Clustering properties of seismicity following the 9 May 1989 earthquake swarms at the Canarian Islands. Evidences of magma intrusions?

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Magma Intrusion as a Driving Mechanism for the Seismic Clustering Following the 9 May 1989 Earthquake Swarms at the Canary Islands

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Abstract

On 9 May 1989 a $M_L = 5.2$ earthquake struck a region between the islands of Tenerife and Gran Canaria. We investigated the time-spatial evolution of seismic patterns affecting the Canary Islands region during 1989-1995, using a quantitative spatial fractal analysis method. This method allows quantitative investigation of subtle trends in seismicity distribution through time. The fractal analysis indicates that epicenters clustered around a large zone during the May 1989 sequence affected narrow zones during 1991-1993, but then larger zones during 1993-1995 with an overall trend to shallower focal depths. The spatial localisation of seismic data and its time evolution appear to be related to magmatic rather than tectonic activity. Spatial clustering properties of seismicity are consistent with a major intrusive episode in 1989, followed by a period of quiescence and renewed deep intrusive activity from 1993 onwards. This interpretation suggests an increasing probability of future volcanic hazard in the region investigated.

Keywords: seismicity, fractal clustering, Canarian Islands, magma intrusion.

1. INTRODUCTION – THE CANARIES HOT SPOT AND ACTIVE DEFORMATION

The Canary Islands are a group of volcanoes built upon oceanic lithosphere. In most respects they have the geochemical (*e.g.*, Hoernle and Schmincke 1993) and geological (Carracedo *et al.* 1998) characteristics of hotspot or plume-related volcanoes, but the characteristic geophysical signatures of a plume are not well developed, although recent studies have identified a weak modified swell (Ranero *et al.* 1995, Canales and Dañobeitia 1998) and Coda-Q anomalies (Canas *et al.* 1995) indicative of the presence of a plume. However, they are unusual amongst oceanic island volcanoes in being located close to the margin of a region of continental lithosphere which is undergoing active deformation: the Atlas zone of North Africa (Fig. 1).

This proximity, complexities in the age sequence of volcanism in the islands, explained in terms of a plume by Carracedo *et al.* (1998), and the lack of a clear geophysical plume signature led to the suggestion (Anguita and Hernán 1975) that the Canaries were formed by movement of melts up a propagating fracture system extending west from the Atlas; and that the Canaries were therefore a plate margin volcanism associated with active re-

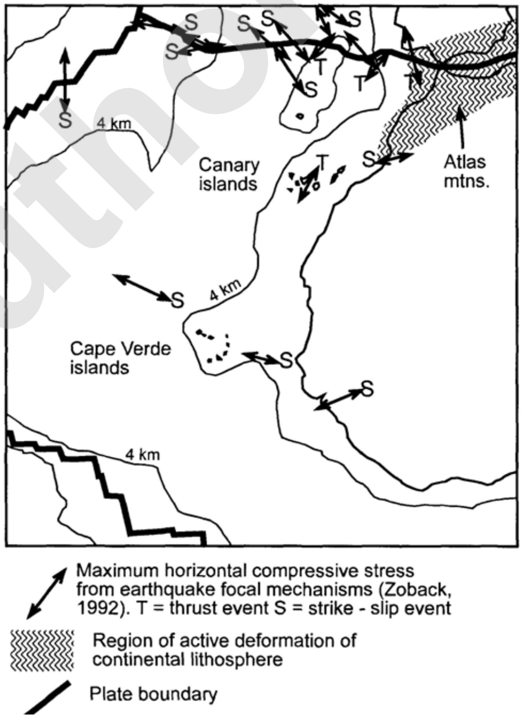

Fig. 1. Tectonic map of the central eastern North Atlantic.

gional-scale deformation. This and similar models (Araña and Ortiz 1991) have been used to interpret a major earthquake in 1989 between the islands of Tenerife and Gran Canaria (Mezcua *et al.* 1992, Jiménez and Fernández 1996) as being of regional tectonic origin. Teleseismic records for the African plate sector of the Atlantic Ocean as a whole led Wysession *et al.* (1995) to conclude that the seismic activity in this sector is concentrated around the Canaries and Cape Verde islands (Fig. 1).

