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Ground deformation and gravity changes on the island of Pantelleria in the geodynamic framework of the Sicily Channel

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Abstract

The island of Pantelleria is an active volcano located in the Sicily Channel (Southern Italy), in the middle of a continental rift system. Since the 1980s the island was periodically surveyed by using geodetic techniques (EDM, levelling, GPS and high precise gravimetry) to monitor the regional and local volcanic dynamics. Gravity data, collected between 1990 and 1998, show short and long wavelength changes due to the combined effect of shallow and deep sources. They reflect, to some degree, the structural setting of the island as delineated by the Bouguer anomaly field, which indicates that the island is broken up into two main basement blocks. The latter are bordered by two lineaments, probably regional faults related to the global geodynamics of the Sicily Channel Rift Zone. Moreover, the inverse correlation between the gravity and altimetric variations suggests that: i) Pantelleria is kinematically divided in two blocks; ii) the observed behaviour is strongly influenced by the geodynamics of the Sicily Channel. A new interpretation of the fully reprocessed data sets is presented, focusing on the spatial–temporal features of the horizontal ground deformation and gravity changes compared to the Bouguer anomaly and altimetric data. This leads to conclude that volcanism on the island has been probably strongly influenced by the global geodynamics of the Sicily Channel, and future eruptions are most likely to occur at the structural boundary separating the two blocks.

Keywords: Pantelleria; geodesy; deformation; gravity; volcanism; geodynamics

1. Introduction

Geodesy is widely and successfully applied to monitor the dynamics of active volcanoes. This is also the case on the island of Pantelleria, an active volcano located in the middle part of the Sicily Channel (Southern Italy) (Fig. 1a), where geodetic and

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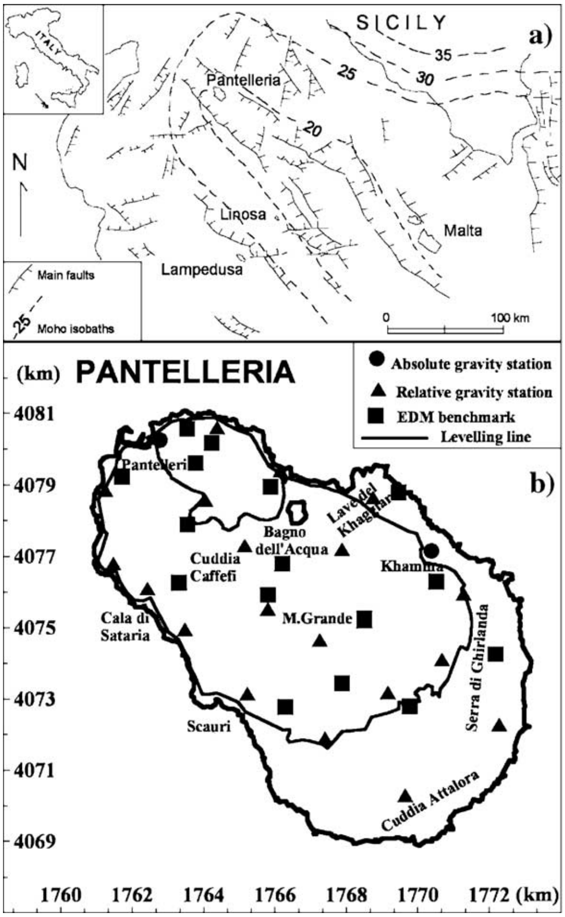

Fig. 1. a) Structural sketch map of the Sicily Channel (modified after Cello et al., 1985); b) Gravity, levelling and EDM networks on Pantelleria Island.

geophysical observations are periodically carried out since 1980s.

A levelling line was established in 1980 by the Osservatorio Vesuviano (Naples, Italy) to detect vertical ground movements and deformation (Berrino et al., 1982). In 1979, the Istituto Internazionale di Vulcanologia (IIV-Catania, Italy), now part of the Istituto Nazionale di Geofisica e Vulcanologia, established an EDM network to detect the horizontal displacements (Bonaccorso et al., 1995). IIV also surveyed, since 1996, a GPS network overlapping the EDM network (Bonaccorso and Mattia, 2000).

A first GPS measurement was made in 1988 in the northern part of the island, in the framework of the "WHAT A CAT" (i.e., West Hellenic Arc Tectonics And Calabrian Arc Tectonics) project. This project was aimed at investigating the kinematics of the African/Eurasian plate boundary in the Central Mediterranean region (Kahle et al., 1993). The benchmark was surveyed again in 1990 and 1992. Moreover, since 1990 repeated high precision gravity observations were made on the island (Berrino, 1997) to detect mass movements.

This paper presents a joint analysis of the spatial–temporal nature of the gravity changes and horizontal ground deformation. Gravity data includes measurements previously published (1990–1995) (Berrino, 1997, 1998), and new data collected in 1996 and 1998. All gravity variations were compared with Bouguer gravity anomalies and altimetric variations, following the procedure of Berrino (1997). The EDM data were reprocessed, mainly to draw the horizontal displacement vectors not previously published, for a proper comparison with gravity and altimetric data; they were subsequently integrated with previous results. This allows a global interpretation of the structural setting and geodynamics of the Sicily Channel to evaluate its influence on the volcanic dynamics of the island.

2. Geological and structural setting of Pantelleria and of Sicily Channel Rift Zone

The island of Pantelleria spans an area of 83 km^2 and lies in the Strait of Sicily, about 100 km from the SW coast of Sicily and only 70 km from Africa's northern coast (Fig. 1a). Pantelleria sits in the central portion of the Sicily Channel Rift Zone (SCRZ) (Illies, 1980, 1981; Reuther and Eisbacher, 1985), the deepest part of the Strait. The floor of the Pantelleria basin is made up of thinned continental crust belonging to the northernmost part of the African plate, with a thickness of only 20 km (Colombi et al., 1973; Finetti, 1984).

The magma compositions of Pantelleria range from peralkaline rhyolites and trachytes to less frequent hawaiites and mildly alkaline basalts, typical products of volcanoes related to continental rifts (e.g., Macdonald, 1974; Mahood and Hildreth, 1986; Civetta et al., 1998). The most recent activity is mainly located in the northern part of the island and is represented by two submarine eruptions in

1831 and 1891. The presence of hot springs and fumaroles is indicative of persistent active magmatism. A seismic survey carried out in 1980 revealed an anomalous seismic noise in the northern area interpreted as coming from shallow thermal fluids rising through the local fault system (Berrino et al., 1982). This is also supported by the presence of fluid inclusions in quartz and feldspar crystals of granitoid xenoliths in recent lavas and ignimbrites (De Vivo et al., 1992, 1993).

The structural setting of the island is delineated by both volcano–tectonic and tectonic lineaments. The first include two nested calderas of different ages and a resurgent block within the younger caldera, in the south-central sector of the island (Villari, 1974; Mahood and Hildreth, 1983, 1986; Cornette et al., 1983; Orsi et al., 1991), where, a shallow, mafic magma reservoir could be located (Civetta et al., 1988), as also suggested by a thermal anomaly (Squarci et al., 1994; Bellani et al., 1995; Chierici et al., 1995; D'Amore et al., 1995). The main geological structures were also defined from gravity prospecting (Gantar et al., 1961; Berrino et al., 1982; Berrino and Capuano, 1995). The most recent Bouguer anomaly map (Berrino and Capuano, 1995) indicates a basement having the top at variable depth, and its large-scale features appear to be cut in two principal blocks (Fig. 2): the first is a subsided northern block and the second, to the south, is uplifted and tilted towards NW. The blocks are bordered by two lineations, possibly regional faults, trending SE–NW and ENE–WSW, respectively. The latter runs from Khaggiar to Cala di Sataria crossing the Cuddia Caffefi area (Fig. 2); here it dislocates the SE–NW fault which continues in the northern part of the island clearly shifted in a NE direction (Berrino and Capuano, 1995). In Fig. 2 the ENE–WSW and SE–NW structures are indicated by dashed lines; in this way the island appears composed of three parts: namely, a north-eastern, a western and a south-eastern sector.

