea level (**Figure 3**). The sampling site was carefully chosen after initial reconnaissance footage taken with an underwater camera in the summit area of the volcano. This reconnaissance ensured sample collection in an area that encountered minimal reworking (i.e., presence of collapsed and/or rotated blocks) or erosive phenomena. It can therefore be assumed that the recovered sample is representative of the volcano's summit

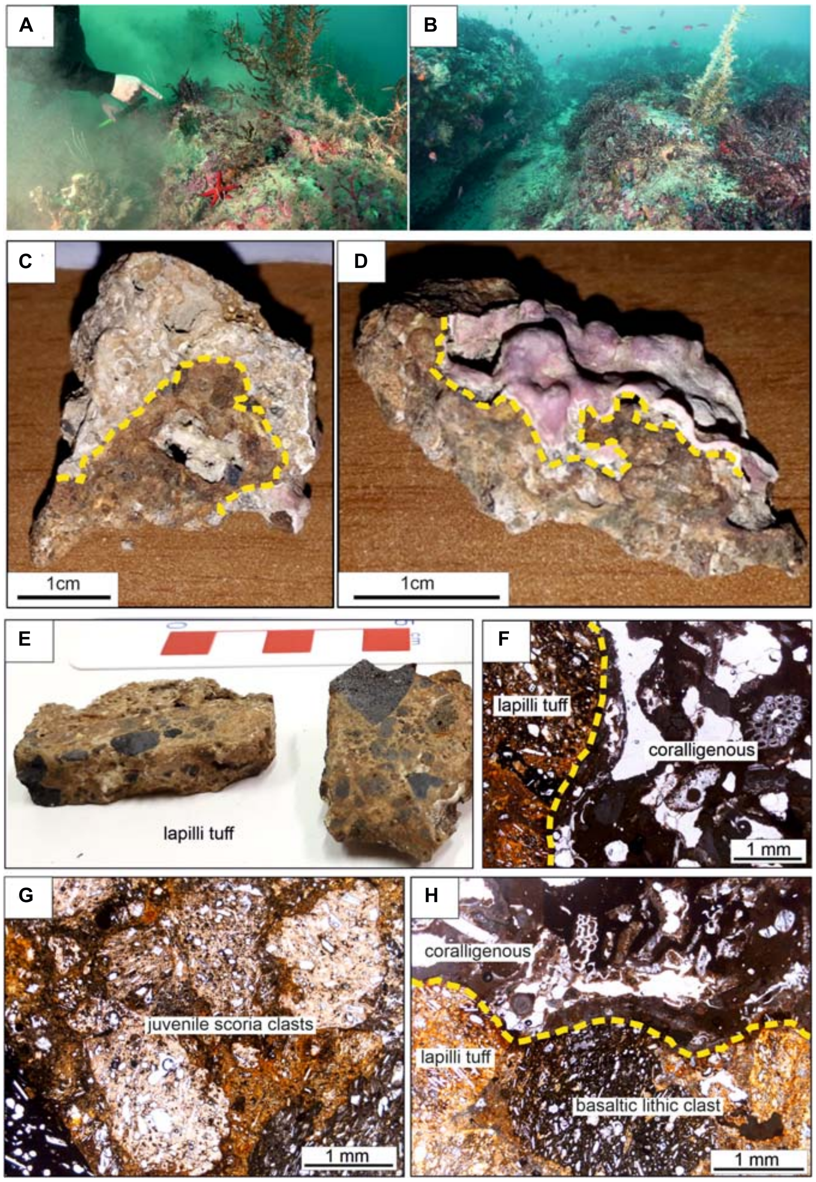

FIGURE 3 | (A) Underwater photo showing the site near the summit of the Actea volcano where the pyroclastic rock-encrusting coralligenous was sampled, as indicated by the diver. **(B)** Underwater photo of the top of the Actea volcano, densely colonized by benthonic communities. **(C)** Sample with the analyzed bioconstruction (coralligenous) grown on the lapilli tuff; the yellow dashed curve indicates the contact. **(D)** Pink coralline algae indicating the first deposition that over time leads to formations such as those of the sample in panel **(C)**. **(E)** Macroscopic features of two fragments of the lapilli tuff sampled at the summit of the Actea volcano. **(F)** Thin section photo (plane polarized light) of the lapilli tuff-encrusting coralligenous (yellow dashed line marks the contact). **(G)** Thin section photo (plane polarized light) of the lapilli tuff, emphasizing juvenile scoria clasts. **(H)** Thin section photo (plane polarized light) of a basaltic lithic clast in the lapilli tuff directly in contact with the coralligenous (yellow dashed line marks the contact).

lithology. According to the structure and the textural features in thin sections, the collected sample consists of a partly palagonitized basaltic lapilli tuff. Relatively fresh (≤1 mm to 2 cm in size) juvenile scoria and basaltic lithic clasts with a micro to cryptocrystalline and glassy groundmass are present. The matrix of the lapilli tuff is mainly represented by pale yellow to pale brown glass and very fine-grained crystals and lithic clasts. The pyroclastic deposit is covered by biogenic concretions having the typical structures of coralligenous, with apposition of thalli of encrusting coralline algae and a small fraction of calcareous tubes secreted by serpulid worms (Ingrosso et al., 2018). The