If the Canaries are located in a region of active deformation, then this imposes an additional layer of complexity upon the interpretation of seismicity in and around the archipelago, for example as an indicator of impending eruptions, as three distinct sources of high-frequency or "tectonic" earthquakes may then be present:

1) earthquakes generated by brittle fracturing and faulting around propagating dykes and other magma bodies (Rubin and Gillard 1998), at any depth in the lithosphere (note that if these events are at depths of more than around 10 km, any associated low-frequency seismicity generated by magma movement is unlikely to be detected);
2) earthquakes generated on active regional fault structures, and ultimately derived from the relative motion of the African and European plates;
3) earthquakes associated with gravitational deformation of the volcanic edifices and loading of the underlying lithosphere.

The latter are unlikely to be important since, in contrast to many other volcanoes, geodetic monitoring (Moss *et al.* 1999), structural geological mapping (Day *et al.* 1999), and the available seismic data (see below) indicate that the Canarian volcanoes do not deform significantly in inter-eruptive periods such as that considered here, and the lack of subsidence on timescales of up to millions of years (see below) indicates that lithospheric flexure due to loading is not significant at least during the post-emergence stages of the islands.

The islands themselves are characterised by a lack of major fault structures, other than those associated with volcanic calderas and giant lateral collapse structures, except in the very oldest rocks of Fuerteventura, La Gomera, and La Palma (Robertson and Stillman 1979, Cendrero 1970, Staudigel and Schmincke 1984). These are seamount series submarine volcanic and intrusive rocks that have been faulted, tilted, and uplifted by up to several kilometres. In all three islands the deformation is associated with intense igneous activity and the emplacement of large intrusions into the seamount rocks, and ends at around the time of emergence and the commencement of subaerial volcanic activity. The subaerial shield stage of growth and subsequent periods of quiescence and post-shield volcanic activity are characterised by little or no faulting, although arguments persist regarding the relative roles of regional, magmatic and topographic-gravitational stress fields in controlling the orientations of dykes and other intrusions (Carracedo 1994, 1996, Marti *et al.* 1996). The widespread occurrence of sea-level markers of various ages, at or close to contemporary sea levels, is a notable feature of the islands. Petrological studies (Klügel *et al.* 1997, Neumann *et al.* 1995) indicate that the subaerial activity is mainly fed by magma reservoirs in the old oceanic crust, or deeper: this is consistent with the lack of onshore deformation.

In this contribution we consider how analysis of the time and spatial distribution of the recent instrumental seismicity itself can be used to determine its origin with respect to the first two alternatives, in particular in relation to geological and geophysical data on the structure and mechanics of the Canarian lithosphere.

2. THE STRUCTURE AND MECHANICS OF THE CANARIAN LITHOSPHERE

The Canary Islands are built upon oceanic lithosphere, as proved by the presence of MORB gabbro and peridotite xenoliths in recent volcanic rocks in all the islands (Neumann *et al.* 1995). Magnetic anomaly mapping (Roest *et al.* 1992) indicates that this lithosphere is some 140 to 150 Ma old (increasing in age eastwards). In the absence of rejuvenation by reheating due to a plume, this lithosphere would be expected to have an elastic thickness (corresponding to the 450°C isotherm) of about 35 km (Canales and Dañobeitia 1998) and a maximum depth of normal seismogenic brittle failure (corresponding to the 600°C isotherm in mantle rocks under typical thermal gradients) of about 45-50 km (Weins and Stein 1983). This is consistent with the depth distribution of earthquakes along the Azores−Gibraltar plate boundary to the north (Grimison and Chen 1986). The extent of rejuvenation of the Canarian lithosphere by heating from below is uncertain but may significantly reduce the maximum depth of normal seismogenic brittle failure. Watts *et al.* (1997) argue for an elastic thickness near Tenerife of as little as 20 km, which would correspond to a maximum depth of normal seismogenic brittle failure of less than 30 km. Without such rejuvenation and weakening it is unlikely that intraplate deformation would occur in the Canaries; but if it is present then this could be the one part of the oceanic lithosphere in the region that is undergoing regional deformation.

