The dark side of the Albano crater lake

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Abstract
The Albano Lake is the deepest volcanic lake among the volcanoes located in the Italian Peninsula. It belongs to the Colli Albani volcanic complex whose last largest eruptions are dated back to about ~30 Kyr, although minor events likely occurred during historical times at 7000 years BP or earlier. After the end of the volcanic activity the Crater of Albano became a lake whose level changes have been known since historical times. In November 2005, the first very high resolution bathymetric survey of the Albano Lake was performed by means of a multibeam echo sounder, integrated with the GPS/RTK positioning technique. Special effort was devoted to produce a high resolution morphobathymetric map, which aims to provide a Digital Terrain Model of the lake floor for wide applications. The surveys did not revealed significant gas exhalative centres, which should indicate a current active gas release from the lake floor. Here we show the technical details of the bathymetric surveys, the very high resolution bathymetric map and the main morphological features of the Albano Lake bottom.

Key words *Colli Albani volcano – Albano Lake – multibeam bathymetry*

1. Introduction

The Colli Albani volcanic complex occupies a wide area about 25 km SE of Rome. Its general structure is a caldera with a central cone. This complex displays two nested calderas and several more or less eccentric post-caldera vents, most of which have been produced by explosive activity. The highest point is Monte Cavo at 949 m, which consists in a scoria cone located in an eccentric position on the SW rim of the younger Faete caldera. The two crater lakes of Albano and Nemi fill the most recent craters of the volcano (fig. 1) (Trigila, 1995).

The former geological studies performed by Mercalli (1883), Fornaseri *et al.* (1963) and De Rita *et al.* (1988, 1992) dated all deposits of the Colli Albani at an age older than Holocene (>10000 years). Until recent times, they have been considered an extinct volcano, although some historical documents reported some eruptive activity around 114 B.C. (Funiciello *et al.*, 2002) and 7000 years BP (Andretta and Voltaggio, 1988). In recent times, evidence of an ongoing volcanic unrest based on instrumental seismological and geodetic data have been detected (Amato and Chiarabba, 1995; Chiarabba *et al.*, 1997; Anzidei *et al.*, 1998), and new researches indicate that an eruptive activity likely occurred during the Holocene (Funiciello *et al.*, 2003; Porreca *et al.*, 2003), as also previously suggested by Andretta and Voltaggio (1998) and Villa *et al.* (1999).

Measurements of ground deformation available from high precision levelling lines established by IGM in 1951, as well as other benchmarks measured at the end of the last century, indicated a uplift at 30 cm in 43 years at a rate at ~0.7 mm/yr (Amato and Chiarabba, 1995). The broad deformation zone evidenced through DinSAR observations by Salvi *et al.* (2004), mainly across the two lakes of Albano and Nemi, was interpreted as related to a superficial source (3-6

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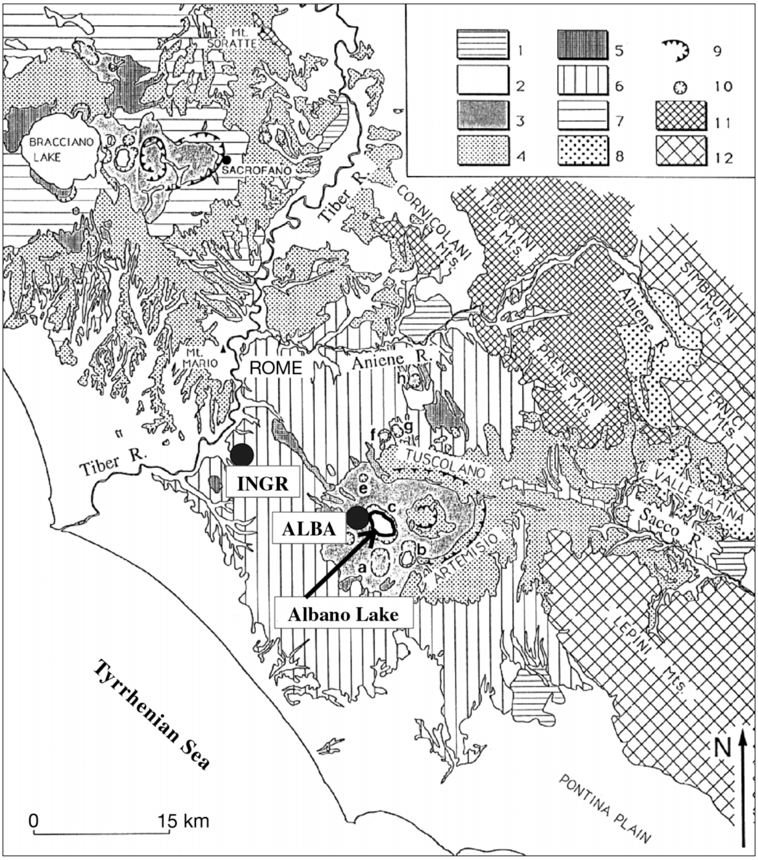

