Fracture System in Phlegraean Fields (Naples, Southern Italy)*

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ABSTRACT

During the 1983 seismic crisis in the Phlegraean Fields bradyseismic region (southern Italy), a structural analysis of the area was carried out.

With a detailed field survey based on a net of 34 measure stations, a total of 536 fractures (mainly joints and a few normal faults) were measured on a 10×10 km area in volcanites capable of memorizing post depositional stress activity by fracturing.

The analysis of the collected data was performed with the data bank of the University of Rome computer facilities. The azimuthal analysis of total fractures showed a non-random distribution with 5 major sets: N13°E, N45°E, N14°W, N55°W and E-W. These preferential orientations have been detected with an automatic fitting of gaussian curves (bell curves) on the azimuthal histograms. The areal distribution showed that all these fracture sets are in general present in the main collapse area. An azimuthal analysis performed by selecting the data collected for rocks older than 4,600 y BP showed a possible youngest age for the N14°W set (domain) (E-W extension). Fractures with an «opening» wider than 1 cm presented the same 5 azimuthal sets and fit fairly well with a concentric distribution around the main collapse area. The presence of an analogous radial pattern is not evident. A tentative interpretation model relates the superficial fracture sets to two possible causes: volcanic activity, including doming and collapsing, and propagation of active tensile deformations in the sedimentary basement due to regional stress trajectories.

INTRODUCTION

A structural analysis of Phlegraean Fields (10 km W of Naples, Italy) was performed covering the area of the caldera collapse up to the outer rims of the structure on the boundaries of the Campania Plain. The principal aim of this work is to provide an exhaustive and objective picture of the fracture pattern as possible effect of the recent evolution of the stress field present in the structure of Phlegraean Fields.

In order to compensate the effects of different superficial lithotypes (pyroclastic flows, surges, welded and loose scoriae, and minor lava flows) data were collected through a measure station net (see methodology). It was also analysed the apparent random pattern of brittle tensile deformations which are frequent all over the caldera but that had never been investigated with statistical stuctural methods. The data were gathered by two reasearch teams of the University of Rome with the cooperation of AGIP-EGEO in order to optimize the location of the measure stations. A simple standard methodology of data collection was used in order to

* Contribution of «Centro di Studio per la Geologia dell'Italia Centrale», CNR, Roma.

guarantee the main objective of this work *i.e.*, the reliability of field data processing and a consequent areal and not puntual significance (FUNICIELLO *et al.*, 1982*b*).

GEOLOGICAL SETTING

The Campanian area of southern Apennines has a very complex structure. Its present geological setting is due to several structural features originated from tectonic phases that affected the area from early Miocene to Quaternary times. The framework of the region is characterized by the overthrusting of a series of structural units, derived from different paleogeographic domains, which took place during the tectonic phases that originated the Apenninic thrust-belt. During the several compressive tectonic phases which affected the area in Neogene times, translational movements caused the overthrusting of the inner stratigraphical units on the