Many thousands of kilometres of seismic line have been shot around the Canarian archipelago during the past two decades (Wissmann 1979, Watts *et al.* 1997, Banda *et al.* 1992, Funck *et al.* 1996). These have revealed intense block-faulting of the original oceanic crust, mainly along NNE-SSW trending faults parallel to the magnetic anomalies and interpreted in terms of extension along the slow-spreading mid-Atlantic ridge at the time of crustal formation, but virtually no deformation of the thick overlying sediment sequences except at the continent-ocean boundary (Wissmann 1979, Hinz *et al.* 1982) to the east of the islands. The termination of the bulk of Atlas deformation at the continental margin, indicated by this seismic data, is as expected from comparison of the relative strengths of oceanic and continental lithosphere (Steckler and ten Brink 1986) in the absence of thermal rejuvenation.

In conclusion, there are no evidences of thermal rejuvenation, but with or without thermal rejuvenation, the seismicity of tectonic origin must be restricted to relatively shallow depths (30-40 km) and the regional tectonic stresses can only be the primary responsible for producing the seismicity recorded in the islands in the inter-eruptive periods.

3. SEISMICITY

3.1 Historical seismicity

Although sporadic information on historical seismicity in the Canary Islands is available for the period from 1341, the record is highly incomplete to the late 18th century. A number of contemporary primary sources as well as local newspapers give more reliable information starting from the mid 1800's (Monge 1980). These more recent records contain sufficient information, in terms of effects and/or damages, to separate deep earthquakes (widely felt, absent to limited effects/damage) from shallow earthquakes (locally felt, mid to high level of local effects/damage).

Overall, the level of historically recorded seismic activity is low in the Canary Islands region and mostly concentrated on the island of Tenerife and between the two main islands, Tenerife and Gran Canaria (Mezcua *et al.* 1992, Jiménez and Fernández 1996). The remaining historical records (Monge 1980) relate to:

- a few isolated deep earthquakes, with small magnitude, slightly felt over the whole area, outside the eruptive periods;
- seismic swarms with some strong shallow shocks (up to felt intensity VIII on the MMI scale), associated with eruptions in a number of cases – Tenerife 1909, La Palma 1949, 1971, but not in others – Fuerteventura 1915, La Palma 1936, 1939. The latter seismic swarms have been interpreted as dike intrusion events.

3.2 Characteristics of instrumental catalogue

A local network of seismographic stations was installed in the Canary Islands region from 1975 onwards. From that time to May 1989, only minor activity was recorded (Mezcua *et al.* 1992). The local network, managed from the Instituto Geografico Nacional of Madrid, has been progressively increased after 1989 (7 local stations).

The seismic data set considered in the present study consists of 156 earthquakes recorded between 1 January 1989 and 31 December 1995. Data for 1989 to 1991 was provided by Dr. J. Mezcua; data for later years is contained in the open file report of the IGN national network. In the following we present the earthquakes parameters as reported by IGN (1992-1995):

- magnitude has been estimated by the following equation: $M_d = -0.87 + 2\log T + 0.0035\,D$, where T is the earthquake duration in seconds, and D the epicentral distance in kilometres;
- hypocentral locations of the events were estimated by adopting the standard location code HYPO71 (Lee and Lahr 1975) with the velocity model reported in Table 1.