Fig. 1. Regional setting of the Colli Albani volcanic complex (from De Rita *et al.*, 1992, modified). Key: 1 – travertine; 2 – Plio-Pleistocene sedimentary units; 3 – «final» hydromagmatic units; 4 – air fall deposits; 5 – lava flows; 6 – pyroclastic flow units of the Colli Albani; 7 – pyroclastic flow units of the Sabatini volcanic field (in northwestern part of the map); 8 – Tortonian flysch; 9 – caldera rims; 10 – late explosion craters (a: Ariccia, b: Nemi, c: Albano, d: Giuturna, e: Valle Marciana, f: Pantano Secco, g: Prata Porci, h: Castiglione); 11 – Meso-Cenozoic pelagic carbonate units (Sabina facies); 12 – Meso-Cenozoic carbonate platform units (Latium-Abruzzi facies). Black dots are the fiducial GPS station of INGR, and the reference station of ALBA. The latter was used as reference for the real time positioning of the vessel during bathymetric surveys.

km), producing a signal similar to many active volcanoes (Amato and Chiarabba, 1995; Chiarabba *et al.*, 1997; Salvi *et al.*, 2004). Dangerous gas releases occurred from the ground in this densely populated area (Chiodini and Frondini, 2001; Annunziatellis *et al.*, 2003; Carapezza *et al.*, 2003) is likely the result of rock fracturing produced during the seismicity of 1989-1990, 1995 and 1999 (Beaubien *et al.*, 2003).

From regional tectonic evidence and long-term behaviour of the volcanic complex, Karner *et al.* (2001a,b) and Marra *et al.* (2003) estimated that the volcano could be at the beginning of a new eruptive phase. The existence of a potentially active volcano so close to the centre of Rome and other minor but not less important towns, all densely inhabited, is now leading scientists to revise the volcanic hazards of this area not only for the scenario of new eruptions but also for the recurrent seismicity that periodically strikes the volcano (Amato *et al.*, 1994) and of the possibility of dangerous sudden gas release, rich in CO_2, from the bottom of the lakes of Albano and Nemi. Such catastrophic events occurred in the recent past in the African crater lakes of Monoun (Sigurdsson *et al.*, 1987) and Nyos (Barberi *et al.*, 1989; Rice, 2000).

The Albano Lake, also known as the Castelgandolfo Lake, is located at 293 m above sea level and it is the deepest among the volcanic crater lakes of Italy, being nowadays 167 m deep. At present it is 3.5 km long and 2.3 km wide with an extension of about 6 km^2. It has been settled since pre-historical times (Meli, 1911; Ryves *et al.*, 1996; Manca *et al.*, 1996; Lowe *et al.*, 1996) and during the Roman epoch became a place of great importance (Carandini, 1997). In recent times, this nice quiet place frequented by tourists, is the summer residence of the Pope at Castel Gandolfo village, located just on the top of the crater rim which contains the Albano Lake. Its frequent level changes (Marra and Karner, 2005), produced by deep water circulation and a likely catastrophic overspill in 398 B.C., induced the Romans to excavate an artificial outlet to control the lake level (Funiciello *et al.*, 2002, 2003).

Based on these data, under the umbrella of the Italian Dipartimento della Protezione Civile, a multiparametric study of the Colli Albani volcano was started, including a high resolution bathymetry of the groundfloor of the Lake of Albano, still not yet investigated by such surveys. This technique is able to produce 2D and 3D images of the morphology of submerged volcanic areas, useful for wide applications, including hazard estimation (Anzidei, 2000; Anzidei *et al.*, 2005; Esposito *et al.*, 2006).

2. Bathymetric surveys

A multibeam high resolution survey that covered the whole area of the lake was performed for the first time in November 2005, using the Alsea boat of Coastal Consulting and Exploration Company (fig. 2), equipped with ultra high resolution multibeams and additional survey instrumentation (fig. 3). Particularly, due to the depth of the lake, an ultra high resolution Reson Seabat 8125 multibeam (250 beams, 0.5°×1.0 sector coverage, 455 Khz) were used up to 80 m depth and a Reson Seabat 8101 multibeam (101 beams, 0.5°×0.5° sector coverage, 455 Khz), in the depth range 80-167 m, down to the deepest point of the lake (table I).

Fig. 2. The ALSEA vessel used during bathymetric surveys of the Albano lake.

