

Integrated geophysical techniques to image short- to very short-term ground deformation associated with unrest at coastal calderas: a case study from the Pozzuoli Bay, Campi Flegrei, South Italy

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Abstract – Campi Flegrei is an active, large (about 200 km²) volcanic complex located offshore in the northern sector of the Naples Bay. The inner, peri-calderic area is characterized by severe, non-linear ground deformation and associated displacement of manufacts (bradyseism). Here we show the results of marine geophysical surveys (multibeam swath bathymetry) and satellite observations (SAR Interferometry) aimed at the detection and measurement of the coastal horizontal and vertical displacements of segments compounding the Pozzuoli Bay, and mostly corresponding to the inner part of the Campi Flegrei Caldera. Radar satellite observations provided a means for the definition of both regional and local displacement (uplift and/or subsidence) of discrete areas and associated infrastrucures (e.g. buildings, landmarks, archeological remains) on the emerged portion of the caldera structure, thus allowing for the understanding of the active trends of bradyseism for each coastal segment over the last 25 years.

At same time, high-resolution multibeam swath bathymetry provided unprecedented accurate imaging of geomorphological lineaments, as well as of the Roman archaeological outliers presently extending over the seafloor. These data served as a constrain to reconstruct the evolution of vertical displacements in the coastal sector of the Pozzuoli Bay over the last 2.000 years ca. The integration of datasets also offers sound base information to define the recentmost-to-current trends of ground deformation at Campi Flegrei.

I. INTRODUCTION AND GEOLOGY

Campi Flegrei is an active volcanic district located on the coastal zone of the Campania region of SW Italy, a large part of which develops in the Naples (Pozzuoli) Bay. The area is structurally dominated by a caldera collapse, ~8 km in diameter, associated with the eruption of the Neapolitan Yellow Tuff (NYT), dated ~15 ka BP [1].

In the last decades many Authors have suggested that the NYT collapse was preceded by a larger collapse during the

eruption of the 100–200 km³ Campanian Ignimbrite (CI) 39,000 years BP [2] although recent investigations suggest that the CI may have been fed, instead, from fissures north of Campi Flegrei (Fig. 1).

Since the NYT event, volcanic activity has occurred episodically along the border of the caldera, mainly between 15,000 years and 8000 years BP, and between 4800 and 3700 years BP. The last eruption occurred in 1538 with the formation of a scoria cone called Monte Nuovo.

Dramatic ground deformation associated with caldera unrest, has long been recognized over the last thousand years at Campi Flegrei. Significant uplift of the central part of the NYT caldera before 4 ka BP has been documented in the area of Pozzuoli where an entire coastal sector (marine terrace of “La Starza”) has been uplifted to an elevation of 30 to 55 m above sea level [3].

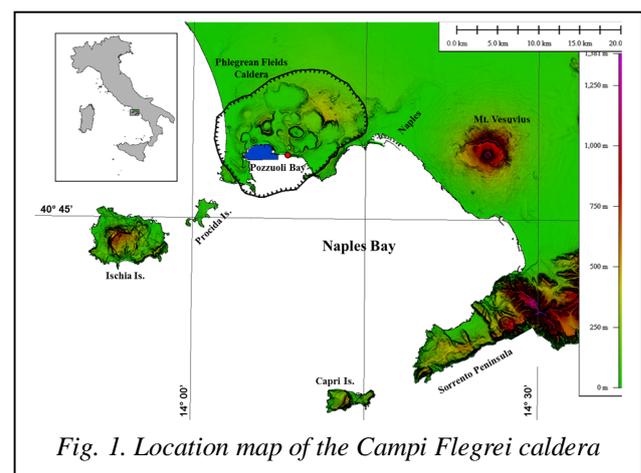


Fig. 1. Location map of the Campi Flegrei caldera

Recent studies have shown that the inner caldera region is characterized by a resurgent dome, ~ 5 km in diameter, bounded by a 1–2 km wide ring fault system. The style of deformation of the resurgent structure can be described in terms of a broad antiformal folding, accompanied by subordinate brittle deformation, mostly concentrated in a small apical graben at the summit of the resurgent dome. The average net uplift rate of the resurgent structure has been in the order of 9–12 mm/year between 10.5 ka BP and 4.0 ka BP [4], with a total uplift recorded at La Starza, on land, that can be estimated in the order of 60–80 m over that period.

