Journal of Geodynamics 66 (2013) 1–12

Contents lists available at SciVerse ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Analysis of vertical movements in eastern Sicily and southern Calabria (Italy) through geodetic leveling data

Cecilia Rita Spampinato[a], Carla Braitenberg[b], Carmelo Monaco[a,*], Giovanni Scicchitano[a,c]

[a] *Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università degli Studi di Catania, Italy*
[b] *Dipartimento di Matematica e Geoscienze, Università degli Studi di Trieste, Italy*
[c] *Studio Geologi Associati T.S.T. Via Galliano, 157, 95045, Misterbianco, Catania, Italy*

ARTICLE INFO

Article history:
Received 10 September 2012
Received in revised form
19 December 2012
Accepted 19 December 2012
Available online xxx

Keywords:
Calabrian arc
Sicily
Geodetic leveling
Vertical movements

ABSTRACT

The analysis of repeated high precision leveling observations during the last 40 years along lines of the Italian fundamental network allowed us to estimate very recent vertical movements in eastern Sicily and southern Calabria (Italy). The network is measured by the Italian Istituto Geografico Militare (IGM) and we have analyzed three leveling lines. Because of the lack of an absolute reference datum, we have conducted the analyses in terms of relative elevation changes compared to reference benchmarks. Although the processing of the different time series obtained from the high precision leveling has allowed us to estimate only relative rates, their extreme accuracy, together with the large extension of networks, makes this type of measurement fundamental for the estimate of recent vertical deformation. In addition, correlating instrumental and geological data makes it possible to identify active tectonic structures whose elastic strain accumulation could be responsible for vertical deformation. In particular, vertical motion can be related to the activity of a W-E trending fault separating the Catania Plain from the Hyblean Plateau in southeastern Sicily, a N-S trending normal fault occurring north of the Messina town and the NE-SW trending Scilla normal fault in south-western Calabria. The last two are located on the sides of the Messina Straits, an area of broad interest for the planning of the single-span bridge between Sicily and mainland Italy.

1. Introduction

The Late Quaternary tectonic evolution of eastern Sicily and southern Calabria (Italy, Fig. 1) has been characterized by strong vertical movements that have been recorded by uplifted marine terraces and palaeo-shorelines. Long term uplift has been constrained by the elevation of the last interglacial (125 ka, MIS 5.5) terraces (Ferranti et al., 2006) and has been related to regional processes to which faulting-related deformation is added along fault-controlled coastal segments (Westaway, 1993). The uplift pattern of the 125 ka terrace is replicated by the Holocene paleo-shorelines. In particular, in north-eastern Sicily and southern Calabria data on vertical movements during the Holocene have been obtained by measurement and radiometric dating of biological and morphological markers (Stewart et al., 1997; De Guidi et al., 2003; Antonioli et al., 2003, 2006a; Ferranti et al., 2007; Scicchitano et al., 2011; Spampinato et al., 2012). In south-eastern Sicily data have been obtained by analysis of boreholes from lagoonal deposits (Monaco et al., 2004; Spampinato et al., 2011) and by measures of submerged archeological markers and of speleothems collected in karstic caves (Scicchitano et al., 2008).

Holocene vertical crustal movements derived from biological, geomorphologic or archeological markers have been estimated using the predicted sea level as reference datum (e.g. Lambeck et al., 2004) but present day precise geodetic estimates are still lacking. Antonioli et al. (2009) and Braitenberg et al. (2011) used the differential sea level changes between tide gauges and altimetric satellites to estimate vertical movements at the tide gauge stations in Sicily, finding that both Messina and Catania have been uplifting at similar rates with respect to the stable Palermo station. Nevertheless, the authors pointed out that the overlapping time window between tide gauges and altimeter was still short to obtain reliable vertical movement rates of the stations. The presently available GPS observations are too short to give reliable vertical movements, as well (Mattia et al., 2009, 2012)

In this work we approach the problem of estimating vertical movements in eastern Sicily and southern Calabria using a network of high precision leveling lines performed by the Italian Istituto Geografico Militare (IGM). Determination of vertical deformation by leveling data has some advantages: (i) it is the only geodetic dataset regarding vertical movements that spans back in time to the past 50–100 years; (ii) the resolution in evaluating the vertical

* Corresponding author. Fax: +39 957195728.
E-mail address: cmonaco@unict.it (C. Monaco).

0264-3707/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jog.2012.12.002

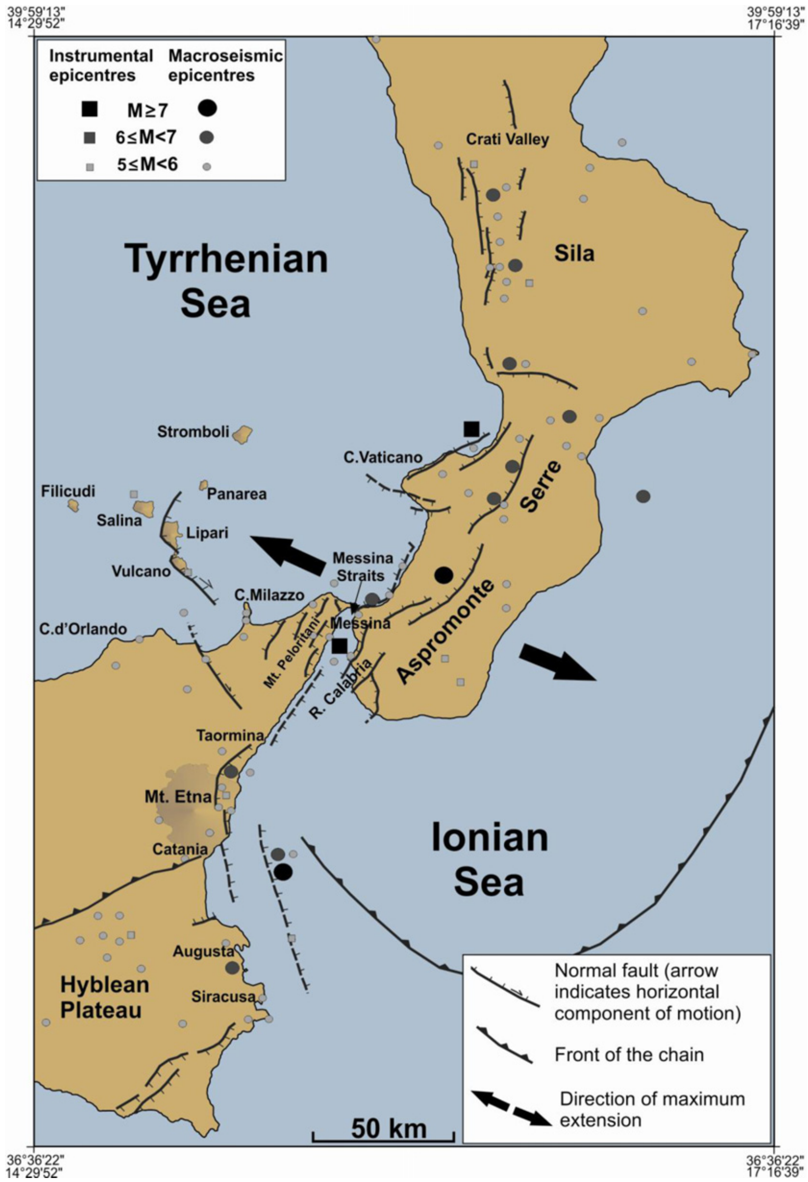

Fig. 1. Tectonic sketch map of southern Calabria and eastern Sicily (after Monaco and Tortorici, 2000; modified). Crustal seismicity (H < 35 km) since 1000 AD is also shown (data from Gasparini et al., 1982; Postpischl, 1985; Anderson and Jackson, 1987; Boschi et al., 1995).

component of motion is one order of magnitude better than GPS estimates; and (iii) anyhow, no comparable sampling of active regions (1 benchmark per km) is presently available from GPS networks in Italy. On the contrary, the main disadvantage of leveling measurements is the lack of an absolute reference datum, and only relative motion can be precisely determined by comparative leveling data (Bomford, 1971). However, we show that cross analysis of instrumental data with structural geological surveys may reveal the activity of tectonic structures, supposedly responsible for the vertical deformation recorded in the areas crossed by leveling lines.

Repeated leveling has been used in different locations to successfully determine tectonic and anthropogenic vertical movements. Rózsa et al. (2005) relate rate changes to the crossing of some main faults in the upper Rhine graben in a slow moving tectonic environment with mean movement rates in 60 years up to 0.25 mm/yr. The GPS observations were too short to give significant results as rates were below the 1 mm/yr level. Grzempowski et al. (2009) observe subsidence of benchmarks in Slesia (Poland) which they ascribe to compaction of sediments. Along the coastline of the Eastern Betic Cordillera, SE Spain, Gimenez et al. (2009) analyzed the repeated leveling over a 27 year time span and found vertical movement rates near to 0.2 mm/yr, which has been estimated to be close the precision of the method. The rates were in good agreement with the geologically determined rates based on geological markers. Short term vertical movement was obtained at a fault by a dedicated repeated leveling experiment near Izmir, Turkey by Ozener et al. (2012). Peak subsidence rates up to 30 cm/yr in Northern Iran were observed with excellent agreement with both Interferometric Synthetic Aperture Radar (InSAR) and leveling and were ascribed to subsurface water withdrawal (Motagh et al., 2007) controlled by the presence of Alpine faults (Anderssohn et al., 2008); the acceleration of rates was shown by using the older and newer leveling repetitions. Drakos et al. (2001) used repeated leveling to invert for the fault mechanism of a 6.5 magnitude earthquake. Repeated leveling was used to quantify subsidence due to magma injection and exploitation of a geothermal field over a Caldera in Eastern California (Howle et al., 2003). Further recent studies using repeated leveling to obtain geodynamic information over volcanic

