INTEGRATED ANALYSIS OF GROUND DISPLACEMENT DATA, SEISMIC ACTIVITY AND MORPHOMETRIC DATA OF THE CAMPI FLEGREI (CAMPANIA, SOUTHERN ITALY) 2000-2006 RECENT BRADYSEISMIC CRISES, IN GIS ENVIRONMENT.

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GEODYNAMIC BACKGROUND OF THE CAMPI FLEGREI AREA

In this paper the results of an integrated analysis of ground displacement data, local seismic activity and DEM image analysis, in GIS environment, which has been performed for the Campi Flegrei volcanic area, are presented and discussed. The study has been carried out for the recent bradyseismic crises of 2000-2006, with the aim of working out a preliminary interpretation of the recent dynamics of the area.

The Campi Flegrei volcanic district formed as a consequence of the lithospheric stretching in the central Tyrrhenian sea and Apennine Belt-parallel extension, in Quaternary time (Malinverno and Ryan, 1986). The Phlegraean caldera, the most relevant tectonic element of the volcanic district, is an active volcanic area located to the west of the town of Naples, and, due to its very intense urbanization, is characterized by high volcanic risk (Orsi et al., 1999).

The morphological features of this caldera are due to the combined action of both volcanism and regional tectonics; in fact the caldera is a nested structure which originated through two major collapses related to the major eruptions of the Campanian Ignimbrite (39 ky) and the Neapolitan Yellow Tuff (15 ky) (De Vivo et al., 2001, Deino et al, 2004). After the Yellow Tuff eruption, volcanic activity and ground deformation have been very intense, with many different eruptive episodes. The last eruption took place in 1538 and formed the Mt. Nuovo cone (Di Vito et al., 1987; Di Vito et al., 1999). The magmatic system of the caldera is still active with low energy seismicity, slight ground deformation and quite intense fumarolic activity (Chiodini, 2009).

GROUND DISPLACEMENT FROM LEVELLING DATA

The deformation history of the Campi Flegrei whole area has been recorded in detail by high precision levelling measurements carried out since the end of the sixties. At the present times, the levelling network extends over an area of about 160 km^2 and consists of 350 benchmarks (bm) covering a circuit of 135 km, with a mean spacing of 400 m, and it is organized into 14 interconnected loops for minimizing errors (fig. 1).

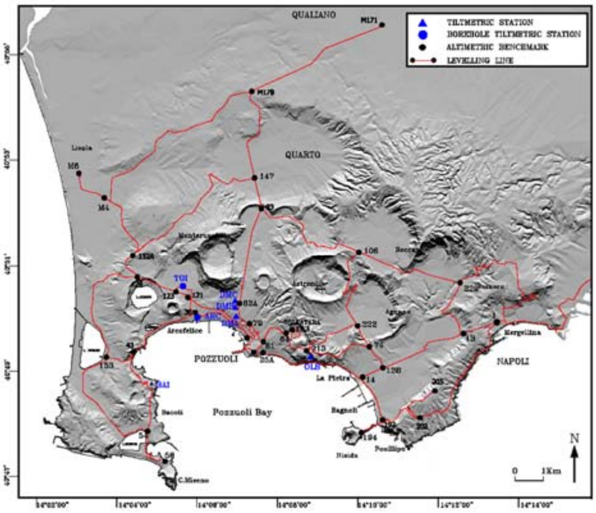

Figure 1 – High precision levelling and tiltmetric network of the Campi Flegrei.

A peculiar behaviour of Campi Flegrei since historical times has been the phenomenon known as the ‘bradyseism’, characterized by alternating intense ground uplift and slow subsidence episodes. The Campi Flegrei major recent bradyseismic crises, which were characterized by remarkable ground uplift and intense seismic activity, occurred in 1969-1972 with a maximum ground uplift of about 177 cm, and in 1982-1984 with a maximum ground uplift of about 179 cm (Berrino et al., 1984; Del Gaudio et al., 2007; Del Gaudio et al., 2009). As regards both crises the geometry of deformation was about bell-shaped and covered an almost circular area centred in the town of Pozzuoli with a radius of 6 km (Orsi et al., 1999). Minor crises were observed more recently with low seismicity, characterized by seismic swarms, and slight ground deformation (fig. 2). Particularly, significant uplift episodes were recorded in 1989, (7.3 cm of uplift), 1994 (1.2 cm of uplift), March-August 2000 (4 cm of uplift) and from June 2004 to October 2006 (5.5 cm of uplift). The detailed study of these last uplift events, from both geodetic and seismotectonic point of view is the object of this paper.

