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EARTH'S GRAVITY FIELD AND EARTH SCIENCES

The state of the art of gravimetry in Italy

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Abstract

Relative and absolute gravimetric measurements are carried out for metrological, geodetic and geophysical (structural and dynamic) studies. Gravimetry is largely used in Italy since long time for vast set of studies. Both relative and absolute measurements are carried out in several fields of geodesy, geophysics and geodynamic with different approaches. After a brief historical excursus, the paper presents the state of the art of "Modern" gravimetry in Italy in its various applications, together the main available results and products, with particular attention to:

- Development of modern gravimetry in Italy: from relative to absolute measurements.
- Italian reference gravity networks: state of the art
- The Italian gravimetric map: its evolution over time, data, the present-day status and related products.
- Dynamic gravimetry: examples of applications in geodynamical areas.

Finally, suggestions for future perspectives for gravimetry in Italy are outlined.

Keywords Gravimetry · Gravity reference networks · Bouguer maps · Dynamic gravimetry

1 Introduction

Relative and absolute gravity measurements are carried out for metrological, geodetic and geophysical (structural and dynamic) studies.

Relative measurements are the most common approach to determine underground mass distribution due to geological structures (i.e. gravity prospecting), or time–space gravity variations due to mass displacement such as those occurring in geodynamical areas. In each case, relative measurements, or repeated gravity measurements, are generally carried out at benchmarks on networks. The main advantage of the relative measurements is that they can be performed almost anywhere, but they can be affected over the long time by changes of instrumental sensitivity and loss of vacuum in the airtight sealing system. Therefore, a good instrumental calibration is strongly required; the instruments must be subject to continuous check on stable calibration lines and returned to the Manufacturer for periodic controls and maintenance. Moreover, to reach high precisions, relative measurements require special operative procedures (e.g. Berrino et al. 2015). Those imply long-time surveys that are consequently spaced out some months or years; a further disadvantage of the repeated relative gravity measurements is the lack of information about the rate and/or quick changes, since gravity variations are assumed linearly changing over the time between two consecutive surveys.

Absolute measurements are generally carried out for metrological studies and to establish long-term stable reference points, or networks, for relative measurements and calibration lines for relative gravimeters. The development, since second half of the twentieth Century, of portable ballistic absolute gravimeters, that permit measures with an accuracy at the μGal[1] level, has brought a great metrological advance. They have provided the possibility of realizing networks of absolute stations, even if in like-laboratory sites, and

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repeated measurements aimed at geophysical/geodynamical studies. Nowadays, the availability of a portable field absolute gravimeter, that permits faster and easier operations also in laboratory, allows to carry out much frequent measurements and the realization of dense networks of points, positioned also in not accessible areas by laboratory instruments. Finally, the recent realization of a portable absolute quantum gravimeter, permitting both indoor and outdoor measurements and the continuous monitoring of temporal gravity variations, has given further development to absolute gravimetry.

The main advantages of the absolute measurements are that they are firstly independent of any reference and are directly linked to standards of time and length; therefore, they are fairly independent of instrumental references and instrumental drift. This avoids loss of long-term information. The absolute value of gravity can be used without loop reductions, post processing and benchmark links. All this can be translated into great advantages, such as saving of human resources, survey's time and costs. The disadvantage of absolute measurements, also if the portable field instrument is used, is that they can be carried out only in accessible areas by the vehicle carrying the instrumentation and are influenced more than the relative measurements by local noise and above all by anthropogenic noise.

Gravimetry, in its variety of applications, is largely used in Italy since long time. Both relative and absolute measurements are carried out in several fields with different approaches. They are mainly aimed to study the general structural setting of Italy, also detailing regions of particular interest, through the interpretation of the Bouguer anomalies, and in active volcanic areas to detect through periodically repeated measurements the underground mass redistribution and magma injections. These aspects will be detailed below.

In Italy, first absolute gravimetric measurements with pendulums started in 1825, carried out by Jean-Baptiste Biot and his son Edouard-Constant in Milano, Padova, Fiume and Lipari. Later from 1871 to 1935, about 600 measurements were carried out. They may be divided into three groups according to pendulum development and precision achieved: (1) 1871–1909: 256 measurements, with very high error; (2) 1912–1926: 48 measures whose precision increased while remaining low; (3) 1926–1935: 393 measurements with "higher" precision (± 2–2.5 mGal[1]). They include measurements carried out by Gino Cassinis in 1912 (Genova, Arcetri, Roma), 1919 (Napoli and Palermo), 1923 (Bologna and Roma) and during submarine cruises in 1931 (83 stations) and 1935 (58 stations extended to the Aegean Sea). These data contributed, though with limited precision, to create a first Bouguer anomaly map (Cassinis and de Pisa 1935) of the Italian territory delineating the first structural characters of the Italian gravimetric framework that will be definitively detailed only after decades.

In fact, the modern gravimetry begins in 1940 when Gino Cassinis, at that time President of the Italian Geodetic Commission (IGC), established the "Gravimetry Section", that first decided to create an Italian Gravity Map for the development of Earth Sciences. This was possible by the contemporary development and availability in Italy of modern relative gravimeters that allowed rapid and precise measurement with root mean square (rms) of the order of about 10 μGal.

However, the real development of gravimetry is due to Carlo Morelli, especially since he founded the Osservatorio Geofisico Sperimentale (OGS) in Trieste. Morelli's greatest merit was not only to start international cooperations and projects, but also:

- to perform and promote since 1940s numerous gravimetric surveys on-land and at sea practically covering the whole Italian territory and also contributing to gravimetric maps of Italy aimed at geological-structural purposes;
- to identify, in late 1940s, the notable bias (about 14 mGal) (Morelli 1948, 1951) affecting the Potsdam value considered at that time the reference system and also used as reference value for the Italian gravity surveys; consequently he proposed the realization of the first Italian gravity reference net to have Italian reference values also useful to standardize the various regional surveys;
- to promote absolute gravity measures of new conception in Italy and Europe and to contribute to the development of a standardized worldwide reference gravimetric network, called International Gravity Standardization Net 1971 (IGSN71), officially adopted by the scientific community until today.

Since 1950s, considerable progresses were made for sea measurements due to the development and transformation of appropriately modified land relative gravimeters. The IGC with the contribution of the Consiglio Nazionale delle Ricerche (CNR) commissioned a sea-bottom gravity survey carried out from 1953 to 1960 (Ciani et al. 1960). 3135 stations, positioned on the sea bottom up to a depth of 222 m, were surveyed in the seas around continental Italy and Sicily; the final Bouguer anomalies, computed including also some stations located on-land along the coastline, were represented in 11 maps at 1:200,000 scale and 2 mGal contour lines. The survey was carried out mainly to extend to the sea portion the on-land First Order Italian Gravimetric Survey

[1] Note: In the SI system, the unit of gravity is ms^{-2}. In geodesy and geophysics the use the auxiliary units mGal and μGal, derived from the unit Gal (1 Gal = 1 cm s^{-2}), is still accepted: 1 mGal = 10^{-3} Gal/10^{-5} ms^{-2}; 1 μGal = 10^{-6} Gal/10^{-8} ms^{-2}.