thickness of the organogenic deposition of the sample varies from 4 to 45 mm. As well known, the growth rates of these bio-constructions are very slow (up to 0.83 mm/year) and regulated mainly by light and temperature, depending on the time period, the depth and the latitude (Ingrosso et al., 2018). The growth is counterbalanced by physical, as well as biological, eroding processes (Calcinai et al., 2015; Bertolino et al., 2017) especially where the coralligenous integrity is altered (Valisano et al., 2019). To determine when the pyroclastics were erupted underwater, we extracted four samples at the interface between the volcanic rock and the coralligenous accretion, and dated with the radiocarbon method using the AMS technique. Four dates have been obtained (**Table 1**). Radiocarbon ages range from 7,387 ± 175 cal years B.P. to modern (post-A.D. 1955) and they are consistent with the expected relative dating depending on the sampling positions. It is worth to note that a very recent phase of coralligenous accretion (sample CG4) was obtained, where living calcareous thalli were evident. For this sample radiocarbon analyses detected man-made "bomb" ^{14}C produced by atmospheric nuclear detonation tests performed after the World War II, and this is indicative of the expected modern age of the sample, and thus of the consistency of the obtained dating information. The coralligenous accretions do not show strong evidence of bioerosion, and are among the oldest ever dated in the Mediterranean Sea (Ballesteros, 2006).

The oldest dating detected in our samples represents a *terminus ante quem,* assuming a colonization of the coralligenous shortly after the shallow-water Surtseyan-type eruption. The two intermediate ones and the recent one (post A.D. 1950) dating testify to the progressive colonization of the coralligenous on the exposed lapilli tuff. The result of these measurements presents an uncertainty about the time elapsed between the eruption of the pyroclastic deposit and its biogenic colonization, which is unknown (probably tens of years). However, this age fixes the submarine eruption at the summit of the Actea volcano in the mid-Holocene, an epoch in which volcanic activity was only hypothesized in this sector of the Sicilian Channel.