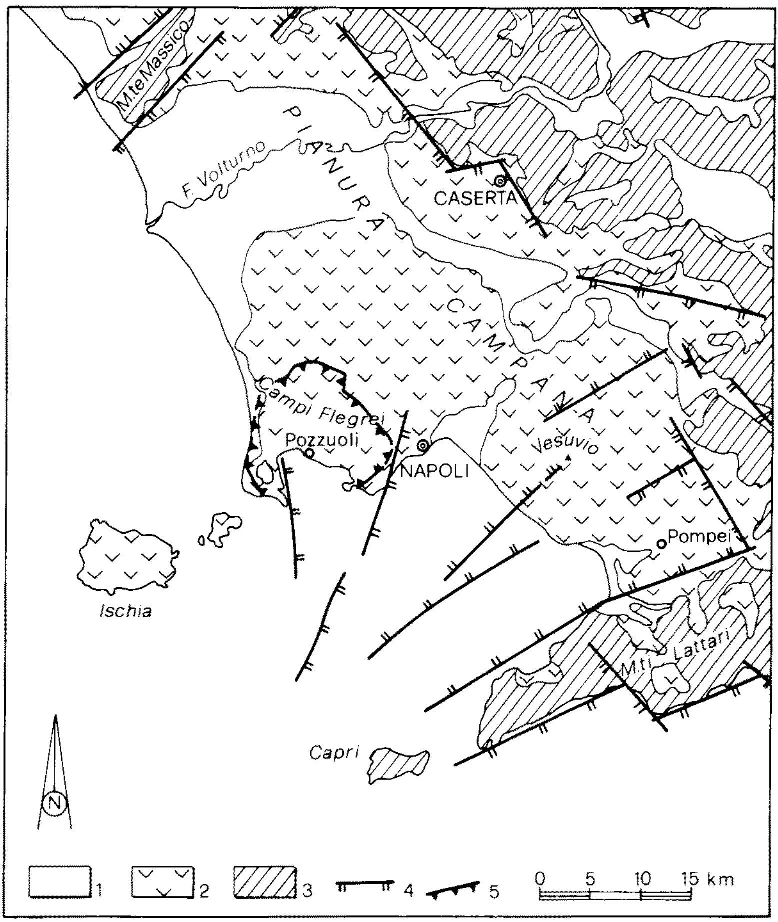

FIG. 1 – Geological sketch map of the Campanian Plain. 1) Alluvial cover; 2) Quaternary to Present volcanites; 3) Pre-orogenetic units; 4) Recent normal faults; 5) Caldera rim.

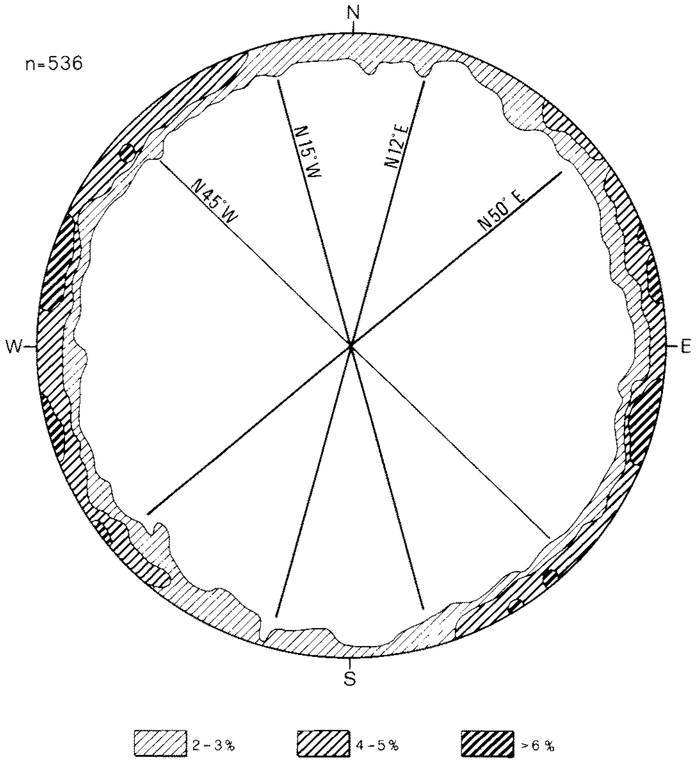

FIG. 2 - Schmidt net (lower hemisphere): contouring of poles of all (n = 536) measured fractures. Intervals are presented as percentage of poles for 1% area. Four main concentrations of poles corresponding to 4 fracture systems (N45°W, N15°W, N12°E and N50°E) can be recognized.

outer ones with an eastward orogenic transport. Afterwards, throughout Plio-Pleistocene times, the ancient structural setting was deeply modified owing to the superimposition of tensional tectonic features upon preëxistent compressive ones.

The Plio-Pleistocenic tensional tectonics, which can be related either to the thrust belt uplift or to the opening of the Tyrrhenian Sea, dislocated into several blocks the pile of structural units forming the framework of the Campanian Apennines by NW-SE and NE-SW stretching normal faults.

The Tyrrhenian margin of the Apennines chain is the region more intensely affected by the vertical displacements connected with the Plio-Pleistocene tensional tectonics. From data obtained by boreholes and geophysical prospecting carried out in the Campanian Plain, IPPOLITO *et al.* (1973) inferred global vertical displacement of about 4,000 m for the normal faults which originated the tectonic depressions of the Volturno Plain (Fig. 1) as well as of the other coastal plains (*e.g.* Garigliano and Sele Plains) by lowering the carbonatic sequence of the Matese-Mt. Maggiore and Alburno-Cervati units.

During the fast sinking (subsidence rate of about 0.3 cm/y; FUNICIELLO *et al.*, 1982*a*) these depressions were filled by a thick sequence of terrigenous Plio-Pleistocene deposits.