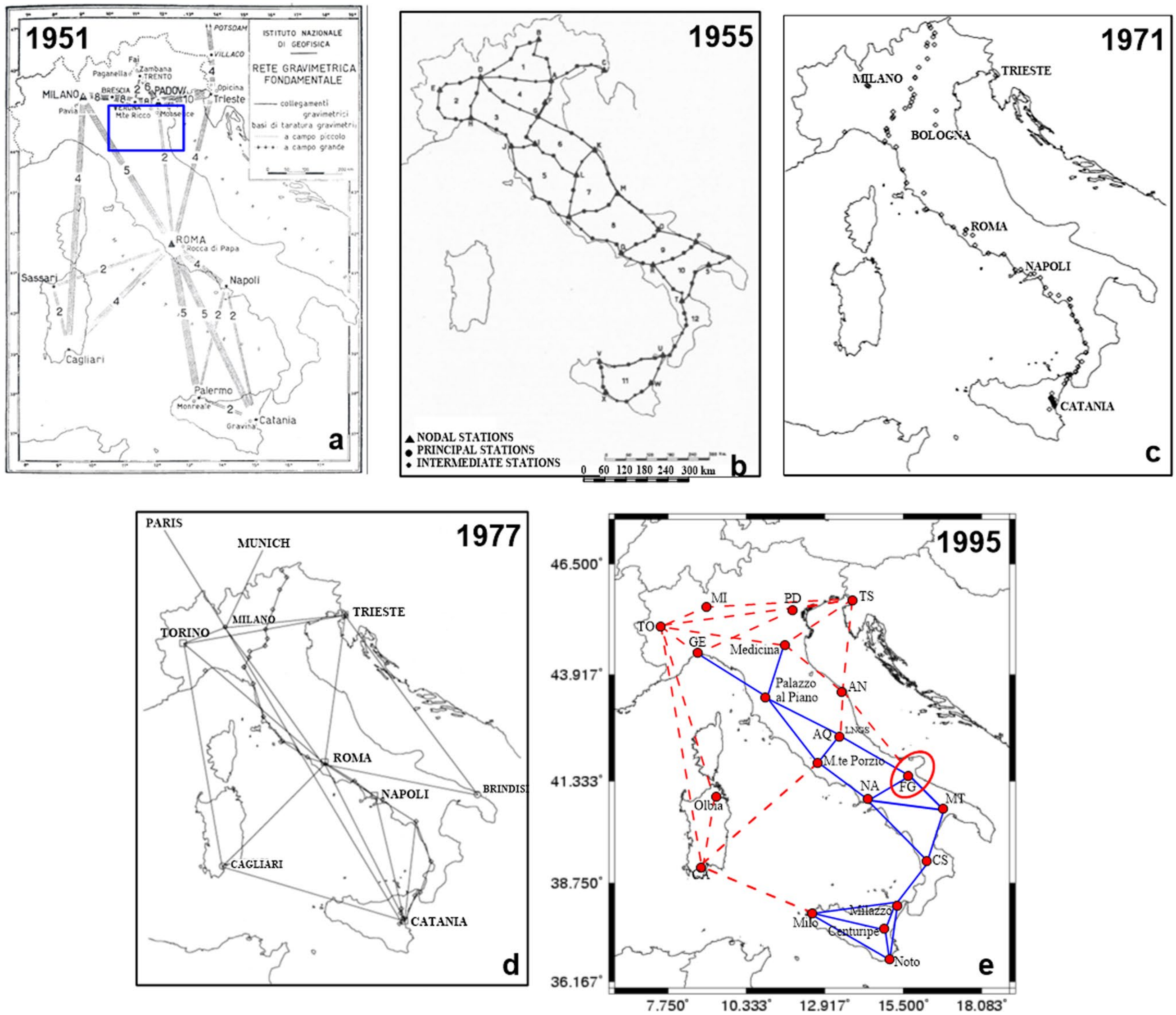

Fig. 1 The gravity reference networks (slightly modified) realized in Italy from 1951 to 1995 (see text for details and References).The blue square in **a** and the red ellipse in **e,** respectively, indicate where the 1952 "Bologna–Ferrara" and the 1988 "Troia–Foggia–Mattinata" Italian calibration lines are located

referred to the 1955 Fundamental Italian Gravity Network (Cunietti and Inghilleri 1955), later discussed.

2 The reference gravity networks in Italy: development and state of the art

A reference gravity network is firstly useful to standardize many independent surveys and homogenize Bouguer's maps at wide area. Its time evolution depends not only on technological evolution of instrumentation. It is particularly important in country like Italy where geodynamic activity is very intense, generating sometimes and somewhere significant long- and short-term time–space gravity changes. Mainly for this reason, but also to be integrated into a standardized worldwide reference system, the Italian gravity reference network has undergone a series of developments over the years.

In 1951 started a preliminary contribution for the first Italian gravity reference network (later realized in 1955 and called "Fundamental Italian Gravity Network") (Morelli 1952, Fig. 1a). Nine base stations were set up; relative measurements were collected with two Worden gravimeters (No. 50 and 52), and connections between the base stations were carried out by flights of civil airlines, as indicated in Fig. 1a. Two links with the stations in Padua (i.e. Padua-Milan, divided in 4 sections, and Padua-Trieste), lacking a flight connection or because the sites were very close, were carried out by car. In addition, several secondary stations (also shown in Fig. 1a), eight of which in the airports, were also established (details are given in Morelli 1952). The reference station was positioned in Padua, the absolute value of which (980 658.55 ± 0.35 mGal) was obtained by links with the Potsdam absolute station (Morelli 1951, 1952). These measures, carried out during European field survey aimed both to calibrate the two gravimeters and to make a first contribution to a European gravimetric network, together with new absolute measures subsequently connected to Potsdam, indicated that the Potsdam value was most likely affected by a noteworthy error (Morelli 1951). This error was not accounted to comply with the decision of the General Assembly of the International Association of Geodesy (IAG) (London 1912), that indicated to base all the measures on the absolute value of Potsdam. Only later in 1967, both IAG, during the General Assembly, and the International Committee for Weights and Measures (CIPM) adopted a resolution for a correction of—14 mGal to the values of gravity in the Potsdam datum to be used for metrological purposes.

In 1952, the IGC commissioned the establishment of a calibration line, the "Bologna–Ferrara" line (in the blue square in Fig. 1a), to calibrate and periodically check the scale constants of relative gravimeters used for the realization of the projected Fundamental Italian Gravity Network (Morelli 1952). This line is formed by five stations, with Δg between 30 and 50 ± 0.01 mGal, and is characterized by short distance among stations (ranging from 7 to 15 km, Cunietti and Inghilleri 1955), almost zero height differences and a total gravity difference (i.e., the sum of the individual gravity differences between two intermediate stations) of about 161 mGal. Measurements were carried out with the two Worden gravimeters already used in 1951 and the absolute values reported at each station are referred to the Potsdam system.

