Multidisciplinary Investigations at Panarea (Aeolian Islands) after the Exhalative Crisis of 2002

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Abstract

Panarea and surrounding Islets form a volcanic edifice, that is part of the Eastern sector of the Aeolian Arc, Southern Tyrrhenian Sea. It is now considered inactive, since last documented activity is 20 Ka old. However, on 2002-11-03, gas started to flow violently from the seafloor in an area E of the Island, mainly along NE and NW structural lineaments, and lasting up to 2003-2004 with a consistent flux, orders of magnitude larger that 'steady-state' fumarolic activity documented there in historical times. On the same period a strong effusive activity of Stromboli (10 NM to NNE) was present. Since then, several investigations have been conducted at sea and on land, with the aim of focusing on the problem of effusive activity at sea, mainly in the light of volcanic surveillance and risk. Among these investigations, some of which have been repeated over years, we present and discuss some data and results from: (a)visual inspection and sampling by divers and ROV, (b)GPS networks and mapping by multibeam and LIDAR, (c) oceanographical measurements by current meters and CTD, and water flux and dynamics measurements, (d)magnetic and gravimetric surveys, (e) multichannel reflection Seismic with OBS and land station networks. Data were used for compilation of high resolution bathymetric, magnetic and gravimetric maps, including the emerged and submerged portions of the edifice.

1 Introduction and setting

On 2002-11-03 a burst of gas occurred in the marine area E of Panarea, lasting for years with a consistent flux from fractures and sinkholes on the seafloor, mostly near the islet of Bottaro (Figure 1). Investigation started immediately to monitor this event from geological and geochemical point of views, also in the light of volcanological surveillance and risk [1, 2, 3, 4, 5, 6, 7], and on the possible connection to regional tectonics [8, 9, 10, 11]. This paper aims at providing a review of the geophysical investigations carried out in the area of the eruption since 2002. The Aeolian Islands are part of the volcanic arc formed by the convergence of the African and Eurasian plates and by the subduction and southeastward rollback of the Ionian lithosphere [12, 13, 14, 15, 16, 17, 18], and is characterized by compression in the western sector, strike-slip faulting and extension in the central and eastern ones. The archipelago is formed by 7 islands and minor islets, including to-

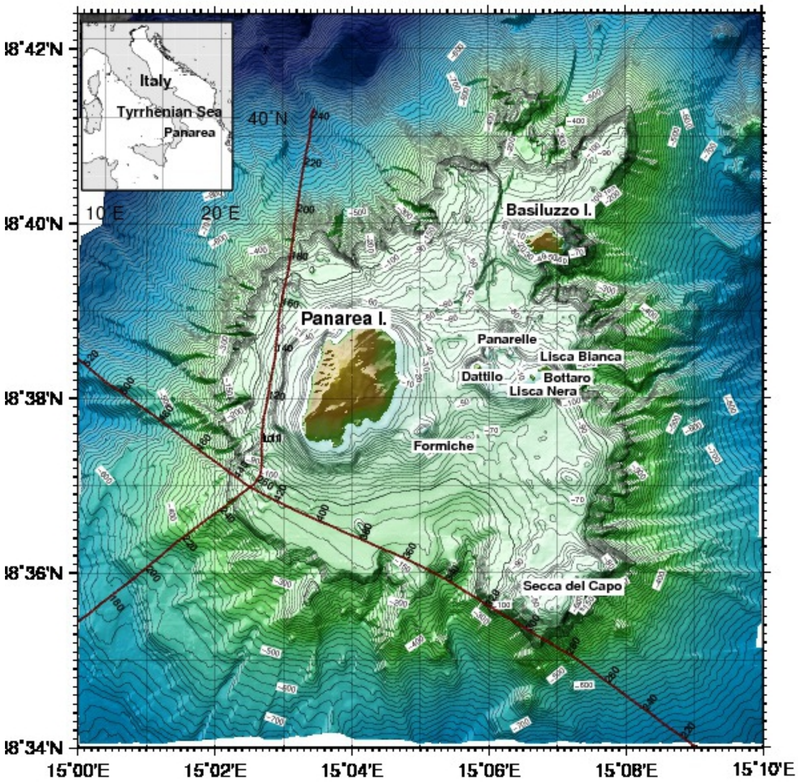

Figure 1: Panarea volcanic complex. Bathymetries from ISMAR. Also shown position of MCS lines L09, L10, L11.

day's active Stromboli volcano. Panarea is considered inactive, however [19] have shown possible recent volcanic outcrops near Basiluzzo; present deformation patterns are likely connected to NE-SW trending faults [20].