The dominant tectonic lineaments on the island, related to regional events, include NW–SE trending fractures and right-lateral strike-slip faults, although NE–SW and N–S trending faults are also common (Colantuoni and Zarudzski, 1973; Cello et al., 1985; Orsi, 2003). According to Orsi (2003), these regional features occur outside the area affected by caldera

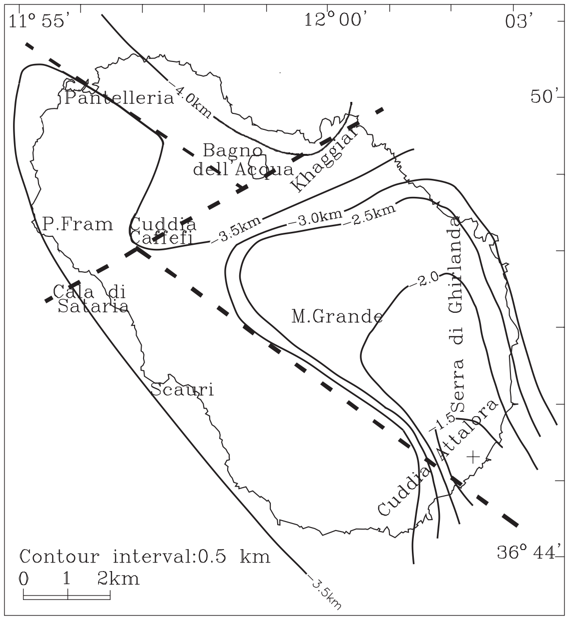

Fig. 2. Maps of the isobaths of the large-scale features of the basement of Pantelleria Island. The dashed lines indicate the positions and the trends of some main regional structures (see text for details) (modified after Berrino and Capuano, 1995).

collapse. This author also indicates the presence of a NE–SW tensile fault system which divides the island into two sectors and most likely represents a crustal discontinuity along the axial ridge of the rift. This system is located in the same area where Berrino and Capuano (1995) suggested the presence of an ENE–WSW regional fault separating the island into two blocks (Fig. 2). The present-day stress field is characterized by a NNW–SSE principal maximum and an ENE–WSW minimum compression (Cello et al., 1985).

The local structural regime reflects that of the SCRZ (Fig. 1a), where the opening of pull-apart basins is the dominant mode of deformation (Finetti, 1984; Boccaletti et al., 1987; Cello, 1987) and it is particularly concentrated along the axial ridge area, where Pantelleria is located. The results of the several studies about the structural setting and the development of the basin have been summarized in Berrino (1997).

The present dynamics of Pantelleria is delineated by geophysical investigations. From 1980 to 1996 and relative to a northern reference, a general subsidence was observed with a maximum of about 11 cm of deflation in the SE sector and within the caldera rims (Obrizzo, 1996). The previously published joint analysis of gravity and altimetric data (Berrino and Capuano, 1995; Berrino, 1997, 1998) suggested that the island is also kinematically divided in two blocks. A direct correlation between gravity changes and Bouguer anomaly was obtained, while an inverse correlation exists for the height variations. That means that a gravity increase and subsidence are observed in the south-eastern part of the island, inside the caldera rims, where the top of the basement is shallower than in the rest of the island. In contrast, gravity decrease and uplift occur in the north-western side of the island characterized by a deepening basement. Following these results and taking into account the structural setting of the Sicily Channel, Berrino (1995, 1997) concluded that most of the observed kinematics of the island can be associated with the dynamics of the Sicily Channel and, if this evolution continues in the future, stretching may affect the island, in the area where the ENE–WSW oriented structure divides it into two blocks, and that this might culminate in an eruption (Berrino, 1997). This is in good agreement with those from GPS surveys carried out in the northern sector of the island in the framework of the "WHAT A CAT" project, and their comparison with the velocity field predicted by simply interpolating ITRF92 velocities from four fiducial SLR/VLBI stations. The results obtained for Pantelleria showed a strike slip motion with a compressive component with respect to the fiducial stations (Kahle et al., 1993) and an absolute velocity of the horizontal movement of about 1.5 cm/y in a NE direction (Kaniuth et al., 1994).

Moreover, the previous analyses of EDM data indicated a general contraction of the island and suggested ongoing deflation in the central-southern part (Bonaccorso and Mattia, 2000). The joint modelling of horizontal and vertical changes, the latter obtained by levelling, explain the short term (tens of years) deflation as due to the de-pressurization of a source about 5 km below the younger caldera (Bonaccorso and Mattia, 2000). Bonaccorso and Mattia (2000) also proposed an interpretative model with long-term (thousands of years) deflation that could be due to readjustment following mass loss associated with recent volcanism.

3. Geodetic investigations: data acquisition

Geodetic observations on the island of Pantelleria started in 1979/1980 when EDM (Bonaccorso et al., 1995; Bonaccorso and Mattia, 2000) and levelling (Berrino et al., 1982) networks (Fig. 1b) were established. At the same time a detailed gravity survey was carried out to determine the local structural setting, helpful to optimize the geodetic networks (Berrino et al., 1982). High precision gravimetry (Berrino, 1997) and GPS (Bonaccorso and Mattia, 2000) monitoring was initiated in the 1990s.

The 1979 EDM network was formed by 15 benchmarks linked by 42 distance measurements; surveys were made in 1979, 1980 and 1982. The network, following a significant modification of its geometry, was reoccupied in 1995, in 1996 and in 1997. The present EDM network configuration is shown in Fig. 1b. More recently, the EDM network was also surveyed using GPS (Bonaccorso and Mattia, 2000).

The EDM measurements were carried out using laser (AGA 6 BL) or infrared (AGA6000) geodimeters having both an accuracy of $\pm$(5 mm + 1 mm/km) and a range of about 20–25 and 13 km, respectively. Angular measurements were performed with a Kern DKM3 first order theodolite. Distances between each pair of stations of the network were measured in one direction and the atmospheric corrections were calculated averaging the air temperature and pressure at both ends of the measured line.

The configuration of the levelling line (Fig. 1b), initially consisting of 56 benchmarks distributed on two main lines (Berrino et al., 1982), was designed to survey mainly the movements of the two calderas in the southern part of the island and the more recent structures in the northern sector. Therefore, a benchmark located in the northern part of the island was chosen as reference (Berrino et al., 1982). At present the network consists of 100 benchmarks, on three lines with a total length of 48 km (Obrizzo, 1996). Levelling surveys were carried out in 1980, 1988, 1991 and 1996 (Berrino et al., 1982; Del Gaudio et al., 1988; Obrizzo et al., 1991, 1993; Obrizzo, 1996). Height differences in 1980 were obtained by geometric levelling using ZEISS Ni2 and Wild NA2 self-levelling instruments, all equipped with a micrometer, and 3 m invar rods calibrated to the Istituto Geografico Militare Italiano (IGMI). The double-run survey met first order standards; the levelling lines were spliced together as loops according to the least-square method in order to adjust the network. Uncertainties in elevation differences resulted to be no larger than ± 2 mm/$\sqrt{\text{km}}$. Data starting from 1988 that are here considered were extracted from Del Gaudio et al. (1988), Obrizzo et al. (1991, 1993) and Obrizzo (1996); they were obtained with the same field procedures as those described above, with an uncertainty of less then ± 2 mm/$\sqrt{\text{km}}$.