The first Fundamental Italian Gravity Network (named "RFI55", Cunietti and Inghilleri 1955) was realized in 1955 (Fig. 1b). It is known as the "Cunietti and Inghilleri" network and consists of 119 stations equally distributed over the Italian territory, along 11 polygons, 10 of which on the Peninsula and 1 in Sicily linked to the peninsular network through a connection with Calabria. The stations are divided into 24 nodals (corresponding to the vertices of the polygons), 44 principals (internal to the polygons and connected with independent direct measurements) and 51 intermediates (placed at the center of the connections each more than 60 km long. Relative measurements were carried out from 1952 to 1953 using three gravimeters (Worden n.53, Western G.A. n.48 and North American n.125). Even if the network includes 7 vertices of the previous wide-mesh network (Morelli 1951), for any checks, to make it independent from any previous absolute or relative measurement, only the gravity differences between pairs of stations and those calculated respect to the fundamental station in Rome were considered (Cunietti and Inghilleri 1955).

In 1971, Italy contributed to realize a worldwide reference network, also to standardize the Italian Reference Systems. The 1971 International Gravity Standardization Network (IGSN71) was based on measurements collected in the previous 20 years integrated with 50 absolute measurements performed with 6 Pendulum and at 11 stations with 3 modern ballistic gravimeters (Cook, Sakuma and Faller–Hammond apparatus) (e.g., Sakuma 1966; Cook 1965; Faller and Hammond 1970). In IGSN71 Potsdam value (and so all gravity values linked to it) was corrected to −14 mGal, corresponding to the bias identified by Morelli (1948) and confirmed by numerous gravimetric links all over the world. The Italian part realized by OGS consisted of stations of the European calibration line "Hannover–Catania" combined with many stations in Rome, Milan and Trieste, the Bologna and Ferrara stations (extremes of the calibration line), and 8 stations of the RFI55 (Morelli et al. 1974a, b—Fig. 1c modified by Marson and Palmieri 1994).

The Italian Reference Network development was favored by the realization in the early 1970s of a transportable absolute ballistic gravimeter, studied, designed and built by the Istituto di Metrologia "Gustavo Colonnetti" (IMGC) of CNR in Turin (presently Istituto Nazionale per la Ricerca Metrologia—INRiM) (e.g. Alasia et al. 1982). This instrument opened a new gravimetric era in Italy. The first measurements were carried out in 1976–1977 in Europe (Cannizzo et al. 1978) to improve the world gravity standard (IGSN71) with new absolute references (IAG Resolution No. 16—1975). In this time interval, IMGC established 17 stations, four of them in Italy contributed to the realization in 1977 of the "First Order Gravity Net in Italy" (FOGN77) (Marson and Morelli 1977). FOGN77 was formed by 49 base stations (10 of which as main), six of which are absolute ones measured with IMGC gravimeter (Fig. 1d). 758 relative links were carried out with five LaCoste and Romberg (LCR) models G (no. 24, 115, 116 and 171) and D (no. 18) gravimeters. From then on, the IMGC gravimeter has undergone a series of developments and improvements, as well as a reduction in size, up to the current IMGC-02 (e.g. D'Agostino et al. 2008) and contributed to realize numerous absolute stations over the Italian territory aimed at several purposes: metrological, geodetic, geophysical, geodynamical. During the International Comparison of Absolute Gravimeters 2005 (ICAG-05), carried out in the framework of the Mutual Recognition Arrangement (MRA) of the CIPM, the IMGC-02 was officially recognized as the instrument "National Primary Standard" in Italy (D'Agostino et al. 2007).

Thanks to the availability of the IMGC transportable absolute gravimeter and the financial support of CNR, starting from 1988 the Osservatorio Vesuviano (OV), in co-operation with the University of Naples and the IMGC, established three absolute stations in Apulia (Troia, Foggia and Mattinata—in the red ellipse in Fig. 1e, see also Figs. 5 and 6) (Berrino 1995, monographs therein). They represented the starting point for a new calibration line for relative gravimeters, based on direct absolute measurements, to replace the Bologna–Ferrara line because of time gravity changes at some intermediate stations (Gantar and Morelli 1959).

Moreover, since 1988, several absolute stations were also established on active volcanic areas of southern Italy, at the reference stations (for example, Naples for Neapolitan volcanoes and Milazzo for the Aeolian networks) and in correspondence of some selected stations of the existing local monitoring relative gravity networks. The absolute stations were also periodically re-measured to check stability of the references and to confirm the gravity changes obtained by relative measurements (e.g., Berrino 2000; D'Agostino et al. 2008; Greco et al. 2012; Berrino et al. 2013, 2015).

The availability of new and numerous absolute stations in Italy up to 1994, and the necessity to periodically update the existing ones, suggested to realize in 1995 a new Italian Reference Network called "Italian Zero Order Gravity Net" IZOGN_1995 (Berrino et al. 1995—Fig. 1e), after a preliminary mathematical network optimization (Benciolini and Crespi 1993). The new network is composed of 20 absolute stations selected among those measured from 1976 to 1994 linked through relative measurements; moreover, the implementation of additional three new stations was also scheduled. The links among the absolute stations were carried out with four LCR model G gravimeters used simultaneously. Measurements were made at a fixed height close or corresponding to those of the absolute measures (about 80 cm). Unfortunately, the network was not completed on Northern Italy and Sardinia (ref. Fig. 1e, where the dotted red lines indicate the planned links not measured), mainly for lack of additional funds.

3 Gravity maps of Italy: development and state of the art

The Gravity Subcommission of IGC drafted a first Project for a Gravimetric Map of Italy in 1952, so that many gravity surveys were carried out from 1953 to 1963. 3560 on-land and 3453 offshore stations (depth up to 222 m) with reference to the RFI55 Fundamental Network were measured. On-land measurements were collected along the levelling lines, surveyed until that time by Istituto Geografico Militare Italiano (IGMI), and were acquired by several University (Milan, Bologna, Padua, Cagliari), Government and Research Institutes (IGMI, Istituto Nazionale di Geofisica—ING, OGS, Servizio Geologico d'Italia—SGI, Istituto Idrografico della Marina—IIM), with Worden and Western gravimeters. The sea-bottom stations were surveyed from 1953 to 1961 by OGS with modified Western gravimeters remotely controlled by the boat. Detailed information about instrument modifications, the remote control system together with a scheme, and field operative procedures are given in Ciani et al. (1960).

All the previously described Reference Networks constituted the useful base for the realization of the Italian Gravity map and its upgrading.

The first edition of the Bouguer gravity map was published in 1963 and was realized using only a part of the data set, precisely 2639 on-land and 448 offshore sea-bottom stations. The map, computed with variable density from an Italian density map [at the scale of 1:1,000,000 drawn by Vecchia (1955)], was represented at the scale of 1:2,000,000 and 10 mGal contour interval; it was presented at the 13° General Assembly of IUGG at Berkeley in 1963 (Ballarin 1963).

A new Bouguer gravity map of Italy was constructed in 1975 using all the available 3560 on-land and 3453 offshore sea-bottom stations, integrated by sea-surface measurements carried out since 1964 by OGS throughout Adriatic and Thyrrenian Sea, between Corsica and Sardinia up to Gibraltar (Morelli 1975, 1994). Sea surface data were reduced with a constant density value of 2670 kg/m^3. The new and complete 1975 map was the first to be superimposed to a structural model of Italy by CNR (Ogniben et al. 1975) and represented at the scale of 1:1,000,000; it was the first to furnish information concerning the structural setting of Italy. From it, some maps of the Moho discontinuity morphology were also produced. The first, published by Giese and Morelli (1972), was calculated integrating gravity and seismic data. Later, Corrado and Rapolla (1981) processed the 1975 gravimetric map through a series of filtering obtaining the morphologies of the Moho discontinuity and of the top of the crystalline basement in Central-Southern Italy.