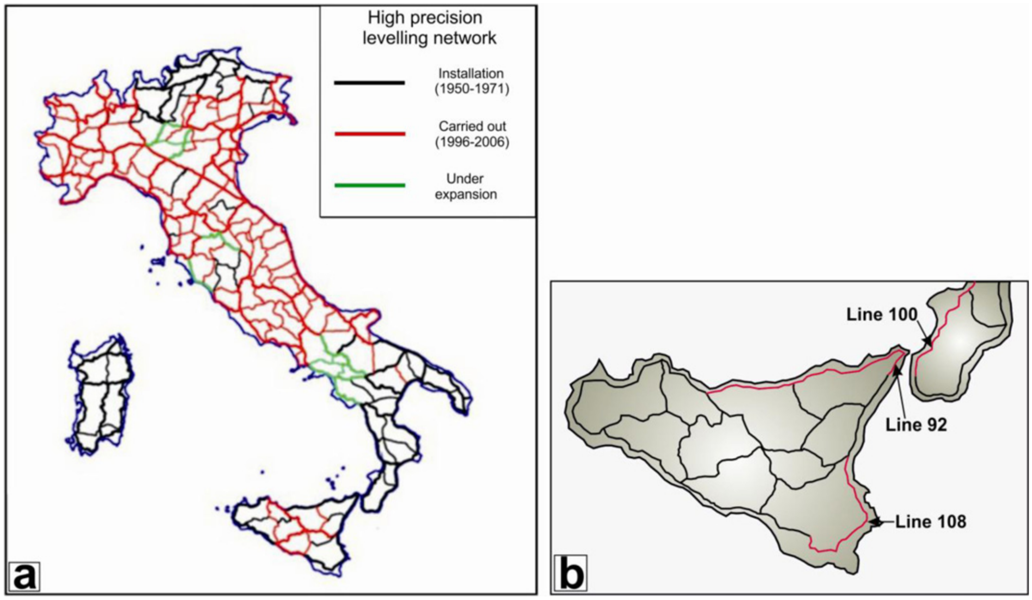

Fig. 2. (a) The IGM high precision leveling network in Italy. (b) Traces of the three analyzed lines (red lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

areas were made by Sarychikhina et al. (2011) and Poland et al. (2006). The Italian leveling lines have been used in the Apennines to reveal short-term vertical velocities by D'Anastasio et al. (2006).

2. Geological setting

The study areas are located along the Calabrian Arc and eastern Sicily (Fig. 1), the most seismically active areas of the central Mediterranean, where the effects of Quaternary tectonics are better preserved. The Calabrian Arc, which includes southern Calabria and north-eastern Sicily, connects the Apennines and the Sicilian-Maghrebian chains that developed during the Neogene-Quaternary Africa–Europe collision (Dewey et al., 1989), and was emplaced to the south-east during north-westerly subduction and roll-back of the Ionian slab (Malinverno and Ryan, 1986). Since Pliocene times, contractional structures of the inner part of the orogen were superseded by extensional faults, both longitudinal and transversal with respect to the arc, that caused the fragmentation into structural highs and marine sedimentary basins (Ghisetti and Vezzani, 1982). In eastern Sicily and Calabria, Quaternary extension at the rear of the thrust belt has been accompanied by a vigorous uplift (1–2 mm/yr) recorded by flights of marine terraces (Westaway, 1993; Miyauchi et al., 1994; Ferranti et al., 2006).

The seismicity of the Calabrian Arc and eastern Sicily is defined by the occurrence of both crustal ($H < 35$ km) and subcrustal ($H > 35$ km) earthquakes. The latter are located beneath the southern Tyrrhenian sea, reaching 470 km of depth and depicting a slab dipping about 45° toward NW (Gasparini et al., 1985; Anderson and Jackson, 1987; Neri et al., 2012). Crustal seismicity is defined by historical and instrumental earthquakes (Postpischl, 1985; Boschi et al., 1995, 1997; Scarfì et al., 2009). The epicentral distribution of the $M \geq 6$ earthquakes (Fig. 1) outlines a seismic belt which runs along the Tyrrhenian side of the Calabrian arc and, southward, along the Ionian coast of Sicily and the Hyblean Plateau, where active WNW-ESE extension is documented by focal mechanisms of crustal earthquakes (Neri et al., 2004; Pondrelli et al., 2006), structural studies (Tortorici et al., 1995; Monaco et al., 1997; Monaco and Tortorici, 2000; Jacques et al., 2001; Ferranti et al., 2007), and satellite geodetic observations (D'Agostino and Selvaggi, 2004; Mattia et al., 2009; Palano et al., 2012).

The southeastern Sicily area (Fig. 1) is characterized by thick Mesozoic to Quaternary carbonate sequences and volcanics forming the emerged foreland of the Siculo-Maghrebian thrust belt (Grasso and Lentini, 1982). This area, mostly constituted by the Hyblean Plateau, is located on the footwall of a large oblique-normal fault system which since the Middle Pleistocene has reactivated the Malta Escarpment (Bianca et al., 1999), a Mesozoic boundary separating the continental domain from the oceanic crust of the Ionian basin (Scandone et al., 1981; Sartori et al., 1991; Hirn et al., 1997). In this area, the vertical component of deformation has been recorded by several orders of Middle-Upper Quaternary marine terraces and paleo-shorelines (Di Grande and Raimondo, 1982; Bianca et al., 1999), which indicate uplift rates of about 0.5 mm/yr during the Late Quaternary (Scicchitano et al., 2008; Dutton et al., 2009). Uplift rates gradually decrease toward the stable areas of the south-eastern corner of Sicily (Antonioli et al., 2006b; Ferranti et al., 2006; Spampinato et al., 2011).

3. Leveling network

For over 120 years the Italian Istituto Geografico Militare (IGM) has repeatedly measured the elevation along the national leveling lines which cover the Italian peninsula (Fig. 2a). The IGM leveling network has been measured with high precision leveling techniques, following the International Geodetic Association standards defined in Oslo in 1948 (Vignal, 1936, 1950) and it is composed by leveling lines over a total length of 14.000 km. Each leveling line is defined by its benchmarks, characterized by the line number and a consecutive identification number. Benchmarks are classified into four categories: category I or nodal benchmark, located at the vertices of the polygon network; category II or fundamental benchmark, located every 25 km along the line; category III or main benchmark, located at the beginning and the end of 5 km long segments; category IV located at a distance of 1 km. For each benchmark there is a monograph where the monographic and numerical data necessary for its finding and for its use are reported. The classification into four categories has only organizational purposes and does not affect the precision, which is uniform for all benchmarks (Muller, 1986).

The leveling is the most accurate method to measure the height difference between consecutive points. To determine the height of a benchmark it is necessary to measure the difference in height between this benchmark and another, whose altitude is known by previous measurements obtained from the fundamental benchmark. The procedure to determine the measurement of the difference of level is called geometric leveling. Depending on the degree of measurement accuracy, the geometric leveling comes classified as technical, precision and high precision. For the study of vertical deformation it is necessary to use the high precision leveling.

The IGM high precision leveling standards, since 1940, require for the measurement campaigns: (a) double leveling between consecutive benchmarks, with maximum allowed discrepancy between forward and backward leveling of $\pm 2.5\sqrt{L}$ mm, where L is the length of the leveled segment, in km, and $L < 4$ km. For $L = 4$ km that amounts to a maximum of 4 mm difference between forward and backward leveling. For a length $L < 50$ km the maximum allowed difference between the forward and backwards operation is limited to 1.5 $L^{3/4}$ mm length, which amounts to a maximum discrepancy of 28 mm for a length of 50 km. For lengths above 50 km the discrepancy is limited to 4 $L^{1/2}$ mm, which for 100 km amounts to 40 mm; (b) equal number of setup for forward and backward measurements; (c) circuit closure with maximum admitted error of $\pm 2.0\sqrt{L}$ mm, where L is the circuit length in km. For a length of 200 km the circuit closure tolerance amounts to 28 mm; (d) instrument calibration before and after each survey; (e) maximum allowed sight length of 50 m; and (f) use of invar rod and rod correction (Salvioni, 1951; Muller, 1986).

The final precision of the geometric leveling is characterized by the probable kilometric error η that is obtained from the compensation of the measurements, through the mean square error of the level difference between two leveled points 1 km apart (Muller, 1986). To this the probable systematic error ζ is added, so the probable total kilometric error γ is defined with $\gamma = \sqrt{\eta^2 + \zeta^2}$. The expected error on the level difference on a line-segment of length L km is $\gamma\sqrt{L}$, according to Vignal (1936) and adopted at the Assembly of the International Geodetic Association in Oslo in 1948 (Bulletine geodesique N° 18, 1950). In that conference a high precision leveling was defined by a kilometric error $\leq$2 mm, and a precision leveling by a kilometric error $\leq$6 mm. For the lines of the Italian high precision network we are using, the value of $\gamma = \pm 0.72$ mm/km is required and guaranteed by the IGM who have carried out the high precision leveling (Salvioni, 1957) for all stations of the leveling network. The absolute levels of the stations were referred in Sicily to the mean sea level in Catania in the year 1965; for the Italian mainland, including the stations we consider for Calabria, they were referred to the mean sea level in Genova in the year 1942.

4. The high precision leveling lines

When leveling data are used for tectonic purposes, it is important to determine the magnitude of systematic and random error and their propagation along a leveling line. Large systematic errors are usually slope-dependent and can be detected by checking the correlation between elevation and elevation change on the analyzed leveling routes. The most important sources of slope-dependent errors are rod calibration and refraction errors (Bomford, 1971). Rod calibration errors are usually detected by using the method proposed by Stein (1981). Refraction errors largely affect leveling data especially when setup length changes occur between repeated surveys (Holdahl, 1981). In Italy, maximum allowed setup length has not changed from 1950 until now, being of 50 m. Moreover, tests performed on our data do not show significant correlations between heights and height changes, which usually indicate the presence of large slope dependent errors (Jackson et al., 1981; Reilinger and Brown, 1981; Stein, 1981). In order to quantify random error propagation, it is important to analyze the original raw height data, but being these not easily accessible in the IGM archive, we are forced to use adjusted heights to define vertical movements. However, D'Anastasio et al. (2006) showed that the use of adjusted heights instead of raw height data does not affect elevation change values.

