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EARTH'S GRAVITY FIELD AND EARTH SCIENCES

Gravity and crustal dynamics in Italy

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Abstract

Mapping the static gravity field in the Italian area is fundamental to identify the main lithospheric structures, to delineate the main geological elements at regional level and to infer the regional geodynamic setting. The ongoing tectonic processes highlight nevertheless the need to measure and model the time-variable gravity field, namely the dynamic gravity field, which requires increased accuracy and long time series of observations to separate the secular from the short-term variable components. The first, with a minor impact in Italy, are due to variations of ice mass balance (the viscoelastic response of the Earth to past changes in ice mass loading, and the elastic response of the Earth to present-day deglaciation), and the sea-level rise; the second are due to space/time variations of underground mass distributions, such as those related to seismic deformations, volcanic dynamics/eruptions and water transfer. Local-scale gravity studies along seismogenic faults may provide useful hints to study the seismic cycle and to unravel those areas more prone to seismic release by studying if the crustal volume is undergoing dilatancy (gravity decrease) or overpressure (gravity increase) before earthquake occurrence. This process, however, is accompanied by possible fluid migration, which can be revealed by other geophysical measurements, for example, by magnetotelluric and geoelectrical surveys. In this short paper, we briefly summarize the main sources of gravity variation providing on the same time orders of magnitude, spatial and temporal scales of their effects.

Keywords Italian area · Geodynamics · Static gravity field · Deformations · Dynamic gravity field

1 Introduction

Gravimetry measures the spatial and temporal variation of the Earth's gravity field. This is useful in physical geodesy to define the Earth's figure in size, shape and orientation, the geoid, a conventional equipotential surface of the gravity field providing the Earth's reference models of heights. Gravimetry highlights the spatial distribution of mass in the inner Earth for geophysics and the temporal variation of mass distribution for geodynamic purposes.

The Earth's gravity acceleration measured on the Earth's surface undergoes small changes over space and time. An observer located on the Earth's surface would measure gravity differences up to $5{\cdot}10^{-3}$ g, due to his difference in position (equator-pole) and elevation (mountain-deep sea), and up to $5{\cdot}10^{-4}$ g with the presence of disturbing masses (deviations from simple Earth model). The temporal variations account for periodic tidal effect up to $3{\cdot}10^{-7}$ g, sub-surface mass displacements up to $3{\cdot}10^{-7}$ g, and changes in elevation, up to $2{\cdot}10^{-7}$ g (Carbone 2016).

In general, the static gravimetric field, i.e. the time-independent (long-term averaged) part of the gravimetric field, is distinguished from the time-dependent part, known as the dynamic gravimetric field. More in detail, the static gravimetric field provides information about the spatial distribution of masses and it is useful to study the near-surface structural geology and tectonic modelling with a requested accuracy of the order of ~ 10^{-6} g (~ 10^{-5} ms^{-2}, ~ 1 mGal), at least.

The dynamic gravimetric field provides information about the time variation of mass/density, useful to model the dynamics of masses and to separate the competing effects of

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deformation and mass/fluid redistribution both of tectonic and climatologic origin. In this case, the requested accuracy is higher and of the order of $\sim 10^{-9} \div 10^{-8}$ g ($\sim 10^{-8} \div 10^{-7}$ m s^{-2}, ~ 1–10 μGal).

The transition from static to dynamic gravimetry has been possible thanks to the technical development of new gravimeters with increasing accuracy, from the mGal level to μGal, and decreasing relative error $\Delta g/g$, from about $\pm 10^{-4}$ to $\pm 10^{-9}$.

The static gravimetric field is nowadays mainly derived from satellite measurements [e.g. Gravity Recovery And Climate Experiment (GRACE), Gravity field and steady-state Ocean Circulation Explorer (GOCE), GRACE Follow On (GRACE FO)], which provide the large-scale component of the estimated gravity models, combined with terrestrial and ocean gravity data accounting for the small wavelength part of the gravity signal useful to resolve small-scale features (Rummel 1993; Barzaghi et al. 2015 and references therein).

The static gravimetric field can be represented in terms of geoidal undulations and gravity anomalies of various kinds. The geoidal undulations are the deviations between the equipotential surface of the Earth's gravitational field and the reference ellipsoid, useful in geodesy to unify the height systems (Sansò et al. 2019). A helpful representation for geophysical purposes is in terms of Bouguer anomalies which are the difference between a gravity measurement and the gravity of the reference potential corrected for the effect of topographic masses above the geoid. Both the undulations of geoid and gravity anomalies are due to density variations of the Earth's interior, and can be in principle transformed one into another (Sansò and Sideris 2013; Li and Götze 2001). They provide a snapshot of the main structural features at different scales, from global to local models, useful to connect the past to present geodynamic history of a region. Their wavelengths are connected with the dimension and depth of bodies with mass/density contrast.

The dynamic field accounts for the temporal variations of the gravity field which are mainly due to the Earth's tides and variable rotation rate, mass redistribution and/or density variations which can occur on different time and spatial scales. Satellite gravity missions provide their contribution to study the time-variable gravity field at global/regional scale with applications to the terrestrial water cycle, ice mass balance and climate change (Tapley et al. 2019). They are also useful to study the seismic cycle and the effect of megathrust earthquakes on the gravity field (Sauber et al. 2016). All these geophysical processes are able to induce variability of the Earth's rotation rate which modify the length of day, the Earth's figure and, therefore, the Earth's gravity field (e.g. Lambeck 1980).