In 1977, the Italian Geodetic Commission was suppressed and from 1980 Geodesy was included in the National Group of Geophysics of the Solid Earth (GNGTS) of CNR, that planned to realize a new structural model of Italy and a new gravimetric map. So that in 1986, a new Gravity Map of Italy was created as a task of the "Progetto Finalizzato Geodinamica" of CNR (Sub-Project Three-dimensional Structural Model), and published in 1991 (CNR-PFG 1991; Morelli 1994). The new map was drawn using all the data available at 1986, with the addition of about 270,000 stations, collected from 1978 to 1983 by ENI-AGIP (Cassano 1983), for a total of about 300,000 stations, referring all data to the IGSN71 Reference System. A constant density value of 2400 kg/m^3 was used for the computation of the Bouguer anomalies (Carrozzo et al. 1981). The map was represented on three sheets at the scale of 1:500,000 and 5 mGal contour interval.

The SGI was in charge to collect and homogenize all gravity data in Italy to compile a new map extended over the entire national territory. Therefore, in 1989, SGI, together with ENI-AGIP, published a new gravity map of Italy (SGI 1989), using 234,100 ground stations provided by AGIP, SGI and several universities, institutions and private companies, and 6200 sea-bottom stations provided by AGIP. In this new map, Bouguer anomalies, calculated with a density of 2670 kg/m^3, were represented at the scale of 1:1,000,000 with a contour interval of 10 mGal. At the same time, in 1990s, SGI started a program for land cartography at the scale of 1:50,000 to unify gravimetric maps to the geological ones, in the framework of the new Italian Geological Mapping program (CARG Project—CARtografia Geologica). A committee of the Italian Geophysical Community drafted a guideline for the procedures to follow for the new Italian Gravity Map, including specific reduction formulas and suggesting the use of a constant nominal density of 2670 kg/m^3.

In 1999, SGI falls in the Agency for Environmental Protection and Technical Services (APAT) (ISPRA website[2]). In 2005, SGI-APAT realized a new gravimetric map of Italy and its surrounding seas recalculating all the available land and marine data extracted by the database of the presently National Institute for Environmental Protection and Research (ISPRA) created in 2008 to combine several Institutes in an unique Agency. The suggested procedures were followed using a constant density value of 2670 kg/m^3. The gridded database was produced interpolating the final homogeneous dataset on a regular grid spaced 1 km; the resulting Bouguer anomaly map was represented at the scale of 1:1,250,000 as a shaded relief in color (APAT 2005).

One of the most important products from recent terrestrial gravimetry is the new Italian Geoid determination carried out by the actual Department of Civil and Environmental Engineering of the Polytechnic of Milan and serviced by the International Service for the Geoid (ISG, previously International Geoid Service, an official Service of the IAG). The project, named ITALGEO[3] (Barzaghi 2010) has produced from 1990 to 2005 several versions (ITALGEO83, ITALGEO90, ITALGEO95, ITALGEO99, ITALGEO05) of Italian Quasi-Geoid. The called Italian Quasi-Geoid used land and marine gravity data integrated with GPS/leveling data.

Finally, since 2008, ISPRA has been realizing the Digital Gravity Map of Italy (ISPRA et al. 2009—Fig. 3c–e). This project is the result of a co-operation among ISPRA, OGS and ENI (in origin Ente Nazionale Idrocarburi); it is aimed to provide a representation of the gravimetric field to define, at regional scale, the deep geological-structural pattern. It also aspires to cover the existing empty areas in the current official gravimetric cartography. It seeks to make available to the scientific community the official SGI's geophysical maps (gravimetric and aeromagnetic published only in paper format) at various scales by means of their digitization and georeferencing and the vectorization of the Bouguer anomalies. The original maps, the anomaly contours and the stations position are available.

The Italian territory and surrounding seas are divided into 39 digital Maps (Fig. 2—black rectangles) at 1:250,000 scale, as in use in different European countries for similar projects. 368,393 gravity values, 4000 of which are grid nodes of foreign land areas, were used for the compilation (Fig. 2—blue points and lines). The observed gravity data, hosted in a geographic database, have been all tidied, reprocessed and referred to IGSN71; the Bouguer Anomalies were computed with a constant density value of 2670 kg/m^3 (ISPRA et al. 2009). Final data have been interpolated on a regular grid of 1 km spacing. A cartographic database has been created including, for each of the 39 sheets, identification and position of the stations, Bouguer Anomalies, presented as both raster (color maps) and vector (contour interval 2 mGal) data and grids (1 km cell dimension;.grd Surfer format). Maps and coordinates of the stations are georeferenced in the Reference System WGS84 and are provided in WGS84-UTM zones 32 N and 33 N. Details are available through the ISPRA website.[4],[5]

4 Application of dynamic gravimetry in Central-Southern Italian geodynamical areas

The development of relative gravimeters permitted the application of high precise gravity measurements for studying geodynamical areas. In Italy, this kind of application systematically started at the beginning of 1980s on some active volcanic areas of Southern Italy. Starting from 1981, periodically field surveys are carried out on dense networks of gravimetric benchmarks realized in the following areas:

- the Neapolitan volcanoes, i.e., Campi Flegrei, Vesuvius and Ischia (Fig. 3a) (e.g., Berrino 1994; Pingue et al. 2000; Berrino et al. 2013). Permanent gravity stations

[2] https://www.isprambiente.gov.it/en/environmental-services/the-geological-survey-of-italy/the-history-of-the-geological-survey-of-italy.

[3] https://www.isgeoid.polimi.it.

[4] https://www.isprambiente.gov.it/en/projects/soil-and-territory/digital-gravity-maps-of-italy.

[5] https://www.sinanet.isprambiente.it/it/sia-ispra/download-mais/cartografia-gravimetrica-digitale.