In theory, the leveling lines give absolute values of height, and the repeated leveling should give absolute vertical rates, if all leveled values are referred to an absolute stable vertical datum. A full control on the consistency of the absolute rates would require the entire network to be available with repeated measurements and to be tied to a stable vertical datum. This information is though not available, as the repeated measurements do not cover the entire network at the same time and on all stations. We prefer to have a conservative estimate of vertical rates, that is to calculate the rates relative to one of the benchmarks of the line. We are therefore not interested in the absolute vertical rates, but in the relative rates along the leveled line. This information is sufficient when investigating the correlation with the local geologic features, as we are not investigating the absolute vertical movement with respect to an external reference frame, as could be sea level or the ellipsoid, but we determine the lateral inhomogeneities of the vertical rate. Therefore, because of the lack of an absolute reference datum, we have conducted the analyses in terms of relative elevation changes. So we have calculated relative vertical rates using the time elapsed between repeated surveys of each line or line section, according to the relationship:

$$\tau_i = \frac{\left(q_i^{t2} - q_i^{t1}\right)}{(t2 - t1)} \quad (1)$$

where q_i^{t2} and q_i^{t1} are the altitudes of the i-th benchmark measured during two measurement surveys. The i-th benchmark elevation is closely linked to the height of the reference benchmark. Taking into account that this height is not measured by method of leveling, and for this reason may be affected by an error, it follows that this error can lead to a constant error along the entire line. To avoid that the error in the measurement of the first benchmark invalids the rate of deformation along the line, in this work we have calculated the rate of deformation of the i-th benchmark relative to the rate of the reference benchmark and applying the following relationship:

$$\tau_i = \frac{\left[\left(q_i^{t2} - q_i^{t1}\right) - q_0^{t2} - q_0^{t1}\right]}{(t2 - t1)} \quad (2)$$

where q_i^{t2}, q_i^{t1}, q_0^{t2}, q_0^{t1} are the altitudes of the i-th benchmark and reference benchmark, respectively, measured during two measurement surveys. This procedure does not affect the analysis of the lateral changes of the calculated rates, but applies only a static shift to the lines. We are therefore sure that the calculated rates are relative to the reference benchmark. If the reference benchmark is uplifting, this value will be added to the entire line. If it is subsiding, this value must be subtracted to the entire line. In either case the lateral changes we are analyzing relatively to the geological features will not be affected and the final results and conclusions will not change. We estimate the standard deviation error on the vertical rate at one benchmark from the equation (Rozsa et al., 2005; Gimenez et al., 2009):

$$\sigma\tau_i = 0.72 * \frac{\sqrt{\Delta l_i}}{t2 - t1}\ \text{mm/yr} \quad (3)$$

With Δl_i the distance to the next leveled benchmark along the line, and assuming that the expected error on nearby benchmarks is independent and of the same order of magnitude, which is taking advantage of the fact that for the lines we are considering the distance between the benchmarks is near to equal.

In order to study the vertical deformation in some areas of eastern Sicily and southern Calabria during the last 40 years, all available high precision leveling lines were analyzed. The major part of lines were only measured once, and are lacking the repetition, and therefore could not be used for the estimate of vertical movements. Three lines had been measured repeatedly and were useful for our purpose: Line 108, Line 92 and Line 100 (Fig. 2b). The last two are very important as they pass through the sites that were chosen for the pylons of the 3 km long single-span bridge crossing the Messina Straits. For each line the elevations and the WGS84 coordinates of the selected benchmarks, have been extracted from IGM monographs. Conversion into kilometric coordinates has allowed to calculate the distance of each benchmark from the reference benchmark. Before proceeding with the calculation of the relative vertical deformation rate, data have been analyzed in order to evaluate if they were suffering by slope-dependent error (D'Anastasio et al., 2006). By plotting the heights of benchmarks (abscissa) with the elevation change (ordinate) (Fig. 3), we observe that there is no linear relationship between the heights and the heights change which normally can indicate the presence of a systematic error related to the slope (Jackson et al., 1981; Reilinger and Brown, 1981; Stein, 1981).

In the following, the main characteristics of each line are summarized.

4.1. Line 108

The Line 108 covers south-eastern Sicily (Fig. 2b) and was measured by IGM for the first time in 1970. It is 148.403 km long and consists of 143 benchmarks; the nodal point from which the line extends is the number #No75, located near the town of Ragusa, whereas the last benchmark (#143) is located in the southern periphery of Catania. In order to determine the relative vertical deformation rate, at least two measurement surveys are required; the benchmarks from #No75 to #106, were measured only once, and were discarded for our purposes. We focused on the line section between the benchmark #107 located near Augusta and the benchmark #143, located in Catania (Fig. 4a). This segment is ∼38 km long and has been measured in two successive surveys, in 1970 and in 1991. By comparing the benchmark heights measured in the two surveys, the total elevation change that occurred in the time interval between 1970 and 1991has been obtained (Fig. 4b). The elevation changes range between −−33 mm and −300 mm, and are much greater than the expected errors on the height differences, which are near to 1 mm, given that the distance between benchmarks is mostly below 2 km.

In order to calculate the vertical deformation rate of each benchmark with respect to the benchmark #107 in the 1970–1991 time interval, the relationship (2) has been applied. In Table 1 the relative rates of vertical deformation (mm/yr) for each benchmark are reported. In order to identify the possible causes of vertical deformation, a schematic geological profile along the line has been carried out (Fig. 4c). Geological data have been obtained from the 1:50.000 scale maps of the Servizio Geologico d'Italia (2009; 2011); and have been reported on a topographic profile drawn from a 2 × 2 m grid digital terrain model (DTM) obtained from Lidar flight (http://www.sitr.regione.sicilia.it/).

4.2. Line 92

The Line 92 covers northern Sicily (Fig. 2b) and was measured by IGM for the first time in 1967. It is 229.43 km long and consists of 221 benchmarks; the nodal point from which the line extends is the number #No68, located near the town of Messina, whereas the last benchmark (#221) is located near the village of Buonfornello. The benchmarks from #18 to #221, measured only once, were discarded. We focused on the line section between the nodal benchmark #No68, located near Messina, and the benchmark #17 (Fig. 5a). This is ∼38 km long and has been measured in three distinct surveys, in 1967, 1986 and 2004.

For this line the three time intervals 1967–1986, 1986–2004 and 1967–2004 have been examined. By comparing the benchmark heights measured in the three surveys, the total elevation change occurred at the considered time intervals has been obtained (Fig. 5b). With respect to line 108 located to the southwards and discussed above, the height differences here are much smaller, between 7 mm and −15 mm, for the longest time interval.

In order to calculate the vertical deformation rate in the 1967–1986, 1986–2004 and 1967–2004 time intervals, the relationship of equation 2 has been applied. The vertical deformation rates (mm/yr) for each benchmark were calculated with respect to the reference benchmark #No68 and are reported in Table 2. For the shortest time interval, less than a decade long, the smaller vertical rates are at the limit of resolution. The three rates, calculated over the two successive intervals and over the entire time interval are perfectly coherent, enforcing the weight of the results. A schematic geological profile along the line (Fig. 5c) allowed us to reconstruct the lithological succession under each benchmark and to identify the possible causes of vertical deformation (geology from Gargano, 1994; topography from a 2 × 2 m grid Lidar flight DTM (http://www.sitr.regione.sicilia.it/)

4.3. Line 100

The Line 100 has been instituted in southern Calabria (Fig. 2b) and measured by IGM for the first time in 1966. It is 134.896 km long and consists of 129 benchmarks; the nodal point from which the line extends is the #No69, located near the town of Reggio Calabria, whereas the last benchmark (#129) is located near the village of Santa Eufemia. The benchmarks from #No69 to #10 and from #33 to #129, measured only once, were discarded. We focused on the line section between the benchmark #11, located near Reggio Calabria, and the benchmark #132P, located near Bagnara Calabra (Fig. 6a), which is ∼24 km long and has been measured in three different surveys, in 1966, 1986 and 2004.

For this line three different time intervals have been studied: 1966–1986, 1986–2004 and 1966–2004. By comparing the benchmarks heights measured in the three surveys, the total elevation change which occurred at the considered time intervals has been obtained (Fig. 6b). The elevation changes range between −40 mm and 8 mm. Again the two consecutive elevation changes and the elevation change over the entire time interval are coherent and significative.

In order to calculate the vertical deformation rate in the time intervals 1966–1986, 1986–2004 and 1966–2004 the relationship (2) has been applied. The vertical deformation rates (mm/yr), for each benchmark, were calculated with respect to the reference benchmark #11. In Table 3 the relative rates of vertical deformation (mm/yr) for each benchmark are reported. A schematic geological profile along the line (Fig. 6c) allowed us to reconstruct the lithological succession under each benchmark and to identify the possible causes of vertical deformation (geology from Atzori et al., 1983; topography from a 2 × 2 m grid Lidar flight DTM, http://www.pcn.minambiente.it/GN/).

5. Data analysis

In this section we discuss, for each analyzed leveling line, the vertical deformation rates obtained by comparison of repeated