The Earth's secular processes generating non-tidal deformations are due to tectonics, glacial isostatic adjustment (GIA) and post-glacial rebound (PGR); the main medium–short-term processes are due to volcanoes, earthquakes, groundwater and atmospheric pressure variations, all of them affecting the gravimetric field both at global and regional scales.

2 Geodynamic evolution of the Italian area and static gravity field

The present-day geodynamics of the Italian area is connected to the relative motions between three main plates Africa, Eurasia and Adria, and it has been and still is mainly dominated by the 'eastward' migration of the Apenninic arc and associated opening of the Tyrrhenian back-arc basin. The following picture is mainly based on Carminati et al. (2012). The Apennines have been interpreted as originating from Alps; going back to ~ 45 Myear, the convergence and the subduction of Eurasia–Iberia between Adriatic and Africa plates generated a long orogen connecting Alps to Betics as one main chain (Fig. 1). Subsequently, since ~ 30 Myear, along the retrobelt of the orogen, started a flip of the subduction with a new westerly directed slab of the Adriatic–Ionian–Africa lithosphere. The subduction hinge migrated generally eastward, generating the opening of the western Mediterranean Neogene back-arc basins (Provencal and Algerian oceans), the rotation of Corsica–Sardinia and later (20–15 Ma) the opening of the Tyrrhenian sea. The motion resulted in an anticlockwise rotation along the northern arm of the arc and clockwise rotation of the southern side of the Apennines–Maghrebides accretionary wedge. The maximum eastward migration was ~ 775 km, and is interpreted as mainly controlled by the retreat of the Ionian–Adriatic slab. The NW–SE convergence between African and Eurasian plates has been estimated in ~ 135 km in the last 30 Myear, therefore, playing a minor role with respect to the eastward migration of the Apennines belt (Carminati et al. 2012).

At present, the Italian area is far from being a geodynamical stable region since it currently undergoes the tectonics driven by the Apenninic and Alpine subduction zones (Fig. 2). Italy is a key region to understand the transition processes from oceanic to continental subduction (e.g. the Alpine collision), slab-rollback, and back-arc basin formation like the Tyrrhenian sea and the entire western Mediterranean (Carminati and Doglioni 2012). The Eurasia plate subducts beneath the northern margin of the Adriatic plate. At the same time, along its western margin, the Adriatic plate subducts beneath the Apennines (W-directed) and along its eastern margin beneath the Dinarides (NE-directed). The subduction and retreat of the W-directed slab causes the eastward migration of the Apennines wedge and the back-arc spreading in the central–western Mediterranean.

All these phenomena are marked by specific large-scale gravity anomalies (Morelli 1975). The Bouguer anomaly

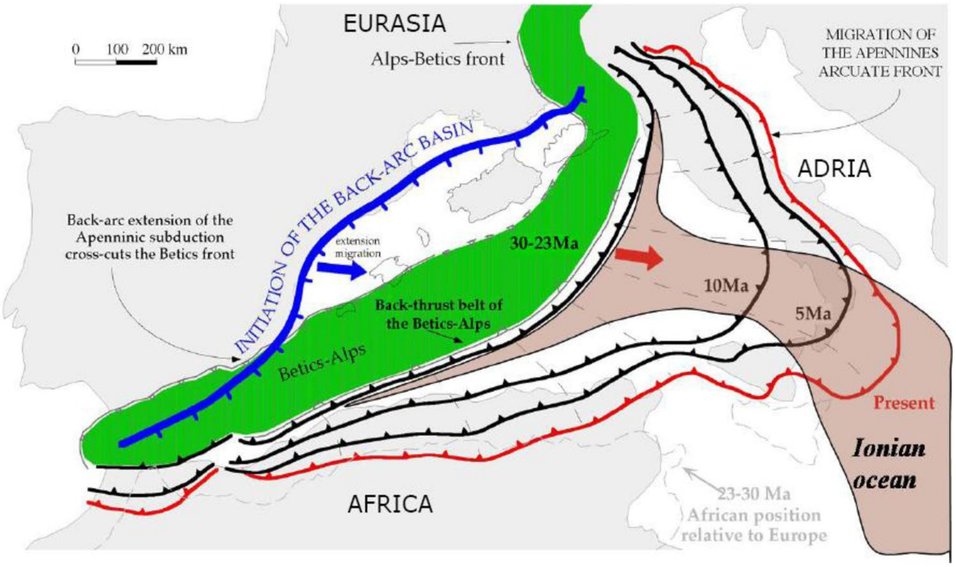

Fig. 1 Geodynamic reconstruction of the central–western Mediterranean: the convergence and the subduction of Eurasia–Iberia between Adriatic and Africa plates generated a long orogen connecting Alps to Betics (45 Myear). Along the retrobelt, initiated a new westerly directed subduction of the Adriatic–Ionian–Africa lithosphere (30 Myear). The subduction hinge migrated generally eastward, generating the opening of the western Mediterranean Neogene back-arc basins (Provencal and Algerian oceans), the rotation of Corsica–Sardinia and later (20–15 Myear) the opening of the Tyrrhenian sea (modified after Catalano et al. 2001)