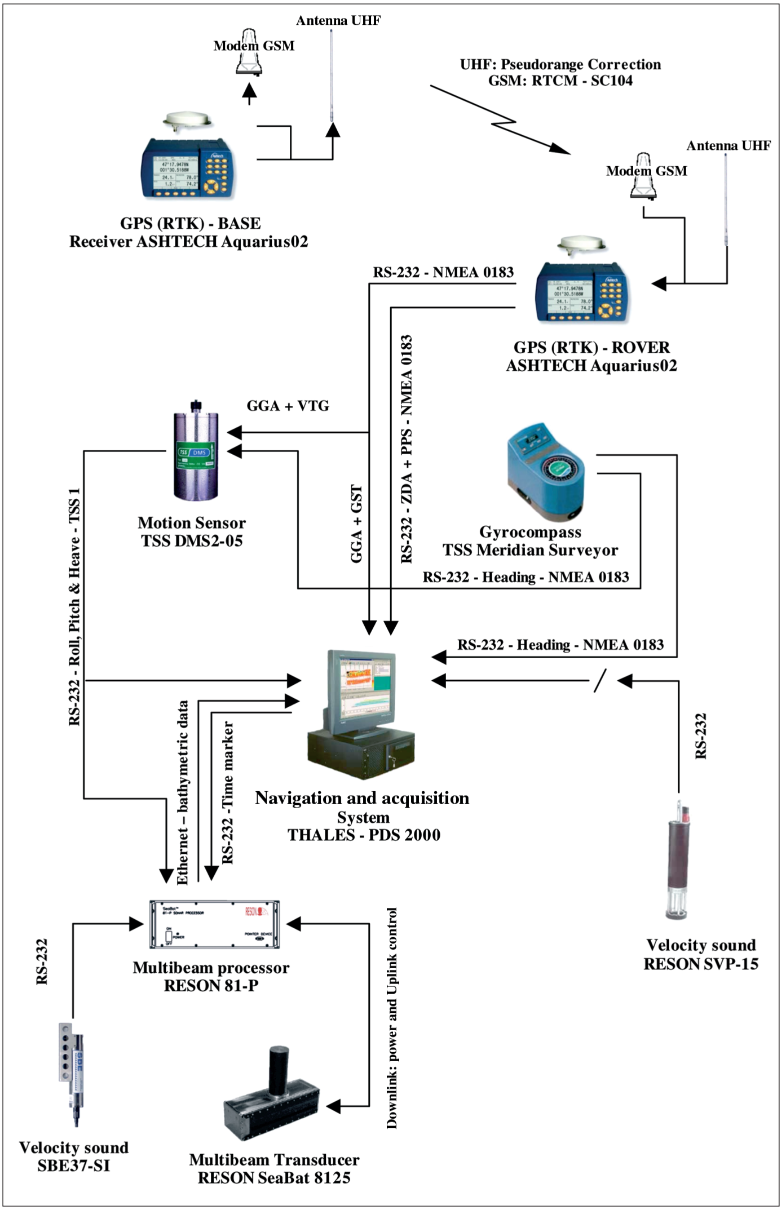

Fig. 3. Sketch of the instrumentation used during surveys.

Before starting the surveys, a check of the health of the GPS/RTK data link, as well as for the other equipments, was performed. The bathymetric datum was established by measuring the water level through some GPS measurements along the shore of the lake. The instrumental height of the zero level was referred to a WGS84 geodetic benchmark (named ALBA), previously set up close to the lake (fig. 1; table II). The latter was measured by geodetic space techniques using a couple of dual frequency GPS receivers, with reference to the GPS geodetic monument of INGR, located at INGV in Rome (fig. 1), which belongs to the National GPS network of the INGV, whose 3D coordinates are known at a few millimeters level (Anzidei *et al.*, 1998; Serpelloni *et al.*,

Table I. Instrumentation used during the bathymetric surveys.