The gas release of 2002-11-03 in the area E of Panarea, known since historical times for fumarolic activities [21], generated 6-7m diameter columns of bubbles from the seafloor to the surface. Several active spots were identified by divers and ROVs' and by repeated multibeam surveys [3, 5]. The most impressive one was just SW of Bottaro (PEG1, Figure2) with gas reaching the surface from 15m depth, from an elliptic depression produced by the explosive collapse of the seafloor; a plume of suspended sediments was present at the sea surface for days.

During the most active degassing up to mid 2003, the emissions were found to be an emulsion of CO_2-dominated gas phase with suspended sediments, colloidal sulfur; the water was acidified by dissolution of SO_2, HCl and HF [2, 7]. [1] estimated a

RESP	CRUISE	Date	Ship	Mapping	F	C	M	G	D	R
ISMAR	1994	1996-11-01	J.Charcot	Sim.EM1000						X
ISMAR	TIR96	1996-09-01	Gelenzhik	Sim.EM12			X			
ISMAR	TIR96	1999-02-01	Strakhov	Sim.EM12			X			
ISMAR-INGV	P2002-11	2002-11-07	Thetis			X			X	X
ISMAR	P2002-12	2002-12-10	Alsea	Res.8125	X		X		X	
ISMAR	P2003-01	2003-01-20	Thetis							
ISMAR	P2003-07	2003-07-27	Alsea	Res.8125		X	X			
ISMAR	P2003-09	2003-09-02	L.Sanzo		X	X			X	X
ISMAR	P2003-12	2003-12-10	Alsea	Res.8125					X	
ISMAR-NERC	P2004-04	2004-04-20	plane	LIDAR		X				
ISMAR	P2006-01	2006-01-20	Alsea	Res.8125					X	
ISMAR-IMM-INGV	P2006-04	2006-04-15	Aretusa	Kon.EM3000			X			
INGV		2006-04-15	land					X		
ISMAR	P2006-05	2006-05-02		SeaInterf.						
ISMAR	PANA07	2007-08-01	Urania	Res.8160						
ISMAR-INGV	CALA08	2008-04-02	Urania	Res.8160				X		
ISMAR-INGV	PANSTR10	2010-02-01	Urania	Kong.EM710			X	X		

Table 1: Data Acquisition Cruises. Measurements: F=Water-gas Fluxes; C=CTD; M=Magnetics, G=Gravity; D=dive; R=ROV.

gas output of $10^9 \mathrm{l}\cdot\mathrm{d}^{-1}$ (November 2002, all emissions) and of 4 to 2 x $10^7 \mathrm{l}\cdot\mathrm{d}^{-1}$ (May to July 2003, PEG1), orders of magnitude higher than the total gas output of $10^6 \mathrm{l}\cdot\mathrm{d}^{-1}$ measured within the Islets in the 1980's [21]. [22] measured the water fluxes at PEG1, deriving also the gas fluxes. The plumes affected the marine environment with changes in the biota [23, 24] and in the water properties [25]. Figure 2a shows the location of the major emissions (named PEG1,2,3,8).

2 Materials and Methods

Several cruises were performed in the area for obtaining geophysical and oceanographic data and to monitor the geomorphological features of the seabed and the evolution of the gas outflow after the 2002-11 crisis. The investigations were coordinated by the Italian Department of Civil Protection (DPC) and 'Commissione Grandi Rischi' and were carried out from immediately after the gas burst up to 2008 (Table 1).

Multibeam data from different cruises and instruments were processed with the Kongsberg's Neptune and RESON's PDS2000 software. Gridding was performed in the geographical and UTM33 projections, at spatial resolution ranging from 10-15m for deeper areas, to 0.20-0.25m for local, shallow areas. Some datasets have been processed separately due to large number of points acquired. Furthermore, a particular attention was paid to the analysys of the gas emissions (Figure2) included in the multibeam data [3]. A LIDAR flight was performed by NERC on April 2004 by the *Airborne Remote Sensing Facility* using an Optechh ALTM 3033 laser scanner; the processed data included first and last pulses and obtained data at the resolution of ~0.2m [26]. Magnetic data were acquired during cruises TIR96, TIR99, P2002-12, P2003-07 and PANSTR10, with GEM GSM19D and Marine Magnetics Sea-Spy 'Overhauser' magnetometers; during cruise P2006-04 the Geometrics G-800 'Cesium magnetometer was used [27]. Data underwent filtering, de-spiking, cross-over error reduction, application of IGRF Models with 2005 coefficients for calculating anomalies and reduction to the Pole.