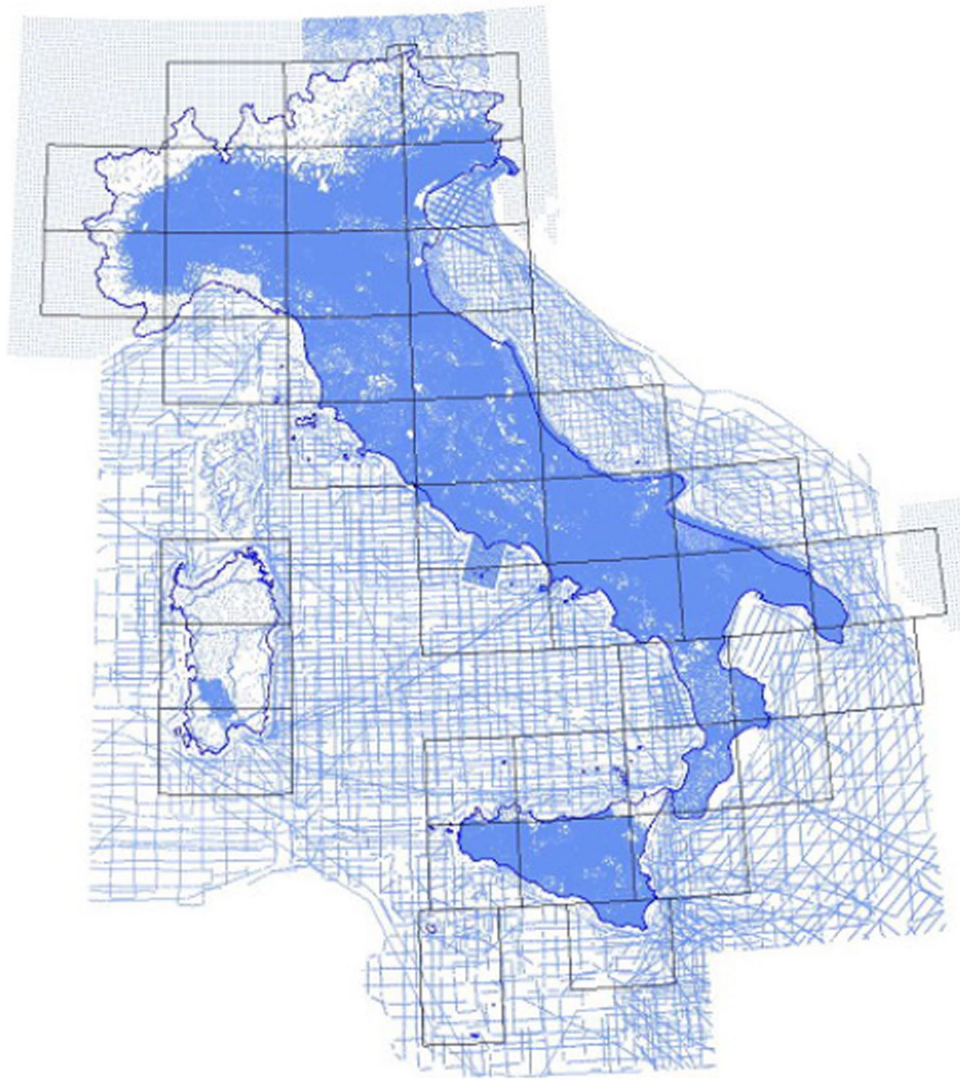

Fig. 2 Up-to-day distribution of the on-land and offshore gravity stations available for present-day Italian digital Bouguer gravity map (slightly modified from ISPRA website https://www.isprambiente.gov.it/en/projects/soil-and-territory/digital-gravity-maps-of-italy/the-gravity-dataset?set_language=en). (ISPRA authorizes to download from its website information content (software, images, etc.) protected by copyright if correctly cited and if used for personal and not commercial use as in the present case. Terms and conditions in)

also operated at Vesuvius (1985–2013) and Campi Flegrei (1983–1985 and 2010–2013);

- some Sicilian volcanic areas, i.e., the island of Pantelleria (e.g. Berrino 1997) (Fig. 3b) and the island of Vulcano (Fig. 4b). The latter is extended to the island of Lipari (Fig. 4c) and included in a larger network covering the whole Aeolian Archipelagos (Fig. 4a), (e.g. Berrino et al. 1988.);
- Colli Albani in Central Italy since 2005 (Berrino et al. 2006) (Fig. 3c).

All these networks have been grown and developed in consideration of the local activity and its time–space evolution. Images in Figs. 3 and 4 show the present-day geometry of the above listed networks. Since 1986, these networks are linked to an absolute reference gravity station, locally measured, and frequently re-measured to check the long-term stability of the reference point. The network on the island of Pantelleria is referred to two local absolute stations, also periodically re-measured, because of the difficulty due to the long distance to link the network to an external site on land (Sicily). The reference stations in Naples and Milazzo also belong to the 1995 Zero Order Gravity Network (IZOGN_1995). Some absolute stations were also set up in the active areas, in correspondence with some selected stations of the corresponding relative net, to control the long-term gravity changes and to validate the gravity variations detected by periodically repeated relative measures. Moreover, in 1992, in the framework of a European Project (EEC Science Project No. ERB 40002PL900491-(90400491) "Volcanic deformation and tidal gravity effect at Mt Etna, Sicily"), the Italian group coordinated by Osservatorio Vesuviano realized on Mount Etna (Serra La Nave Astrophysical Observatory), and its surroundings (i.e., Centuripe), two absolute stations that were re-measured several times