High precision gravity measurements started in 1990 (Berrino, 1997) on a network that now consists of 20 stations, most of which coincide with benchmarks of the levelling line (Fig. 1b). Two gravity stations are placed in the south-eastern region, outside the caldera complex, where the oldest rocks crop out. Because the southern area is believed to be the most stable, these stations were chosen as reference for gravity differences (Berrino, 1997). The network was fully surveyed in 1990, 1995, 1996, and 1998, and partially in September 1993 when the gravity acceleration was measured at Pantelleria Harbour and Khamma (Berrino, 1997) (Fig. 1b); the measured gravity values (g_{mis}) are listed in Table 1 together with the parameters necessary to identify the station and to reduce the measured gravity values to the ground. The given g_{mis} value is the mean value of the gravity acceleration of a series of values corrected by earth tide effect and obtained by several hundred drops spanned on few days. Absolute gravity measurements were carried out in cooperation with the Metrological Institute "Gustavo Colonnetti" (IMGC), of the Italian National Research Council, where the instrumentation was built (Alasia et al., 1982). Subsequently, g_{mis} is corrected for air pressure and polar motion effects. The first is reduced using an admittance value of 0.35 μGal/mbar and, as pressure value, the difference between the measured value and the normal atmospheric pressure at the station. The polar motion effect is determined by the ephemerides available at the International Earth Rotation Service (IERS).

Table 1
Absolute gravity values (g_{mis}) measured at the stations Pantelleria Harbour and Khamma (ref. Fig. 1b)

Station	Pantelleria Harbour	Khamma
Latitude	36° 50′ 00″ N	36° 48′ 00″ N
Longitude	11° 56′ 30″ E	12° 02′ 00″ E
Elevation	20 m m.s.l.	170 m m.s.l.
g_{mis}	979 951 232 ± 1.5 μGal	979 923 486 ± 1.5 μGal
H_{mis}	0.900 ± 0.001 m	0.895 ± 0.001 m
P_{mis}	1015 ± 1 mbar	998 ± 1 mbar
dg/dg_{mis}	−302 ± 3 μGal/m	−330 ± 3 μGal/m

The parameters necessary to reduce the measured gravity to the ground are also given. Data are reproduced from Berrino (1997).
g_{mis} = measured absolute gravity value.
H_{mis} = height of measurement.
P_{mis} = measured local pressure value.
dg/dh_{mis} = measured vertical gravity gradient.

Because the measured value of the gravity acceleration is not referred to ground level, it is necessary to know the local value of the vertical gravity gradient (dg/dh) to reduce the measured value of g to the ground. Therefore, the dg/dh value has been experimentally established at each station. The LaCoste and Romberg (LCR), model D, number 136 gravity meter, equipped with LCR analog Feed Back system, was used for this measurement.

From each absolute station a satellite station was derived, close to the main station, to retrieve the absolute value of g in the site in case of inaccessibility or destruction of the main station. Because of the difficulties in linking the island to a stable area on land (i.e., Sicily), these absolute stations provide an absolute reference system for the relative measurements and for long term variations (Berrino, 1995; Berrino et al., 1999). The absolute stations were selected also as benchmarks of the relative network that thus consists of a total of 24 stations. Relative gravity measurements were made during the same season to reduce seasonal effects.

The LCR, model D, numbers 62 and 136 intercalibrated (Berrino et al., 1988; Becker et al., 1995, 2000) gravity meters were jointly used to measure the gravity differences between each pair of stations. Field procedures follow the standards: any gravity differences between couples of stations were measured in an independent way from the rest by means of at least three links in reverse way. No less then four gravity readings were done with every instrument at each station at any occupation and only the readings with a repeatability of 1–2 μGal after reductions were accepted. The gravity readings were corrected for tidal effects, atmospheric loading (Spratt, 1982), and instrument drift. Because no tidal parameters from gravity records were available for the island, the gravimetric tidal reduction was determined using Tamura's (1987) tidal generating potential and adopting a global gravimetric factor $\delta = 1.16$ and phase shift of zero. Pressure was corrected using the admittance value of 0.35 μGal/mbar. The corrected and weighed gravity differences were organized on joined loops and then adjusted according to the least square method; finally, the gravity value at any station was computed relative to the reference station. The adjustment errors, for the several campaigns from 1990 to 1998, were within a range of 3–10 μGal.

4. Data analysis: results and discussion

Gravity data were updated to include those carried out in 1996 and 1998. To compare the latest results to those from the period before 1996, all gravity differences were referenced to the Cuddia Attalora station in the southern part of the island (Fig. 1b), and relative counts were created using the Kriging grid method (e.g.,: Cressie, 1991). In the same manner we have reproccessed the 1990–1995 data for global discussion and compared the complete data set with the Bouguer gravity anomalies and altimetric data.

The new data agree with previous results (Berrino, 1997); namely, a superposition of short and long-term changes, a good direct/inverse correlation with structural setting and height changes, respectively, and a possible influence of the regional on the local dynamics. In Fig. 3a–d the short-term spatial distribution of gravity changes is represented, including additional stations beginning in 1995. The gravity distribution shows different patterns in the central and south-eastern part of the island than in the north-western area. From 1990 to 1995 (Fig. 3a,b) the gravity variation field is smoother in the northern part and shows a gravity decrease, while the central-south sector shows a gravity increase extending and shifting NE during 1993–1995 (Fig. 3b). A ~NE–SW trending demarcation line is evident in Fig. 3a, in the same area where Berrino and Capuano (1995) indicate a regional fault. This trend is also well visible in Fig. 3c, where the 1995–1996 space gravity field is inverted with respect to that prior to 1993: a gravity increase involves the northern part, while a well defined gravity decrease is localized around Montagna Grande, in the central part of the island and inside the caldera complex. The gravity field inverts again between 1996 and 1998 (Fig. 3d), although a closed anomaly persists around Montagna Grande. The most disturbed fields after 1995 are due to increased station coverage. Because no levelling data are available for the Montagna Grande area, it was not possible to assess the extent to which observed gravity changes correlate with surface height changes or, alternatively, to subsurface mass changes. If we attribute the gravity changes exclusively to mass changes, we can infer, for both the 1995–1996 and 1996–1998 anomalies, a source at about 1 km depth with a mass change of about 10^7 kg. Alternatively, the largest observed gravity changes in the area (-40 ± 12 and $+65 \pm 7$ μGal) could be associated with height changes (+13 and −21 cm), assuming a theoretical $\mathrm{d}g/\mathrm{d}h$ of −308.55 μGal/m. The same values of Δh are obtained using both measured $\mathrm{d}g/\mathrm{d}h$ at the absolute stations. No Δh were measured in such a short time interval anywhere in the rest of the island. It is, of course, possible to assume some combination of height and mass changes as a plausible alternative explanation.

The shortest wavelengths of the anomaly field are indicative of shallow and local sources, whose effect is reduced if the long-term gravity changes are considered (Fig. 4a–d). In this case, the NE–SW demarcation line which separates the two areas showing different patterns is more evident, as well as the strength of the gravity change observed in 1995–1996 that persists also over a longer time interval (Fig. 4c). The 1990–1996 anomaly centred on Montagna Grande confirms a mass change of about -10^7 kg in a local source about 1 km deep. In the long-term gravity field, two areas of gravity increase, whose extension again suggests shallow sources, are localized in the north-eastern (close to Bagno dell'Acqua) and south-western sectors. They coincide with the zone of anomalous seismic noise, where shallow thermal fluids rise through the local fault system (Berrino et al., 1982), and where a thermal anomaly is indicated by geothermal prospecting (Squarci et al., 1994). The contour lines between the south-western and the Montagna Grande anomalies on the long-term gravity fields also seem to reflect a possible influence of the SE–NW lineation belonging to the large-scale feature of the basement, in the southern part of the