Phlegraean Fields, which are situated in the Campania tectonic depression bordered by the Mt. Massico structural high on the NW, by the Caserta and Nola mountains on the NE, and by the Lattari Mountains structural high on the SE, lie on the most intensely collapsed region (Fig. 1). Besides the formation of the Campania tectonic depression, the severe tensional tectonic phase that affected the Tyrrhenian margin of the Campanian Apennines led to the intense volcanic activity that has characterized this region since Pleistocene times.

Three main periods of volcanic activity have been recognized (ROSI *et al.*, 1982):

— Pre-caldera period, dated 35,000 years BP. After a very early phase of submarine activity, volcanism occurred mainly from monogenetic centres spread all over the Phlegraean area which produced mainly loose materials and subordinate hydromagmatic products. The period ended with the Campanian Ignimbrite eruption and the caldera formation.

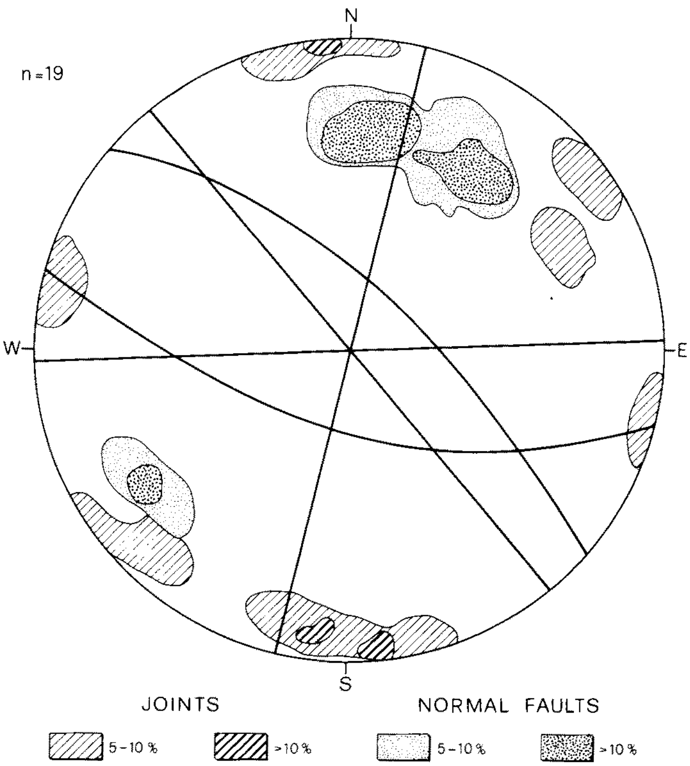

FIG. 3 - Example of geometric analysis of fractures: station no. 13 «Solfatara» (measured fractures, n = 19). Contouring represents the distribution of poles of joints and normal faults that are present in the area of this station. Three systems of joints (N15°E, N88°E and N40°W) and a conjugate system of N50°W normal faults can be seen.