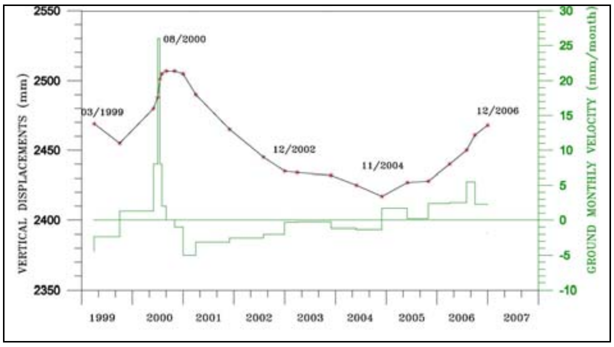

Figure 2 – Vertical displacements, March 1999 - December 2006, measured at Benchmark n. 25A (Pozzuoli Corso Umberto); in green the monthly velocity of the ground.

GROUND INCLINATION FROM TILTMETRIC DATA

Since the last ten years, the Campi Flegrei tiltmetric monitoring network has provided additional information related to the angular component of strain in the different station sites and has allowed to follow in better detail the evolution of the deformation pattern of the area.

The Campi Flegrei tiltmetric network consists of 7 stations, 5 of which equipped with surface sensors (DMA, DMB, DMC, BAI and OLB) and 2 boreholes (TOI and ARC) (fig.1). With respect to the bm n.25A of the levelling route (located in the town of Pozzuoli), the tilt stations are respectively located: DMA 1.6 km NNW, DMB 1.8 km NNW, BAI 4 km WSW, TOI 3.6 km NW, ARC 2.7 km NW and OLB 1.5 km ESE (Aquino et al., 2006).

Beginning from year 2000, the deformation field has appeared to be more asymmetrical relatively to past years, when it had radial symmetry around the maximum uplift area, close to Rione Terra in Pozzuoli. In order to work out a quantitative estimate of the deformation unhomogeneity in the eastern sector compared to the western sector of the area, in this paper two profiles WSW-ENE (benchmark 22-72) and SE-NW (benchmark 25A–81) respectively oriented, which are convergent towards the town of Pozzuoli, have been extracted from the altimetric network. For both profiles, the vertical displacements of a benchmark closer to this town with respect to that one more distant have been divided by their horizontal distance; the obtained derivatives represent the mean ground tilt along each profile.

In the period 3/1999-8/2000 (which included an uplift episode, fig. 2) a tilt of 6 μradians (in modulus) was observed along both profiles. In the following period 8/2000-11/2004 (when a deflation episode occurred, fig. 2) the tilt value measured along the profile WSW-ENE resulted 1.6 times greater than the value observed along the SE-NW profile (25.3/15.7 μradians), showing higher deformation to the east of the town of Pozzuoli during deflation. In the last period 11/2004-12/2006, along the WSW-ENE profile it was observed a tilt value of 9.4 μradians, about half the value of 13 μradians computed along the SE-NW profile; since the last period included an uplift episode (see fig. 2), it seems that in this sector (east of Pozzuoli) it is necessary a greater force in order to reverse the sense of movement from deflation to uplift.

The ground inclinations above reported refer to distances of some km (the previous profiles have respective lengths of 1.654 km and 2.331 km); investigating on smaller sections it can be found further evidence of the displacement field unhomogeneity. Indeed, on the section 20-19A (444 m long) of the first profile and on the section 81-82B of the second profile (102 m long), located near the tilt stations OLB and DMB respectively, tilt values of 24.8 and 9.8 μradians have been measured in the last of the three time intervals considered (11/2004-12/2006). The higher gradient near OLB is confirmed by the signals acquired by this tilt station (and decorrelated from soil temperature effects through a statistic procedure applied to the original tiltmetric series) between July 25 and November 2, 2006 (fig. 3), during a phase of slow unrest, when a significant rotation of the tilt vector with 39 μradians in N55E direction has been observed (Ricco et al, 2007).