Multichannel data (48 active, 12.5 m group interval, 2xGI Harmonic mode), were acquired during cruise PANA_07, complementing MESC2001 ISMAR's cruise (http://www.ismar.cnr.it/prodotti/reports-campagne). On the same cruise a seismic network was set on Islets and on the seafloor by deploying seismometers and OBSs from INGV and University of Trieste. Seismic shots sequences were performed along lineaments connecting the instruments. The gravity data on land [27] were sampled using a pair of LaCoste&Romberg microgravimeters (Aliod model) equipped with a digital data acquisition system, GPS tracking and automatic tide corrections, with a nominal resolution of 1 μgal. Marine gravity data were acquired with a Lacoste&Romberg 'AirSea' gravimeter, directly interfaced to DGPS, during cruises CALAMARE08 and PANSTR10 (http://www.ismar.cnr.it/prodotti/reports-campagne). Data were de-spiked, corrected for drifts and Eötvös effects, and Free air and Bouguer anomalies were calculated.

Flux of water entering the vent at PEG-1 was estimated by geometry of the ascending gas column and by measuring water velocities inside and outside the gas column. Rotor (Aanderaa and Datasonics) and ADCP current meters were positioned 1m above the sea floor in the gas, and few m away, respectively (Figure 4). Estimates of the venting surface was done by divers and high resolution bathymetries, since multibeam used were able to detect the gas in the water column. Once obtained the water fluxes entering at the base and exiting the vent, the gas fluxes were estimated by applying reduction factors accounting for (a) the bubble sizes and voids, as seen by divers and ROV, and (b) considerations about reduced velocities at the boundary layers of the cell.

R/V Thetis and R/V L.Sanzo deployed ROV systems, on 2002-11, few days after the burst, 2003-01 and 2002-09. During this last deployment the instrument was also moored on bottom in front of the degassing area for hours, aiming at recording flagged poles on seafloor and dye releases able to visualize the water dynamics at the base of the vent. ROV records confirmed the bathymetric and divers investigations about changes in topography and geometry of the gas column.

CTD investigations were performed on 2002-07, 2002-09 and 2004-04, to evaluate possible plumes and modifications of water column properties. Standard sensors mounted on SBE probe were used and pH was found to be particularly effective for tracing the acid fluid releases.

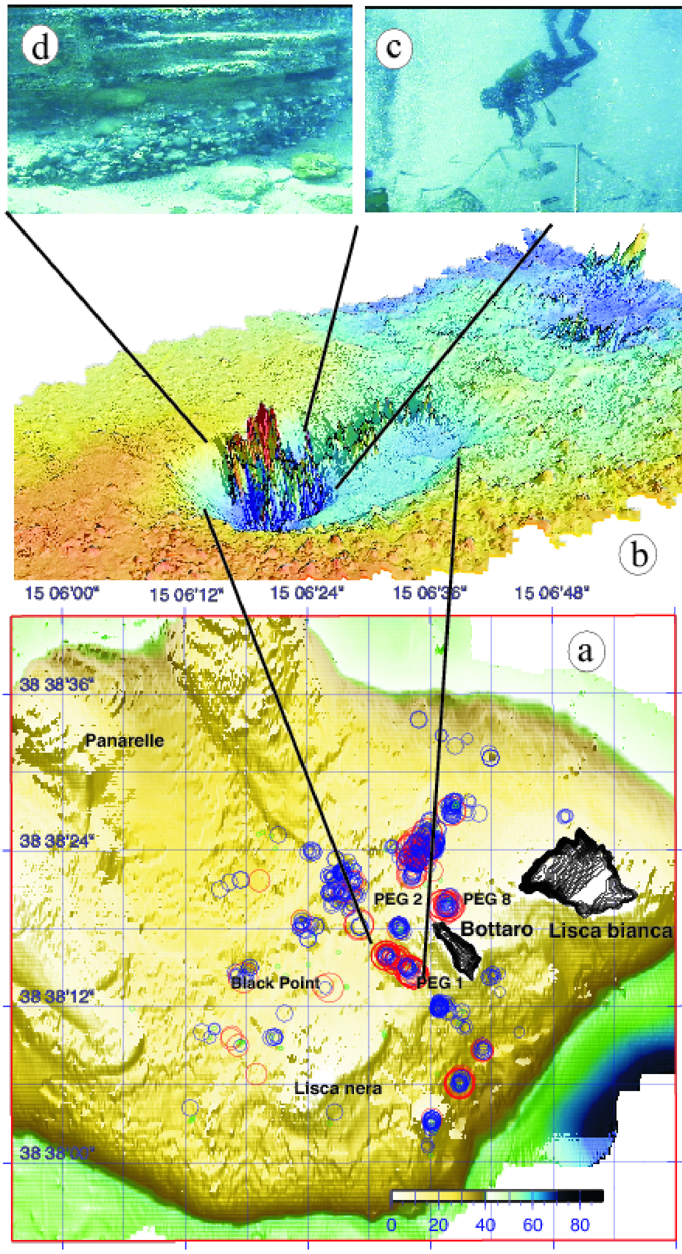

Figure 2: Gas emitting points (a) and 3D rendering of PEG1 multibeam data (b). Photos on top: (c) the divers' positioning the lander with a rotor current meter into the gas column, and (d) the exposed cemented breccia at the vertical borders of the sinkhole. Images from [2,4], modified.