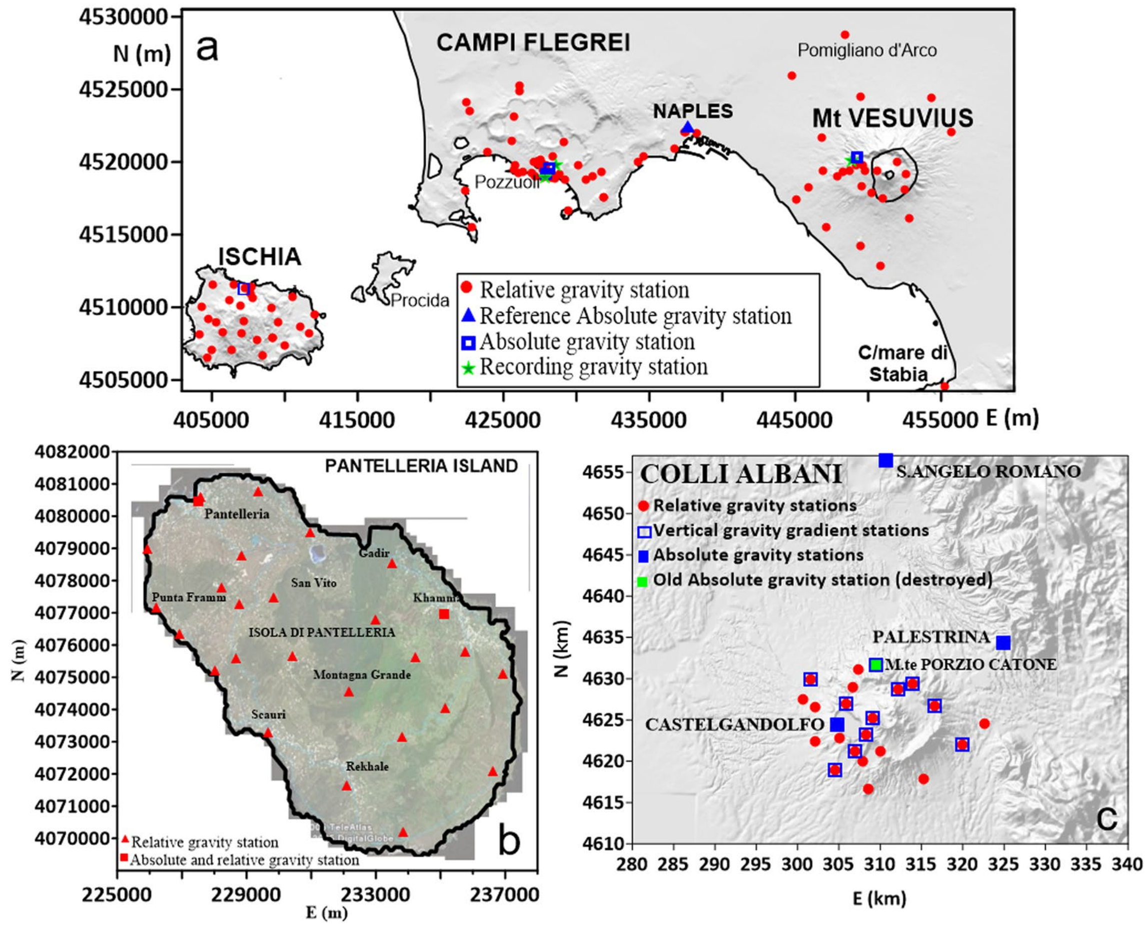

Fig. 3 Present state of the Relative Gravity Networks on some Italian active volcanic areas. **a** Neapolitan volcanoes (Campi Flegrei, Vesuvius and Ischia); **b** Pantelleria island; **c** Colli Albani.The meaning of the symbols is specified for each area in the insets of the figures (see text for details and References)

(Berrino 1992, 1995). In these sites, also two permanent gravity stations recorded data for the whole length of the Project. The station in Centuripe was intended to be the reference for the relative networks operating on the upper part of the volcano and measured during the same EU Project; it was later included in the IZOGN_1995 (Berrino et al. 1995).

The networks aimed at geodynamic control were built taking into account both the particular local dynamics and the local geological-structural situation. Therefore, new detailed prospecting gravimetric surveys were also carried out, during 1980s and until the early 1990s, in some areas both on-land (Berrino et al. 1982, 2006; Berrino and Capuano 1995) and at sea, as in the case of the Neapolitan areas (Berrino et al. 1998, 2008). The new data were integrated with those already existing in the territory, collected in the past mainly by SGI, OGS, AGIP (Ciani et al. 1960; References listed in Berrino et al. 1998, 2008), and for Colli Albani by University "La Sapienza" of Rome (Di Filippo and Toro 1995). All data were standardized and reprocessed. In the case of the survey in the Neapolitan area, the reference was the absolute station in Naples later selected as a node of the IZOGN_1995. For Colli Albani the station in S. Angelo Romano (one of the three new absolute stations there realized) was chosen as reference firstly for the lack of IZOGN_1995 vertex in the area (the absolute station in Rome selected for IZOGN_1995 was destroyed); it has been identified as possible node for a future new reference network.

As already mentioned in the Sect. 1, the development of absolute gravimeters, has allowed a metrological advance in the study of dynamic gravimetry.

Today, four absolute gravimeters (INRiM IMGC-02; ASI micro_g-LaCosteFG5#218; ENI micro_g-LaCoste FG5#238, on loan for use at INGV-CT, and INGV-OV micro_g-LaCoste A10#39) are available in Italy. Among them, the micro_g_LaCoste A10 is a portable instrument specific for field measurements. It is known than different absolute gravimeters are affected by systematic errors (offset) resulting in a difference on the measured values that can be larger than the declared uncertainties. When

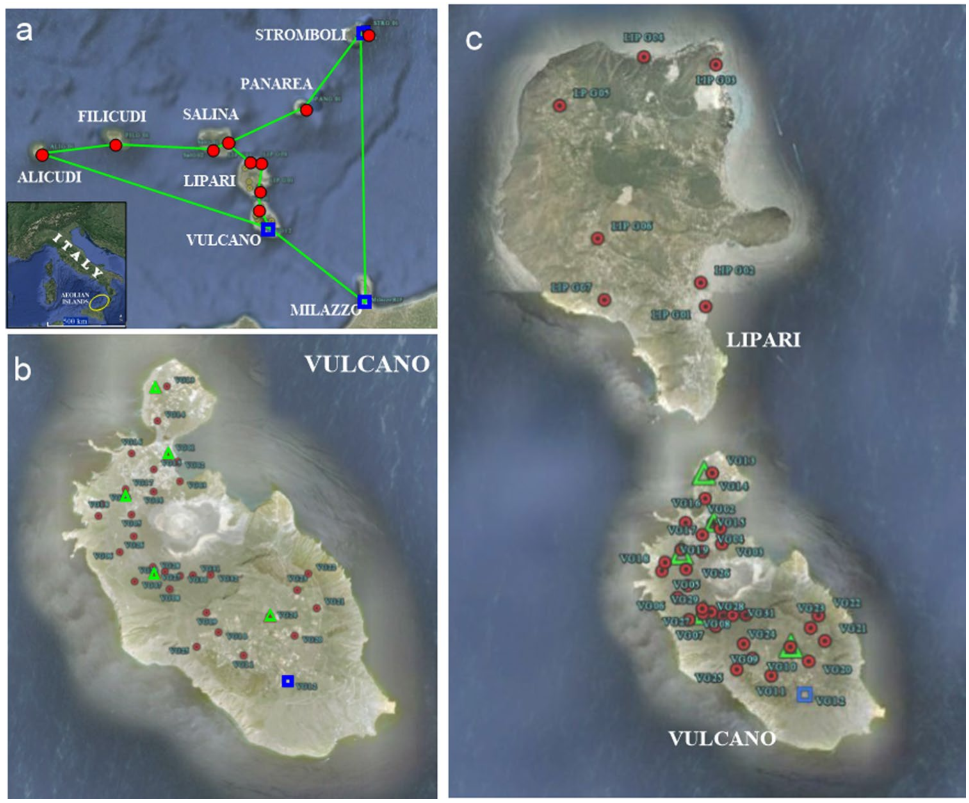

Fig. 4 Relative gravity networks at the Aeolian Islands volcanic arc: **a** the wide network spanning on the whole Aeolian Islands. The inset shows the geographic position of the archipelagos and the green lines points out the gravity links; **b** detailed network at Vulcano island; **c** the network of the Vulcano extended on Lipari island. In all the sub-figures the red full points indicate the relative gravity stations, the green open triangles on Vulcano are relative stations also sites for the measurements of the vertical gravity gradient; the blue open squares show the absolute gravity stations (see text for References)

different instruments are used, inter-instrument differences should be taken into account; the offsets can be determined through the inter-comparison of instruments (Van Camp et al. 2016 and references therein). Therefore, they all are inter-compared with the Italian National Primary Standard gravimeter IMGC-2, following at least one of the procedures suggested in 2013 by the Commission 2 (Gravity Field) of the Consultative Committee for Mass of the International Association of Geodesy (CCM-IAG) to ensure traceability to the International System of Units (SI) for gravity measurements (Marti et al. 2014). Over time, the availability of many absolute gravimeters permitted to create a large number of absolute stations throughout the entire territory, as shown in the Fig. 5. This also permitted to develop absolute gravimetry to monitor Italian geodynamical areas through single stations (Fig. 6) or networks (Fig. 7). The first represent the reference stations for local relative networks or they are some selected stations positioned in strategic areas and periodically measured to calibrate the relative gravity changes (e.g., Berrino 1995); the second are the dense distribution of absolute benchmarks that all together permit to define the evolution of the space–time gravity field. Those last are the cases of the Campi Flegrei (Berrino et al. 2015—Fig. 7a—red full points) and Etna (Greco et al. 2012—Fig. 7b) where absolute gravity networks of, respectively, 35 and 13 stations exist. A wide network of five absolute stations was recently set up in the seismically active area in Central Italy (Berrino et al. 2018—Fig. 7c).