Albano Lake bathymetry – Instrumental features		
Instrumentation	Type	Features
Vessel	M/B ALSEA	-
Differential GPS receiver (RTK mode)	Ashtech-Aquarius 02	10 mm+0.5 ppm, *XY* 20 mm+1.0 ppm, *Z*
Multi beam	Reson SeaBat 8125	Frequency 455 KHz Angle 120° Beams 240 Swath 0.5°×1.0° Max depth 120 m Resolution 6 mm
	Reson SeaBat 8101	Frequency 240 KHz Angle 150°-210° Beams 101 Swath 1.5°×1.5° Max depth 300 m Resolution 12.5 mm
Gyrocompass	SG BROWN Meridian	0.05° static secant latitude 0.2° dynamic secant latitude
Velocity sounder	NAVITRONIC SVP 15	Resolution 0.1 m/s Accuracy ±0.25 m/s
CTD	MICROCAT SBE 37-SI	Conductivity accuracy 0.0003 S/m Temperature accuracy 0.002°C
Motion Sensor	TSS DMS 2-05	*Waves* Static accuracy 5 cm Dynamic accuracy 0÷20 s period *Pitch and roll* Static accuracy 0.025° Dynamic accuracy 0.03°±5°
On board Computers	Pentium IV-Windows 2000	Data acquisisition
Software	RESON B.V. PDS 2000	Navigation and data analysis
Software	CARIS HIPS 5.2	Data analysis
Software	ArcView GIS 8.2	Data management

Table II. Coordinates of INGR station and ALBA GPS stations (WGS84, ellipsoidal heights).

Albano Lake bathymetry – Reference survey coordinates (WGS84, UTM33)			
Station	Geographic	UTM	Height (m)
ALBA	Lat N38°37′58.909 Long E15°04′26.457	N4276057.468 E506442.1583	144.554
INGR	Lat N38°38′16.772 Long E15°04′40.257	N4276608.335 E506775.313	43.30

2005). Elevation data of the lake floor were thus given into the WGS84 reference system (ellipsoidal heights) because the reference benchmark ALBA was not linked to any levelling line and its hortometric elevation was not available.

The centimetric positioning of the vessel was computed by GPS technique in RTK mode during surveys. Real time coordinates were obtained by installing an Ashtech Aquarius reference station located on the GPS station ALBA and transmitting the differential corrections by a High Frequency link at 1 Hz rate to the mobile Aquarius GPS receiver, placed on board the vessel. In addition to this, a Sg-Brown Meridian Surveyor gyrocompass, a Tss DM505 MRU and a Fugro Omnistar Differential GPS, were coupled with the Reson PDS2000 Navigation software for data acquisition (multibeam and positioning), control, calibration and pre-processing. An SBE 37-SI Microcat CTD probe was located at the sonar head and interfaced to the sonar processor, providing in real time speed of sound data for the beam production, whereas the Navitronics SVP15 and a SeaBird CTD probes were also used for profiling the temperature, conductibility and the speed of sound along the water column (fig. 6a,b). Additional details on the employed instrumentation are reported in table I.

Navigation routes (fig. 4) were performed to achieve the full coverage of the lake bottom, with at least 20-30% overlap between parallel swaths, up to the lake surface (fig. 5a,b). The Reson PDS2000 software was able to show in real time to the operator and the pilot the ongoing multibeam and Digital Terrain Model (DTM) and the positioning information that were used for guidance.

At the beginning of each survey session, a full set of multibeam calibration lines were acquired, on flat bottoms and steep targets at about 30 m water depth. The roll, pitch and yaw