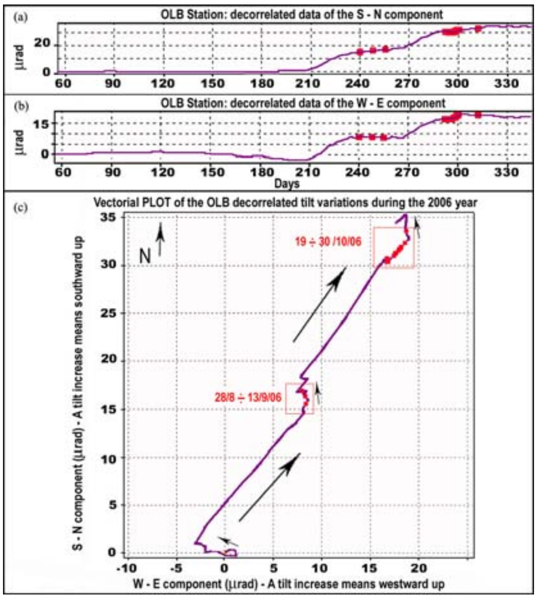

Figure 3 –(a/b) the decorrelated signals of the SN and WE tilt components recorded at OLB in 2006.
(c) the vectorial plot of the tilt variations; black arrows indicate tilt vectors while red squares represent seismic events recorded at STH seismic station (near Solfatara).

This value is about 15 times greater than the value of DMB, DMA and ARC tilt stations, all placed to the west of the maximum uplift area (Pozzuoli). Such high ratio can be due to the location of the OLB station, placed on a site which shows much higher tilt gradient. The observed anomaly could be explained through the presence of a structural discontinuity whose near-field effect can induce a greater deformation (fig. 4).

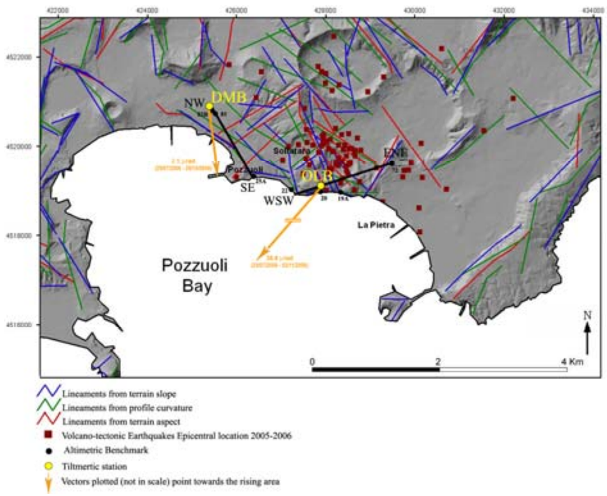

Figure 4 - The map shows three different thematic layers overlapped: instrumental seismic events (VT 2005-2006) with red squares, shaded relief and structural lineaments from image analysis. The two black lines indicate the profiles considered in this paper, respectively close to DMB and OLB tilt stations. The orange arrows show the uplift recorded by DMB and OLB tilt stations during the 2006 deformation episode.

SEISMICITY

The major bradyseismic episodes of Campi Flegrei have always been accompanied by subsequent seismic crises. The 1969-1972 episode has been the first one to be recorded instrumentally, it consisted of about 4000 earthquakes of moderate energy (maximum magnitude M=2.5), which were located along the Pozzuoli coast and near Solfatara. The following significant unrest episode, the 1982-1984 bradyseismic crisis, was characterized by about 15000 earthquakes, well located by modern seismic networks (Osservatorio Vesuviano O.V. and others) mostly in the central area of maximum deformation. Important seismic swarms have been recorded, like the 1984 1st April swarm (500 events in 6 hours) and located near the harbour of Pozzuoli, as well as many high energy events occurred, mostly located on the eastern side of the Solfatara crater, with maximum magnitude M=4.2 in December 1984.