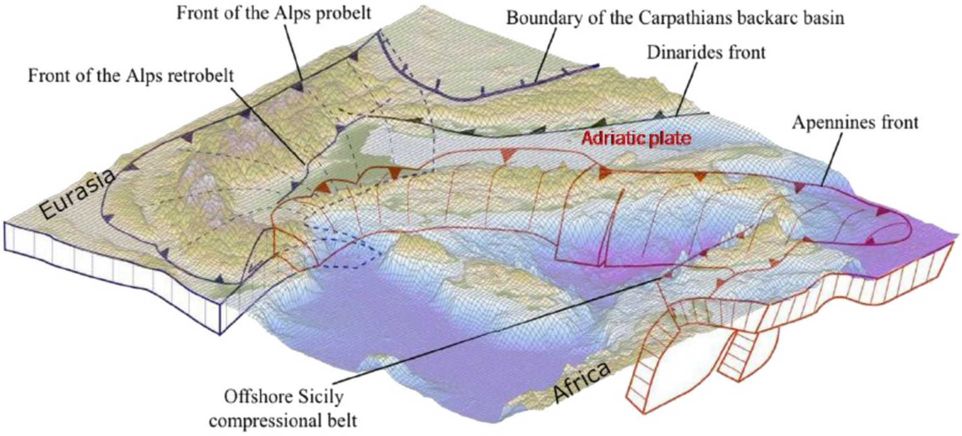

Fig. 2 Sketch showing the Apenninic and Alpine subductions zones from a northern Africa perspective. The Alps have a shallower and less steep slab with respect to the Apennines, higher elevation and no back-arc basin. The Apennines arc is subdivided into sub-arcs, possibly due to variable slab retreat, lengthening of the slab and opening of vertical slab windows, which may have triggered magmatic upraise (modified after Carminati and Doglioni 2012)

map of Italy shows large wavelength of positive and negative anomalies ranging from ~ -200 to ~ 140 mGal (Apat 2005). Positive anomalies indicate the presence of denser bodies with respect to the average density value (2.67 g cm^{-3}) used to model the gravity field, or thinned crust, shallower asthenosphere, large heath flow: areas with positive anomalies are Ligurian and Tyrrhenian seas, Ivrea's body, the zone where a relict of mantle outcrops, and Euganei hills. Negative anomalies indicate lighter bodies or thickened crust, deeper asthenosphere, low heat flow: the Alpine and Adriatic subduction zones and sedimentary basins are areas of negative anomalies.

The subduction zones are accompanied by negative anomalies due to the presence of the lighter composition of the downgoing slabs (e.g. the Alps, even < -170 mGal, or the Apennines -100 mGal) The Alps have a shallower and less steep slab with respect to the Apennines and in the Alpine domain, the negative anomalies correspond to a thickening of lithosphere, due to the subduction of Eurasia underneath Adria, whereas across the Apennines, we first have a shallower asthenosphere due to the extension in the Tyrrhenian area then a decrease due to lower asthenosphere below the Adriatic domain (Fig. 3). On the other hand, the back-arc basin (the Tyrrhenian sea) or inherited oceanic embayments (e.g. Ionian) have a shallower asthenosphere and a larger gravity anomaly, even > 140 mGal. These features are also well identified looking at the heat flow, the Moho depth and the lithospheric thickness maps (Carminati and Doglioni