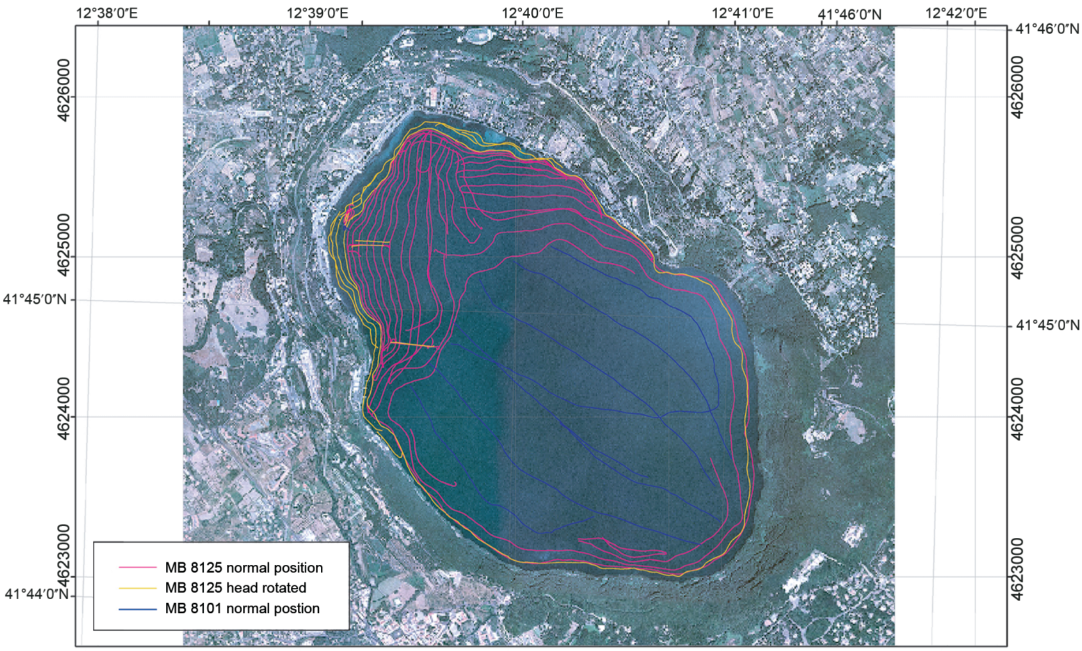

Fig. 4. Course over the ground performed by ALSEA vessel during bathymetric surveys. The 30% overlapping between parallel lines guarantee the full coverage of the area.

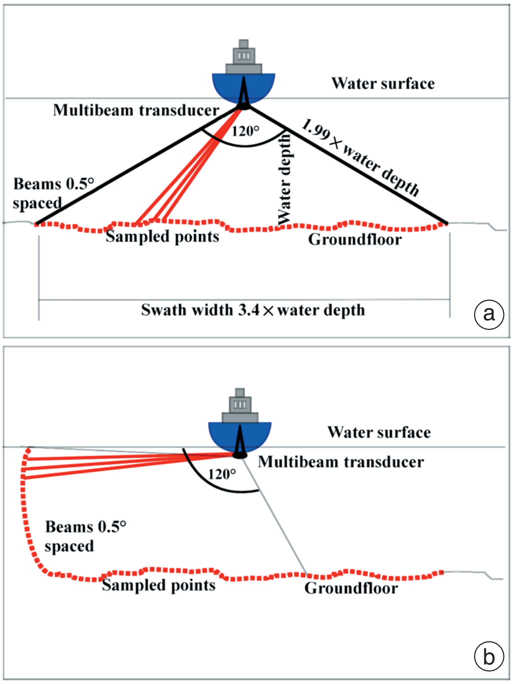

Fig. 5a,b. Sketch of the swath with the multibeam head in a) vertical and b) rotated positions to collect data up to the lake surface.

correction angles were then used to adjust the installation geometries. Calibration parameters were then taken into account during data analysis to adjust the observations.

3. Data analysis and bathymetric map

Data analysis was performed by the Computer Aided Resource Information System-Hydrographic Information Processing System (CARIS-HIPS, 2002) PRO V5.2 software, specifically designed to process multibeam data under Windows NT® and able to manage images of the lake floor in a mosaic and produce raster and analytical maps. The processing sequence was as follows:

i) system calibration and multibeam data reprocessing;

ii) data quality check: low quality data were discarded due to a not optimal signal to noise ratio;

iii) zero level correction, using the RTK data;

iv) high and medium frequency spike removal, but keeping intact eventual signatures produced by uprising gas bubbles from the lake floor;

v) production of high accuracy Digital Elevation Models (DEM).

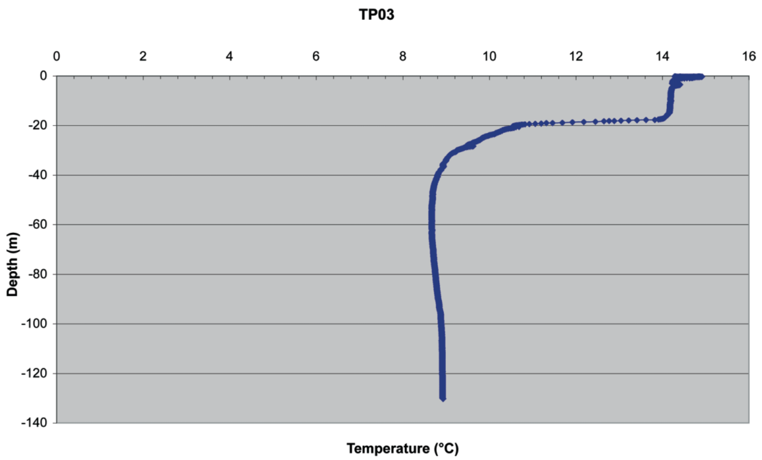

Fig. 6a. Temperature vertical profiles from lake surface to the bottom. Data were collected along the water column above the central crater (deepest point of the lake) and used to calibrate the multibeam system for sound speed velocity in the water to determine depths at 1 cm average formal accuracy.