Tabela 1

HYPO 71 Velocity model

Thickness [km]	Velocity [km/s]
0-4	4.20
4-12	6.30
12-18	7.50
> 18	8.00

Epicentre locations are plotted in Fig. 2. The bulk of activity is concentrated between Tenerife and Gran Canaria in the vicinity of the 1989 earthquake (Mezcua *et al.* 1992), but with significant concentrations of activity

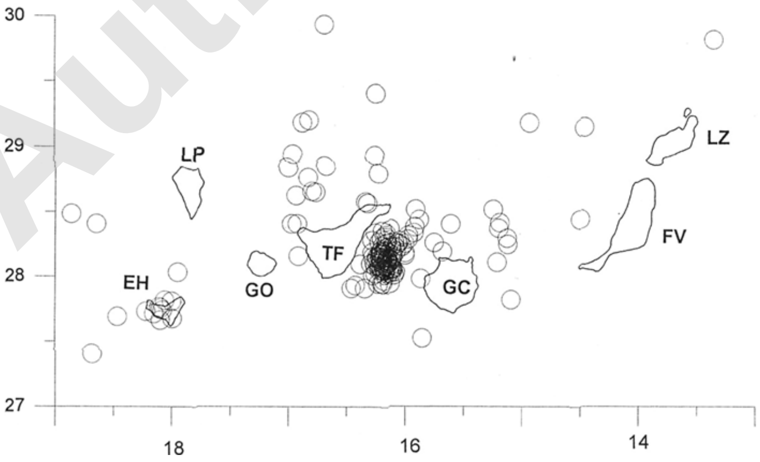

Fig. 2. Epicentral locations for earthquakes located by IGN Canaries network, 1989-1995. TF – Tenerife, GC – Gran Canaria, LP – La Palma, EH – El Hierro, GO – La Gomena, FV – Fuerteventura, and LZ – Lanzarote.

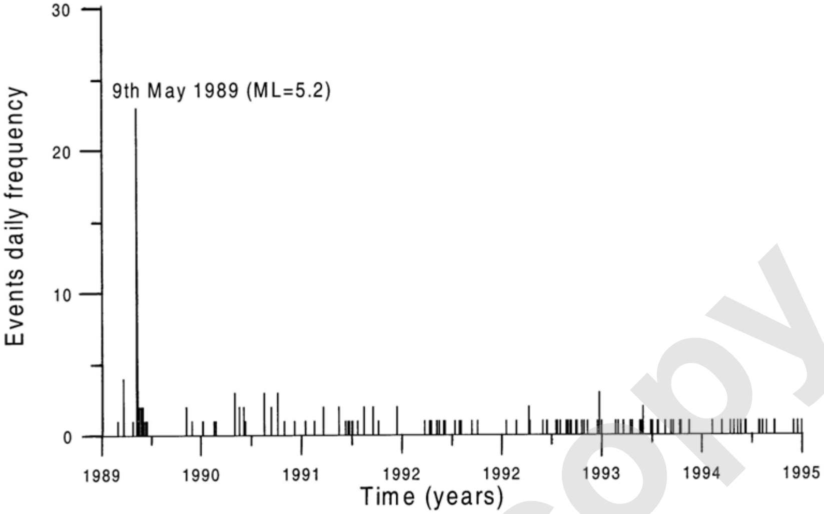

Fig. 3. Seismic events daily frequency distribution during 1989-1995.

below the island of El Hierro and beneath and to the north of Tenerife. In Fig. 3 the daily frequency distribution shows a maximum peak related to the 9 May 1989 earthquake ($M_L = 5.2$) and its aftershock sequence (Mezcua *et al.* 1992, Jimenez and Fernandez 1996).

By plotting the depth distribution *versus* time (Fig. 4) it is possible to see, despite the location uncertainty (indicated as error bars), that the 1989

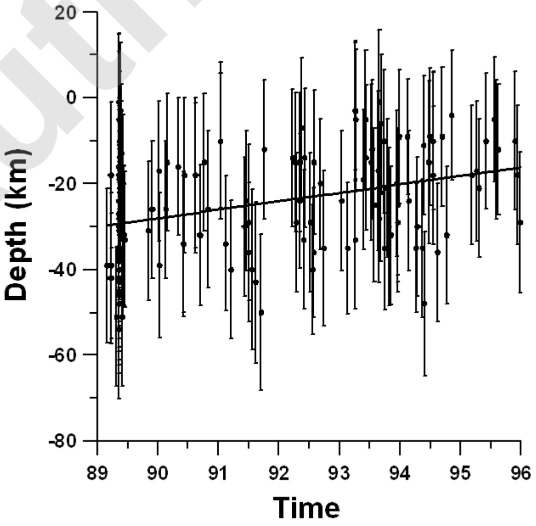

Fig. 4. Focii depth *versus* time. A linear fit suggests that hypocentres became shallower in time.