In this paper we have not considered the Long Period (LP) seismic events, occurred in 2000 and 2006 mostly, but we have focused our analysis on the Volcano-Tectonic (VT) seismic events associated with the 2004-2006 bradyseismic episodes, in order to identify which sector of the Caldera could have been activated during such episodes, from a seismotectonic point a view. In Fig. 4 we have plotted the epicentral locations of about 90 well located VT events (courtesy of M. Castellano) that have been recorded from 2005 to 2006 by both the permanent and temporary I.N.G.V.-O.V. seismic networks (Saccorotti et al., 2007). The magnitude of the events were not greater than 1.4 , while their hypocentral depths had values between 0.5 and 4 km approximately. Most of these earthquakes have occurred as seismic swarms, and their epicentral locations cluster in the eastern side of the Solfatara crater and towards south-east, a zone quite close to the deformation anomaly detected by the OLB tilt station, and associable to many coincident morphometric lineaments with NNW-SSE direction, identified on the eastern border of Solfatara, as it can be seen in Fig.4. For this reason, the above lineaments can be considered responsible for the observed 2005-2006 VT seismicity.

MORPHOMETRIC DATA FROM IMAGE ANALYSIS

The tectonic elements outcropping in the area are mainly correlated with a circular geometry of deformation, and could also have been inherited by the regional NW-SE and NE-SW normal faults; likely, such faults acted as preferential magma rise conduits feeding the active Campanian volcanoes.

In order to identify the important structural lineaments of the area under study, which could have been responsible for the observed VT seismicity, the high resolution DEM (5x5 pixel m) of the Campi Flegrei area (Vilardo et al., 2008) has been used in this paper first of all for calculating the morphometric parameters as the terrain slope, terrain aspect, and profile curvature.

The image processing techniques (Math et al., 1995) are among the most used methods for locating and mapping structural lineaments. The criteria of lineament extraction is based on the identification of linear topographic surface features, such as valleys, ridges, breaks in slope, boundaries of elevated areas aligned in a rectilinear or slightly curvilinear shape and that distinctly differ from the patterns of adjacent features (Jordan et al., 2005).

We have identified significant structural lineaments extracting the linear continuity of the morphostructural features observed on the DEM (Mitasowa and Hofierka, 1993), examining their spatial and statistical coherence, and carrying out the comparison and correlation with the structural lineaments already known from literature (Orsi et al., 1999) The aim of our analysis has been validation of the lineaments extracted from DEM (Nappi et al., 2008), for constraining and correlating the active structural lineaments with the recent local seismic swarms as well as with the local displacements data. Accordingly, as a final step of our work, all the geodetic, seismological and morphotectonic data collected and analysed in this paper have been geo-referred into the UTM-WGS84 reference system in GIS environment, so that their cartographic restitution and multi-layers representation have allowed us to analyse the whole dataset jointly and carry out mutual correlations and new interpretations. In fig. 4 it is shown the integrated multi-layer map obtained, which has given us new seismotectonic insights for this sector of the Campi Flegrei area.

CONCLUSIONS

In conclusion, the obtained results have allowed us to hypothesize a remarkable change as regards the deformation pattern active in the Campi Flegrei area in 2000-2006, respect to the previous periods. In detail, the eastern sector of the Campi Flegrei caldera, east to the town of Pozzuoli, seems to be affected by a different and complex kinematic behaviour, compared to the other sectors. These results are strongly supported by high precision levelling and tiltmetric new data, which together with the seismic data and new morphotectonic lineaments identified through image analysis, allow us to hypothesize significant structural discontinuities NNW-SSE oriented and located in the M. Olibano zone (near OLB tilt station), probably responsible for seismic activity and for the anomalous deformation field observed.

REFERENCES

AQUINO, I., RICCO, C., DEL GAUDIO, C., 2006. Rete tiltmetrica dell'area napoletana. Open File Report n.4 (2006) Osservatorio Vesuviano – INGV

BARBERI, F., CASSANO, E., LA TORRE, P., SBRANA, A., 1991. Structural evolution of Campi Flegrei Caldera in light of volcanological and geophysical data. J. Volcanol. Geotherm. Res. 48 (1-2), 33-49.

CHIODINI, G., 2009. CO_2/CH_4 ratio in fumaroles a powerful tool to detect magma degassing episodes at quiescent volcanoes. Geoph. Res. Lett. Vol. 36, L02302, doi:10.1029/2008GL036347.

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 40Ar/39Ar dating method. J. Volcanol. Geotherm. Res. 133, 157–170.