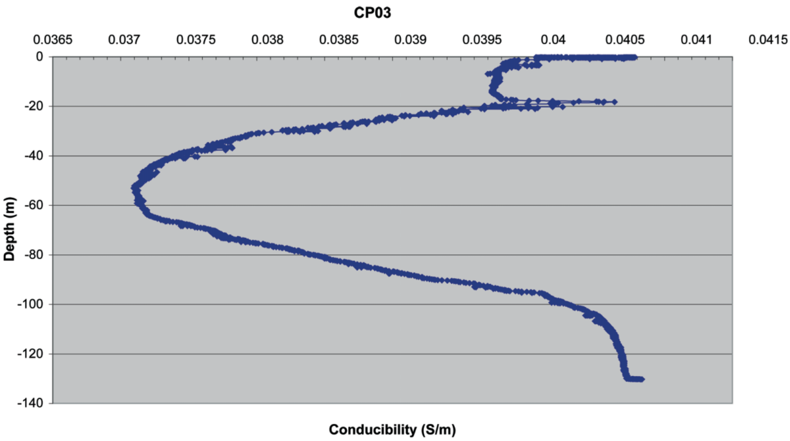

Fig. 6b. Conducibility vertical profiles from lake surface to the bottom. Data were collected along the water column above the central crater (deepest point of the lake) and used to calibrate the multibeam system for sound speed velocity in the water.

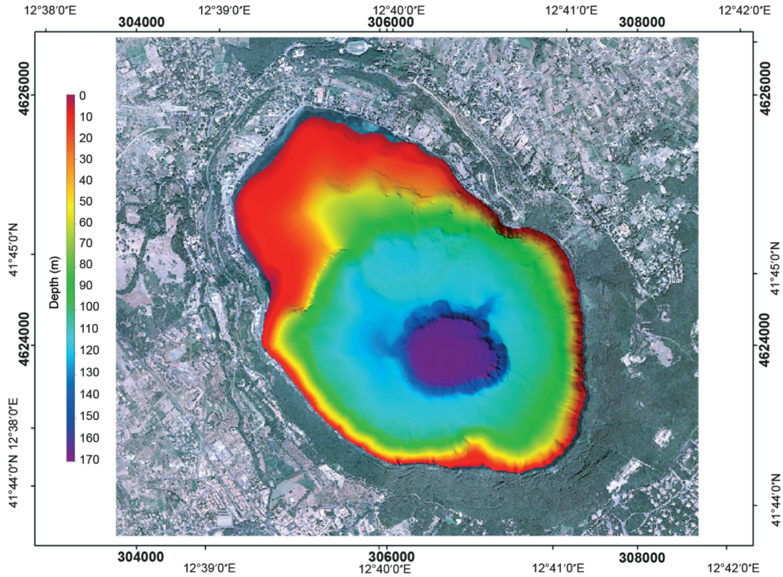

Fig. 7a. Digital Elevation Model (DEM) showing the morphobathymetry of the area. Scale colour shows depths ranging between 0 and –167 m.

To produce the MDEM, were used a total of 1466914 of 3D punctual data (latitude, longitude and depth), that were converted in the UTM33-WGS84 coordinate system.

The survey data set was analysed to reduce any positioning offset or error in the MDEM together with the analysis of the standard deviations of the mutibeam data. The latter show values

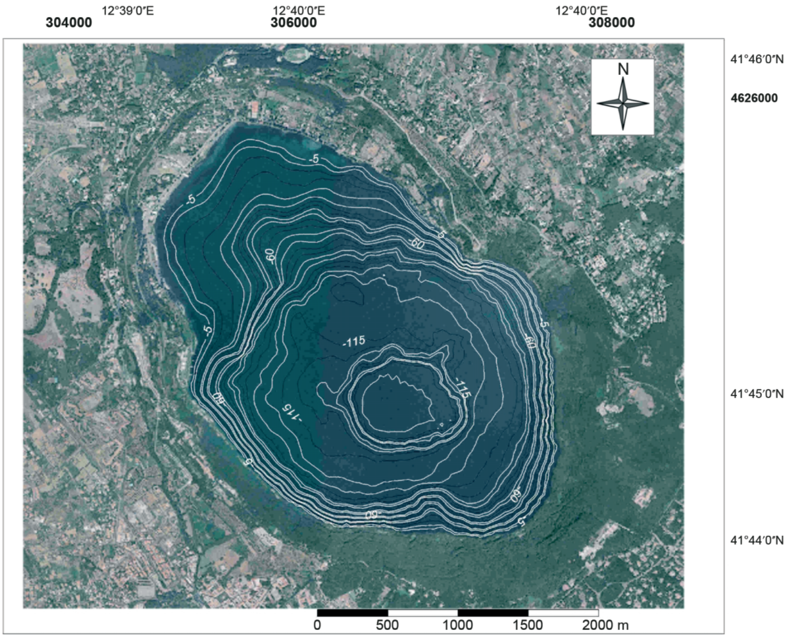

Fig. 7b. Ortophoto of the subaerial part of crater and and lakefloor isobaths computed from the multibeam surveys.

ranging between 10-15 cm up to depths of −20m; 15-30 cm at depths between −20 and −50 m and 30-50 cm at depths greater than −50 m.