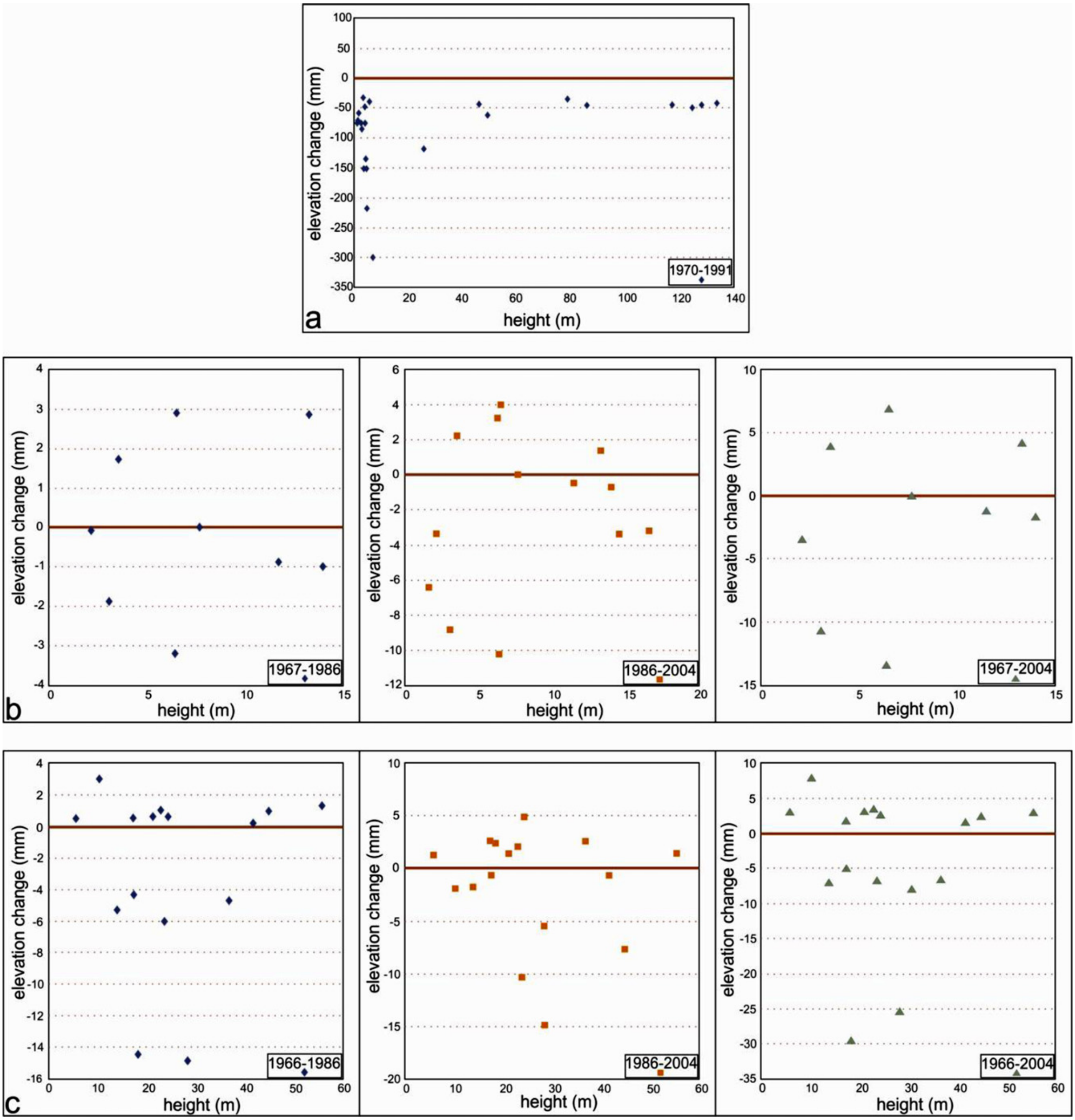

Fig. 3. Heights versus elevation changes plotted in order to verify the occurrence of slope dependent errors along the Line 108 (a) along the Line 92 (b) and along the Line 100 (c).

leveling measurements and the possible sources that caused this deformation.

5.1. *Line 108*

In Fig. 7a, the trend of vertical deformation rates along the Line 108 is shown. This line has by far the greatest elevation change rates, with maximum change rate difference of 12 mm/yr between the two extreme benchmarks. The calculated rates are all significant. By analyzing in detail the vertical deformation along the line, sectors characterized by different rates can be identified (see also Table 1). The section between the benchmarks #111 and #119 is raised in comparison to the reference benchmark (#107) with a relative and constant rate of ~3.5 mm/yr, reaching a peak of 4.0 mm/yr in correspondence of the benchmark #118. Similarly, the section between the benchmarks #120 and #126 shows uplifting, although it is characterized by rates lower than the previous area, with average rates of ~2.0 mm/yr and with a peak of 2.5 mm/yr at the benchmark #126. These different values can be explained by geological features: the benchmarks between #120 and #126 are located on alluvial deposits (Fig. 4c) and may be subject to compaction of unconsolidated sediments, unlike the benchmarks #111 and #119 that are located on more competent lithologies (Fig. 4c). Alternatively, the difference could be related to the Quaternary W-E trending fault located between the benchmarks #119 and #120 (Fig. 4a; Servizio Geologico d'Italia, 2011), whose elastic strain accumulation could give rise to a greater relative uplift (~3.5 mm/yr) of the section between #111 and #119, located on the raised block,

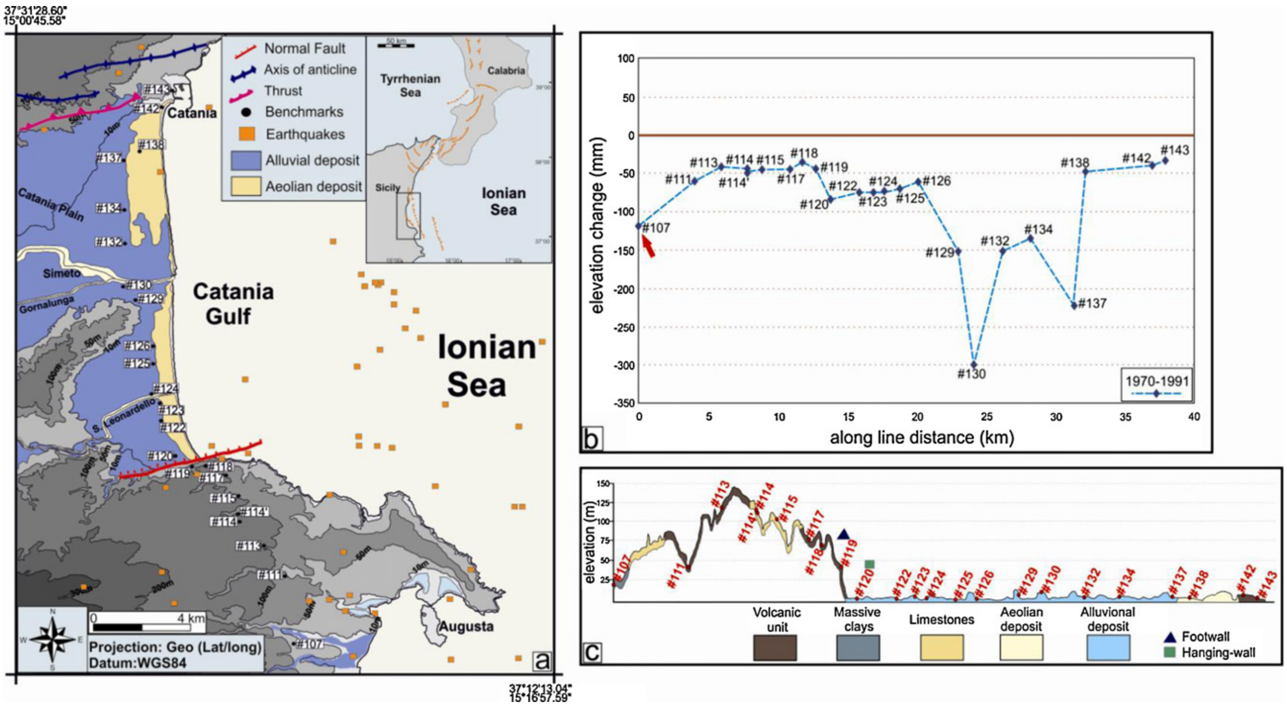

Fig. 4. (a) Benchmarks of the Line 108, located in eastern Sicily between Augusta and Catania, measured in 1970 and 1991. Crustal seismicity of the last 10 years from Gruppo Analisti Dati Sismici, 2012. (b) Elevation change from Augusta to Catania along the Line 108 measured between 1970 and 1991. The arrow shows the reference benchmark. (c) Topographic and lithologic profile along the Line 108. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and a lower relative uplift (~2.0 mm/yr) of the section between #120 and #126, located on the downthrown block. The analysis of crustal seismicity for the last 10 years (Gruppo Analisti Dati Sismici, 2012) shows that the many events are located near the fault, especially along its offshore extension (Fig. 3a). It's worth to note that this structure is mapped as a normal fault in the geological map of Servizio Geologico d'Italia (2011) and previous literature, but recent geological data (Catalano et al., 2006) and ground deformation pattern reconstructed by GPS velocity fields (Mattia et al., 2012) clearly define an area of prevailing contraction along the northern rim of the Hyblean Plateau. This suggest that tectonic inversion could have recently occurred and Pleistocene normal faulting superseded by current contractional activity.

To the north, we observe a local subsidence along the area between the benchmarks #129 and #137 (Fig. 7a; Table 1), with a maximum peak of −8.6 mm/yr in correspondence to the benchmark #130. Taking into account that these benchmarks are located above the recent unconsolidated silt deposits of the Simeto river (Fig. 4c; Servizio Geologico d'Italia, 2009), their subsidence can be related to strong sediment compaction (Fig. 4a). Most

Table 1
Elevation change rate and change rate estimated rms error along the Line 108 for the 1970–1991 time span.

Locality	Line	Benchmark name	Along line distance (km)	Elevation change rate 1970–1991 (mm/yr)	Error 1970–1991 (mm/yr)
Melilli	108	107#	0.000	0.000	±0.00
Augusta	108	111#	4.144	2.767	±0.07
Melilli	108	113#	6.023	3.690	±0.05
Melilli	108	114#	7.909	3.560	±0.05
Melilli	108	114#	7.909	3.367	±0.00
Augusta	108	115#	8.947	3.537	±0.03
Augusta	108	117#	10.969	3.517	±0.05
Augusta	108	118#	11.860	4.010	±0.03
Augusta	108	119#	12.828	3.582	±0.03
Augusta	108	120#	13.906	1.660	±0.04
Augusta	108	122#	16.008	2.105	±0.05
Augusta	108	123#	17.010	2.075	±0.03
Carlentini	108	124#	17.718	2.100	±0.03
Carlentini	108	125#	18.902	2.329	±0.04
Catania	108	126#	20.224	2.793	±0.04
Catania	108	129#	23.087	−1.540	±0.06
Catania	108	130#	24.267	−8.646	±0.04
Catania	108	132#	26.320	−1.558	±0.05
Catania	108	134#	28.296	−0.781	±0.05
Catania	108	137#	31.417	−4.796	±0.06
Catania	108	138#	32.267	3.423	±0.03
Catania	108	142#	37.021	3.780	±0.07
Catania	108	143#	38.061	4.113	±0.04