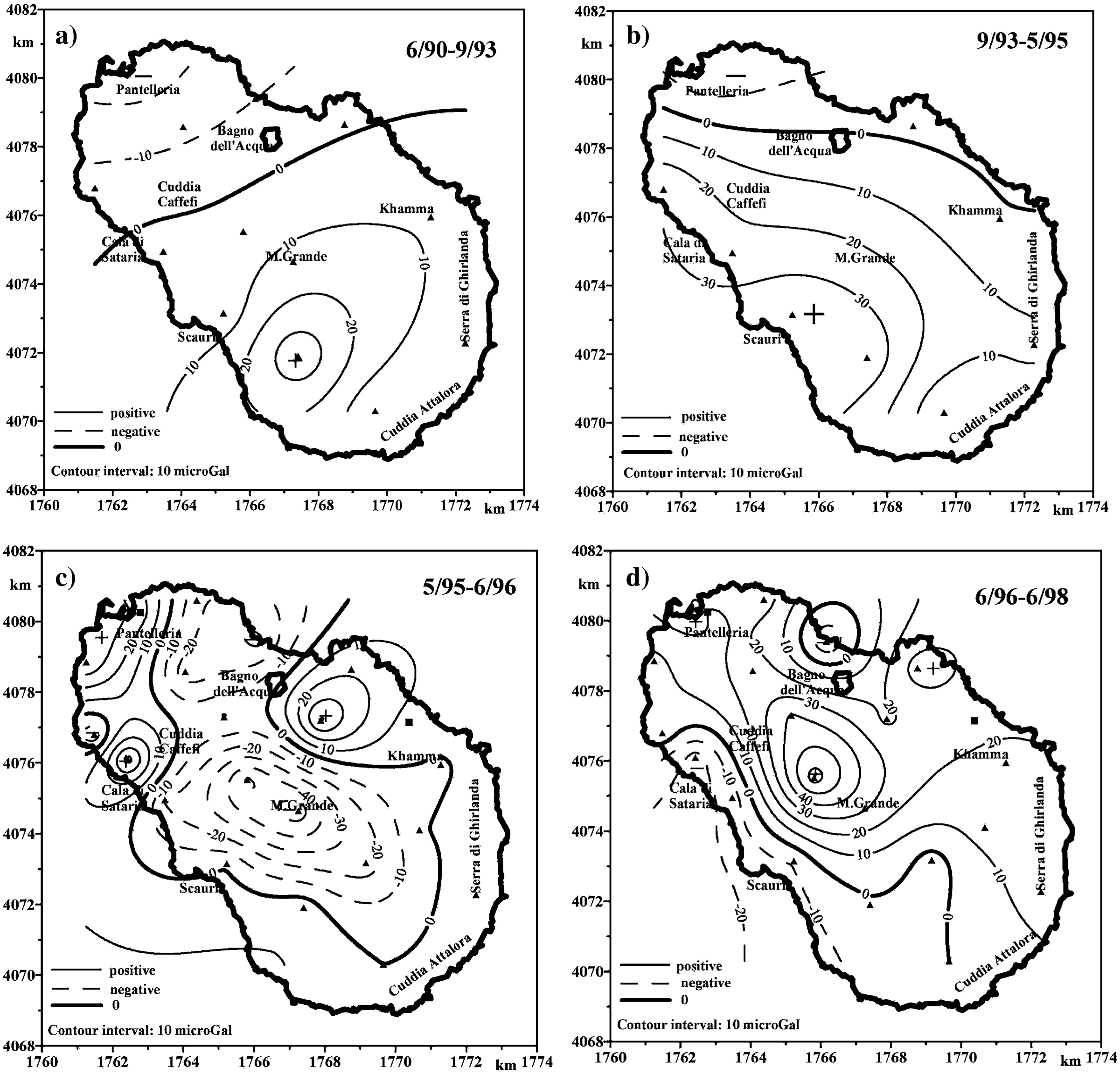

Fig. 3. Short-term gravity changes during a) June 1990–September 1993, b) September 1993–May 1995, c) May 1995–June 1996, d) June 1996–June 1998 time intervals. Gravity changes are referred to the benchmark in the south-eastern part of Pantelleria Island, close to Cuddia Attalora (see Fig. 1b for reference).

island from Cuddia Caffefi to the rim of the ancient caldera (Fig. 2).

In addition, gravity changes from 1993 have been computed using as reference the absolute station in Khamma, in the eastern sector of the island and close to the ENE–WSW structure. The results for several time intervals are represented in Fig. 5a–d. Comparing the field related to the 1993–1995, 1995–1996 and 1996–1998 periods with those drawn with respect to stations in the southern part of the island (Fig. 3a–c), no significant differences appear. This confirms the stability of the south-eastern part of the island and of the eastern coast close to the ENE–WSW structure that divides the island.

The new gravity data support the observations of Berrino (1997), i.e.,: (a) the space distribution of the

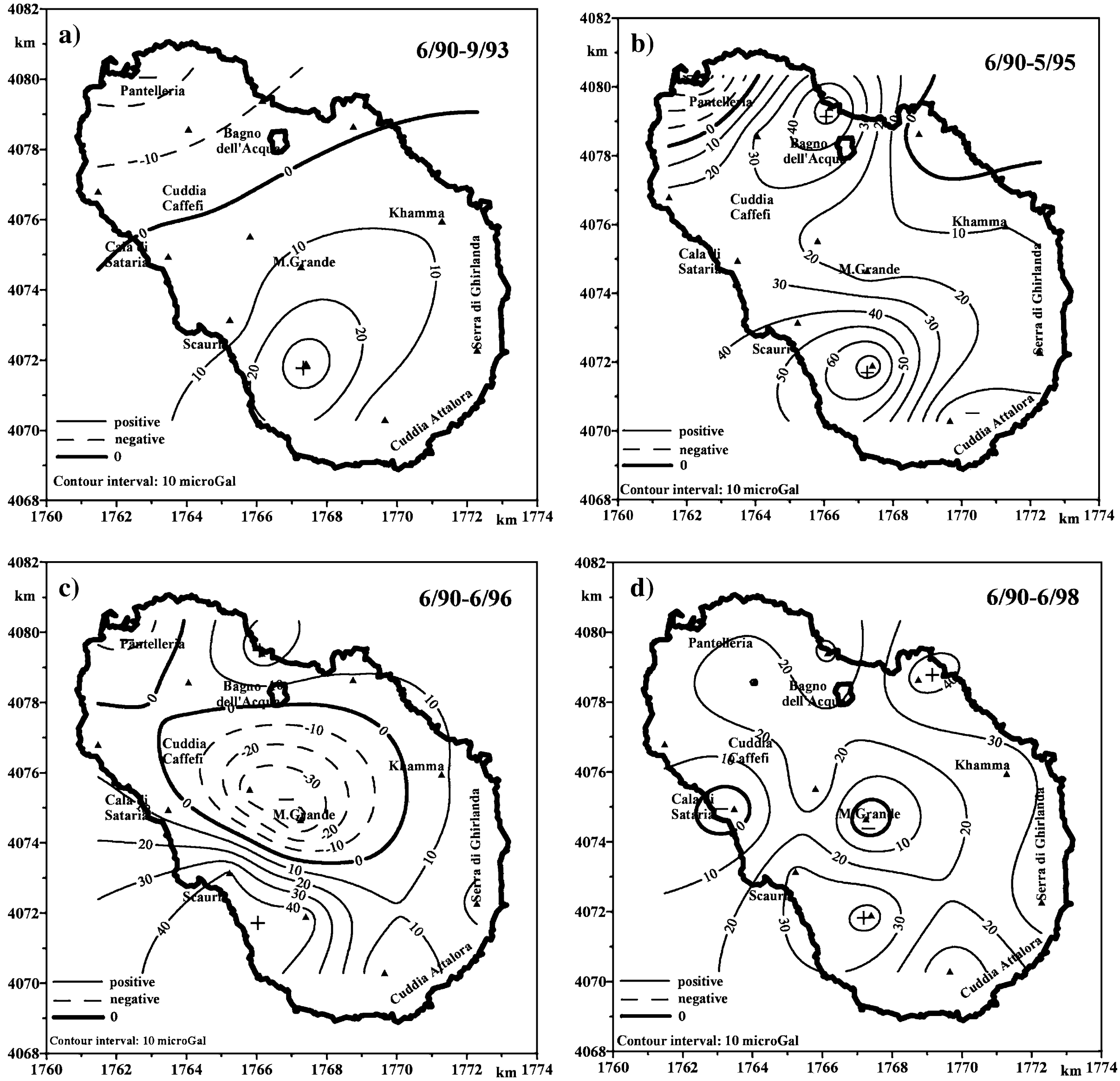

Fig. 4. Long-term gravity changes during a) June 1990–September 1993, b) June 1990–May 1995, c) June 1990–June 1996, d) June 1990–June 1998 time intervals. Gravity changes are referred to the benchmark in the south-eastern part of Pantelleria Island, close to Cuddia Attalora (see Fig. 1b for reference).

gravity changes is strongly similar to the Bouguer anomaly field and to the large-scale features of the basement of the island; (b) the gravity changes indicate that the island of Pantelleria is divided into two blocks in a kinematic as well as in a volcanological and structural sense.