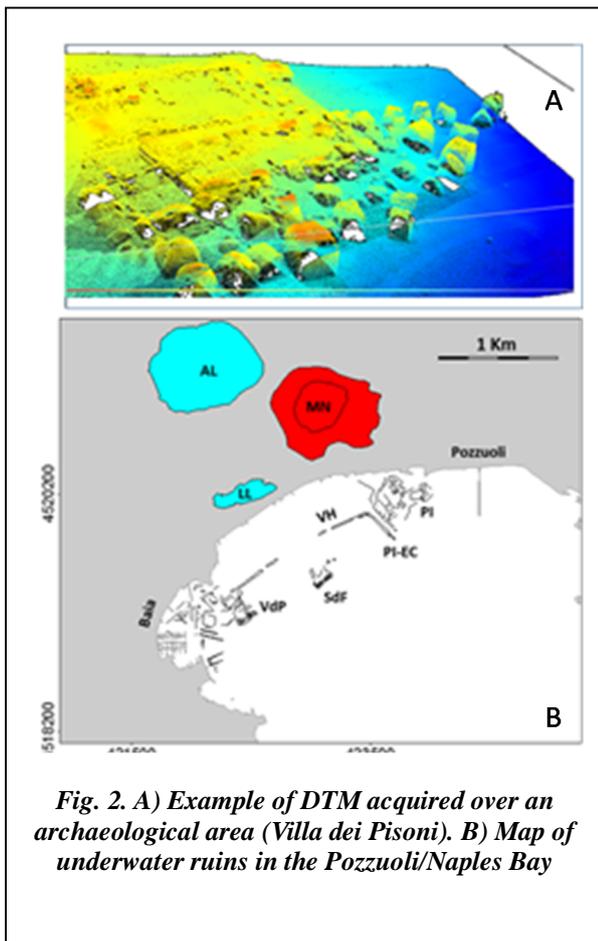


Fig. 2. A) Example of DTM acquired over an archaeological area (Villa dei Pisoni). B) Map of underwater ruins in the Pozzuoli/Naples Bay

Archaeological remains of Roman age, nowadays submerged at a water depth of ~10 m along the western infralittoral zone of the Pozzuoli Bay [5] indicate that the entire area underwent subsidence since Roman time. The relatively long post-Roman subsidence phase was interrupted at least once in the Middle Ages, and then followed by uplift that started at least 40 years before the 1538 Monte Nuovo eruption. Recent ground deformation documented in the Pozzuoli area was accompanied by two bradyseismic crises occurred in 1970–71 and 1982–84, with a cumulative ground uplift of 3.5 m in 15 years and maximum uplift rates of 100 cm/year in the period 1983–1984. After 1984, the ground slowly subsided until 2004–

2005, when a new of deformation phase and enhanced hydrothermalism started in 2005–2006, with ~0.45 m of uplift at the end of 2016.

II. DATA AND METHOD

Multibeam Swath Bathymetry

Multibeam (swath) bathymetry data acquisition was carried out by IAMC-CNR, Naples Geophysical Laboratory during a series of oceanographic cruises from 1997 to 2013 [6, 7]. Some very limited, shallow water areas were surveyed in single beam mode, while land topography was obtained by the Italian Istituto Geografico Militare (IGM) through interferometric survey topographic maps. Most of the bathymetric dataset result from the use of the Reson Seabat 8125 equipment, a 240 beam array with 120° of Swath Coverage and a pulse frequency of 455 KHz, particularly suitable for shallow water settings. During the acquisition, the use of a GPS with differential correction ensured a sub-metric precision on positioning. All components of the acoustic equipment were managed by using the PDS2000 package, a standard hydrographic software for data acquisition, navigation and processing. Measurement errors were manually deleted with a reply of swaths pattern, etc. The final resolution ranges 0.2 m / 1 m in grid cell size.