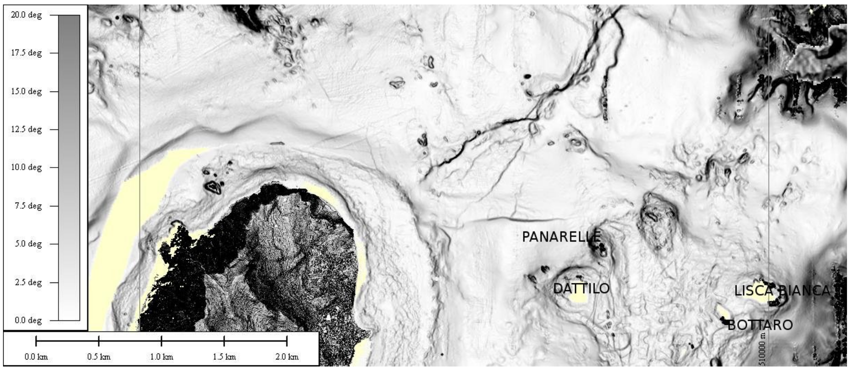

Figure 3: Area E of Panarea (slope shading). Topography by NERC's LIDAR flight.

Figure 4: September 2003 flux-measurement experiment: the ADCP and rotor current meter (within gas, on the frame) are visible.

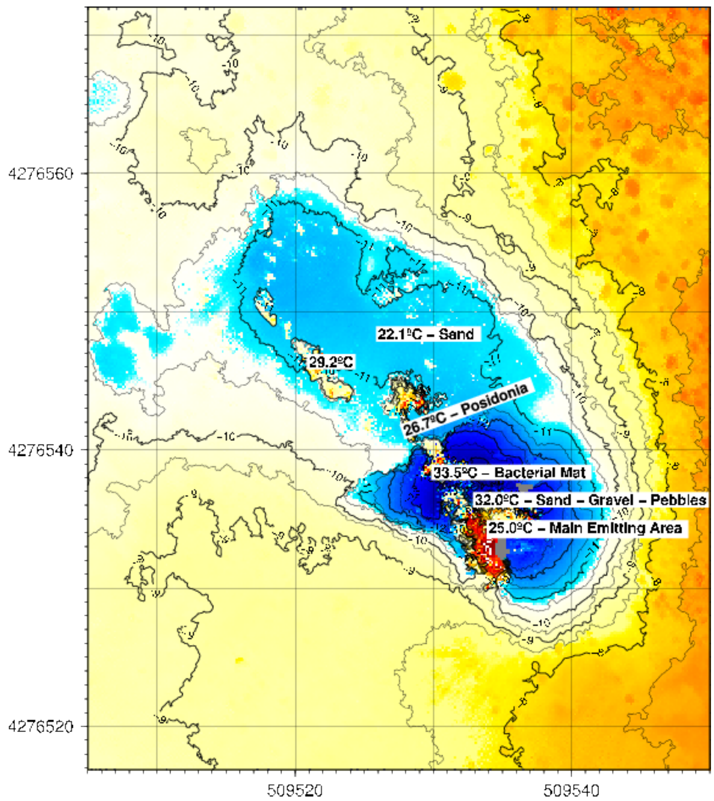

Figure 5: Bathymetry and diving observations on 2002-12. Also shown the temperature measured at the seafloor close to emitting spots. Sea water temperature was ∼17°C.

3 Results and Discussion

3.1 Bathymetry

ISMAR performed a high resolution multibeam bathymetric cruise on 1994 [29]. A wide portion of the Aeolian Central sector was imaged down to ∼800 m depth, except for very shallow waters, including the area of the Islets. The TIR96 and TIR99 cruises [30] mapped the deeper portions. After 2002 crisis several cruises were able to map almost entirely the submerged edifice, collecting also data near the shoreline of Panarea and Islets.

Panarea and islets (Figure 1, 3, [31]) emerge from a volcanic edifice (diameter of ∼18 km at the -1000 m isobath), dissected by gullies and channels and largely dismantled by erosion and by neo- and volcano-tectonics. Its flat summit, with edge at about 80-130 m bsl, is almost totally covered by volcanoclastic sedimentation, arranged in its upper part in sequences of terraced, wedge-shaped prograding units [32]. Several, partly buried, primary volcanic features are present and partially outcrop in the southern sector, among them the