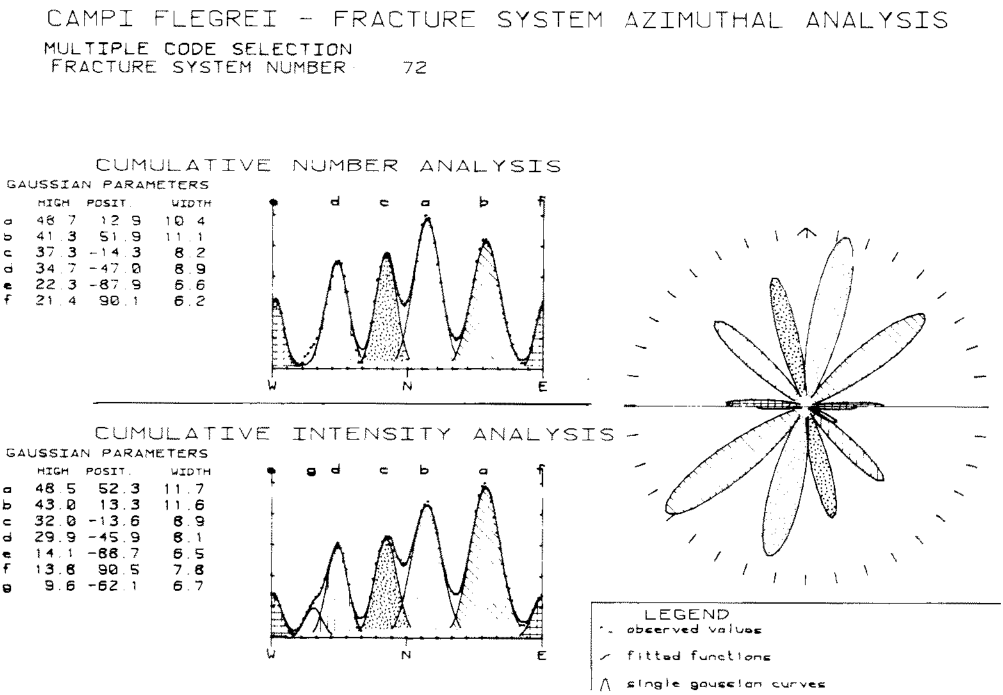

FIG. 4 - Azimuthal distribution of the fracture systems (n = 72) detected in the Phlegraean Fields area. The histograms show the comparison between distribution of the fracture system strikes and gaussian curves; these are presented in a wind-rose diagram (on the right) for the immediate comprehension of the azimuths. The parameters for each peak are shown on the left.

— Post-caldera period, dated between 35,000 and 8,000 years BP. Until 10,500 years BP volcanism was submarine. Between 10,500 and 8,000 years BP subaerial activity took place in two sectors of the Phlegraean area: the western sector (Baia, and Fondi di Baia) and the central eastern sector including Montagna Spaccata, S. Martino and Agnano. This phase produced mainly loose volcanic rocks.

— A recent volcanic period (4,500 y BP - 1538 A.D.). Due to the injection of a shallow subvolcanic body 5,400 years ago, the northern part of the Gulf of Pozzuoli was lifted, resulting in the La Starza terrace (SEGRE, 1972). Volcanism started again both in the western (Averno-Mt. Nuovo) and eastern zone (Solfatara, Astroni, Agnano, Mt. Spina and Senga) (4,400-3,800 years BP) and finally Mt. Nuovo (1538 A.D.).

METHODOLOGY

The methodology hereafter briefly described follows the scheme adopted by the authors in other similar studies (FUNICIELLO *et al.*, 1982*b*; SALVINI and VITTORI, 1982). The data were collected through a net of measure stations selected as regular as possible with a density meaningful at the scale of the study. Thirty-four measure stations corresponding to a density of about 1 station each 3 km^2 were set. Each station consisted of an outcrop (or several close outcrops) exposed for almost some ten m^2 possibly according to various azimuths.

For each station it was prepared a detailed geological description with the orientation of all the meaningful structural elements characterizing the outcrop. In particular, in this work, such elements – probably because of the recent age of the lithotypes cropping out and due to the tensional tectonic style of the region – are brittle deformations, mostly tensional