Once the offsets and errors were analysed and corrected, the final MDEM was produced and made available for the morphostructural analysis, production of contour maps at 1:2500 scale (fig. 7a,b) and shaded reliefs (fig. 9a-c), which show the roughness and complexity of the crater of the Albano lake.

4. Discussion and conclusions

The high resolution multibeam technique provided the first 3D detailed morphobathymetric map of the Albano Lake at <1 m average pixel resolution (fig. 7a,b). These data are useful for a wide range of applications and to improve and support the geological, geomorphological, volcanological, geochemical, geophysical research and monitoring of this volcanic area.

As the volcanological interpretation is not the specific goal of this paper, which aims to describe the technique used and to shows the first images of the submerged part of the Albano Lake crater, these data can provide new information on the still unknown morphological features of the submerged part of the crater. The lakefloor shows past episodes of its history, strictly connected with the geological and volcanological evolution of the area. Surface features due to volcanic activity, lake level changes and sliding or rock fall events arise from the data.

The first main results obtained from the bathymetric surveys can be summarized as follows:

– The total water volume of the lake at the time of the surveys is 447.495.490 m^3.

– The lake is characterized on its northern side by a flat area at depth between 0 and 25 m below lake surface and by two concentric circular basins bordered by steep flanks, which can

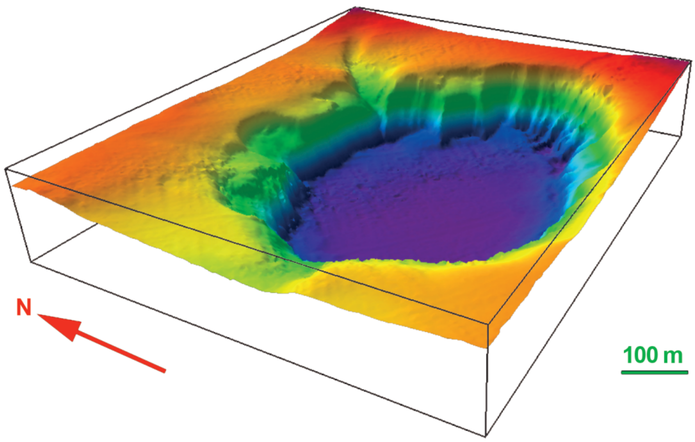

Fig. 8. Multibeam image of the central crater.

be addressed to crater rims. The first is between about –50 and –120 m; the second between –120 and –167 m.

– The deepest point of the lake is at –166.86 m, lower than the previous measurements (173 m). This value could be explained with the lowering of the water table around the basin which can reduce the hydrologic balance of the area, as reported by Capelli *et al.* (2000).

– The deepest point coincides with a circular crater about 1000 m wide, with steep inner flanks about 45 m height. The steep flanks show erosion phenomena, likely sub aerial, that could have occurred before the crater was filled with water. The flatness of this area suggests a continuous sedimentation at this depth, in agreement with Oldfield *et al.* (1996) (fig. 8).

– Other sub circular depression size could be addressed to craters. But without further evidence from seismic soundings or drillings, with the exception of those reported in Oldfield *et al.* (1996), we cannot confirm or exclude this hypothesis.

– Slides or rock fall of different sizes have occurred in the lake since its formation. They mainly occurred along the steepest inner flanks of the crater and partially in the central crater (fig. 9a,c).

– Three levels of submerged shores, at the moment of unknown age, are clearly located at depths between –31 and –41 in the north-eastern side of the lake. They witness the past lake level standings at these heights likely due to a change in the environment as also reported by Chondrogianni *et al.* (1996), Ryves *et al.* (1996), Lowe *et al.* (1996) and Marra and Karner (2005).

– Data did not reveal any relevant gas exhalative centres in the whole basin. This is in contrast with previous observations (Oldfield *et al.*, 1996) that disclosed some exhalative points mainly in the eastern side of the basin. This can be explained by a temporary change in the gas exhalation from the ground or with the sealing of fractures which prevent the gas release up to the surface.