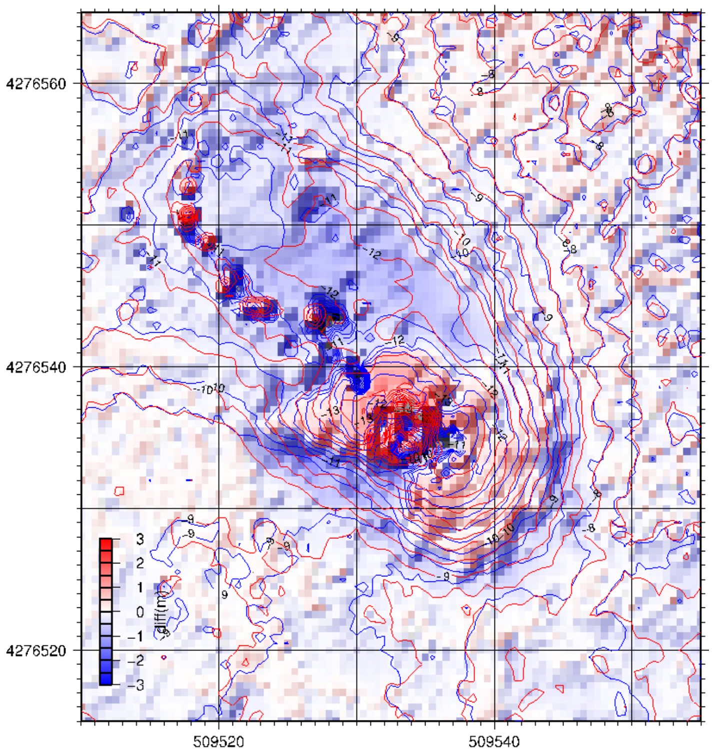

Figure 6: Bathymetry 2002-12, 2003-12, one year after. Also shown the difference in depth.

shoal of Secca del Capo [33, 34, 19, 29, 35].

East of the island, a relief of $\sim$ 1.5km diameter is present at depth $<$ 30m, partially emerging in the Islets and enclosing depressed areas where intense exhalative activity occured. The northeastern summit of the edifice presents a NNE-SSW and NE-SW structural lineament (on the $\sim$ 20 m high fault scarps, fresh rocks and mineralization as well as gas venting are present [36, 29, 35]) and further extends from Basiluzzo with NE-SW direction.

The repeated bathymetries over the years on the PEG1 area 5 showed that less than a year after the gas burst, the depression was already partially infilled by sediments transported from the flanks by the dismantling of the sub-vertical wall to the N, exposing cemented breccias and rocks of holocene age [5] (Figure6). The survey of 2006-01 further confirmed this infilling, producing variation of bathymetries of 2-3m. Pebbles rolling on the seafloor under wave and current dynamics kept on filling the sinkhole and very likely will produce a new non-active meter size depression filled with sandy or gravel materials similar to others discovered in the area by multibeam. On 2006 and 2007 the flux of gas was visibly reduced to a small area, and similarly the transport caused by entrainment at the

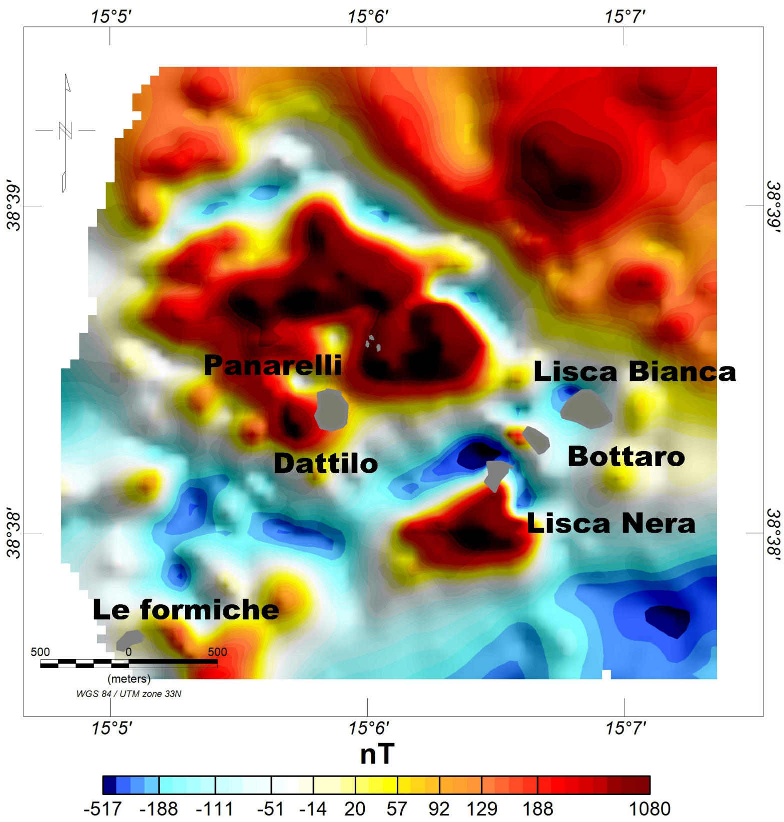

Figure 7: Magnetic anomaly data. 2002-12 Alsea cruise.

base of the degassing cell also reduced. The wave and current dynamics will probably be able to continue the filling process on the medium period. On the plateau just N of the depression, a wide area was covered by sediments, very likely ejected during the explosive collapse of 2002-11-03, and the sizes and water depth seem suitable for bedload transport and distribution. ROV on the field few days after revealed sand dunes and ripples crossing at 30-40°.