SAR Interferometry

Synthetic Aperture Radar Interferometry (InSAR) is used worldwide for detecting and measuring ground-surface deformations occurred since early '90's. InSAR technique provides very accurate, unidimensional, sub-centimetric measurements of slow ground movements along the Line of Sight (LOS), referred to the straight line between radar sensor and the ground target [8].

Several interferometric techniques have been proposed for the measurement of the ground deformation from SAR data, such as Permanent Scatterers (PS). The PS-InSAR technique requires a master scene and a stable reference point, assumed stable, to which the zero in the time series and the relative measurements of deformation are respectively referred [9]. The Persistent Scatterer Pair (PSP) approach has been recently developed for the identification of Persistent Scatterers. The PSP technique is intrinsically free from artifacts slowly variable in space, like those depending on atmosphere or orbits, and it does not require data calibration or pre-selection of radiometrically stable points.

In the Campania region, the interpretation of spatial

distribution of ground deformation due to dynamic processes, including volcanism, tectonics and natural to human-induced subsidence can be assisted by space-borne InSAR techniques, exploiting the C-band sensors onboard ERS (from 1992 to 2001), ENVISAT (from 2002 to 2010) and RADARSAT (from 2003 to 2007) satellites.

The PS material used in this study is represented by three PS datasets selected respectively from: a) ERS-1/2 ascending and descending orbits, b) ENVISAT ascending and descending orbits, c) RADARSAT ascending and descending orbits, obtained by the TELLUS Project [21] and by the Not-Ordinary Plan of Environmental Remote Sensing (EPRS-E) [9]. The PS datasets have been referenced to WGS-84 Datum UTM Projection, 33N Zone, geometrically checked and spatially processed using GIS software.

In the analysis of the PS data, ground deformation values are measured along the satellite LOS, which is not vertical, but ranges from 22° to 34° in the study area. In order to limit the geometrical effects induced by the side-looking view of SAR satellite sensors the derived velocity measurements may be expressed in terms of two spatial components of ground deformation (vertical and E-W horizontal components) because the N-S horizontal component cannot be determined by the SAR satellite acquisition system.

III. RESULTS AND DISCUSSION

Seafloor archaeological data

Due to the concomitant action of subsidence and, subordinately, sea level rise, the coastline of Baia-Pozzuoli has retroceded by several hundred meters in the last $\approx 2\text{Ka}$, thus submerging a large archaeological complex. The Pozzuoli-Baia underwater ruins include a port infrastructure (Portus Julius) and a residential area (Baianus Lacus).

Portus Iulius was a military harbour, occupied by the ancient Lucrino Lake. This construction was built from Marco Vipsanio Agrippa in the 37 BC for military purposes. The harbour was connected to the adjacent Averno Lake by a 300 m long and 50 m wide artificial channel. The Port had a pier coastline (370 m) built with arches settled on 15 pillars with a squared plant, and it was linked with the open sea by a 360 m long, 60 m wide $N130^\circ E$ striking artificial channel made by two protected parallel piers.

Baianus Lacus was a natural harbourage located between Punta Epitaffio to the North and Punta del Castello to the South. This area was linked to the Pozzuoli Bay with a $N100^\circ E$ striking, 220 m long and 30 m wide channel that is actually partially covered by sediment. In this area there are the remains of the nymphaeum triclinium (1st Century BC), and findings of thermal bath plants, villas with mosaic floors and wine shops [10].