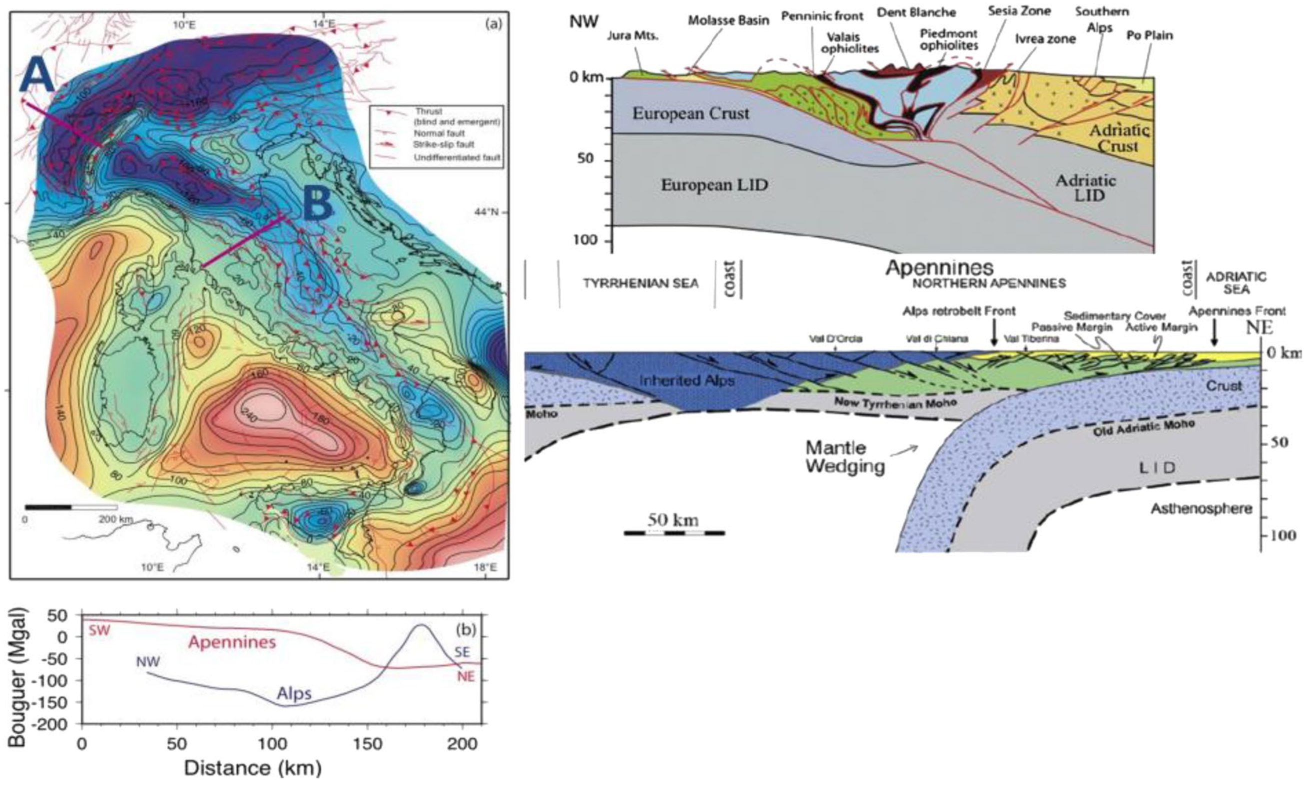

Fig. 3 **a** Bouguer gravity map of the Italian area; **b** the Alps display low gravity anomaly, apart the Ivrea zone where a relict of mantle outcrops. The Apennines show lower values in the foredeep and accretionary prism, whereas the internal part and the back-arc basin show higher values to the west due to a shallower asthenosphere. **c** Section across the western Alps showing the subduction of European plate underneath Adria with a thickening of lithosphere corresponding to negative anomalies. **d** Section across the Apennines from SW to NE: a shallower asthenosphere with mantle wedging due to the extension in the Tyrrhenian area, then a decrease due to lower asthenosphere below the Adriatic domain (modified after Carminati and Doglioni 2012)

2012). In fact, the Alps are characterized by thickened continental crust (> 50 km) and lithosphere (> 130 km) due to the duplication of the Adriatic plate overriding the European plate, Moho deepening and low heat flow. The Apennines separate the Adriatic from the Tyrrhenian domains: in the first the heath flow is low with Moho and lithosphere base becoming deeper from the Adriatic sea to the chain. In the Tyrrhenian sea, the Moho is shallower (5–20 km) and the lithosphere is thin (30–50 km), the heat flow is high due to the shallower asthenosphere (Fig. 4). In the Ionian sea, the Moho is still shallow (15–20 km) but the lithosphere is thicker (70–80 km, Brandmayr et al. (2011); the heat flow is low due to the deeper asthenosphere with respect to the Tyrrhenian sea. These differences can be inferred as related to the young age (Neogene) of the Tyrrhenian sea with respect to the older oceanic spreading (Catalano et al. 2001) of the Ionian sea.

All the subduction zones experience seismicity, which is more pronounced along the ridge of the Apennines, and in the foothills of the Alps and Dinarides. The Apennines subduction is characterised by compressional seismicity east of the chain, in the frontal accretionary prism, and extensional tectonics to the west, associated with the opening of the Tyrrhenian back-arc basin and slab retreat. The present subduction of the Ionian oceanic crust beneath the Calabrian arc is testified by the intermediate depth and deep seismicity and by the Aeolian arc volcanism in the southern Tyrrhenian sea, whereas the slab is seismically active down to about 100 km where the sinking lithosphere is continental. This can be related to the different rheological behaviour of the oceanic versus continental composition of the slab (Carminati et al. 2002).

The joint inversion of Bouguer gravity anomalies and seismic data allow to model the structure and density distribution of the inner Earth's layers. Recently, Brandmayr et al. (2011) modelled the lithosphere density in the Italian area and inferred that the subduction slabs, even if seismically faster, are not denser than the ambient mantle, but they are slightly lighter, pointing out that the slab pull cannot be efficient as mechanism to move plates. At local scale, a refined iterative procedure based on the inversion of seismic data and Bouguer gravity anomalies provided a detailed 3D density and shear wave velocity models which

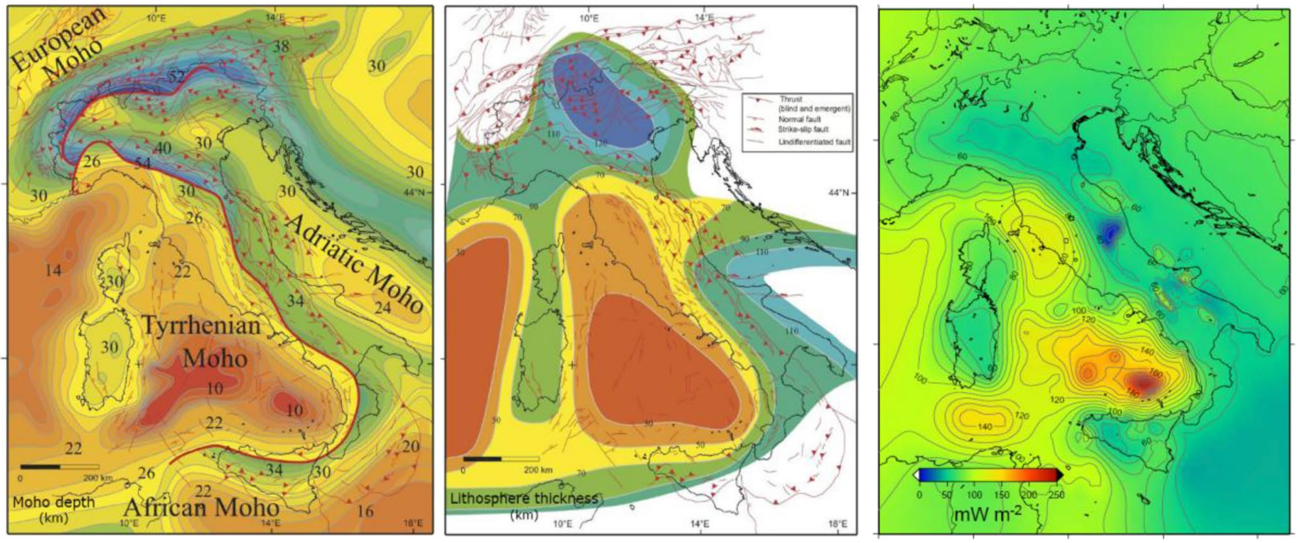

Fig. 4 Italian area maps of Moho depth (**a**), lithosphere thickness (**b**) and heat flow (**c**) (modified after Carminati and Doglioni 2012)

constrain the crustal structure beneath the Po plain up to 20 km depth (Tondi et al. 2019).