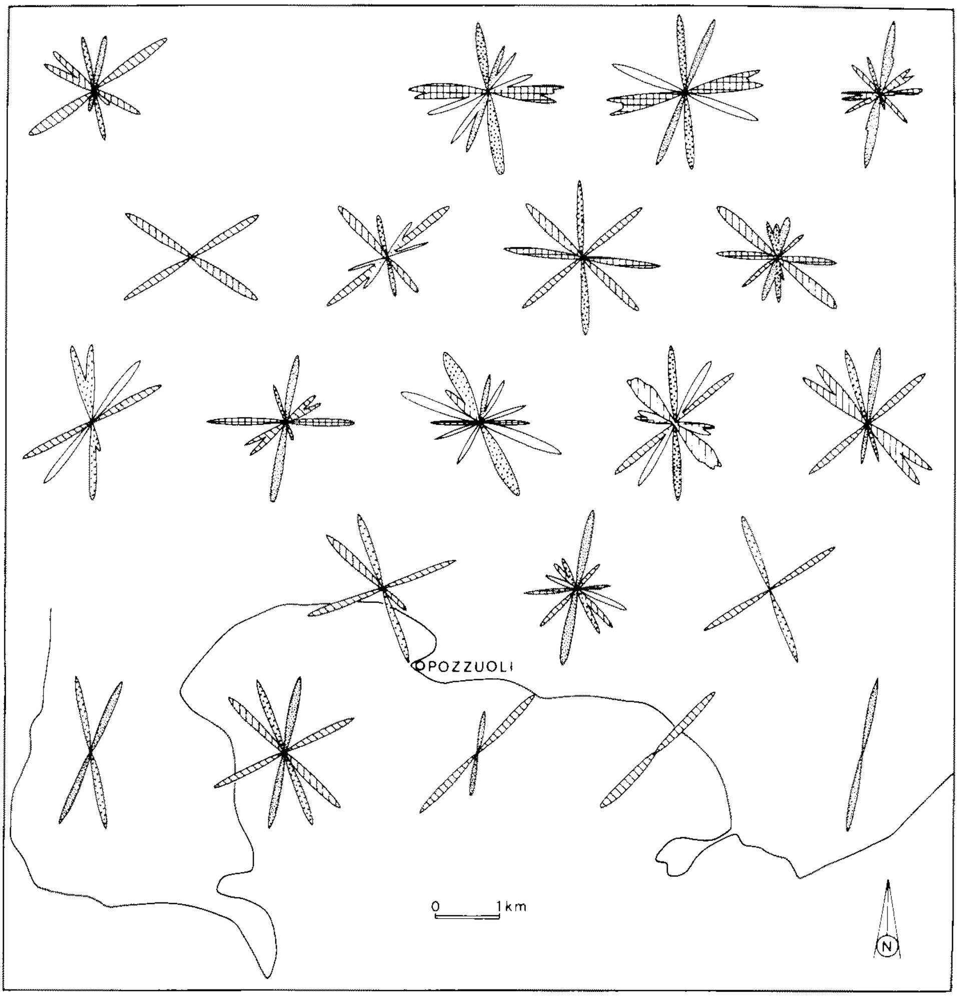

FIG. 5 – Areal azimuthal analysis of all the fracture systems. The same analysis as that of Fig. 4 was progressed graphically by selecting the data by means of circles displaced in the Phlegraean area (see text). Peaks (marked as in Fig. 4) show the distributions of the main fracture domains. Note that some of the domains are present as a couple of peaks or show moderate variations in the azimuth throughout the area.