swarm affected deeper crustal volumes and subsequent events foci tend to become shallower in time. Apart from this swarm, the depth range of activity is similar throughout the archipelago, with events occurring at depths of 40 km or more from El Hierro (18.5°W) to Gran Canaria (15°W), except that the shallowest activity is concentrated in the vicinity of Tenerife consistent with the depth distribution of inferred magma reservoirs.

4. SPATIAL FRACTAL DIMENSION ANALYSIS

4.1 Previous studies on spatial clustering of earthquakes

Seismogenic structure/fault zones are not often precisely identified by the location of individual epi/hypocenters. In the majority of cases, such as the one studied, spatial distribution of hypocenters appears to be homogeneous, or with an intermediate character between randomness and organised clustering. Whereas the random arrangement of a set of points can be considered homogeneous, a regular grid of points can also be considered homogeneous even though it is absolutely not random (Tosi 1998). The fractal approach has introduced a new statistical tool to quantify the scale invariant distribution of seismicity and, with that, the properties of randomness and clusterization. Time variations of the spatial fractal dimension of seismic events have been found for different areas in the world allowing a quantitative characterisation over time of scale invariant failure processes acting in seismogenic volumes/fault zones (Lomnitz-Adler 1992, De Rubeis *et al.* 1993, Öncel *et al.* 1996, Tosi 1998, Xu and Burton 1999, Gospodinov *et al.* 2012). The method often preferred for calculating the fractal dimension D on time-spatial earthquake sequences is the correlation integral method (Grassberger and Procaccia 1983). Its simplicity and reliability with respect to the box counting algorithm has been widely discussed (among others, by Henderson *et al.* 1992, De Rubeis *et al.* 1993, Öncel *et al.* 1996, Tosi 1998, Xu and Burton 1999).

Fractal analysis has been particularly useful in volcanic areas. Time evolution of the time-spatial fractal dimensions of seismic events affecting Mt. Etna Volcano (De Rubeis *et al.* 1997, Barbano *et al.* 2000, Vinciguerra *et al.* 2001) calculated on a moving window suggested correlation between seismic patterns with eruptive processes at different time scales. Long-term fractal dimension variations, on the order of years, have been interpreted as due to magma rise from depth; mid to short term variations (months to days) have been attributed to changes in the stress regime of the volcano edifice associated with the onset of eruption. These studies indicate that fractal dimension D and its time evolution provide a reliable quantification of seismic activity related to changes of the state of the volcano and eruptive processes. Here our intention is to apply the same methods, in a different tectonic context, by investigating the spatial fractal dimension (D_s) of epicenters in the Canary islands area, focusing on the time variation of this parameter.

4.2 The fractal two point correlation dimension

The method used to calculate the fractal dimension D_s, as for previous studies, was the correlation integral (Grassberger and Procaccia 1983) defined as follows:

$$C(r) = \frac{2N_{R<r}}{N(N-1)} , \tag{1}$$

where N is the number of earthquakes and $N_{R<r}$ is the number of event pairs separated by an epicentral distance $R < r$. If the correlation integral distribution is $C(r) \propto r^{Dc}$, the set is fractal over a specified range of r, with the correlation dimension identified by D_s and calculated by measuring the slope of the best fit of $C(r)$ *versus* r on a log-log plot (see De Rubeis *et al.* 1997, for further details). In general, the fractal dimension gives us quantification of the clustering properties of the data: a low value of D_s means that events are very clustered; conversely, a high D_s indicates that inside that window the events are uniformly distributed. Embedded in two dimensions, for our data we have $0 \le D \le 2$. A moving overlapping time window of 40 events was adopted and the value calculated inside each window was assigned to the time occurrence of the last event. The shift between successive windows was set at 1 event, permitting a sufficient smoothing among D values. Reliability of the minimum number of events and the overlapping has been discussed in De Rubeis *et al.* (1993) and reference therein.