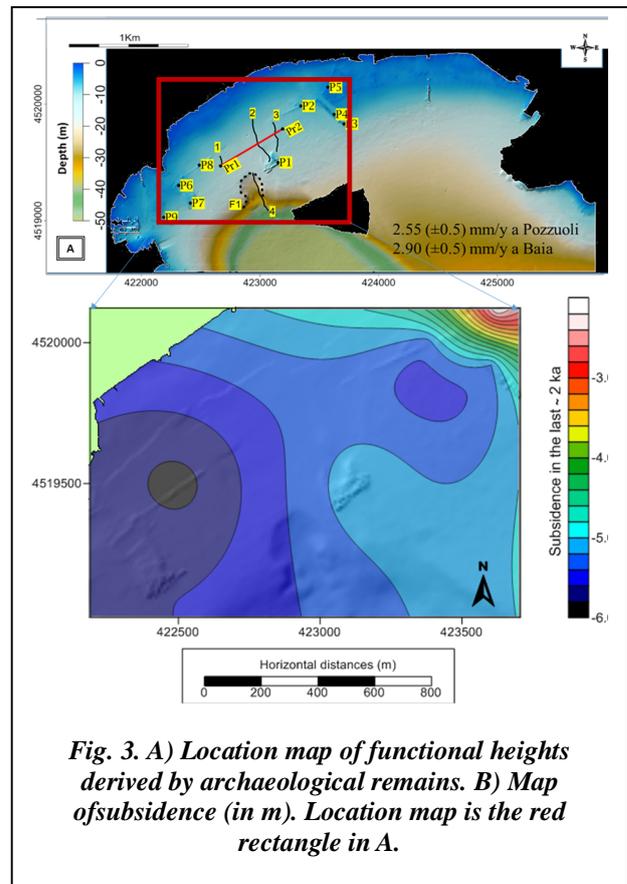


Fig. 3. A) Location map of functional heights derived by archaeological remains. B) Map of subsidence (in m). Location map in A is the red rectangle in A.

As a consequence of the bradyseism, the ancient ports of Miseno, Baia and Portus Julius (Pozzuoli) are presently drowned several metres below the actual mean sea level. These features are actually partially visible in bathymetric records (Fig 2A and 2B).

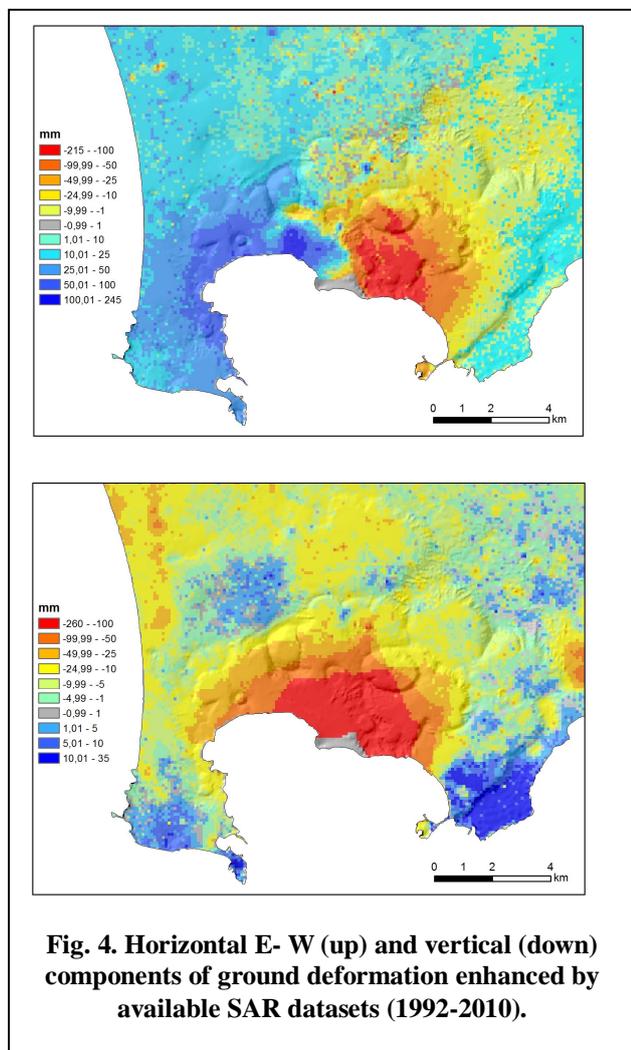
Taking into account the present-day depth of archaeological manufacts below the sea level, their “functional height, (i.e. the expected original height of manufacts with respect to the past mean sea level), and the rate of sea level rise of the last 2 ka, is it possible to calculate the ground deformation associated with the bradyseism magnitudo in the last 2 kaduring this time interval (Fig. 3A). Its vertical computation resulted to be not homogeneous along EW, and mostly altered by the presence of fractures and/or faults. Results are summarized in Fig 3B.