DEL GAUDIO, C., AQUINO, I., RICCO, C., SERIO, C., 2007. Movimenti verticali del suolo ai Campi Flegrei: risultati della livellazione geometrica di precisione eseguita nel periodo Dicembre 2006-Gennaio 2007 . Open File Report n.3 (2007) Osservatorio Vesuviano – INGV

DEL GAUDIO, C., AQUINO, I., RICCO, C., SERIO, C., 2009. Monitoraggio geodetico dell’area vulcanica napoletana: risultati della livellazione geometrica di precisione eseguita ai Campi Flegrei a settembre 2008. Quaderni di Geofisica, in press.

DE VIVO, B., ROLANDI, G., GANS, P.B., CALVERT, A., BOHRSON,W.A., SPERA, F.J., BELKIN, H.E., 2001. New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy). Mineral. Petrol. 73, 47–65.

DI VITO, M., LIRER, L., MASTROLORENZO, G., ROLANDI, G., 1987. The Monte Nuovo eruption (Campi Flegrei, Italy). Bull. Volcanol. 49, 608–615.

DI VITO, M., ISAIA, R., ORSI, G., SOUTHON, J., DE VITA, S., D’ANTONIO, M., PAPPALARDO, L., PIOCHI, M., 1999. Volcanism and deformation since 12,000 years at the Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 91, 221–246.

JORDAN, G., MEIJNINGER, B.M.L., VAN HINSBERGEN, D.J.J., MEULENKAMP, J.E. AND VAN DIJK, P.M., 2005. Extraction of morphometric features from DEMs: Development and applications for study areas in Hungary and Greece. Int. J. of Appl. Earth Observ. And Geoinf., 7, 163-182.

MALINVERNO, A., AND RYAN, W.B.F., 1986. Extension in the Tyrrenhian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. Tectonics 5, 227-245.

MATH, A., TAYLOR, G.R., LENNOX, P., AND BALIA, L. 1995. Lineament analysis of Landsat Thematic Mapper Images, Northern Territory, Australia. Photogramm. Eng. Remote Sens. 61 (6), 761-773.

MITASOVA, H. AND HOFIERKA, J. 1993. Interpolation by Regularized Spline with Tension: II. Application to Terrain Modeling and Surface Geometry Analysis. Mathematical Geology, 25, (6), 657-669.

NAPPI, R., ALESSIO, G., BRONZINO, G., TERRANOVA, C., VILARDO, G 2008. Contribution of the SISCam Web-based GIS to the seismotectonic study of Campania (Southern Apennines): an example of application to the Sannio-area. Natural Hazards, 45, 73-85.

ORSI, G., CIVETTA, L., DEL GAUDIO, C., DE VITA, S., DI VITO, M.A., ISAIA, R., PETRAZZUOLI, S.M., RICCIARDI, G., RICCO, C., 1999. Short-term ground deformation and seismicity in the nested Campi Flegrei caldera (Italy): an example of active block-resurgence in a densely populated area. J. Volcanol. Geotherm. Res. 91, 415-451.

RICCO, C., AQUINO, I., BORGSTROM, S., DEL GAUDIO, C., 2007. A study of tilt change recorded from July to October 2006 at the Phlegraean Fields (Naples, Italy). Annals of Geophysics, 50, 661-674.

SACCHI, M., ALESSIO, G., AQUINO, I., ESPOSITO, E., MOLISSO, F., NAPPI, R., PORFIDO, S., VIOLANTE, C., 2009. Risultati preliminari della Campagna Oceanografica CAFE_07-Leg 3 nei Golfi di Napoli e Pozzuoli, Mar Tirreno Orientale. Quaderni di Geofisica, n. 64, (INGV ed.), Roma, 28 pp.

SACCOROTTI, G., PETROSINO, S., BIANCO, F., CASTELLANO, M., GALLUZZO, D., LA ROCCA, M., DEL PEZZO, E., ZACCARELLI, L., and CUSANO, P., 2007. Seismicity associated with the 2004-2006 renewed ground uplift Campi Flegrei caldera, Italy. Phys. Earth Planet. interiors, 165, 14-24.

VILARDO, G., BRONZINO, G., ALESSIO, G., BELLUCCI SESSA, E., NAPPI, R., 2008. GeoDATA Finder: Sistema di consultazione on-line della banca dati territoriali del Laboratorio di Geomatica e Cartografia. Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli Osservatorio Vesuviano http://ipf.ov.ingv.it/dbnas/login_user.asp.