To confirm this, all gravity data between 1990 and 1998 were compared with the Bouguer gravity anomalies and the altimetric data as already done for data until 1995 (Berrino, 1997). This is illustrated in Fig. 6, where the gravity changes on several time intervals spanning from 1990 to 1998 are compared along the levelling route with the Bouguer anomalies and the height changes from 1980 to 1996 (Berrino et al., 1982; Del Gaudio et al., 1988; Obrizzo et al., 1991, 1993; Obrizzo, 1996).

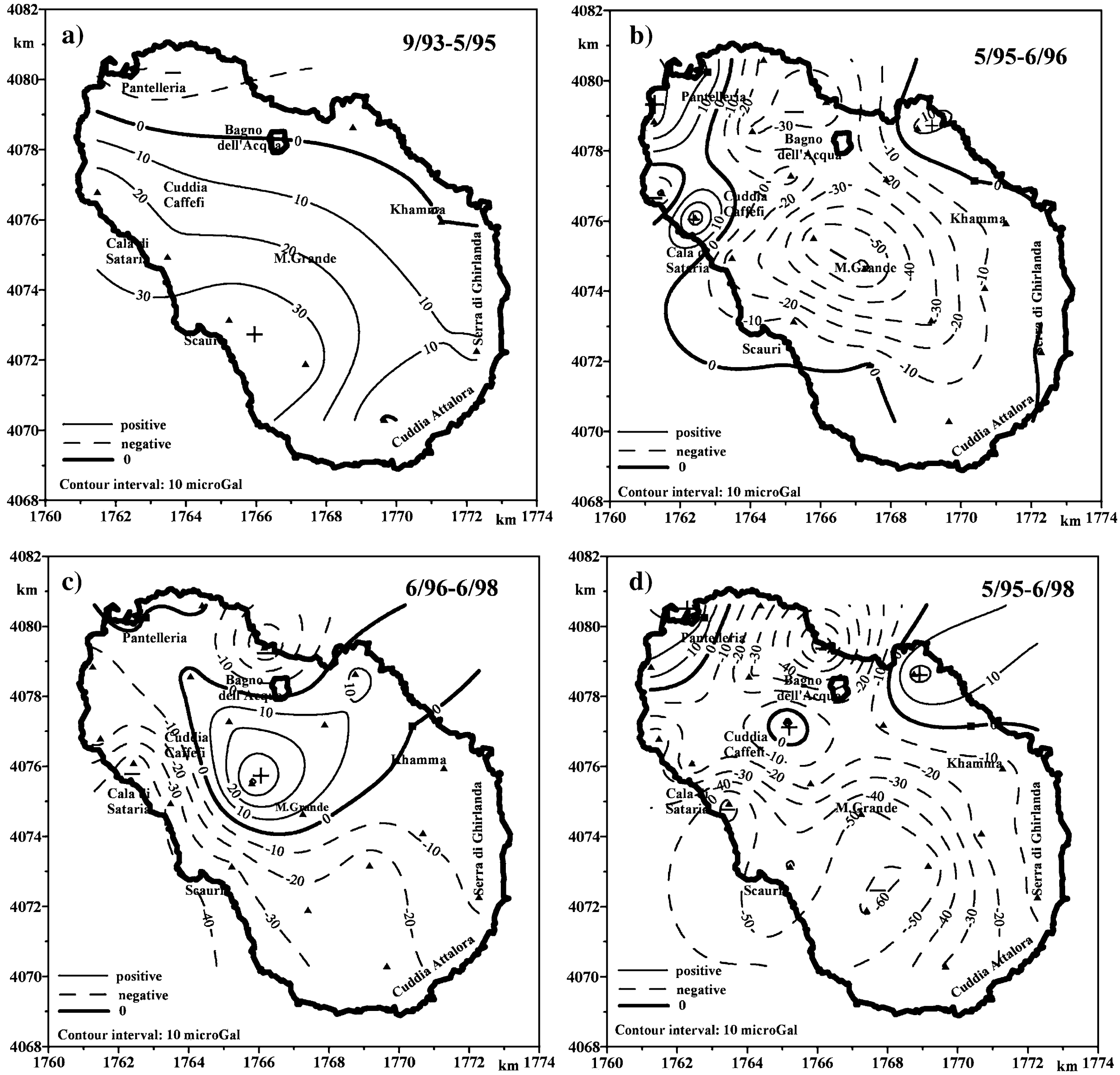

Fig. 5. Long-term gravity changes during a) September 1993–May 1995, b) September 1993–June 1996, d) September 1993–June 1998, d) May 1995–June 1998 time intervals, referred to the absolute station in Khamma (see Fig. 1b for reference).

First of all the altimetric data were updated and re-analyzed as suggested by Berrino and Capuano (1995) who observed that a meaningful pattern of the vertical ground movements from 1980 to 1991 is obtained if they are referenced to any benchmark located along the central-western coast of the island instead of the northern reference. In this way subsidence is seen to persist in the southern part of the island, but uplift appears in the northern part. An inverse correlation with the gravity anomalies was also highlighted, i.e., uplift corresponds to gravity lows and subsidence to gravity highs. Berrino and Capuano (1995) stressed that the ~SW–NE trend of the zero deformation axis (from Cala di Sataria to Khaggiar) is very close to the ENE–WSW regional fault obtained by the interpretative gravity model (Fig. 2).

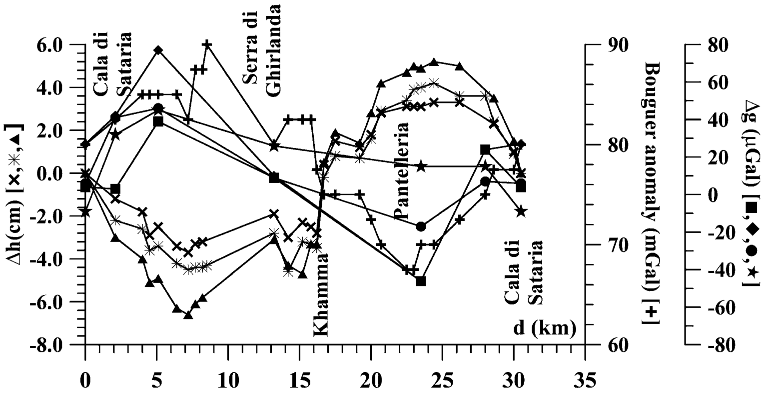

Fig. 6. Comparison, along the levelling route, among Bouguer gravity anomaly, elevation changes during 1980–1988 (×), 1980–1991 (*) and 1980–1996 (▲) and gravity changes during 1990–1993 (■), 1990–1995 (◆), 1990–1996 (●), 1990–1998 (★).

This updated comparison shows again a direct correlation between gravity changes and Bouguer anomalies and an inverse one with the height changes. It also confirms that the zero deformation line and the NE–SW demarcation line observed in the long-term gravity changes fields run very close to the ENE–WSW regional fault depicted by the Bouguer anomaly interpretative model. Taking into account the rate of the vertical ground movements in the 1980–1996 time interval, and calculating and extrapolating it to the 1990–1998 period spanned by gravity data, it follows that the altimetric variations are not able to fully justify the observed changes and, therefore, a significant mass redistribution is implied. A quantitative interpretation of the long-term gravity changes aimed to detect the depth of the responsible sources is not possible because of the limited extension of the island and consequently of the observed gravity changes field. The influence of some regional structures of the Sicily Channel is evident, so that an influence of the SCRZ dynamics cannot be excluded on the island, as already suggested by Berrino (1997).

