SEISMICITY AT FOGO AND FURNAS VOLCANOES
(SÃO MIGUEL IS., AZORES):
EVIDENCES FOR FLUID INVOLVEMENT

In the framework of the EU project ‘e-Ruption’, a joint Italy-Portugal-Spain team conducted a seismicity study at the Fogo-Furnas volcanoes and adjacent areas on São Miguel island, in the Azores archipelago. The last represent the subaerial expression of a mantle plume located in a triple junction zone, i. e. the junction between North-American, Eurasian, and African plates.

Aim of the experiment was to collect high-quality data in order to characterize the present-day level of activity of these quiescent volcanoes and then identify its contributions. This is a necessary step for the knowledge of the volcanoes and a correct discrimination of the sources in case of renewed seismic alert.

A sparse network of 30 stations equipped with both short-period and broad-band seismometers recorded continuously from April to July 2003. More than 1000 earthquakes were detected by our systems, and about 500 of these were energetic enough to allow for well-constrained hypocentral solutions. A big part of this seismicity is associated to an intense swarm on April 26, 2003 (160 micro-earthquakes (Md < 2) over a period of a few hours), whose temporal evolution, does not depict a classical mainshock-aftershock sequence.

A preliminary location of the overall seismicity recorded in São Miguel during the field experiment has been obtained by using the probabilistic approach of Lomax et al. (2000), that allows for a global and stable estimate of uncertainties associated to both data and model errors. The resulting hypocentral spatial distribution has been highly sparse, with two main clusters, NE of the Fogo crater and NW of the Furnas caldera, respectively.

In order to gain further constraints for a seismotectonic interpretation of the observed seismicity, we performed several analysis on both the seismograms and the obtained hypocenter data: 1) Principal Component Analysis (PCA) of the hypocenter locations; 2) relative earthquake relocations of cluster of similar events; 3) determination of the fault plane solutions of the better constrained earthquakes. Such analysis are conducted separately for the April 26 swarm dataset and for the complementary one, under the hypothesis of some possibly different origin of these seismicities.

The PCA is a statistical elaboration providing a straightforward geometrical interpretation of a dataset of variables. Its application in seismology aims at searching the rupture local ellipsoids (sensu Michelini and Bolt, 1986), i. e. the ellipsoids locally fitting subsets of hypocenters. When two axes of such an ellipsoid are much larger then the third, it can be approximated to a planar structure that can be interpreted as reflecting the spatial setting of the seismogenic fault. The PCA is performed through diagonalization of the variance-covariance matrix of the three spatial focal coordinates whose eingevectors and eingevalues represent directions and square length of the ellipsoid axes, respectively.

The PCA has been carried out by means of a cubic window sliding by an half window size along the three cartesian directions; at each window position a solution
is retained, providing the ellipticity ratio is larger than 5. The arrows represent the maximum slope direction of the found planes. Their length is proportional to $\cos(\phi)$, where $\phi$ is the plane dip measured from the horizontal plane. Therefore, for the April 26 data, a moderate heterogeneity is found in the orientations of the planes at all the depths, the average strike being N-S. Indeed, for the complementary dataset, E-W-striking, N-dipping planes are evident, corresponding to the easternmost spatial cluster (Fig. 1).

The relative earthquake location is a methodology aimed at obtaining very precise locations for clustered events depicting very similar waveforms. Precise time differences among the phase onsets for pairs of similar seismograms are obtained from the maxima of the interpolated cross-correlation function.

We tested different cross-correlation coefficient thresholds as criteria to individuate families of similar seismograms and judged the results in the light of temporal residuals of the subsequent location procedure. Namely, we performed a normalized cross-correlation analysis among all the seismograms recorded to each station, separately for the P and S phases, inside a window starting 2 seconds before and stopping 3 seconds after the manually picked phase. The families have been built, step by step, by including events respecting the cross-correlation thresholds relatively to, at least, one event already admitted in the family. High levels of threshold guarantee for a good correlation between each couple of events of the family; in any case, an a posteriori visual inspection of the signals similitude is always performed. Once created a family, the earthquake better localised in the previous absolute location process is chosen as event ("master event") relatively to which the other components of the family ("slave events") are localised. Therefore, an ordinary (probabilistic) location process with these accurately determined data, starts. At its end, the temporal station residuals of the master event are used to correct the P and S times of all the family, under the assumption of the same travel path and, therefore, of the same modelling errors. Thus, the final location process is carried out and the goodness of the new station temporal residuals of the slave events will reflect the goodness of the assumption at the base: we interpreted residuals larger than 0.05 s as effect of too dissimilar mechanism or path. On the basis of this procedure, a
cross-correlation coefficient threshold of 0.75 has been chosen. Fig. 2 shows the results of the relative earthquake location process on our dataset. All the three located clusters (families) belong to the April 26 swarm. They strike E-W (cluster C) or ENE-WSW (cluster A and B) and describe sub-vertical (cluster C) or N-dipping (clusters A and B) planes. This is consistent with the focal solutions of the respective master events. The circles in the map and the bars in the vertical sections roughly represent the horizontal and vertical errors, respectively, on the cluster centres. Even considering such uncertainty, the clusters seem intersect, at high angle, the main NW-SE brittle structure located in the São Miguel central sector.

![Fig. 2 - Results of the relative earthquake location.](image)

Fig. 2 shows also the distribution in the time of the clustered events: the middle cluster activates after the bottom and the top clusters, respectively. This seems to suggest a random activation of the patches of the hypothetical E-W trending, N-dipping fault passing through the clusters. Moreover we verified that such a chaoticity appears also at small scale, inside each single cluster. Focal solutions (Fig. 3) have been determined for the twelve better constrained hypocenters of the absolute location process, using both weighted P-polarities and SH/P amplitude ratios,
following the method of Snoke (2003). It consists on performing an efficient systematic search of the focal sphere and reporting acceptable solutions based on selection criteria for the number of polarity errors and errors in amplitude ratios. The maximum allowed number of P-polarity discrepancies and SH/P amplitude ratio errors has been set equal to two. Weighting the different results of the different analysis carried out, we conclude that the seismicity preceding and following the April 26 swarm, occurring along E-W trending faults, is a “normal” (ordinary) seismicity, related to the plate divergence on the Terceira Rift. This is also consistent with the interpretation of Jónsson et al. (1999) of the results of the GPS data, possibly suggesting an accommodation of 75% of plate divergence inside the island of São Miguel.

The explanation of the April 26 seismicity, instead, is less straightforward. It could be related to a pore pressure increment inducing reverse movement along mainly E-W striking faults affecting an extremely heterogeneous medium. This interpretation is compatible with different observations: 1) the very low Vp/Vs ratio (1.4 -1.7), obtained from both our data, by means of Wadati diagrams, and data from Dawson et al. (1985); 2) the temporal and spatial behaviour of the April 26 seismicity.

In fact the April 26 swarm could be representative of lubrication process associated to intense fluid circulation.

Fig. 3 - Focal solutions.

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REFERENCES