DISCUSSION

Radiocarbon dating of faunal assemblages associated with fossil red coral deposits found in the vicinity of Graham Bank has been used in the attempt to reconstruct past submarine eruptions in the NW Sicilian Channel. Results indicate an emplacement spanning the last 7.3 ka, suggesting that these voluminous material were accumulated during the Holocene due to periodic slope failures, possibly triggered by volcanic and/or seismo-volcanic activity dislodging corals (dead or alive) from the steep flanks of volcanoes on which they lived (Lodolo et al., 2017). However, if we exclude the well-documented eruption of Ferdinandea, none of these analyses have allowed us to unambiguously and precisely date any eruption that occurred from the Late Pleistocene to the pre-historic times. For example, there have been numerous phreatomagmatic eruptions producing new islands over the last century, one of the most known was that occurred in 1963 at 17 nautical miles SW of Iceland, where Surtsey Island was formed (Kokelaar and Durant, 1983). Photographic documents have testified the explosive nature of this event and its affinities with the emergence of the Ferdinandea, as represented in paintings by various artists. For the new formed underwater scoria cones, suitable conditions (water depth, presence of nutrients, relatively calm environment) may eventually favor the development of biogenic communities, like the case of the top of Ferdinandea (now at 7 m below the sea level), populated by a dense and very large variety of benthonic species. On one of the world's youngest volcanic islands created by an eruption of a submarine volcano (December 2014 into early 2015) in Tonga (Garvin et al., 2018), scientists have found signs of life just 4 years later, nurturing flowering plants. As an additional example, Álvarez-Valero et al. (2018) described the immediate colonization of black corals on the basanites just erupted during the Tagoro volcano (Canary Islands) submarine event occurred in October 2011. In general however, the existence of pyroclastic cones may be extremely short, because after the cessation of the volcanic processes the parts emerging above sea level are subjected to rapid tidal and wave-current erosion, resulting in formation of shoals (Schmidt and Schmincke, 2002).

The lapilli tuff volcaniclastic deposit sampled from the summit of the Actea edifice is typical of shallow subaqueous basaltic volcanism producing tuff cones, frequently developing in clusters (Kokelaar and Durant, 1983). In addition, the Actea pyroclastic edifice is associated to a large lava flow having an E-W elongation. This morphological feature represents an exception compared to the other volcanic edifices of the NW Sicilian Channel, including the N-S aligned tephra cones of the Graham Bank (Cavallaro and Coltelli, 2019). The great lava flow that extends from the SW flank of Actea is the only emplacement found, with the sole exception of the fan-shaped lava flow present on the western flank of the volcanic cone located a few hundred meters NW of Ferdinandea (Cavallaro and Coltelli, 2019). When Actea volcano last erupted (~7,300 years ago) the sea level was ~10 m lower than today. In addition, geophysical data analysis has revealed a Quaternary tectonic vertical uplift of ~0.6 mm/year (Lodolo et al., 2020) in the coastal sector where Actea volcano is rooted. Assuming that there have been no significant variations in the height of the volcanic edifice in the past compared to present-day, we may speculate that the eruption took place at ~14 m below the former sea level. It is well known that water depth is one of the main controls of the mode and consequences of submarine eruptions since high hydrostatic pressure generally inhibits the amount of magma erupted and the explosivity of the eruption (Kokelaar, 1986). Despite these water depths represent the lower limit of the action zone of the storm-waves and surface currents, the acquired video images around the sampling did not reveal significant evidence of erosive phenomena and related reworking deposits. Thus, the oldest age yielded by the radiocarbon dating on our sample can be considered with a good degree of confidence.

FINAL CONSIDERATIONS

Since volcanic activity in shallow water may result in explosive eruptions (Kokelaar and Durant, 1983), with possible generation of tsunami waves reaching the shoreline, the knowledge of time-space activity forming submarine volcanic fields is imperative for volcanic hazard assessment, especially if located close to coastal areas and where portual infrastructures and local navigation are particularly developed. Dating the encrusting bioconstructions on the submarine volcanic products may offer a valuable approach to reconstruct the time occurrences of pre-historical events, which represent the decisive information to properly asses a volcanic hazard plan. This method can be effectively used to bridge the gap between historical accounts and the geological record, and offers a new perspective for determining patterns of Holocene submarine volcanic activity. The better we can reconstruct the timing of past eruptions, the better we can mitigate potential future volcanic episodes and associated tsunamis.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

EL designed and coordinated the study, performed the geophysical data analysis, and wrote the manuscript. AR performed the analysis of the volcanic rocks and contributed to write the manuscript. CC and BC performed the analysis on coralligenous and contributed to write the manuscript. DC analyzed the geophysical data and contributed to write the manuscript. GQ and LC performed the ^{14}C measurements and contributed to write the manuscript. All authors contributed to the article and approved the submitted version.

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