In the light of the previously published and new gravity data, we have re-organized and re-analyzed the EDM data and computed the displacement vectors. In fact, the previous study of the horizontal component of the deformation field on Pantelleria allowed the evaluation of the uniform strain tensor components computed as a function of the variations of the line lengths (Jaeger, 1969); it also provides the representation of the areal dilatation, D, the maximum shear, MS, and the maximum dilatation, E_1, and maximum contraction, E_2, axes. EDM data were analyzed only in terms of strain changes. So far, no displacement vectors were computed from the EDM data, although this was done for GPS measurements in the period 1996–1997 (Bonaccorso and Mattia, 2000), referred to a station in the northern part of the island. The results shown that only the vectors in the southernmost stations are oriented towards the interior of the caldera complex with a maximum value of about 2 cm.

As mentioned before, the geometry of the EDM network was significantly modified, resulting in the change of 5 benchmarks and the establishment of two new ones. This change in the time interval 1982–1995, during which significant deformations took place, renders any analysis problematic.

First of all, we distinguish two periods, one starting in 1979 and ending in 1982, and the second one lasting from 1995 until 1997. The data for each period have peculiar characters with respect to geometry of the network and number of measured lines. For this reason the comparison between the first and second data sets can be made only for a smaller number of measured lines, which indeed renders somewhat weaker results that mainly affect the drawing of the displacement vectors of the network benchmarks.

The first period of observations (1979–1982) is characterized mostly by contraction on the island (Fig. 7 and Table 2a) that is well evident from the main strain axes calculated for the periods 1979–1980 (Fig. 7a), 1980–1982 (Fig. 7b) and 1979–1982 (Fig. 7f). The maximum contraction axis E_2 has a NNE–

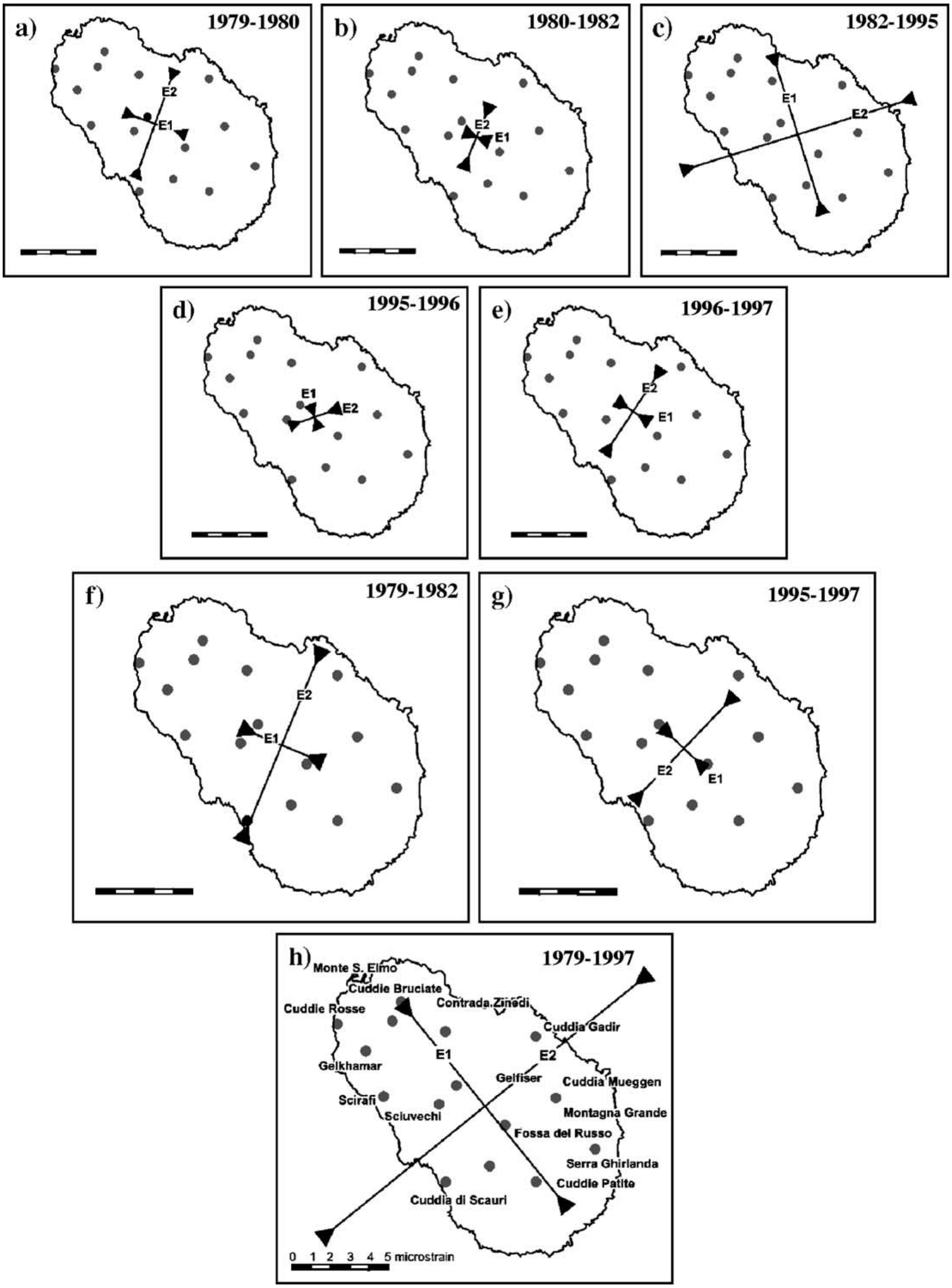

Fig. 7. Main strain axes calculated from the global EDM network during several time intervals between 1979 and 1997. Scale bar in each frame represents 5 microstrain; note different scale of frames.

Table 2
Main strain parameters calculated from the EDM network in several time intervals for: a) global network; b) the northern part of the network; c) the southern part of the network

Time interval	E_1 (ppm)	TH_1 (°)	E_2 (ppm)	MS (ppm)	D (ppm)
(a)					
10/79–10/80	−2.8 ± 1.3	108.7 ± 14.7	−6.2 ± 1.3	3.4 ± 1.8	−9 ± 1.9
10/80–04/82	0.5 ± 1.2	112.5 ± 19.7	−3 ± 1.2	2.4 ± 1.7	−3.5 ± 1.8
04/82–09/95	−9.5 ± 4.7	162.7 ± 33.3	−14.6 ± 4.7	5.1 ± 6.4	−24.1 ± 6.8
09/95–09/96	−0.4 ± 0.9	160.7 ± 22.9	−1.9 ± 0.9	1.5 ± 1.3	−2.3 ± 1.4
09/96–09/97	−0.9 ± 0.9	123.5 ± 8.5	−5.3 ± 0.9	4.4 ± 1.1	−6.1 ± 1.3
10/79–04/82	−3 ± 1.9	112.6 ± 11.4	−9.3 ± 1.9	6.3 ± 2.5	−12.3 ± 2.7
10/79–09/95	−13.9 ± 5.6	154 ± 44.5	−19 ± 5.6	5.1 ± 7.5	−32.9 ± 8.4
10/79–09/97	−12.1 ± 5.7	141.2 ± 30.9	−20.2 ± 5.7	8.1 ± 7.4	−32.3 ± 8.9
09/95–09/97	−1.5 ± 1	133.7 ± 10.4	−6 ± 1	4.5 ± 1.3	−7.5 ± 1.6
(b)					
10/79–10/80	−3.2 ± 3.6	93.1 ± 10.1	−16 ± 3.6	12.8 ± 5.2	−19.3 ± 5.2
10/80–04/82	6.1 ± 1.7	131.7 ± 5.9	−5.7 ± 1.7	11.8 ± 2.4	0.5 ± 2.5
10/79–04/82	0.8 ± 5.1	113.9 ± 10.1	−19.7 ± 5.1	20.6 ± 7.2	−18.9 ± 7.2
09/95–09/96	−1.1 ± 1.9	145.6 ± 47.2	−2.9 ± 1.9	1.7 ± 2.6	−4 ± 2.9
09/96–09/97	−0.1 ± 2.3	97.3 ± 28.3	−4.3 ± 2.3	4.2 ± 3.3	−4.4 ± 3.3
09/95–09/97	−0.4 ± 2.3	80.2 ± 23.2	−5.3 ± 2.3	4.8 ± 3.3	−5.7 ± 3.2
(c)					
10/79–10/80	−0.8 ± 0.9	27.4 ± 16.6	−3 ± 0.9	2.2 ± 1.1	−3.8 ± 1.4
10/80–04/82	−0.3 ± 1.2	123.1 ± 14.3	−4.1 ± 1.2	3.8 ± 1.5	−4.5 ± 1.9
10/79–04/82	−3.5 ± 1.5	135.7 ± 47.6	−4.9 ± 1.5	1.5 ± 1.8	−8.4 ± 2.4
09/95–09/96	0.07 ± 1.5	6.9 ± 23.4	−1.9 ± 1.5	1.9 ± 2.1	−1.8 ± 2.1
09/96–09/97	−0.9 ± 1.2	119.6 ± 9.9	−6.1 ± 1.2	5.2 ± 1.5	−7 ± 1.9
09/95–09/97	−2.4 ± 1.5	129.1 ± 18.4	−6.4 ± 1.5	4.1 ± 1.7	−8.8 ± 2.4