A test of completeness carried out according to the procedure of Tinti and Mulargia (1985) indicates that the data set can be considered complete at about $M > 2$. Restricting the analysis to larger events would imply the discarding of 14 earthquakes of the 156 in the data set. However, since we were limited in the overall number of events and in order to not decrease either the number of events per window or the number of D values, we kept this slight incompleteness, as it did not influence the reliability of the results found.

The available seismic data only covers part of the present inter-eruptive period, and so we are unable to evaluate changes associated with an eruptive episode, but it is sufficiently long to potentially reveal variations in the fractal dimension D (De Rubeis *et al.* 1993, Tosi 1998).

4.3 Results

Figure 5 shows the log-log graph of $C(r)$ *versus* r. By fitting the linear portion of the curve the distribution of D_s, *i.e.*, spatial fractal dimension over two dimensions can be found. Epicenter distribution is scale invariant in the

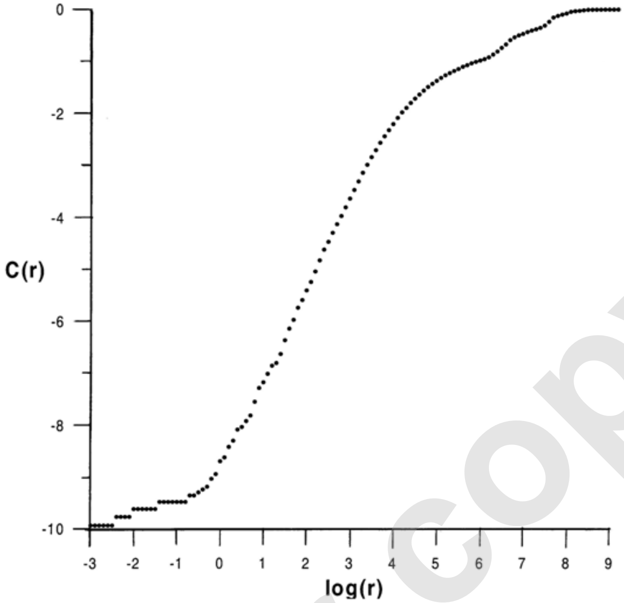

Fig. 5. Log-log graph of *C*(*r*) *versus* *r* relative to spatial distribution of seismic events.

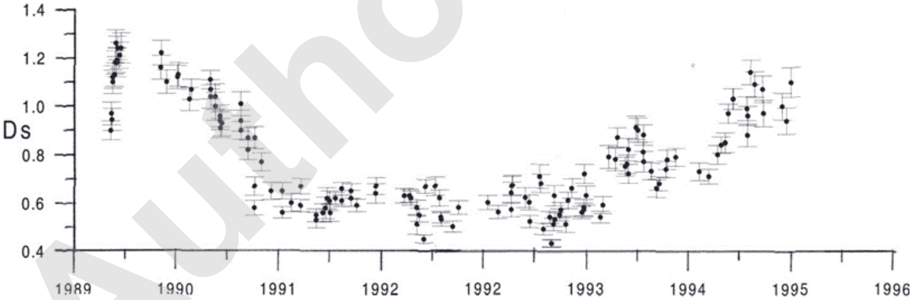

Fig. 6. Spatial fractal dimension variation *versus* time.

spatial range of 1-16 km. This range of values of *r* is dominated by the aftershocks of the 1989 earthquakes. In contrast, at larger values of *r* the straight-line relationship breaks down, indicating that the more widely-spaced events elsewhere in the archipelago do not follow a linear distribution. There are no structures larger than about 16 km across in the archipelago, which generates scale-invariant groups of earthquakes: this is consistent with the lack of large active regional fault structures.