A model based on a finite-element approach, including the compositional stratification of the lithosphere into a light upper crust and a dense lithospheric mantle, allowed to study the gravitational signatures of different subduction styles (Marotta et al. 2006). This approach allowed to infer the gravity signature of Calabrian arc subduction, which is characterized by a minimum of gravity anomaly located at the trench, bounded by two highs located on the overriding and subducting plates, with a variation in magnitude of the order of 200 mGal along a wavelength of 200 km, in agreement with the isostatically compensated component of gravity anomaly observed along a transect crossing the Calabrian arc, from the Tyrrhenian to the Ionian seas (Marotta et al. 2007).

3 Deformations and dynamic gravity field

Gravity changes recorded by an absolute gravimeter consist of two terms: the effect of vertical displacement of Earth's surface and a internal mass redistribution. Gravity observations alone cannot differentiate between the two. Therefore, the simultaneous and continuous measurement of gravity and deformations helps to separate the competing effects of deformation and mass/fluid redistribution.

The recent development of several permanent GNSS networks has significantly improved the spatial and temporal resolution of deformation monitoring in the Italian area. At present, at least 30 GNSS networks maintained by different institutions constitute the grid of monitoring sites that includes over 1000 permanent stations, mainly devoted to real-time positioning services but that has proven to be suitable also to detect slow deformations (Devoti and Riguzzi 2018). The whole set of raw GNSS data is routinely processed at INGV providing daily solutions of station coordinates and estimating velocities from the coordinate time series of each station. The information content of the time series is wide, they can contain linear and non-linear effects caused by geophysical phenomena of different nature and offsets due to instrumental changes. The site velocities are estimated fitting simultaneously a linear drift, episodic offsets and annual sinusoids to the coordinate time series. The average horizontal and vertical velocities are estimated after combining the solutions obtained by three different scientific softwares (Bernese, Gamit and Gipsy); the final uncertainties are 0.3 mm/year and 0.7 mm/year for the horizontal and vertical velocities, respectively (Devoti et al. 2017).

Focusing on the Italian area, the plot of horizontal velocities (Fig. 5a) shows a coherent pattern with extension across the Apennines which marks a separation in the velocity direction and extension rate of ~ 3–4 mm/year; convergence in NE Italy and offshore N Sicily of ~ 2 mm/year. A major impact on the gravity field is given by vertical deformations (Fig. 5b), with pattern of significant subsidence in the eastern Po plain and Aeolian islands area of ~ 2–8 mm/year and uplift of ~ 1–3 mm/year along the Alps and Apennines.

Recent studies have shown that hydrological events, like heavy rainfall or water level variations in confined aquifers, are able to induce significant sporadic or long-term periodical deformations that affect the GPS time series, if the stations are located on fractured carbonates (e.g. D'Agostino et al. 2018; Devoti et al. 2018; Serpelloni et al. 2018). Even if such effects are probably not cumulative over time, the