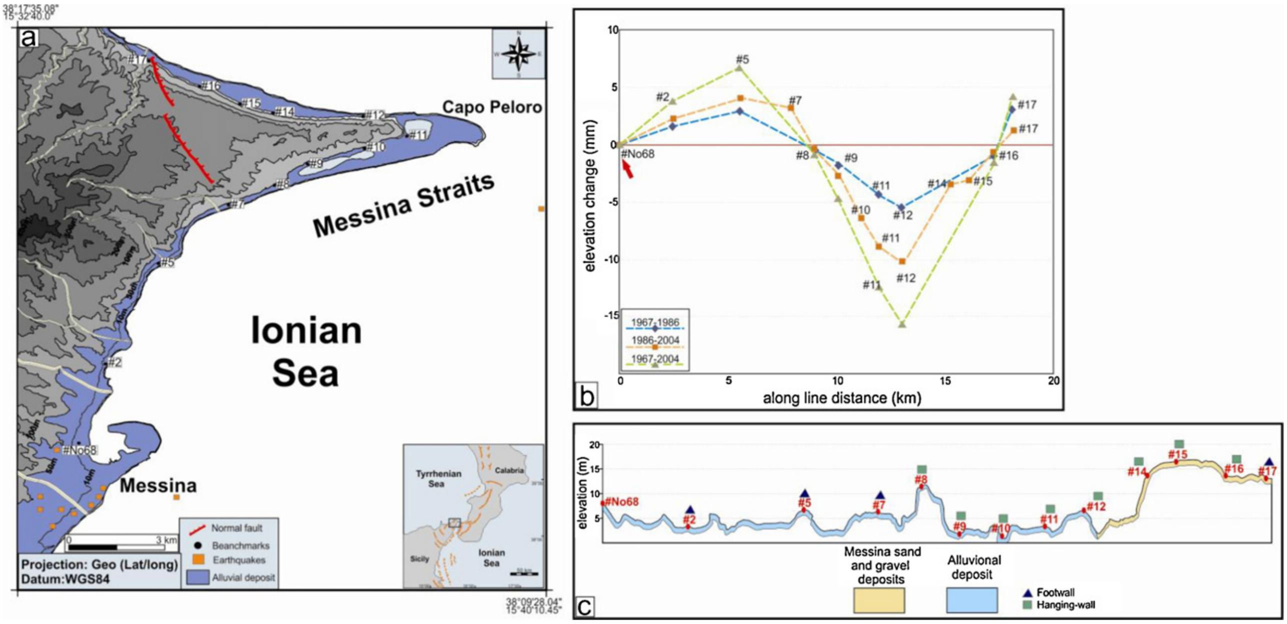

Fig. 5. (a) Benchmarks of the Line 92, located in northeastern Sicily, north of Messina, measured in 1967, 1970, 1986 and 2004. Crustal seismicity of the last 10 years from Gruppo Analisti Dati Sismici, 2012. (b) Elevation change along the Line 92 measured in the periods 1967–1986, 1986–2004, 1967–2004. The arrow shows the reference benchmark. (c) Topographic and lithologic profile along the Line 92. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Elevation change rate and change rate estimated rms error along the Line 92 for the 1967–1986, 1986–2006, 1967–2004 time spans.

Locality	Line	Benchmark name	Along line distance (km)	Elevation change rate 1967–1986 (mm/yr)	Elevation change rate 1986–2004 (mm/yr)	Elevation change rate 1967–2004 (mm/yr)	Error 1967–1986 (mm/yr)	Error 1986–2004 (mm/yr)	Error 1967–2004 (mm/yr)
Messina	92	No68	0.000	0.000	0.000	0.000	±0.00	±0.00	±0.00
Messina	92	002#	2.456	0.089	0.122	0.105	±0.13	±0.06	±0.03
Messina	92	005#	5.625	0.153	0.222	0.186	±0.14	±0.07	±0.03
Messina	92	007#	7.897		0.178			±0.06	
Messina	92	008#	8.831	−0.047	−0.022	−0.035	±0.08	±0.04	±0.02
Messina	92	009#	9.949	−0.105	−0.139	−0.122	±0.08	±0.04	±0.02
Messina	92	010#	11.139		−0.356			±0.04	
Messina	92	011#	12.164	−0.221	−0.472	−0.343	±0.08	±0.04	±0.02
Messina	92	012#	13.173	−0.305	−0.561	−0.430	±0.08	±0.04	±0.02
Messina	92	014#	15.228		−0.189			±0.06	
Messina	92	015#	16.110		−0.178			±0.04	
Messina	92	016#	17.219	−0.053	−0.039	−0.046	±0.09	±0.04	±0.02
Messina	92	017#	18.123	0.150	0.075	0.114	±0.08	±0.04	±0.02

Table 3
Elevation change rate and change rate estimated rms error along the Line 100 for the 1966–1986, 1986–2006, 1966–2004 time spans.

Locality	Line	Benchmark name	Along line distance (km)	Elevation change rate 1966–1986 (mm/yr)	Elevation change rate 1986–2004 (mm/yr)	Elevation change rate 1966–2004 (mm/yr)	Error 1966–1986 (mm/yr)	Error 1986–2004 (mm/yr)	Error 1966–2004 (mm/yr)
RC	100	011#	0.000	0.000	0.000	0.000	±0.00	±0.00	±0.00
VSG	100	014#	3.169	0.315	0.200	0.261	±0.06	±0.07	±0.03
VSG	100	015#	4.307	−0.530	−0.544	−0.537	±0.04	±0.04	±0.02
VSG	100	016#	5.297	−0.090	0.000	−0.047	±0.04	±0.04	±0.02
VSG	100	017#	6.438	0.225	0.111	0.171	±0.04	±0.04	±0.02
VSG	100	018#	7.490	0.245	0.178	0.213	±0.04	±0.04	±0.02
VSG	100	020#	9.812	0.240	0.100	0.174	±0.05	±0.06	±0.03
Scilla	100	022#	12.070	0.240	0.172	0.208	±0.05	±0.06	±0.03
Scilla	100	023#	13.344	−0.020	−0.072	−0.045	±0.04	±0.04	±0.02
Scilla	100	025#	15.457	0.365	0.306	0.337	±0.05	±0.06	±0.03
Scilla	100	026#	16.607	0.245	0.144	0.197	±0.04	±0.04	±0.02
Scilla	100	027#	17.699	0.265	0.167	0.218	±0.04	±0.04	±0.02
Scilla	100	028#	18.758	−0.510	−0.794	−0.645	±0.04	±0.04	±0.02
B Calabra	100	031#	21.859		−0.394			±0.07	
B Calabra	100	032#	23.069	0.265	0.111	0.192	±0.04	±0.04	±0.02
B Calabra	100	032P	23.326	0.280	0.128	0.208	±0.02	±0.02	±0.01

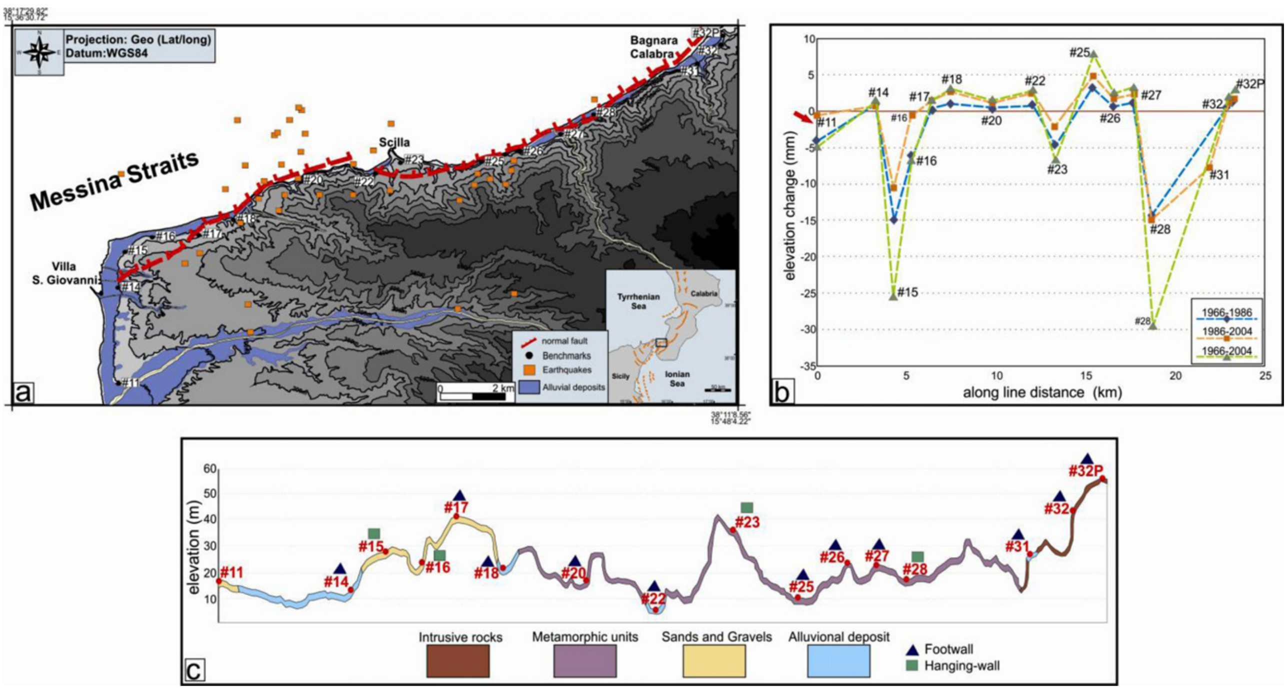

Fig. 6. (a) Benchmarks of the Line 100, located in southwestern Calabria between Villa San Giovanni and Bagnara Calabra, measured in 1966, 1970, 1986 and 2004. Crustal seismicity of the last 10 years from Gruppo Analisti Dati Sismici, 2012. (b) Elevation change along the Line 100 measured in the periods 1966–1986, 1986–2004, 1966–2004. The arrow shows the reference benchmark. (c) Topographic and lithologic profile along the Line 100. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

likely, this subsidence is the main cause of structural failure of the Primosole Bridge on the Simeto River which occurred in 2009. (http://www.blogcatania.it/blog/2009/07/02/ponte-primosole-chiusura-e-disagi/).

Finally, the northernmost section of the Line 108, between the benchmarks #138 and #143, shows uplift in comparison to the reference benchmark with a relative rates of ~4.0 mm/yr (Fig. 7a and Table 1). This deformation may be related to the processes of active folding (Laboume et al., 1990; Bonforte et al., 2011) at the front of the Sicilian chain (Fig. 4a).

5.2. Line 92

Fig. 7b shows the trend of vertical deformation along the Line 92 for the three analyzed time intervals (see also Table 2). The rate change difference between the two extreme values is only 0.8 mm/yr, more than an order of magnitude less than the previous line 108. The three time intervals give coherent change rates which are all significant, except for the smallest values. During the first time interval (1967–1986) a general uplift of the benchmarks #2 and #5, compared with the reference benchmark #68, occurs. The maximum rate of vertical deformation is 0.16 mm/yr at the benchmark #5. Proceeding along the Line 92 we can observe that the section between the benchmark #8 and #16 has undergone subsidence, with a maximum peak at the benchmark #12 (−0.17 mm/yr). Finally, the benchmark #17 has been uplifted in comparison to the benchmark #68 with a rate of 0.15 mm/y.