The results obtained by the comparison between absolute and relative gravimetry (e.g., Berrino 2000; Greco et al. 2012; Berrino et al. 2013) are very encouraging in claiming that over time relative gravimetric networks can be replaced with absolute ones, with all the advantages deriving from the absolute methodology (Berrino et al. 2015). This does not mean that the relative measures will be definitively discarded. They will always be necessary for gravity prospecting, for the transfer of the absolute value in satellite stations and/or inaccessible areas even for field absolute gravimeters. Above all, they will always be necessary as a support for absolute gravimetry, in particular for measuring the vertical gradient of gravity useful for carrying the absolute value (referenced to variable or fixed instrumental height) to the ground or to any other reference height.

5 Conclusions

Since long time, Italy has advanced in the study of the gravimetric field and in the use of gravimetry in its great variety of applications. However, Italy needs to upgrade some almost obsolete products and develop the application of new methodologies and new metrological advances in the study

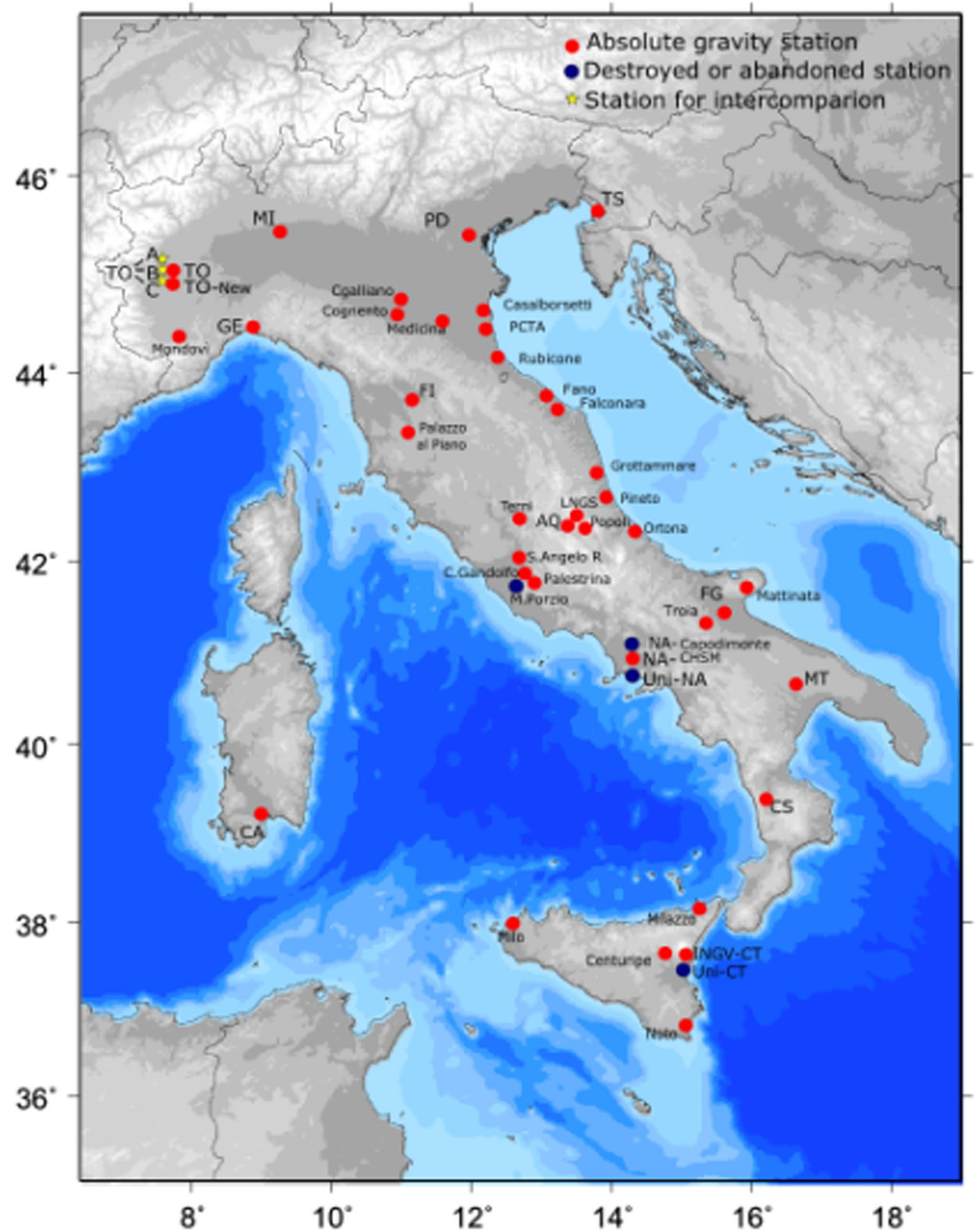

Fig. 5 Absolute gravity stations established in Italy from 1976 to 2018 (full red points). The yellow stars (TO—**a**–**c**) indicate the stations at the INRIM used for inter-comparison of absolute gravimeters. The blue full points indicate old absolute stations presently destroyed or abandoned

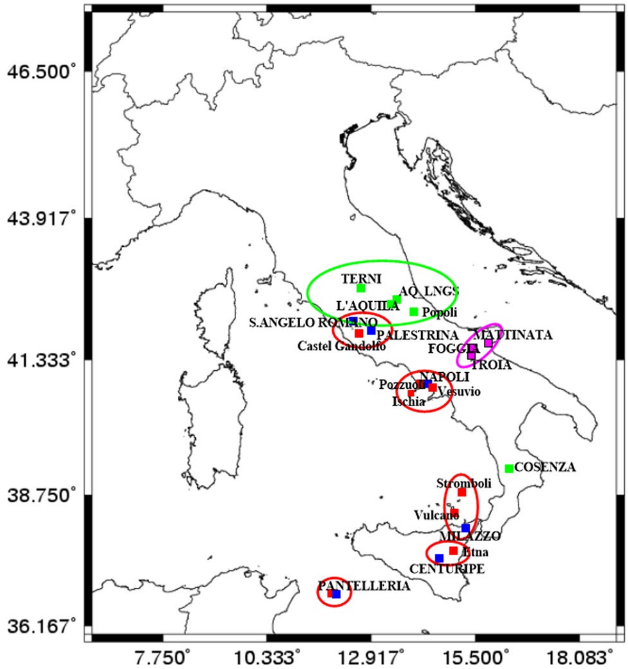

Fig. 6 Present-day distribution of absolute gravity stations in some Italian geodynamical areas (see text for details and References). Blue full squares indicate the reference stations for local relative networks (ref. also Figs. 3 and 4). The red squares are stations on volcanic areas (bounded by red ellipses); those on Neapolitan volcanoes and Mt Etna indicate the first selected absolute stations there established. The green full squares indicate the stations in Central (bounded by a green ellipse) and Southern Italy seismic areas. The stations of the "Troia–Foggia–Mattinata" Italian calibration lines are also shown with magenta full square bounded by a magenta ellipse. The names of cities highlighted in bold and capital letters indicate the sites belonging to, or chosen for, the IZOGN_1995