E_1 = maximum extension axis; TH_1 = azimuth of the maximum extension axis referred to the North and measured in a clockwise direction; E_2 = minimum extension axis; MS: maximum shear; D: spatial dilatation.

SSW trend, while the smaller axis E_1, indicating the minimum contraction, follows a WNW–ESE trend.

In the same way the second period (1995–1997) (Fig. 7 and Table 2a) has been analyzed. Also during this time interval contraction is mainly observed. The main strain axes in the periods 1995–1996 (Fig. 7d), 1996–1997 (Fig. 7e) and 1995–1997 (Fig. 7g), indicate a weaker deformation with respect to the 1979–1982 period (Fig. 7f), with an axis of maximum contraction E_2 having an overall NNE–SSW or NE–SW trend, in agreement with the trend observed during the period 1979–1982 (Fig. 7f).

Finally, the entire period was considered (1979–1997; Fig. 7h and Table 2a) within the limits expressed above. The changes in the network geometry allow to comparing each data set using only 21 lines, with much of the lines located in the central-southern part of the island. The main strain axes calculated for the periods 1982–1995 (Fig. 7c) and 1979–1997 (Fig. 7h), show the existence of a strong contraction component, mainly acting in the southern part of the island, which took place mainly in the 1982–1995 period (Fig. 7c). The direction of the main contraction axis E_2 follows again the same NE–SW trend.

Considering that the main axis E_2 is always oriented NE–SW, and taking into account the results obtained by gravity analyses, the EDM data of the same periods were analyzed dividing the network in two, northern and southern, parts (Table 2b–c and Fig. 8) separated by a line corresponding to the ENE–WSW lineation suggested by Berrino and Capuano (1995).

Data for the 1979–1980 period (Fig. 8a) indicate that the stronger negative variations are confined to the northern sector of the island. In contrast, during the 1980–1982 period (Fig. 8b), a large part of the lines in the northern sector underwent moderate exten-

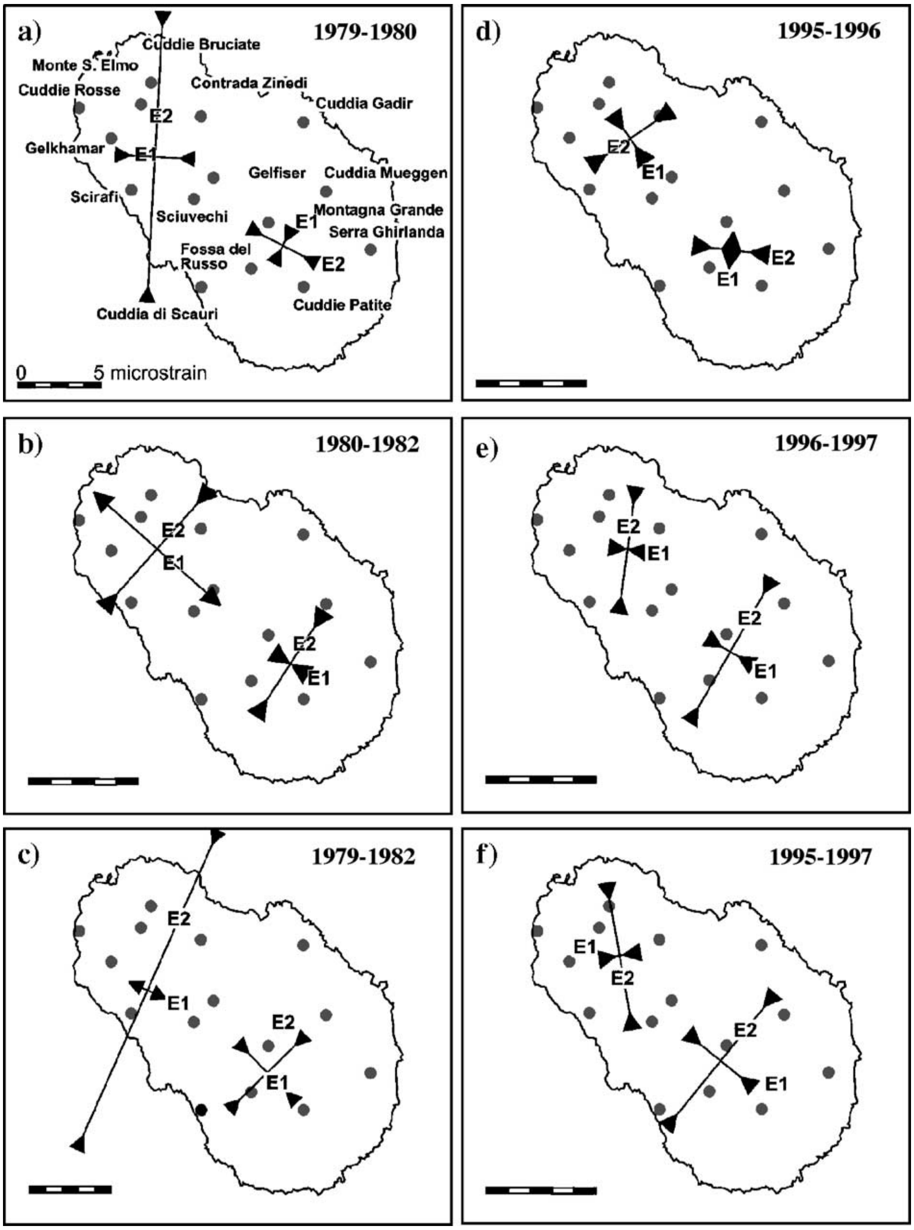

Fig. 8. Main strain axes calculated respectively from the northern and the southern part of the EDM network during several time intervals between 1979 and 1997. Scale bar in each frame represents 5 microstrain. Errors on main strain axes and relative azimuths are listed in Table 2.

sion, while contraction still characterized the southern sector. If the entire 1979–1982 period is considered (Fig. 8c), there is again prevailing contraction in the northern sector, along a NNE–SSW direction (E_2 axis), with a less important extension trending WNW–ESE (E_1 axis). Regarding the second period 1995–1997 (Table 2b–c and Fig. 8d–f), and still dividing the network in two parts and considering the same time intervals as before (1995/1996 — Fig. 8d; 1996/1997 — Fig. 8e; 1995/1997 — Fig. 8f), the same trend is observed for the entire network, that is: contraction in both sectors and the main axis E_2

generally oriented NE–SW. No larger differences between the lengths of the axes in the northern and southern sectors appear from 1996. The EDM data therefore confirm the observation of a differential kinematic behaviour of the island, even though this is not clear from 1996.