Figure 6 shows the variations of D_s through the complete period analyzed (1989-1995). In general, values range between 0.4 and 1.3. An initial increase in D_s is consistent with the progressive activation of the seismogenic volumes/faults that produced the 1989 seismic swarms, with a peak in May 1989 of $D_s = 1.3$. After this phase, D_s decreases constantly, reaching low values close to 0.5 at the end of 1990 which persist until the end of 1993. Seismicity during this period clusters over relatively smaller seismogenic volumes (Vinciguerra *et al.* 2001, Tosi *et al.* 2008). This implies that smaller events occurred, which involved the rupture of relatively small volumes/faults. After 1993, the D_s values gradually increase, reaching values close to 1 at the end of 1995. Taken at face value, this new increase indicates that seismic epicenters tended to occupy increasingly large seismogenic volumes from 1993 to 1995. However, improvements to the monitoring network after 1993 and a possible consequent increase in its sensitivity may have contributed to this trend even though the removal of the events below the completeness threshold is unlikely to have affected the results. Thus, no thresholds were applied to the catalogue.

In terms of interpretation, the observed D_s time variations and the trend toward shallower hypocenters (Fig. 4) might imply that intrusive activity beneath the islands is increasing in the period 1993-1995 after a period of quiescence following the 1989 earthquake and seismic swarm. This is also supported by fractal dimension variations over time spans of a few years in association with intrusive episodes in other volcanic provinces (Barbano *et al.* 2000, Vinciguerra *et al.* 2001).

5. DISCUSSION AND CONCLUSIONS: INTEGRATION OF THE SEISMIC DATA WITH THE TECTONIC SETTING OF THE CANARY ISLANDS

Seismicity affecting Canary Islands region during 1989-1995 show the following patterns:

- ☐ the bulk of activity occurred in a crustal volume located between Gran Canaria and Tenerife;
- ☐ depth distribution of hypocentres suggests, within the high error bars associated, that the 1989 sequence affected deeper seismogenic volumes (depths > 40 km) than would be expected for earthquakes produced by regional deformation;
- ☐ the spatial fractal analysis evidences that epicenters clustered around a larger crustal volume during the May 1989 sequence and affected narrow volumes during 1991-1993; the 1989 sequence also extended to greater depths than the 1991-1993 activity;
- ☐ results might be interpreted as a major intrusive episode in 1989, followed by a period of quiescence; renewed deep intrusive activity may have occurred from 1993 onwards.

These patterns can be related to a number of features of both the tectonics and the volcanism of the islands. Firstly, the different crustal volumes involved indicate that seismicity in the Canaries can be interpreted as a product of the movement of magma at depth beneath the volcanoes. Moreover, there is no evidence for regional deformation in the seismic data. Nor are there indications of association with measurable ground deformation on the volcanoes themselves, in contrast to observations made during the seismic crisis of May 2004 that occurred at shallower depths in the Tenerife volcanic edifice (Almendros *et al.* 2007). This suggests that the lithosphere on which the islands are located is essentially rigid at depth, hence that the islands are truly intraplate in their tectonic setting and do not seem to be affected by the presence to the north of the Atlas plate boundary zone. The persistence of seismic activity throughout the period considered, especially in the deeper depth ranges, indicates the presence of persistent magma bodies within the oceanic lithosphere beneath the archipelago, consistent with the petrological data that implies the presence of long-lived magma bodies in which the magmas equilibrate before eruption. The increased depth of seismicity during the 1989 sequence may reflect inflation or deflation of magma bodies in the deeper parts of the magmatic system in response to a major intrusive episode at shallower depths. Although the period of activity considered here is short compared to the typical time interval between eruptions in the Canaries, the temporal variation in the depth and clustering characteristics observed during the 1989-1994 period suggests that future monitoring of such variations in the characteristics of the "background" seismicity may be valuable in understanding the long term behaviour of the Canarian magmatic systems and even in identifying precursors to future eruptions.

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