The trend of vertical deformation during the second time interval (1986–2004) has been similar to that of the first interval, even though different rates were measured (Table 2 and Fig. 7b). Also in the second time interval the section between the benchmarks #2 and #5 shows a general uplift compared with the reference benchmark #68, with rates reaching a peak of 0.22 mm/yr in correspondence of the benchmark #5, whereas the section between the benchmark #8 and #16 shows subsidence, with rates reaching a peak of −0.57 mm/yr in correspondence of benchmark #12. These data confirm the increase of the vertical deformation in the second time interval.

Moreover, we calculated the average rates of vertical deformation for the whole time interval 1967–2004. Fig. 7b shows uplift between the benchmarks #2 and #7 relative to #68, with a 0.19 mm/yr maximum rate (see also Table 1), subsidence between the benchmarks #8 and #16, with −0.36 mm/yr maximum rate in correspondence of benchmark #12, and finally uplift of the benchmark #17 with a rate of 0.12 mm/yr. These data suggest that the trend of the vertical deformation has remained constant.

The observed vertical deformation along the Line 92 can be explained by elastic strain accumulation along the ~N-S oriented normal fault (Fig. 5a) located north of Messina (Gargano, 1994), which has caused uplifting of the area between the benchmarks #2 and #7 and in correspondence of the benchmark #17, that are located on the footwall of the fault, and subsidence of the area between the benchmarks #8 and #16, that is located on the hanging-wall of the same structure.

5.3. Line 100

Fig. 7c shows the trend of the vertical deformation along the Line 100 for the three analyzed time intervals. This line is located on the opposite side of the Messina straits, on the Italian mainland. The rate change difference between the two extreme values is 1.2 mm/yr, an order of magnitude less than the costal line 108. Again the three time intervals give coherent change rates which are all significant, although the smallest values are close to the resolution of the method. The coherence between the results calculated at the three time intervals is excellent, showing that the calculated rates are stable in time. Examining the first time interval (1966–1986), a general uplift relative to the reference benchmark #11 can be observed, except for a few benchmarks that show significant subsidence (see also Table 3). In particular, the benchmark #14 shows uplift with a rate of ~0.27 mm/yr, the benchmarks #15 and #16 show subsidence with rates reaching a minimum value of

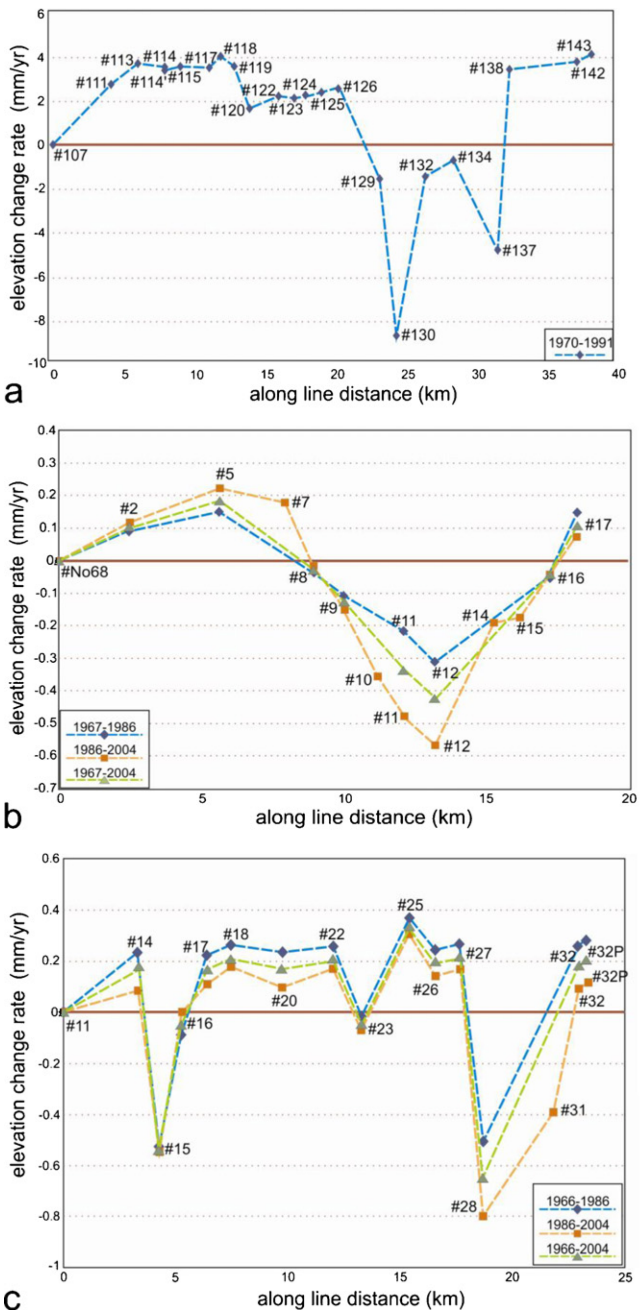

Fig. 7. Elevation change rate versus distance along the Line 108 for the 1970–1991 time span (a), along the Line 92 for the 1967–1986, 1986–2004, 1967–2004 time spans (b) and along the Line 100 for the 1966–1986, 1986–2004, 1966–2004 time spans (c).

−0.53 mm/yr in correspondence of the benchmark #15, the section from #17 to #22 has been uplifted with a constant rate of ~0.24 mm/yr, the benchmark #23 shows subsidence with a rate of −0.02 mm/yr, the section from #25 to #27 has been uplifted with rates up to 0.35 mm/yr in correspondence of the benchmark #25. A significant subsidence is shown by the benchmarks #28–31 that have been lowered at a maximum rate of −0.51 mm/yr in correspondence of the benchmark #28. Finally, the benchmarks #32 and #32P have been uplifted with rates ~0.27 mm/yr.

The trend of the vertical deformation during the second time interval (1986–2004) is similar to that of the first interval even though a change in the rate of deformation is evident (Table 3 and Fig. 7c). In fact, the benchmark #14 shows relative uplift rate of 0.09 mm/yr, the section between the benchmarks #15 and #16 shows subsidence with rate similar to that of the first time interval (−0.54 mm/yr), the section between the benchmarks #17 and #22 has been uplifted with a rate reaching a maximum peak of 0.18 mm/yr in correspondence with the benchmark #18, the benchmark #23 has been lowered with a rate of −0.07 mm/yr, the section #25–27 has been uplifted with rates ranging between 0.14 and 0.30 mm/yr. The strong subsidence of the section #28–31 is confirmed also during the 1986–2004 time interval when a maximum rate of −0.80 mm/yr in correspondence to the benchmark #28 has been calculated. Finally, the benchmarks #32 and #32P have been raised with a lower rate of ~0.10 mm/yr.

Also for this line we calculated the average rates of vertical deformation for the whole time interval 1966–2004 (Table 3 and Fig. 7c). During this period the benchmark #14 shows uplift with a rate of 0.18 mm/yr, the benchmarks #15 and #16 show subsidence with a maximum peak of ~−0.54 mm/yr in correspondence with the benchmark #15, the section from #17 to #22 shows an uplift with maximum values of 0.21 mm/yr in correspondence to the benchmark #18, the benchmark #23 documents a subsidence characterized by a rate of ~−0.05 mm/yr, the section #25–27 shows uplift with rates ranging between 0.2 and 0.34 mm/yr. Finally, the benchmark # 28 shows −0.64 mm/yr average rate of subsidence, whereas the benchmarks #32 and #32P document ~0.2 mm/yr average rate of uplift. We observe that the trend of vertical deformation along the Line 100 has remained constant during the past 40 years, being characterized by alternations of uplift and subsidence relative to the reference benchmark #11.

One possible cause of the vertical deformation along the Line 100 is the occurrence of elastic strain accumulation along active tectonic structures intersecting the line in south-western Calabria. By comparing data obtained from high precision leveling with the trace of the SW-NE striking Scilla normal fault (Ferranti et al., 2007, 2008) along the coast between the towns of Bagnara Calabria and Villa San Giovanni (Fig. 6a), we can observe subsidence and uplift of the benchmarks located on the hanging-wall and on footwall of the fault, respectively. In particular, an excellent correlation between the instrumental data and the geometry of the fault is suggested by the benchmarks #14, #17, #18, #20, #22, #25, #26, #27, #32 and #32P, which indicate uplift at the footwall of the fault, and by the benchmarks #15, #16, #23 and #28, which document subsidence at the hanging-wall of the same structure (Figs. 6a and 7c). The only incompatibility between instrumental and geological data has been observed in correspondence of the benchmark #31, which indicates a subsidence although located on the footwall of the fault. This can explained by the site of the cornerstone #31, that it is located above unconsolidated and saturated alluvial deposits (Fig. 6c) subject to compaction processes.

The recent activity of the Scilla normal fault is confirmed by macro-seismic and palaeo-seismological data (Jacques et al., 2001; Ferranti et al., 2007, 2008) and by the crustal seismicity of the last 10 years (Fig. 6a) (Gruppo Analisti Dati Sismici, 2012; see also Scarfì et al., 2009; Neri et al., 2012).

6. Discussion and conclusions

The analysis of instrumental data obtained by repeated measurements of high precision leveling during the last 40 years allowed us to estimate very recent vertical movements in some sectors of eastern Sicily and southern Calabria (e.g. the Messina Straits). We can summarize the results as follows:

- Line 108 (Fig. 7a), measured in two different campaigns (1970 and 1991) in south-eastern Sicily, shows a general uplift proceeding from south to north with the exception of the area between the benchmarks #129 and #137 which results in subsidence due to compaction of alluvial deposits of the Simeto River. Moreover, major uplift of the section between the benchmarks #111 and #119 with respect to the section between the benchmarks #120 and #126 can be related to elastic strain accumulation along the W-E striking fault separating the Catania Plain from the Hyblean Plateau (Fig. 4a). However, the diffused low-energy seismicity shows that elastic strain accumulation can be released also by small ruptures along this structure.