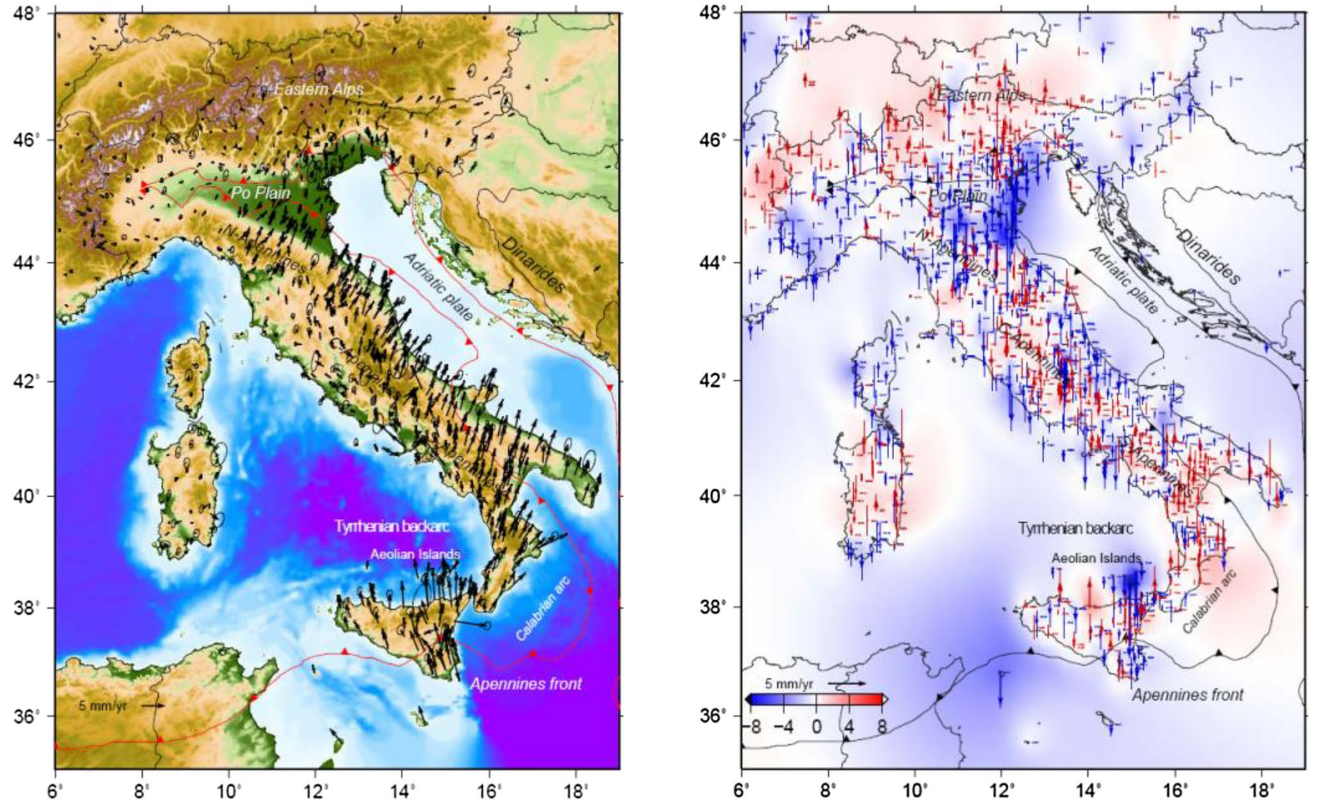

Fig. 5 The Italian area allows to evidence peculiar features both in the horizontal velocity field (**a**, with respect to Eurasia) and vertical velocities (**b**, the background colour map is obtained after interpolation with GMT sw, Wessel et al. 2013). The velocities are obtained after processing GPS observations and combining three independent solutions (Devoti et al. 2017)

modelling of the residual tectonic signal would benefit from the simultaneous measurement of gravity changes.

4 Subsidence and gravity changes

Subsidence of the Po plain is an interesting combined process which modifies the gravimetric field due to both natural and anthropogenic factors in which we can identify a very long-term (> 1 Myear) component of geodynamic origin due to flexure and the NE-ward retreat of the Adriatic plate, which is subducting under the Apennines (~ 1 mm/year); a mid-term component (glacial cycles, ~ 10^4 year), controlled by climatic changes; and short-term processes like sediment compaction/loading of river deltas and anthropic actions (water and hydrocarbons exploitation and storage).

Geology helps to infer long-term rates of deformation; in particular, studies conducted on the stratigraphic data of wells located in the Po plain allowed to evaluate from the thickness of Quaternary sediments, in the last Myear, a variable pattern of subsidence between 0.4 and 2.4 mm/year (Carminati and Di Donato 1999).

The vertical velocities of permanent GPS stations located in the Po plain highlight a variable pattern of subsidence due to the combination of all the processes, in which the anthropogenic signature plays a major role due to the limited time span of observations (last 20 years), and the significant impact of water and hydrocarbon extraction and storage. Subsidence rates from GPS are affected locally by these factors and range within ~ 1–8 mm/year (e.g. Zerbini et al. 2015). A multidisciplinary approach that combines observations from GPS, InSAR and terrestrial gravimetry allowed to study the subsidence in the southeastern Po plain, and in particular in the site of Medicina, where a permanent GPS station (MSEL) is working since about 1990s and a superconducting gravimeter (SG) since 1996 (Zerbini et al. 2007). SGs are relative instruments providing time variations of local gravity with high stability. The continuous monitoring of gravity and height changes over long time allowed Zerbini et al. (2007) to infer and model the contribution to height changes due to sub-surface mass redistribution and subsidence. The study indicated a trend of gravity increase of + 0.72 ± 0.02 μGal/year (1998–2004) without significant mass redistribution processes.

5 Glacial isostatic adjustment (GIA) and post-glacial rebound (PGR)

GIA is a very long-term geophysical process which modifies the gravimetric field as a "second-order" effect. The change in cryosphere causes global deformations of the solid Earth, variations of gravitational potential, changes of Earth's angular velocity and sea-level variations. The load and unload of ice sheet during glacial cycles produces vertical and horizontal deformations due to elastic flexure of lithosphere and viscous flow of the asthenosphere. The initial uplift following deglaciation is fast due to the elastic response of the lithosphere; afterwards, the uplift proceeds by slow viscous flow at an exponentially decreasing rate. The present-day GIA signature originates from the last ice age which occurred ~ 18,000 years ago, when great ice sheets, 2–3 miles thick, covered much of Earth's northern hemisphere. Several models have been exploited to estimate at the global scale the horizontal and vertical velocities induced by deglaciation; they are sensitive to mantle viscosity, which increases with depth and ranges within 10^{20}–10^{23} Pa s (e.g. Mitrovica and Peltier 1991; Sabadini and Vermeersen 2004). GIA models predict vertical rates larger than horizontal ones, land uplift north of latitude 50 N and subsidence south of it. The maximum uplift occurs where the ice sheets were located, it reaches up to ~ 1 cm/year in Fennoscandia, Greenland and North America. At global scale, GIA models predict present-day free-air gravity anomalies within about − 18 mGal in the northern hemisphere (Sabadini and Veermersen 2004). The predicted horizontal velocities consist of two components, the first along the N–S direction, accounting for the mantle material redistribution toward the polar cups and the second directed outward the deglaciation centres (Marotta 2003).