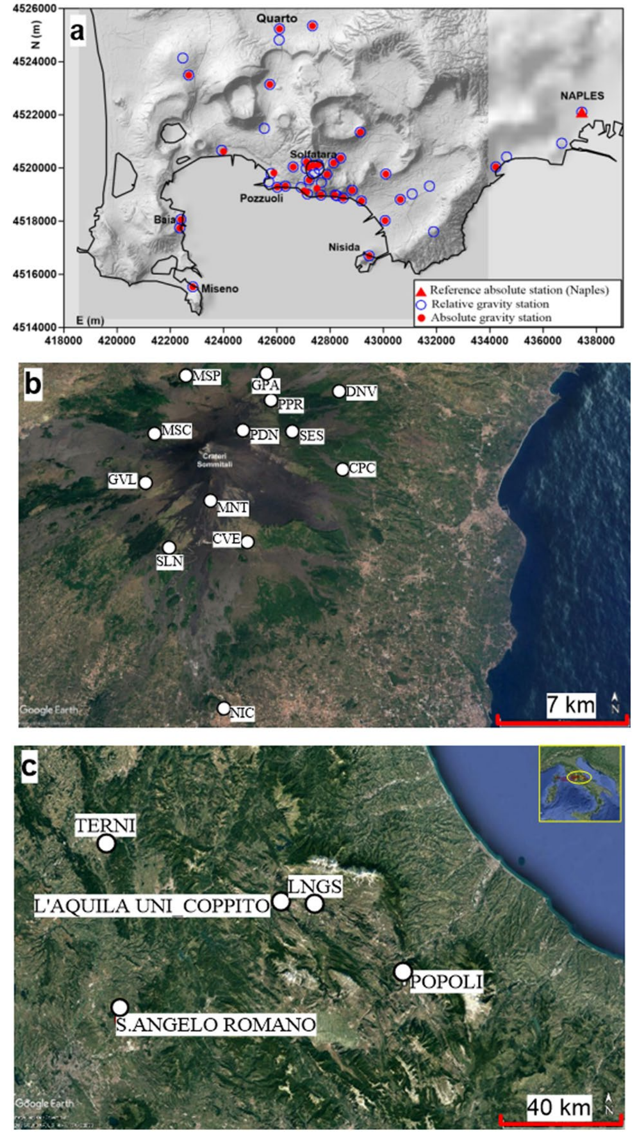

Fig. 7 Networks of absolute gravity stations presently realized at: **a** Campi Flegrei volcanic area (red full points). Here also the stations forming the relative gravity network (blue open circles) are shown. The meaning of the symbols is also specified in the inset; **b** Mt. Etna active volcano (figure personally provided by F. Greco and slightly modified); **c** Central Italy seismic area (see text for details and References)

of some gravimetric aspects, such as the study of geodynamic areas.

Some remarks for future perspectives may be suggested and outlined below.

A new Italian Absolute Gravity Reference Network is needed to update or replace the current obsolete reference IGSN71 (IAG Resolutions adopted by the 2015 IAG Council at the XXVIth IUGG General Assembly; e.g. Wilmes et al. 2016) already in use also because the IZOGN_1995 Reference Network was not completed. It will also permit to align Italy to the new international standards, as suggested by the International Association of Geodesy (IAG), which adopted a Resolution (No 2) for the establishment of a global absolute gravity reference system, realized by a network of "gravity gauges" connected by Absolute Gravimeters comparisons (Wziontek et al. 2015). The Working Group formed on purpose (IAG JWG 2.1.1) encourages the National Agencies to establish compatible national first-order networks, based on absolute gravity measurements, also using field absolute gravimeters (like micro_g LaCoste A10). Absolute gravity reference networks are developing, or have already developed or up-to-date, in several countries all over the world (e.g., BGI web page[6]; CGSN web page[7]; Rodríguez Pujol 2005; Mäkinen et al. 2010; Wilmes et al. 2010; Marti et al.

[6] https://bgi.omp.obs-mip.fr/data-products/Gravity-Databases/Absolute-Gravity-data.

[7] https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cgsn-rncg.php?locale=en.

2019; Rülke et al. 2019). Data are achieved and distributed by the International Gravimetric Bureau (BGI), jointly with the Federal Agency for Cartography and Geodesy (BKG), under the auspices of IAG (Wilmes et al. 2009, BGI web page—Note 6); presently the database contains about 1200 sites all over the world.

In turn, a new reference network will allow to revise the entire available Italian gravity database. Given the importance of such advancement, the Italian Research Institutes, owners of absolute gravimeters, coordinated by the Polytechnic of Milan and with the participation of the University "La Sapienza" of Rome, are already planning a new Italian Gravity Reference Network named "G0". It will take into account the existing absolute gravity stations (see Fig. 5) and should consist of the majority of them, selected to have a homogeneous distribution of absolute gravity points all over Italy. All the stations should be measured again, possibly with all the available absolute gravimeters, integrating new stations in empty areas.

As already mentioned, all instruments will be preliminarily inter-compared following the CCM–IAG procedures.

Another important development should consider the upgrade of the current Italian gravimetric map, based on very old data (collected since 1950s). These data, although they have been tidied and reprocessed also in digital format, are not homogeneous having mainly been acquired with instruments with very different characteristics and sensitivity. Moreover, they are again referred to an obsolete reference system (IGSN71). A more detailed, homogeneous and updated Bouguer anomaly map could be realized by means of a new airborne survey over the whole on-land and offshore Italian territory. Airborne Gravimetry is a crucial method to improve knowledge in hard-to-access regions. A new gravimetric database is necessary to obtain a general and more homogeneous geological framework. In fact, the gravimetric maps of Italy currently available are lacking in homogeneity, quite-poor in the Alpine region and in some areas of the Apennines, and quite-obsolete. Regarding this suggestion, two tests were already carried out in Italy in 2005 and 2012. The first was performed by ENI in co-operation with the Polytechnic of Milan and the Danish National Space Center in two test areas (Calabria and Maiella Mountains; Barzaghi et al. 2009). A residual gravity field at ground level was obtained using both airborne and available ground data. The second test collected data, available at German Research Centre for Geosciences (GFZ), along several profiles during an experiment aimed to test at high altitudes the new German fast aircraft "HALO" and at gaining experience for future missions to improve gravity models in remote areas. The flight mission over Italy, performed within the "GEOHALO" Project (Barzaghi et al. 2015; Lu et al. 2017), covers the Central-South part of Italy. 7 main NW—SE tracks spaced about 40 km at an altitude of 3500 m, 8 tracks at an altitude of 10,000 m and 4 perpendicular cross tracks were surveyed, using the airborne/marine gravimeter Chekan-AM. Both experiments could represent the basis for a new survey.

Finally, a larger use of the absolute gravimetry in geodynamic areas would be not only desirable but also necessary. This, will allow a metrological advancement and lead a series of operative and economic benefits, and comply with the already mentioned recommendations of the International Association of Geodesy.

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