Ground deformation trends in the emerged area

The vertical and E-W horizontal deformation patterns of study area obtained by PS-InSAR processing are showed in (Fig. 4A and 4B).

The analysis of 1992-2000 ERSSAR datasets shows that the Campi Flegrei area is characterized by negative vertical velocity, i.e. subsidence. Referring to the horizontal deformation field, the western sector is characterized by eastward velocity values, while the

eastern sector is characterized by westward velocities with maximum values within the inner caldera region. This deformation framework is due to the strong pattern suggests a contraction (deflation) of Campi Flegrei



caldera, during 1992-2000, possibly due to a depressurization of the hydrothermal system. The described trends are only partially influenced by the During 2003-2007 and 2002-2010 years (Radarsat and Envisat datasets) the vertical velocity distribution shows a regional pattern characterized by positive values vertical uplift in at Campi Flegrei and in the western sector of Ischia island, which identify areas affected by significant uplift, ostensibly related to current volcano-tectonic processes occurred in 2003-2010 in respectively active at Campi Flegrei caldera and Monte Epomeo. As to horizontal deformation fields, in 2003-2010 the western sector is characterized by stability or westward velocity values, while the eastern sector is characterized by stability or eastward velocities.

REFERENCES

- [1] Deino, A.L., Orsi, G., de Vita, S., Piochi, M., 2004. The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera-Italy) assessed by $^{40}\text{Ar}/^{39}\text{Ar}$ dating method. *Journal of Volcanology and Geothermal Research* 133, 157–170.
- [2] De Vivo, B., Rolandi, G., Gans, P.B., Calvert, A., Bohrsen, W.A., Spera, F.J., Belkin, H.E., 2001. New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy). *Mineralogy and Petrology* 73, 47–65.
- [3] De Natale, G., Troise, C., Mark D., Mormone A., Piochi M., Di Vito M. A., Isaia R., Carlino S., Barra D., Somma R., 2016. The Campi Flegrei Deep Drilling Project (CFDDP): New insight on caldera structure, evolution and hazard implications for the Naples area (Southern Italy), *Geochem. Geophys. Geosyst.*, 17, 4836–4847.
- [4] Sacchi M., Pepe F., Corradino M., Insinga D.D., Molisso F., Lubritto C., 2014. The Neapolitan Yellow Tuff caldera offshore the Campi Flegrei: Stratigraphic architecture and kinematic reconstruction during the last 15 ky. *Marine Geology*, 354, 15-33.
- [5] Passaro, S., Barra, M., Saggiomo, R., Di Giacomo, S., Leotta, A., Uhlen, H., Mazzola, S., 2012. Multi-resolution morpho-bathymetric survey results at the Pozzuoli-Baia underwater archaeological site (Naples, Italy). *Journal of Archaeological Science* 40, 1268–1278.
- [6] D'Argenio et al., 2004. Digital elevation model of the Naples bay and adjacent areas (Eastern Tyrrhenian sea). *Mapping Geology in Italy*. Ed. APAT (S.EL.CA. Firenze), 21-28.
- [7] Somma R., Iuliano S., Matano F., Molisso F., Passaro S., Sacchi M., Troise C., De Natale G. 2015. High resolution morpho-bathymetry of Pozzuoli Bay, Southern Italy. *Journal of Maps*, 12(2), 222-230.
- [8] Gabriel, A.K., R.M. Goldstein, H.A. Zebker, 1989. "Mapping small elevation changes over large areas: Differential radar interferometry." *Journal of Geophysical Research* 94: 9183–9191.
- [9] MATTM, 2015. "Not-Ordinary Plan of Environmental Remote Sensing (EPRS-E)." The National Geoportal (NG) of the Italian Ministry of Environment and of Protection of Territory and Sea. Accessed at: <http://www.pcn.minambiente.it/GN/en/projects/not-ordinary-plan-of-remote-sensing>.
- [10] Davide, B., 2002. Underwater archaeological parks: a new perspective and a challenge for conservation - the Italian panorama. *International Journal of Nautical Archaeology* 31, 83-8