The issues related to the occurrence of slides and gas exhalative points are relevant for scientific discussion and hazard assessment of the Albano crater lake volcano and its bathymetry open new questions on its recent evolution, thus suggesting further investigations through the integration of different geological and geophysical studies. Mainly, if the central crater is a suitable trap for CO_2 accumulation that can be suddenly released, as occurred in lake Nyos (Rice, 2000), taking into account that the Albano Lake has the highest CO_2 concentration among the Italian crater lakes (up to 200 mg/l at –175 m) (Martini *et al.*, 1994). In such case, it would be subjected to a water rollover with dangerous consequences of gas or hot fluids release from the deepest part

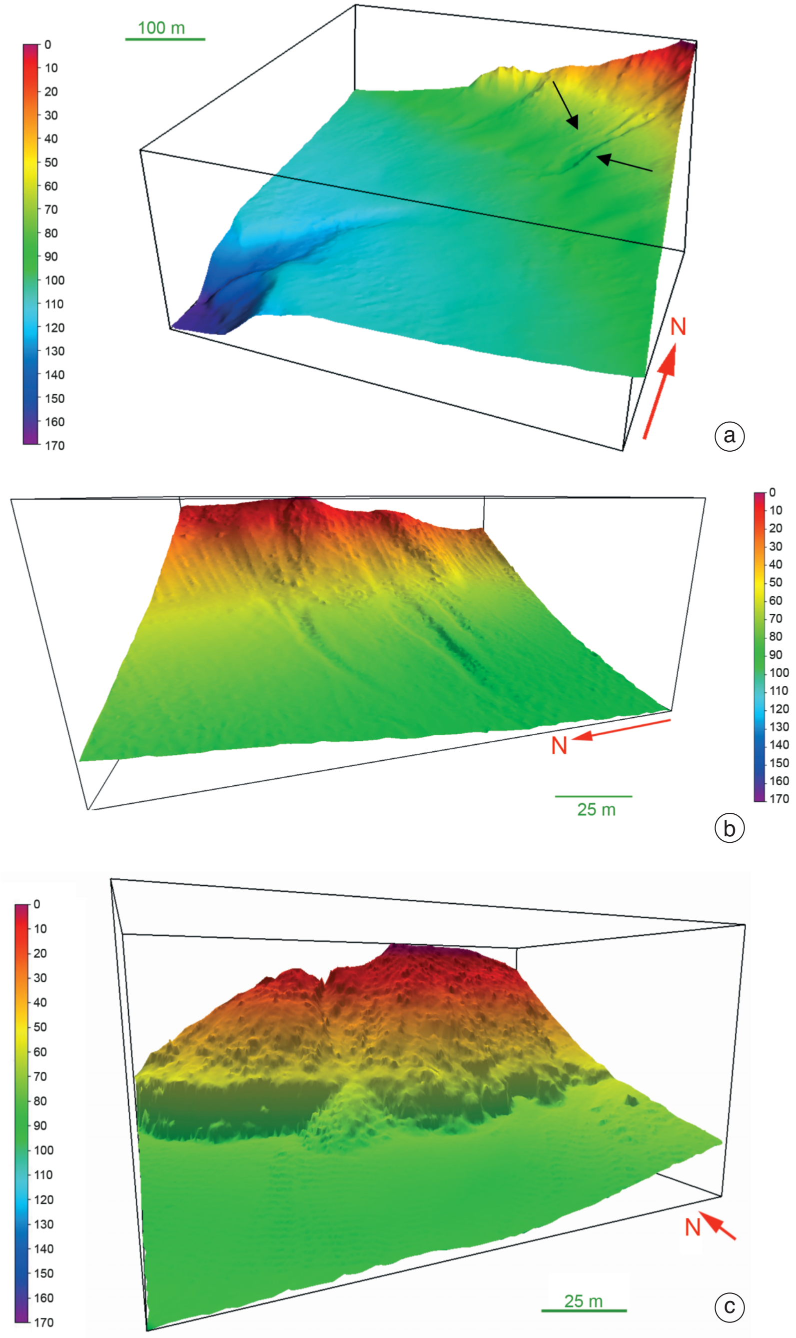

Fig. 9a-c. Multibeam images of slides located along a,b) the north eastern side and c) the southern side of the crater, respectively.

of the lake. Concerning slides, a slide hazard must be taken into account because their occurrence would induce tsunami lake waves, dangerous for humans and the environment. Some cases of tsunamis triggered by slides in closed basin, are reported in the literature such as that which occurred in the artificial lake of Vajont, Italy, in 1963 which produced heavy destruction and about two thousand victims. So far, the occurrence of such events in the Albano Lake should not be excluded due to the seismicity of the area, the features of the lake floor and to the steep slopes of the inner side of the crater facing the lake. The morphological features of the lake floor suggest the existence of at least two larger craters and three more coalescent smaller eruptive centres (Anzidei *et al.*, 2007). Further surveys, such as seismic soundings and sub bottom profiles, should be performed to provide data on the still unknown structural features of the lake floor.

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