3.2 Magnetics and Gravity

On 2002-12 ISMAR collected high resolution data within the Islets (Figure7). The same pattern of lines was repeated by Geophysics and Marine Technology Unit of Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Portovenere in Spring 2006, together with gravity data on the islets and on Panarea [27]. Magnetic anomaly pattern of islets area is dominated by the high positive (500-750 nT) north of Panarelli shoal in correspondence of a topographic high. This anomaly seems related with the

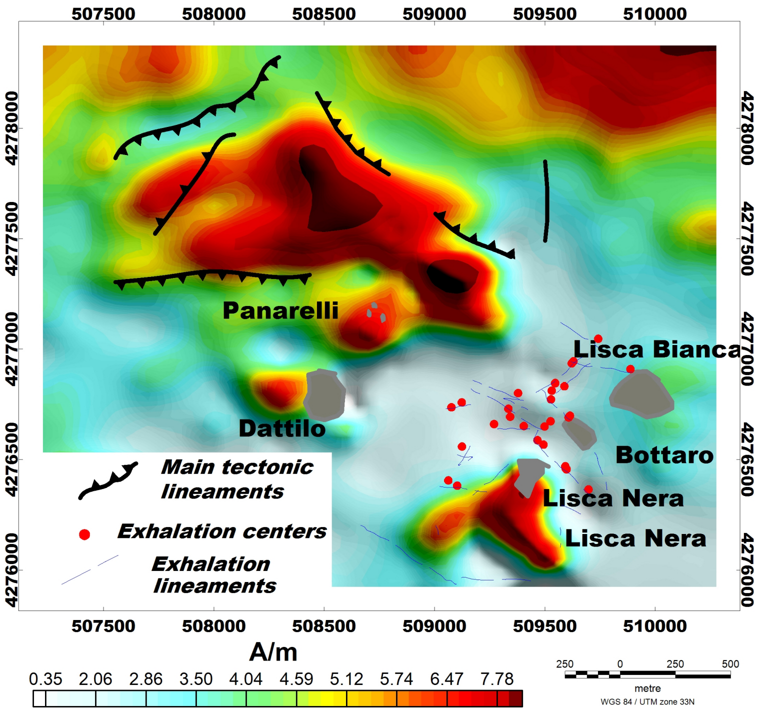

Figure 8: 2D Apparent magnetization map. Structural lineaments from [5], exhalative centers from [28].

main tectonic lineaments and it can be interpreted as the signature of an ensemble of magmatic sources. Rock-sampling by [5] showed andesitic lava products correlated to a shallow cryptodome-like structure. A 2D inversion of the data was performed to evaluate the magnetization pattern of the area, using an FFT-algorithm (Parker inverse approach, [37, 38]), applied to a crustal portion of 1Km below sea bottom. Figure 8 suggests a clear separation between the high magnetized region between Dattilo and Basiluzzo and the region among Lisca Bianca, Bottaro and Lisca Nera where the exhalative crisis of 2002 occurred. In this region the magnetization pattern decreases with a null-value strongly driven by the hydrothermal alteration which affects the seafloor.

During cruise CALAMARE08 marine gravity data around Panarea and Islets were acquired, and were integrated with the above cited survey on land (see Figure 9). The two dataset were collected by different methodologies and instruments, and the merging was achieved without any fictitious grid-knitting process but using the absolute gravity data from a station in Panarea for reducing the offsets. The offshore gravity mapping shows several gap, making these results preliminary, while awaiting for on-going data processing of