- Line 92 (Fig. 7b), measured in four distinct surveys (1967, 1970, 1986 and 2004) shows a constant trend of vertical deformation. For the three analyzed time periods (1967–1986, 1986–2004 and 1967–2004), an uplifting sector (benchmarks #2, #5, #7 and #17) can be distinguished from a subsiding area (benchmarks between #8 and #16; Fig. 7b), as a possible consequence of elastic strain accumulation along a N-S striking fault occurring north of the town of Messina (Fig. 5a).
- Line 100 (Fig. 7c), measured in 4 different campaigns (1966, 1970, 1986 and 2004) shows a constant rate of vertical deformation. For the three analyzed time periods (1966–1986, 1986–2004 and 1966–2004) uplifting sectors (benchmarks 14, #17, #18, #20, #22, #25, #26, #27, #32 and #32P) can be distinguished from subsiding ones (benchmarks #15, #16, #23 and #28). This vertical deformation can be related to elastic strain accumulation along the NW-SE striking Scilla normal fault (Fig. 6a). It is interesting to note that Ferranti et al. (2008) estimated a co-seismic throw rate of ~1 mm/yr along this structure during the last 3.5 ka, as effect of two large pre-historic earthquakes. This value is very close to that estimated here by the difference between uplifting and subsiding benchmarks, indicating that over the last 40 yr the strain accumulation is comparable to that coseismically released in the past.

Although the processing of the different time series high precision leveling has allowed us to estimate only the relative rates due to the lack of an absolute reference point, their extreme accuracy, together with the large extension of networks, make this type of measurement fundamental for the estimate of recent vertical deformation. In addition, correlating instrumental and geological data makes it possible to identify active tectonic structures responsible for vertical deformation. Taking into account that it is mostly related to elastic strain accumulation along crustal discontinuities (King et al., 1988; Stein et al., 1988; Yeats et al., 1997; Scholz, 2002), this kind of analysis can provide important clues for the reconstruction of the seismic cycle of seismogenic faults. This proposition has important engineering implications for the planning of the ~3 km long single-span bridge on the Messina Straits.

We show that the active normal faults, identified from geological mapping, have an imprint on the present vertical movements roughly between 0.5 and 1 mm/yr. The vertical movements due to compaction of fluvial sediments are much higher, and reach the value of up to 13 mm/yr relative to the nearby consolidated rock.

Acknowledgements

We thank L. Ferranti ant an anonymous reviewer for their comments that helped to clarify some aspects of the work and M. Mattia for helpful discussions. The research was funded by grants from University of Catania (responsible C. Monaco) and University of Trieste (responsible C. Braitenberg).The leveling data were provided by the Italian Istituto Geografico Militare (IGM) only for scientific purposes.

References

Anderson, H., Jackson, J., 1987. Active tectonics of the Adriatic region. Geophysical Journal of Royal Astronomical Society 91, 937–983.

Anderssohn, J., Wetzel, H.U., Walter, T.R., Motagh, M., Djamour, Y., Kaufmann, H., 2008. Land subsidence pattern controlled by old alpine basement faults in the Kashmar Valley, northeast Iran: results from InSAR and levelling. Geophysical Journal International 174, 287–294, http://dx.doi.org/10.1111/j.1365-246X.2008.03805.x.

Antonioli, F., Kershaw, S., Rust, D., Verrubbi, V., 2003. Holocene sea-level change in Sicily an its implications for tectonic models: new data from the Taormina area, northeast Sicily. Marine Geology 196, 53–71.

Antonioli, F., Ferranti, L., Lambeck, K., Kershaw, S., Verrubbi, V., Dai Pra, G., 2006a. Late Pleistocene to Holocene record of chancing uplift rates in southern Calabria and northeastern Sicily (southern Italy, Central Mediterranean Sea). Tectonophysics 422, 23–40.

Antonioli, F., Kershaw, S., Renda, P., Rust, D., Belluomini, G., Cerasoli, M., Radtke, U., Silenzi, S., 2006b. - Elevation of the last interglacial highstand in Sicily (Italy): a benchmark of coastal tectonics. Quaternary International 145–146, 3–18.

Antonioli, F., Ferranti, L., Fontana, A., Amorosi, A., Bondesan, A., Braitenberg, C., Dutton, A., Fontolan, G., Furlani, S., Lambeck, K., Mastronuzzi, G., Monaco, C., Spada, G., Stocchi, P., 2009. Holocene relative sea-level changes and vertical movements along the Italian and Istrian coastlines. Quaternary International 206, 102–133.

Atzori, P., Ghisetti, F., Pezzino, A., Vezzani, L., 1983. Carta geologica del bordo occidentale dell'Aspromonte. S.E.L.C.A., Firenze.

Bianca, M., Monaco, C., Tortorici, L., Cernobori, L., 1999. Quaternary normal faulting in southeastern Sicily (Italy): a seismic source for the 1693 large earthquake. Geophysical Journal International 139, 370–394.

Bomford, G., 1971. Geodesy. Oxford University Press, New York, 731 pp.

Bonforte, A., Guglielmino, F., Coltelli, M., Ferretti, A., Puglisi, G., 2011. Structural assessment of Mount Etna volcano from Permanent Scatterers analysis. Geochemistry Geophysics Geosystems, 12–22, http://dx.doi.org/10.1029/2010GC003213.

Boschi, E., Ferrari, G., Gasperini, P., Guidoboni, E., Smriglio, G., Valensise, G., 1995. Catalogo dei Forti Terremoti in Italia dal 461 A.C. al 1980. Istituto Nazionale di Geofisica, S.G.A., Roma.

Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G., Gasperini, P., 1997. Catalogo dei forti terremoti in Italia dal 461 a.c. al 1990. Istituto Nazionale di Geofisica, S.G.A., Roma.

Braitenberg, C., Mariani, P., Tunini, L., Grillo, B., Nagy, I., 2011. Vertical crustal motions from differential tide gauge observations and satellite altimetry in southern Italy. Journal of Geodynamics 51, 233–244, http://dx.doi.org/10.1016/j.jog.2010.09.003.

Catalano, S., De Guidi, G., Lanzafame, G., Monaco, C., Torrisi, S., Tortorici, G., Tortorici, L., 2006. Inversione tettonica positiva tardo-quaternaria nel Plateau Ibleo (Sicilia SE). Rend. Società Geologica Italiana, 2, Nuova Serie, 118–120.

D'Agostino, N., Selvaggi, G., 2004. Crustal motion along the Eurasia-Nubia plate boundary in the Calabrian Arc and Sicily and active extension in the Messina Straits from GPS measurements. Journal of Geophysical Research 109, B11402.

D'Anastasio, E., De Martini, P.M., Selvaggi, G., Pantosti, D., Marchioni, A., Maseroli, R., 2006. Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data. Tectonophysics 418, 219–234.

De Guidi, G., Catalano, S., Monaco, C., Tortorici, L., 2003. Morphological evidences of Holocene coseismic deformation in the Taormina area (NE Sicily). Journal of Geodynamics 36, 193–211.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the western Mediterranean. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics. Geological Society London Special Publication 45, London, pp. 265–283.

Di Grande, A., Raimondo, W., 1982. Linee di costa pliopleistoceniche e schema litostratigrafico del Quaternario siracusano. Geologica Romana 21, 279–309.

Drakos, A.G., Stiros, S.C., Kiratzi, A.A., 2001. Fault Parameters of the 1980 (Mw 6.5) Volos, Central Greece, Earthquake from Inversion of Repeated Leveling Data. Bulletin of the Seismological Society of America 91 (6), 1673–1684.

Dutton, A., Scicchitano, G., Monaco, C., Desmarchelier, J.M., Antonioli, F., Lambeck, K., Esat, T.M., Fifield, L.K., Mcculloch, M.T., Mortimer, G., 2009. Uplift rates defined by U-series and 14C ages of serpulid-encrusted speleothems from submerged caves near Siracusa, Sicily (Italy). Quaternary Geochronology 4, 2–10.

Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of the last interglacial sea level highstand along the coast of Italy: tectonic implications. Quaternary International 145–146, 30–54.

Ferranti, L., Monaco, C., Antonioli, F., Maschio, L., Kershaw, S., Verrubbi, V., 2007. The contribution of regional uplift and coseismic slip to the vertical crustal motion in the Messina Straits, Southern Italy: evidence from raised Late Holocene shorelines. Journal of Geophysical Research 112, B06401.

Ferranti, L., Monaco, C., Morelli, D., Antonioli, F., Maschio, L., 2008. Holocene activity of the Scilla Fault, Southern Calabria: Insights from coastal morphological and structural investigations. Tectonophysics 453, 74–93, http://dx.doi.org/10.1016/j.tecto.2007.05.006.

Gargano, C., 1994. Carta Geologica di Messina e del settore nord orientale dei Monti Peloritani (Sicilia NE). S.E.L.C.A., Firenze.

Gasparini, C., Iannacone, G., Scandone, P., Scarpa, R., 1982. Seismotectonics of the Calabrian Arc. Tectonophysics. 82, 267–286.

Gasparini, C., Iannaccone, G., Scarpa, R., 1985. Fault-plane solutions and seismicity of the Italian Peninsula. Tectonophysics 117, 59–78.

Ghisetti, F., Vezzani, L., 1982. The recent deformation mechanisms of the Calabrian Arc. Earth Evolution Sciences 3, 197–206.

Gimenez, J., Boruq, M.J., Gil, A.J., Alfaro, P., Estevez, A., Surincah, E., 2009. Comparison of long-term and short-term uplift rates along an active blind reverse fault zone (Bajo Segura, SE Spain). Studia Geophysica Et Geodaetica 53, 81–98.

Grasso, M., Lentini, F., 1982. Sedimentary and tectonic evolution of the eastern Hyblean Plateau (southeast Sicily) during late cretaceous to quaternary times. Palaeogeography Palaeoclimatology Palaeoecology 39, 261–280.

Gruppo Analisti Dati Sismici, 2012. Catalogo dei terremoti della Sicilia Orientale – Calabria meridionale, 1991–2011. INGV, Catania. <http://www.ct.ingv.it/ufs/analisti/catalogolist.php>.

Grzempowski, P., Badura, J., Cacon, S., Przybylski, B., 2009. Recent vertical movements in the Wroclaw section of the middle Odra fault zone. Acta Geodynamica et Geomaterialia 6 (3), 339–349 (155).

Hirn, A., Nicolich, R., Gallart, J., Laigle, M., Cernobori, L., 1997. ETNASEIS Scientific Group. Roots of Etna volcano in faults of great earthquakes. Earth and Planetary Science Letters 148, 171–191.

Holdahl, S.R., 1981. A model of temperature stratification for correction of levelling refraction. Bulletin Géodésique 55, 231–249.

Howle, J.F., Langbein, J.O., Farrar, C.D., Stuart, K., Wilkinson, S.K., 2003. Deformation near the Casa Diablo geothermal well ¢eld and related processes Long Valley caldera, Eastern California, 1993–2000. Journal of Volcanology and Geothermal Research 127, 365–390.