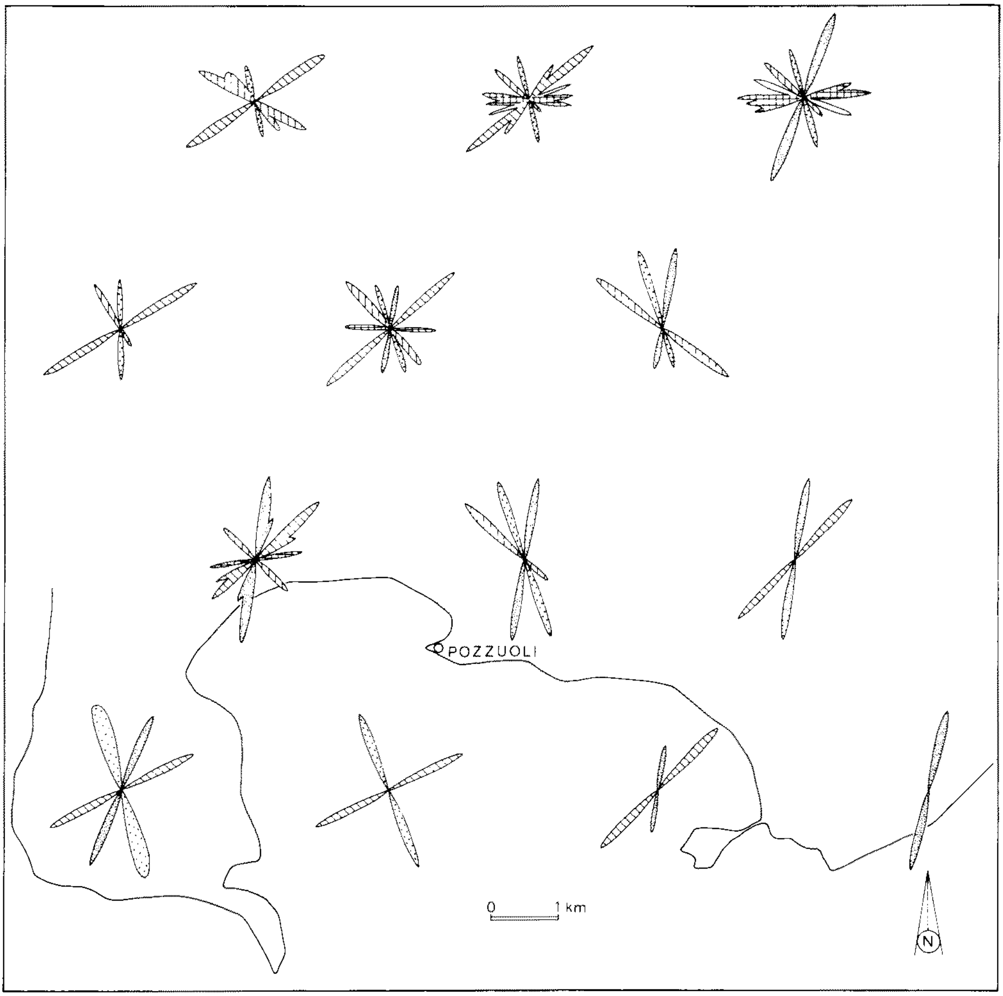

FIG. 6 - Azimuthal distribution of fracture systems belonging to stations located on lithotypes older than the main collapse of the area (4,600 y BP). there is a good agreement between this distribution and that of the total data.

fractures (joints) and local normal faults. A total of 536 elements have been measured.

Obviously not all the lithotypes are affected by regional stress jointing; lavas and very hot pyroclastic flows, for instance, are heavily broken due mostly to setting and cooling processes. This situation can mask the regional stress fracturing at all, and was not considered in preparing the stations net.

Data collected were classified according to their « opening » by grouping them into 3 classes: less than 1 mm, less than 1 cm, and more than or equal to 1 cm.

It is easily understood that a single joint has a very little significance for our purposes. It may be of some value only if it is considered as a part of an extensive pattern, *i.e.* if it can be compared to a certain number of data of the same type.

The collected data were first codified according to their nature, and then memorized into a first data-bank in the Computer Facilities of the University of Rome. Among other minor information, for each element it was memorized: number of data for each station; standard coordinates; code of the lithotype; intensity of fracturing; code of the type of element; azimuth and dipping of the element.

A first programme produces contouring plots of data on a Schmidt net (lower hemisphere) (SALVINI and VITTORI, 1982). Data can be selected by codes, lithotypes, stations (see below). Countourings are presented as percentage of data falling into 1% of the area of the projection. As usually planes are represented by their poles. In countouring data from more than 1 station, each datum is weighted with the reciprocal of the number of data collected in its station in order to give the same weight to each station.

Countour plots allow the identification of preferential orientation of joints for each station, which gives the *fracture systems* of that station.

The azimuths of the fracture systems of all the stations together with a code containing the characteristics of the single stations were introduced in a new data-bank from which the preferential orientations of all the fractures present in the area (*fracture domains*) can be obtained.

This analysis brings the automatic detection of fracture domains through a best fit analysis of their azimuthal distribution with a series of gaussian curves (bell curves) (see, *e.g.*, the curves on the