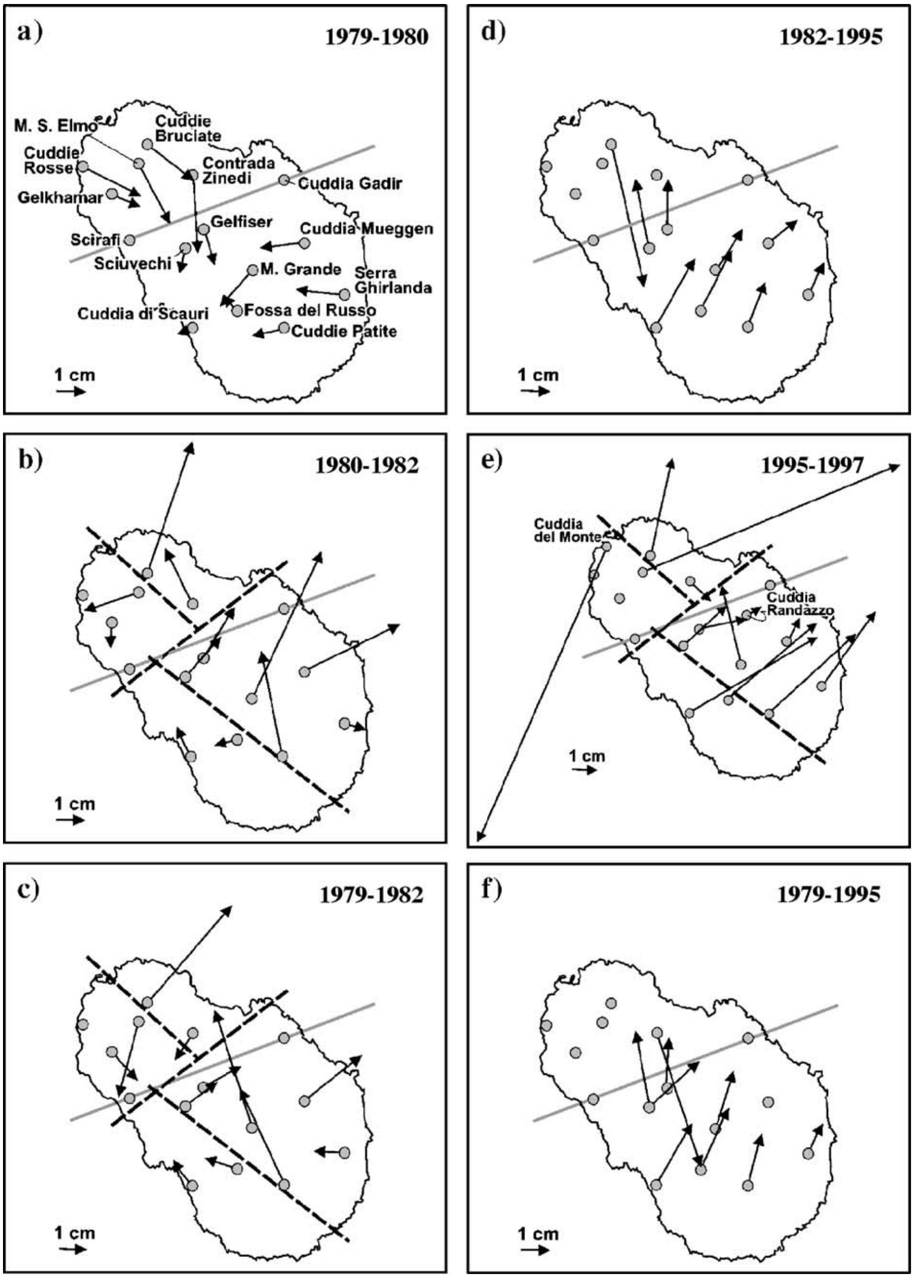

Fig. 9. Displacement vectors from the northern and the southern part of the EDM network during several time intervals between 1979 and 1997. The separation line between the two sectors (continuous line) represents the reference line for their calculation, while black dashed lines in b, c and e indicate the main structures depicted on the large-scale basement by Berrino and Capuano (1995) (see also Fig. 2). Note different scale of frame (e) due to large displacement vectors. Error ellipses are not shown for clarity (see text for further detail).

Though there were problems caused mainly by the modification of the geometry and weak network constraints, we attempted to determine displacement vectors. We acknowledge that this includes very large ellipse errors, often of the same order as that of the vectors themselves; furthermore the vectors are not well constrained, both in amplitude and direction, so they have to be considered qualitatively. The main limit in describing a displacement vector from EDM data is to adequately define a stable reference. In the case of a volcanic island as Pantelleria, this criterion can be very difficult to satisfy. In the light of the results obtained from gravity and from the new EDM analyses, two benchmarks located respectively in Cuddia Cadir and Scirafi, very close to the supposed ENE–WSW regional fault, have been chosen as reference line to compute the displacement vectors. Several time intervals have been selected for the first (1979–1982) and the second (1995–1997) networks. An attempt to analyze long-term intervals (i.e., 1982–1995 and 1979–1997) has also been made, but unfortunately no or very little information can be obtained for the northern sector. Results are shown in Fig. 9a–f, where the error ellipses are not shown for the reasons previously mentioned.

In spite of these limits, some interesting information can be obtained. The first is that most of the larger vectors are generally located in the northern sector, while small horizontal movements are close to the reference line and in the central-western and south-western sides. The second, and more interesting information, is that the direction of vectors seems to divide the island into three blocks, delimited by three lines coincident with the main lineations of the large-scale basement (Berrino and Capuano, 1995) (Fig. 2). This behaviour is evident in the vector displacement fields referred to the 1980–1982 (Fig. 9b), 1979–1982 (Fig. 9c) and 1995–1997 (Fig. 9e) time intervals; in the corresponding images the three lineaments are also drawn with dark dashed lines. Both eastern blocks indicate a movement towards NE with larger movements of the northern block; pointing to a relative shift of the northern block in a NE direction with respect to the southern block. This is supported by the "WHAT A CAT" GPS data which detected, in the northern part of the island, a NE movement (Kahle et al., 1993; Kaniuth et al., 1994). These findings justify the interpretation of the large-scale basement made by Berrino and Capuano (1995), who suggested a break of the SE–NW regional fault in the central part of the island and a NE shift of the north-eastern block. Finally, the EDM data also seem to reflect the influence of the regional on the local dynamics.

5. Conclusions

New gravity and EDM data and their integration with, and re-interpretation of, previously published data show the recent dynamics of Pantelleria to be much more complex than revealed by previous studies. Generally Pantelleria appears to be divided into two main blocks from a kinematic, structural, and volcanological point of view. Namely, the northern block — the area of the most recent volcanism on the island — is mainly affected by stronger or more vigorous dynamics than the southern block. An influence of regional structures on the observed dynamics is evident, mainly regarding the ENE–WSW structure identified on the large-scale basement from the interpretation of the Bouguer anomalies. In addition, the EDM data also show the influence of the SE–NW lineament, its break in correspondence of the ENE–WSW lineament, and its shift towards NE. The general contraction and the prevalent NE direction of the displacement vectors observed on the island are consistent with the general present-day compressional stress field and with the position of the island relative to the rift axis.

It must be taken into account that all the results depend on a local reference and only the repetition of absolute measurements (gravity, GPS and other space-geodesy) will discriminate between local and regional movements. Moreover, all studies carried out so far concern only the sub-aerial portion of the island, while much of the Pantelleria volcanic edifice lies below the sea level (note that the most recent eruptive activity occurred below the sea level to the northwest). Thus, any inference is to be considered quite partial and does not allow conclusive statements regarding the current dynamics of the volcano. In order to obtain a more complete understanding of the dynamics of the island, future studies should be extended to the submarine portion of the volcanic edifice and to the entire SCRZ. Nevertheless, the obtained results lead us to conclude that a future eruption could be triggered by the global influence of the dynamics of the Sicily Channel on the Pantelleria volcano, mainly in the area where the ENE–WSW structure divides the island into two blocks.

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