Jackson, D.D., Lee, W.B., Liu, C., 1981. Height dependent errors in Southern California levelling. In: Simpson, David, W., Richards, P.G. (Eds.), Maurice Ewing series 4, Earthquake Prediction – An International Review. American Geophysical Union, Washington, DC, pp. 457–472.

Jacques, E., Monaco, C., Tapponnier, P., Tortorici, L., Winter, T., 2001. Faulting and earthquake triggering during the 1783 Calabria seismic sequence. Geophysical Journal International 147, 499–516.

King, G.C.P., Stein, R.S., Rundle, J.B., 1988. The growth of geological structures by repeated earthquakes. Journal of Geophysical Research 93, 13307–13318.

Laboume, p., Bousquet, J.C., Lanzafame, G., 1990. Early deformation at a submarine compressive front: the Quaternary Catania foredeep south of Mt. Etna, Sicily, Italy. Tectonophysics 177, 349–366.

Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004. Sea level change along the Italian coast for the past 10,000 y. Quaternary Science Reviews 23, 1567–1598.

Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere. Tectonics 5, 227–245.

Mattia, M., Palano, M., Bruno, V., Cannavò, F., 2009. Crustal motion along the Calabro-Peloritano Arc as imaged by twelve years of measurements on a dense GPS network. Tectonophysics 476, 528–537.

Mattia, M., Bruno, V., Cannavò, F., Palano, M., 2012. Evidences of a contractional pattern along the northern rim of the Hyblean Plateau (Sicily, Italy) from GPS data. Geology Acta 10, 1–9, http://dx.doi.org/10.1344/105000001705.

Miyauchi, T., Dai Pra, G., Sylos Labini, S., 1994. Geochronology of Pleistocene marine terraces and regional tectonics in the Tyrrhenian coast of South Calabria, Italy. Quaternario 7 (1), 17–34.

Monaco, C., Tapponnier, P., Tortorici, L., Gillot, P.Y., 1997. Late Quaternary slip rates on the Acireale-Piedimonte normal faults and tectonic origin of Mt. Etna (Sicily). Earth and Planetary Science Letters 147, 125–139.

Monaco, C., Tortorici, L., 2000. Active faulting in the Calabrian arc and eastern Sicily. Journal of Geodynamics 29, 407–424.

Monaco, C., Antonioli, F., De Guidi, G., Lambeck, K., Tortorici, L., Verrubbi, V., 2004. Tectonic uplift and sea-level change during the Holocene in the Catania Plain (eastern Sicily). Quaternaria Nova 8, 171–185.

Motagh, M., Djamour, Y., Walter, T.R., Wetzel, H.U., Zschau, J., Arabi, S., 2007. Land subsidence in Mashhad Valley, northeast Iran: results from InSAR, levelling and GPS. Geophysical Journal International 168, 518–526, http://dx.doi.org/10.1111/j.1365-246X.2006.03246.x.

Muller, G., 1986. Appunti di Livellazione. Collezione dei Testi Didattici dell'Istituto Geografico Militare, 92 pp.

Neri, G., Barberi, G., Oliva, G., Orecchio, B., 2004. Tectonic stress and seismogenic faulting in the area of the 1908 Messina earthquake, south Italy. Geophysical Research Letters 31, L10602, http://dx.doi.org/10.1029/2004GL019742.

Neri, G., Marotta, A.M., Orecchio, B., Presti, D., Totaro, C., Barzaghi, R., Borghi, A., 2012. How lithospheric subduction changes along the Calabrian Arc in southern Italy: geophysical evidences. International Journal of Earth Science (Geol Rundsch), http://dx.doi.org/10.1007/s00531-012-0762-7.

Ozener H., Dogru A., Acar M., 2012. Determination of the displacements along the Tuzla fault (Aegean region-Turkey): preliminary results from GPS and precise leveling techniques. Journal of Geodynamics. <http://dx.doi.org/10.1016/j.jog.2012.06.00.1>.

Palano, M., Ferranti, L., Mattia, M., Monaco, C., Aloisi, M., Bruno, V., Cannavò, F., Siligato, G., 2012. GPS velocity and strain fields in Sicily and southern Calabria, Italy: updated geodetic constraints on tectonic block interaction in the central Mediterranean. Journal of Geophysical Research 117, B07401, http://dx.doi.org/10.1029/2012JB009254.

Poland, M., Bürgmann, R., Dzurisin, D., Lisowski, M., Masterlark, T., Owen, S., Fink, J., 2006. Constraints on the mechanism of long-term, steady subsidence at Medicine Lake volcano, northern California from GPS, leveling, and InSAR. Journal of Volcanology and Geothermal Research 150, 55–78.

Pondrelli, S., Salimbeni, S., Ekström, G., Morelli, A., Gasperini, P., Vannucci, G., 2006. The Italian CMT dataset from 1977 to the present. Physics of the Earth and Planetary Interiors 159, 286–303.

Postpischl, D., 1985. Catalogo dei terremoti italiani dall'anno 1000 al 1980. In: Consiglio Nazionale Richerche, Progetto Finalizzato Geodinamica. Graficoop, Bologna, 239 p.

Reilinger, R., Brown, L., 1981. Neotectonic deformation, nearsurface movements and systematic errors in U.S. relevelling measurements: implications for earthquake prediction. In: Simpson, D.W., Richards, P.G. (Eds.), Earthquake Prediction: An International Review. Maurice Ewing Ser, vol. 4. AGU, Washington, DC, pp. 422–440.

Rózsa, S., Heck, B., Mayer, M., Seitz, K., Westerhaus, M., Zippelt, K., 2005. Determination of displacements in the upper Rhine graben Area from GPS and leveling data. International Journal of Earth Sciences 94 (4), 538–549.

Salvioni, G., 1951. Manuale di Livellazione. Collezione dei Testi Tecnici dell'Istituto Geografico Militare, Firenze.

Salvioni, G., 1957. I movimenti del suolo nell'Italia centro settentrionale, dati preliminari dedotti dalla comparazione di livellazioni. Bollettino di Geodesia e Scienze Affini XVI (3), 325–366.

Sartori, R., Colalongo, M.L., Gabbianelli, G., Bonazzi, C., Carbone, S., Curzi, P.V., Evangelisti, D., Grasso, M., Lentini, F., Rossi, S., Selli, L., 1991. Note stratigrafiche e tettoniche sul rise di Messina (Ionio nord-occidentale). Giornale di Geologia 53, 49–64.

Sarychikhina, O., Glowacka, E., Mellors, R., Suárez Vidal, F., 2011. Land subsidence in the Cerro Prieto Geothermal Field, Baja California, Mexico, from 1994 to 2005. An integrated analysis of DINSAR, leveling and geological data. Journal of Volcanology and Geothermal Research 204, 76–90.

Servizio Geologico d'Italia, 2009. Carta Geologica d'Italia, Foglio 634 – Catania. Ispra, Roma.

Servizio Geologico d'Italia, 2011. Carta Geologica d'Italia, Foglio 641 – Augusta. Ispra, Roma.

Scandone, P., Patacca, E., Radoicic, R., Ryan, W.B.F., Cita, M.B., Rawson, M., Chezar, H., Miller, E., Mckenzie, J., Rossi, S., 1981. Mesozoic and Cenozoic rocks from Malta Escarpment (Central Mediterranean). AAPG Bulletin 65, 1299–1319.

Scarfì, L., Langer, H., Scaltrito, A., 2009. Seismicity, seismotectonics and crustal velocity structure of the Messina Strait (Italy). Physics of the Earth and Planetary Interiors 177, 65–78.

Scicchitano, G., Antonioli, F., Castagnino Berlinghieri, E.F., Dutton, A., Monaco, C., 2008. Submerged archaeological sites along the Ionian coast of south-eastern Sicily (Italy) and implications with the Holocene relative sea level change. Quaternary Research 70, 26–39.

Scicchitano, G., Spampinato, C.R., Ferranti, L., Antonioli, F., Monaco, C., Capano, M., Lubritto, C., 2011. Uplifted Holocene shorelines at Capo Milazzo (NE Sicily, Italy): Evidence of coseismic and steady-state deformation. Quaternary International 232, 201–213.

Scholz, C.H., 2002. The Mechanics of Earthquakes and Faulting, 2nd edition. Cambridge University Press, Cambridge, New York, Melbourne.

Spampinato, C.R., Costa, B., Di Stefano, A., Monaco, C., Scicchitano, G., 2011. The contribution of tectonics to relative sea-level change during the Holocene in coastal south-eastern Sicily: new data from boreholes. Quaternary International 232, 214–227.

Spampinato, C.R., Scicchitano, G., Ferranti, L., Monaco, C., 2012. Raised Holocene paleoshorelines along the Capo Schisò coast, Taormina: new evidence of recent coseismic deformation in northeastern Sicily (Italy). Journal of Geodynamics 55, 18–31.

Stein, R.S., King, G.C.P., Rundle, J.B., 1988. The growth of geological structures by repeated earthquakes. Field examples of continental dip-slip faults. Journal of Geophysical Research 93, 13319–13331.

Stein, R., 1981. Discrimination of tectonic displacement from slope dependent errors in geodetic levelling from Southern California, 1953–1979. In: Simpson, David, W., Richards, P.G. (Eds.), Earthquake prediction, An International Review. Maurice Ewing series 4. American Geophysical Union, Washington, DC, pp. 441–456.

Stewart, I., Cundy, A., Kershaw, S., Firth, C., 1997. Holocene coastal uplift in the Taormina area, north-eastern Sicily: implications for the southern prolongation of the Calabrian seismogenic belt. Journal of Geodynamics 24, 37–50.

Tortorici, L., Monaco, C., Tansi, C., Cocina, O., 1995. Recent and active tectonics in the Calabrian Arc (Southern Italy). Tectonophysics 243, 37–49.

Vignal, J., 1936. Evaluation de la précision d'une méthode de nivellement. Bulletin Géodésique 18, 401–565.

Vignal, J., 1950. Comptes rendus des séances de travail de la Secion II. Nivellements, de l'Assocation Internationale de Géodésie à l'Assemblée Générale d'Oslo (Aout 1948). Bulletin Géodésique 49, 1–159.

Westaway, R., 1993. Quaternary uplift of southern Italy. Journal of Geophysical Research 98, 21, 741-21, 772.

Yeats R. S., Sieh K., Allen C.R., 1997. The geology of earthquakes. Oxford University Press, USA.