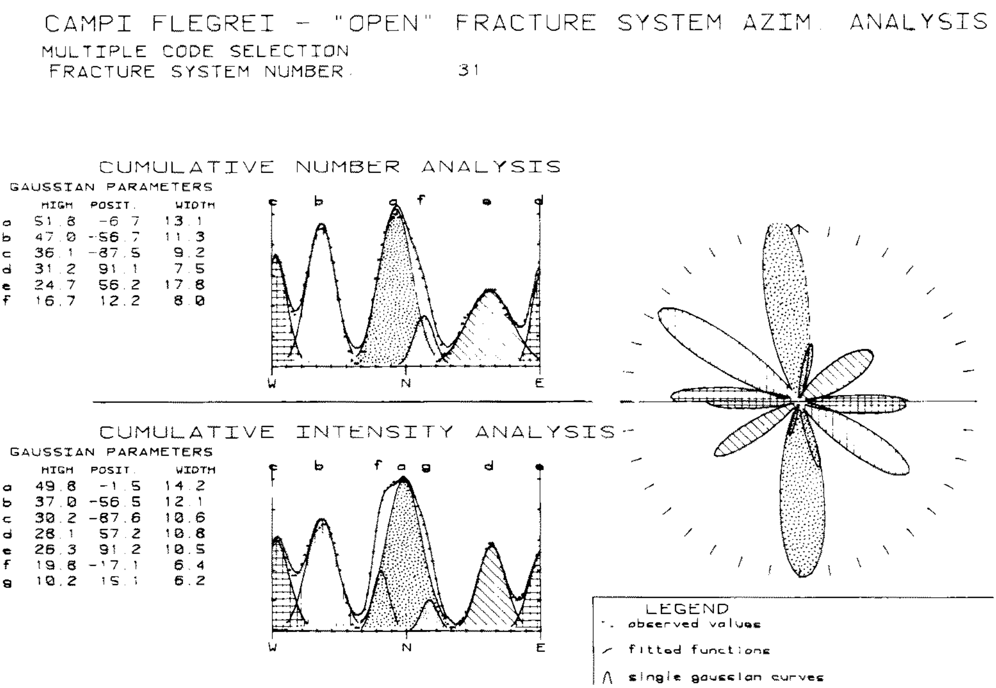

FIG. 7 - Azimuthal analysis of the fracture systems that showed on the field an opening larger than 1 cm.

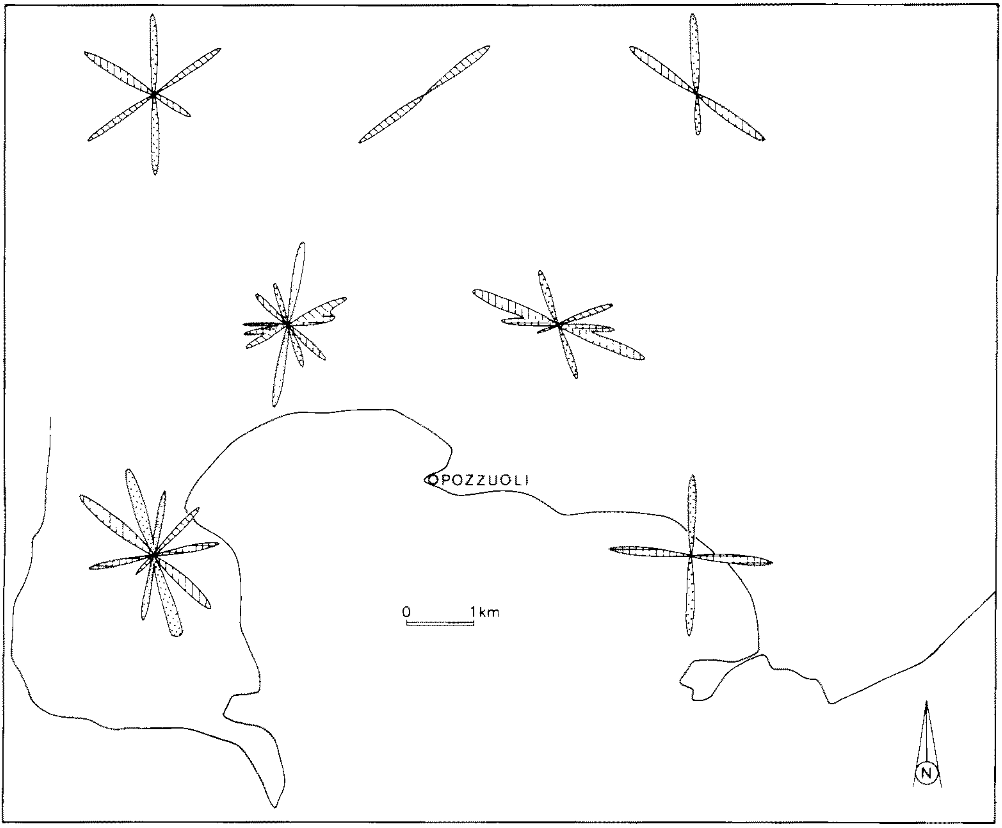

FIG. 8 - Areal distributions of the «open» fracture systems shown in Fig. 7. The map was prepared with the same technique used for Figs. 5 and 6. A concentric distribution of these fractures around the main collapse zone is quite clear.

right of Fig. 4 in a wind-rose shape for the immediate comprehension of the azimuths. The upper half of the figure refers to the cumulative numbers vs azimuths analysis, whereas the lower half shows the analysis of azimuths vs cumulative relative values of the fracture systems in their stations, *i.e.* percentage of data in the station belonging to that system).

The same methods of analysis were applied on data automatically selected through their coordinates into circular areas centered on a hexagonal net. Circles radius were computed so as to obtain a total of 50% overlap between a circle and the six ones surrounding it. The resulting wind-rose diagrams were plotted directly on a map of the area, each one centered on the corresponding point of that net. Figure 5 shows this analysis as applied to the total (72) fracture systems. As for Fig. 4, the upper and lower halves of the wind-roses refer to azimuth vs cumulative number and azimuth vs cumulative relative value analysis, respectively.