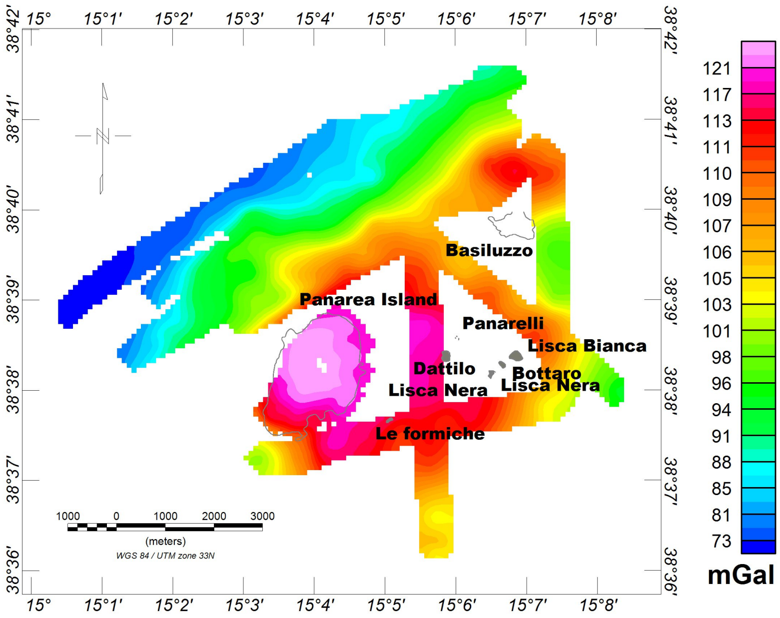

Figure 9: Free Air gravity anomaly map.

cruise PANSTR10.
Multichannel seismic acquired during cruise PANA07 were shot for investigating the regional tectonic and setting, other than for illuminating the OBS and land station seismological network. The data provide important information on plio-quaternary sediment thickness, to be used for proper gravimetric analysis and modelling. Some examples of the lines are on Figures 10, and 11 (positioning data in Figure1).

3.3 Flux estimation and Oceanography

The water and gas fluxes that we estimated for the main emission at PEG1 [22] are of the same order of magnitude of those calculated as in [1]. The experiment of December 2002 encountered problems because of the gas flowing violently from the depression; divers experimented strong ascensional force and heavy ballasts had been used for securing the instrumentation on bottom. Similarly [1] was able to measure the flux of gas at PEG1 only on 2002-05, due to such difficulties. Figure 12 shows the data obtained during the 2003-09 experiment and the instruments' deployment. The ADCP data have been influenced by tidal components, while rotor current meter data had a rather constant flux, being anchored well into the gas column. The ADCP to the E measured a much higher number of erratic values, and this is probably due to the beams being invested directly by gas bubbles, which are known to strongly reduce the data quality. These errors depend on the entrainment of gases at intermediate depths, in contrast, with data of 2002-12 when the gas ascending

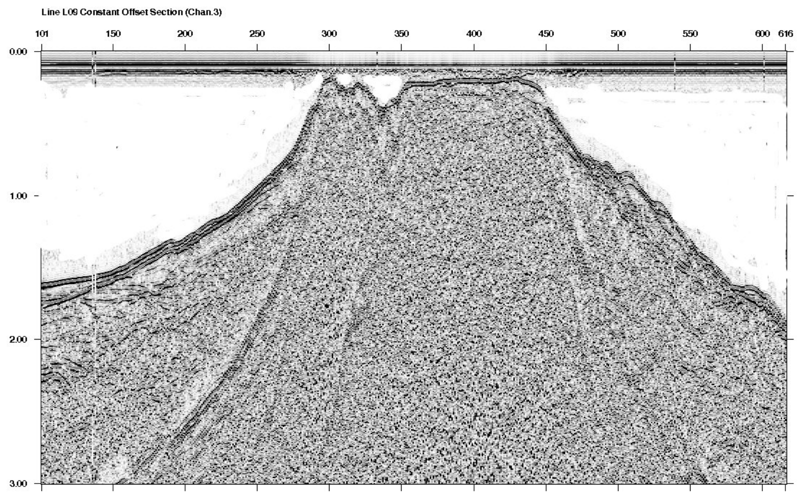

Figure 10: MCS Line L09, neartrace.

speed was higher and diverged at the surface without reaching buoyancy at intermediate depths. The CTD data of 2003-07 were able to depict a plume of acidified water (pH <6.5) centered on the PEG1. The data of 2004 cruise, instead, showed pH anomaly mostly centered on the PEG8 site to the N, which is up to now the lonely active emitting area left.

4 Conclusions

The Panarea area has been largely investigated through a number of geophysical surveys in the area and a comprehensive description of the event was achieved trough an intensive and continuous monitoring. A further step in multidisciplinary knowledge of degassing events was put forward and a number of papers has been published. A lot of scientific discussion arose from this large work and many new insights have been highlighted. This brief description summarizes some of the results.