GIA models predict low rates of land subsidence in the Italian area increasing from north to south within ~ 0.3–0.8 mm/year, and Mediterranean sea-level rise within ~ 0.2–0.6 mm/year (Sabadini and Vermeersen 2004; Stocchi and Spada 2009). The expected free-air gravity anomalies should be of the order of 2–3 μGal/year.

While GIA is a long-term process involving the mantle rheology, PGR is the elastic response of lithosphere to ice mass loss and retreat (Sabadini et al. 2016), as the case of Alpine glaciers whose reduction is currently evident and accelerated since the end of 1970s (Fig. 6). The mass loss in terms of water equivalent reduction can reach ~ 1 m/year in the southernmost exposed glaciers (Barletta et al. 2006). The consequent unloading contributes to the Alpine arc uplift. GPS and levelling observations detected in the Alpine area vertical rates of the order of 1–3 mm/year which include both tectonics and PGR contributions. Elastic unloading model shows that the present-day glacier reduction contributes to a substantial fraction of the observed uplift rate (Barletta et al. 2006) with a maximum predicted value of 0.9 mm/year, which in terms of free-air gravity anomaly is ~ 2–3 μGal/year. If the trend of reduction were linear, in 40 years, the gravity change could reach ~ 80–120 μGal, value that can be considered as lower bound. As far as it concerns tectonics, the Alps are absorbing the convergence between plates with active orogenic uplift. Gravity measurements should be able to distinguish whether the process consists of a pure crustal uplift or even crustal thickening and isostatic Moho lowering. It has been shown that the concurrent processes of tectonics and hydrological effects are hardly separable with the present resolution of satellite gravity models. The combined model GOCO05S obtained from GRACE and GOCE observations predicts for the Alpine region gravity change rate within ± 0.5 μGal/year with a very smoothed spatial pattern, smaller than expected by a simple uplift process (Chen et al. 2018 and references therein).

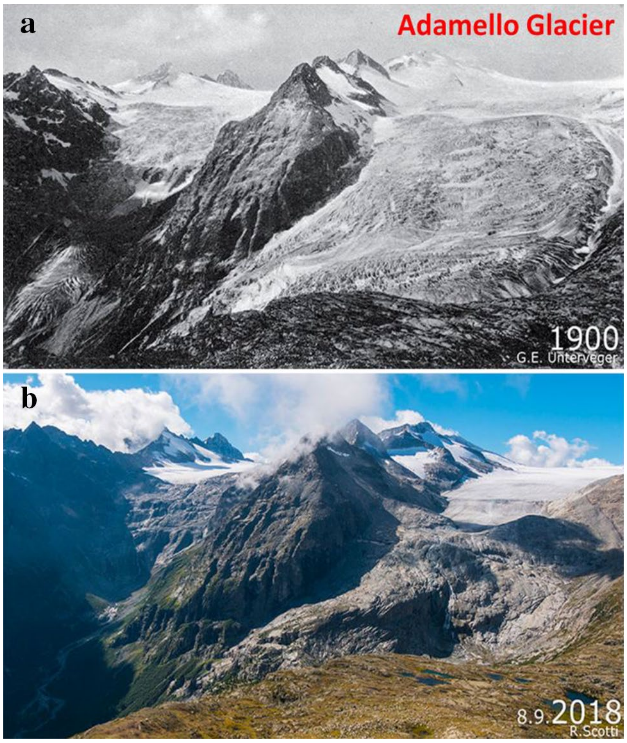

Fig. 6 The Alpine glaciers reduction is accelerated since the end of 1970s and it is currently evident by comparing their images at different epochs. As example we show the Adamello-Mandron glacier in 1900 (**a**) and in 2018 (**b**). The ice mass loss produces elastic unloading with consequent uplift

6 Gravity changes due to earthquakes

An earthquake is an instantaneous frictional sliding along the part of the fault area which causes coseismic deformations and mass redistribution; a gravimeter located on the Earth surface could measure changes of gravity acceleration associated with such event. Static gravity changes have been measured (very far field amplitude ~ 1 µGal) by superconducting gravimeters and satellite gravity gradiometers long after the end of the rupture in occasion of large seismic events (e.g. in Japan: 2003, Tokachi-oki Mw 8.0 and 2011, Tohoku Mw 9.0; Imanishi et al. 2004; Cambiotti and Sabadini 2013 and references therein). Recently, transient gravity field perturbations generated during the fault rupture have been modelled and measured (far field amplitudes of ~ 10^{-1} µGal); such gravity signals reach a gravimeter located at a certain distance from the source before the arrival of seismic P waves, with amplitude decaying as ~ $1/r^2$ (e.g. Vallée et al. 2017 and references therein), thus throwing new light on early warning systems (Juhel et al 2018). If the same gravimeter were continuously working, it could also record postseismic relaxation and redistribution of fluids due to viscoelastic and poroelastic transient phenomena and probably gravity variations connected with the preparatory phase of significant earthquakes. Pre-seismic gravity changes based on repeated relative surveys have been reported in China and Tibet before the occurrence of the 2008 Wenchuan (Mw 7.9) and 2015 Nepal (Mw 7.9) earthquakes (see e.g. Shen et al. 2012; Chen et al. 2016 and references therein); however, the results of these studies did not take into account possible hydrological and instrumental effects on the sporadic surveys (Van Camp et al. 2017 and references therein). Therefore, only joint studies based on the analysis of long time series of continuous GNSS and absolute gravity measurements could unravel the existence of precursory gravity signals.