RESULTS

The contouring of poles of total fractures (n = 536) as projected on a Schmidt net (lower hemisphere) is given in Fig. 2. The almost vertical dip of the fracture planes is clearly visible. Four major pole concentrations are evident as related to four different fracture domains, *i.e.*: N45°W, N15°W, N12°E and N50°E, the intermediate two being more marked than the others. Similar contourings were made for the data of each single station (Fig. 3) in order to identify the main fracture systems. As shown in Fig. 2, also the fracture systems show a general vertical dip of their planes which allows us to consider as meaningful only their strike.

The azimuthal distribution of all fracture systems detected in the Phlegraean Fields area is shown in Fig. 4. The distribution is clearly not random, and 4 peaks (a, b, c, and d in Fig. 4) can easily be recognized. The particular stratistical technique adopted has allowed us to identify 5 major regional fracture domains similar to those shown in Fig. 2. The main difference between the two figures is a small E-W trending domain. The distributions by number (upper half) and weighted by intensity (lower half) are very similar to one another, and the main peaks show the average azimuths (in order of importance): N13°E, N52°E, N14°W, N45°W and E-W. The single peaks are distinguished on the figures by different marks in order to recognize them easily.

The areal distribution of the fracture systems is shown in Fig. 5. The identified 5 domains show a rather homogeneous distribution throughout the Phlegraean Fields area. Some of them, however, show double peaks or a small rotation in azimuth throughout the area. In particular, the N13°E domain is stronger in the south-western, northeastern and eastern sectors whereas it lacks in the central part of the area. The N52°E domain is strong almost everywhere but in the central and northern sectors. The N14°W domain is present on the entire area with some azimuth rotations and double peaks. The N46°W domain, although showing an azimuth variation and double peaks, is well present all over the area with a few exceptions on the SW and SE. Eventually, the E-W domain is present in the northern and central sectors, showing a double peak problem. A few peaks have not been marked because they do not seem to correlate with any of the main domains (central and northern sectors).

An analogous areal analysis was made (Fig. 6) by selecting only the data from lithotypes older than 4,600 y BP. The presence of all the above mentioned 5 domains with a deviation in azimuth of the N14°W domain has been confirmed.

In order to identify possible younger fracture domains an azimuthal analysis was made (Fig. 7) by including only the systems that showed on the field fractures with average opening larger than 1 cm. All the 5 main domains are present but with different relative importance: the N10°W is the major domain, followed by a N55°W domain and an E-W domain, while the N52°E domain is much smaller than in the analysis of total data (Fig. 4) and the N13°E domain is practically absent. Such differences between analyses suggest an extension more active on the first three domains. In particular the N10° to 14°W domain might be the youngest fracture domain and would be related to a recent up to present E-W extension. The areal distribution of the «open» fracture systems considered in the analysis shown in Fig. 7, more than corresponding to the above mentioned domains, seems to match rather well a concentric distribution around the main collapse area (Fig. 8). Such pattern is well enhanced by comparing it with the Bouguer anomaly map of Phlegraean Fields. An analogous radial pattern is not as evident as the concentric one.

CONCLUSIONS

The pervasive superficial structural field survey and the statistical approach adopted have shown the non-random distribution of fractures in the Phlegraean area. The fracture pattern evidences a state of stress of the superficial lithological units, and the anisotropic reaction of the thin and brittle film of recent volcanic materials to the differential stress pulses produced by the volcanic activity.

A N-S fracture domains appears to be superimposed on previous ones, and to reflect the deep structural trend of the coastal area involved in the recent setting of the southern sector of the Tyrrhenian Sea. In particular, a twin domain of N-S fractures (N13°E and N14°W) crosses the entire Phlegraean area. These fractures could be linked to the brittle reaction of the superficial lithological units to differential movements of the regional structures mainly with E-W tensile axis. This hypothesis is in agreement with the most recent deformational structure of the brittle carbonate mesocenozoic coastal units which are characterized by the same fractures pattern.

Therefore, the directions of the most frequent fracture domains may be related to different and subsequent local geological processes. The concentric system of open fractures is attributable to recent and maximum values of vertical displacement and gravimetric anomaly in the Phlegraean area.

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Ms. received Dec. 1984; Revised ms. received April 1985.