- High resolution bathymetric surveys have imaged important structural lineaments and morphologies, and helped in studying the evolution of gas emissions near the Islets;
- High resolution magnetic and gravity data provided insights into the volcanic complex; a marked decrease of magnetization is present in the exhalative areas, due to hydrothermalism alteration, whereas strong values were found just to the N and NW of Dattilo and the Panarelli;
- The importance of measuring the effects of the eruptions on seawater properties and dynamics has been stressed, also as a possible new tool for monitoring the evolution of hydrothermal acitvity over time. Strong pH anomalies were reported and seawater was largely acidified. The effects of the acidification of seawater is an imporant issue and shallow vent systems are excellent sites where the effects of ocean acidification can be studied. Diving and morphobathymetric in-

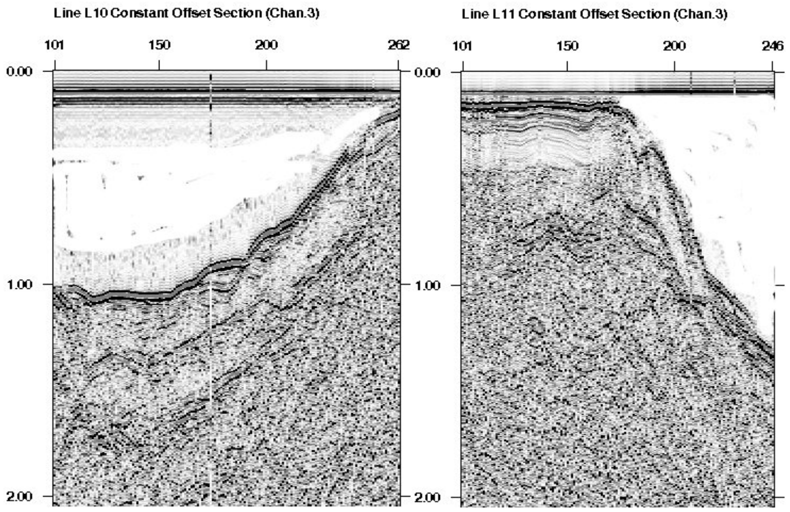

Figure 11: MCS Lines L10 and L11, neartraces.

vestigations reported of the infilling of PEG1 by sediment transport, suggesting a fate similar to other depressions found in the area.

5 Acknowledgments

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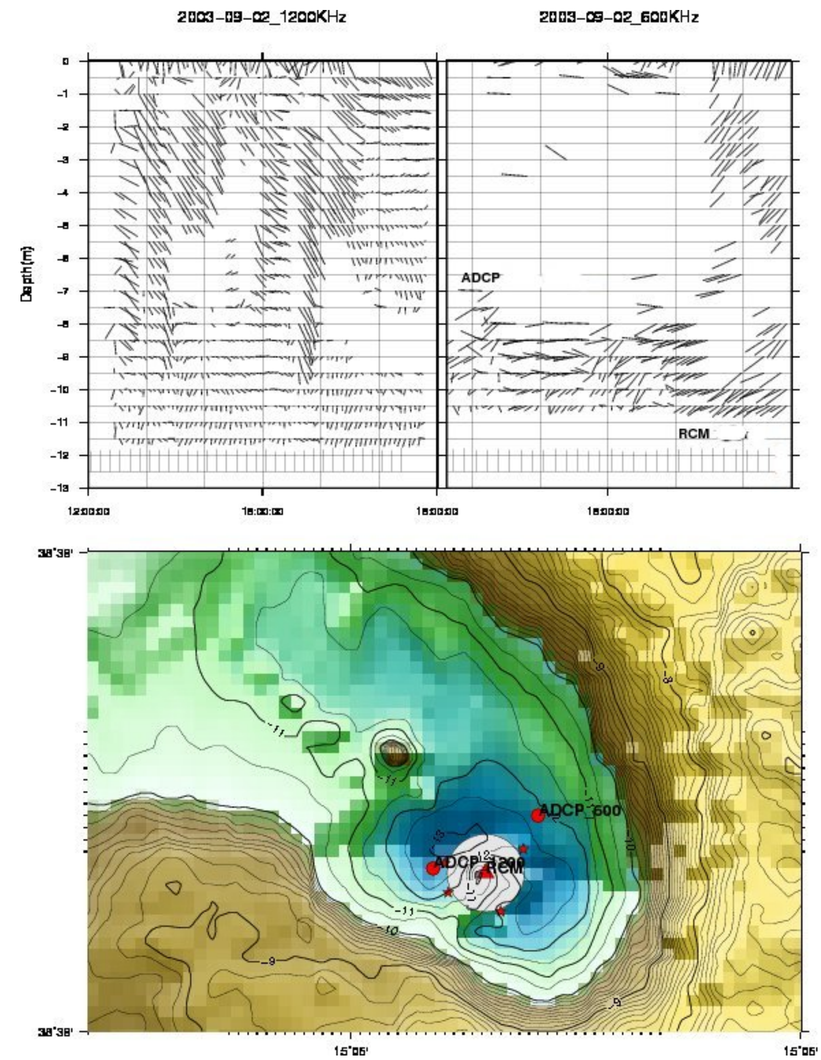

Figure 12: September 2003 flux-measurement experiment.

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