Gravity changes measured just before and after the epoch of earthquake occurrence have never been measured in Italy, but they have been recently modelled for the three main shocks (Mw 6.0, 5.9, 6.5) of the last seismic sequence started on 2016, August 24, and the 2009, April 6 L'Aquila earthquake (Mw 6.3) (Riguzzi et al. 2019). The total predicted gravity variations are of the order of ~ 1 µGal in the far field, and ~ 170 µGal in the near field. The area affected with a gravity change of 1 µGal is ~ 140 km long and ~ 57 km wide, parallel to the Apennine chain. The larger contribution is given by positive variations which account for the extensional tectonic style of deformation and larger subsided area (Fig. 7). However, it has to be stressed that since 1 µGal is more or less the accuracy level reached by continuous absolute gravimetry, the conclusion is that either a permanent station is more or less close to the epicentre of the event or many stations are present in the wide area, to detect the gravity signal of a seismic event.

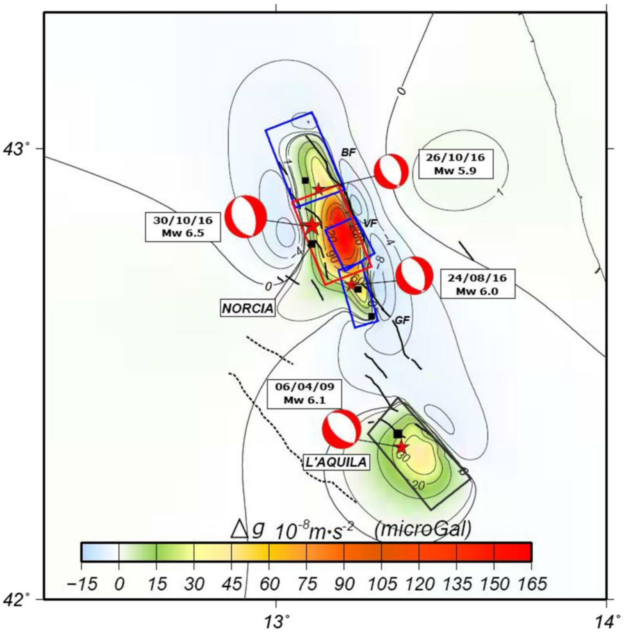

Fig. 7 Coseismic gravity changes modelled for the April 6, 2009, L'Aquila earthquake, and the August 24, October 26 and 30, 2016, events (modified after Riguzzi et al. 2019). In blue are indicated the areas of negative gravity variation (uplift), from green to red colours the positive changes (collapse). The source models of the 2016 (blue boxes) and 2009 (black box) events are projected on the topographic surface. The epicentre locations are indicated with red stars, their focal mechanisms with the red–white beach balloons

7 Gravity changes due to volcanoes

The Italian area is an interesting natural laboratory due to the presence of at least ten active volcanoes; some of them deserve particular attention and are continuously monitored since they are considered highly hazardous. The identification of pre-eruptive conditions, characterized by motion and rising of magmatic masses with surface deformation and in-depth density variations, can be useful to prevent and mitigate the socio-economical impact of eruptions in highly urbanized areas. The Neapolitan region is a typical example, where are located the Vesuvio and Campi Flegrei volcanoes.

Long-term volcano deformations due to magma and gas intrusion are detected through episodic measurements of crustal deformation and gravity variations; emblematic is the case of bradyseism affecting the Campi Flegrei area (Naples). During the 1981–1984 crisis, a maximum uplift of ~ 1.80 m and gravity decrease of some hundred µGals were measured. The difference between the observed gravity and the gravity variations predicted by height changes allowed to model volume and depth of magma source responsible for the event (Berrino et al. 1984; Berrino 1994).

Short-term events like the sudden occurrence of lava fountains at Etna can be detected by continuous gravity measurements. It has been shown that gravity decreases several μGal just the last few hours before the start of lava fountains; such drop off has been interpreted due to foam formation after gas intrusion (Carbone et al. 2015).

8 Conclusions

The Italian area is subjected to an increased human vulnerability to terrestrial hazard and global climate change so that the continuous monitoring of time-variable processes in a stable reference frame should be considered a major challenge for the future.

Terrestrial and satellite gravimetry/gradiometry, especially when used in a combined form, allow to monitor many geophysical and human-induced processes associated with deformations and mass/fluid transfer. However, the challenge to carry out simultaneous and continuous measurement of gravity and deformations should be pursued to separate the competing effects of these different processes. In the last years, there has been a worldwide development of GNSS networks useful to detect deformations; on the contrary, the high costs of terrestrial gravimeters have limited their use.

The Italian area is affected by ongoing deformations and/or mass transfer of different origins acting on very different temporal scales which modify significantly the gravity field over time.

The main contributions to gravity changes are induced by episodic events due to volcanoes and earthquakes which individually can affect the gravity field generally within the mGal level. However, since these events often repeat over time, their effects can cumulate significantly.

The gravity changes induced by continuous deformations and/or mass transfer have impact over large time spans and depend on the linearity or less of the inducing physical process. For example, PGR in the last years and subsidence due to water withdrawal are non-linear processes, and at present, they produce increasing rates of gravity changes. Secular processes (geodynamics, GIA, sea level) can be considered linear over larger time span, with rates of the order of a few μGal/year, so with a minor impact with respect to the previous ones. Therefore, the complete picture of the geophysical/geological behaviours in a complicated area like Italy can be achieved only by combining the essential information of geodetic deformations and continuous gravimetry with all the other sources of geophysical data as well as larger scale geophysical models.

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