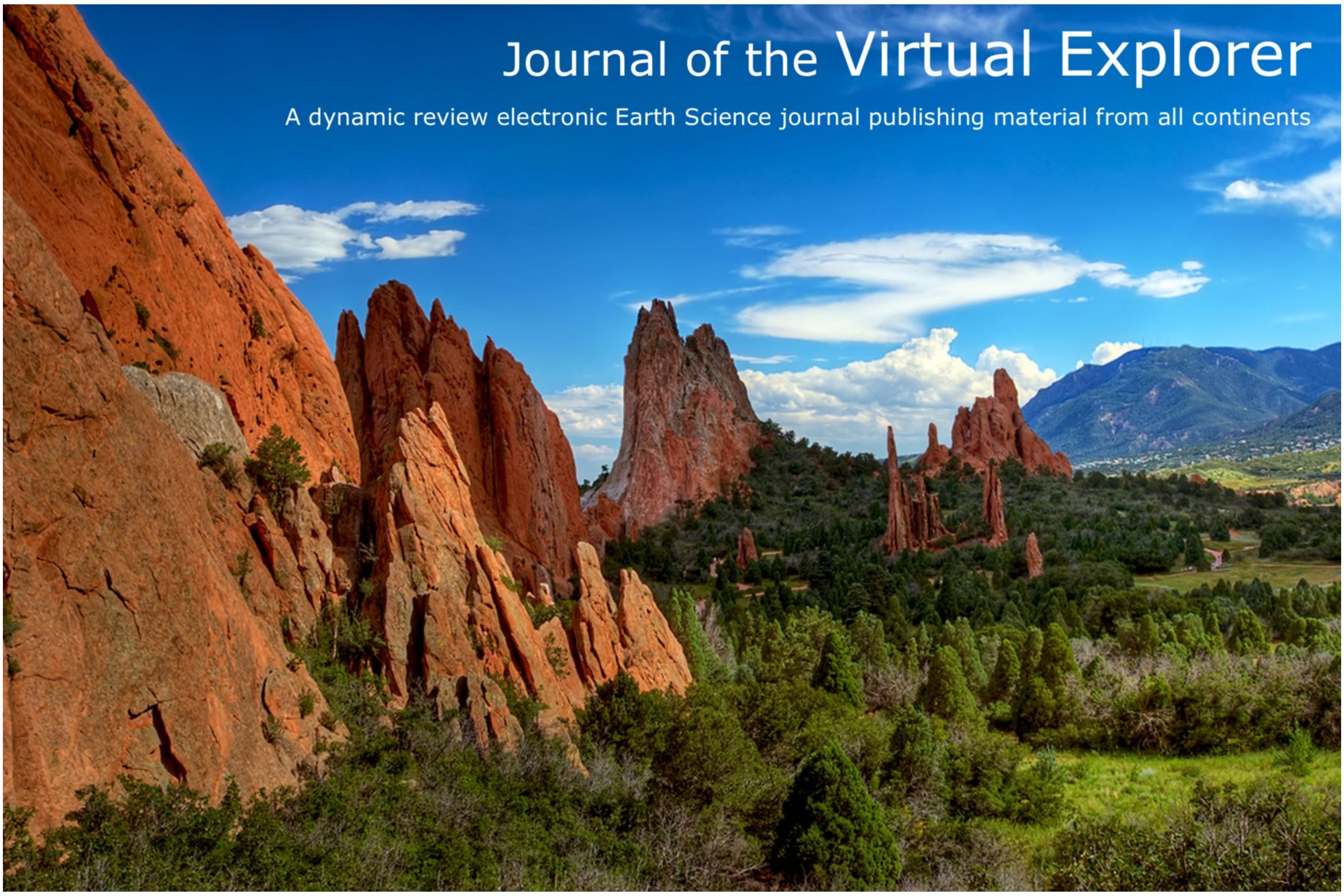

The timescale and spatial extent of recent vertical tectonic motions in Italy: insights from relative sea-level changes studies

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The timescale and spatial extent of recent vertical tectonic motions in Italy: insights from relative sea-level changes studies

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Abstract: Vertical tectonic displacements in Italy since 125 to 1 kyr BP are drawn from relative sea-level (RSL) history studies at coastal sites, and, together with instrumental observations, allow to bridge the gap with events recorded in the geologic (1 Myr) archive. Our analysis aims at establishing the appropriate spatial extent, rate and duration of vertical tectonic motion within individual crustal segments, and at placing constraints on the contribution to displacements coming from regional (deep) and local (shallow-crustal) sources. The central and northern Tyrrhenian Sea and the Ligurian Sea margins are nearly stable during the last 100 kyr, except for subsidence in coastal basins and uplift, at places high, at volcanic centers. On the contrary, sustained, large magnitude uplift of Calabria and eastern Sicily embeds a deep-seated contribution, highlighted by the spatial coincidence of the uplifting province with a lithospheric slab, and a contribution from local faults and folds. Holocene uplift was higher than uplift recorded by Middle-Late Pleistocene markers, and the rate of changes was tuned among all coastal sites. The recent increase in uplift rate, detected also in the instrumental record, is related to clustering of fault strain release, possibly triggered by the isostatic response to deglaciation. A weak deformation signal is recorded on the central Adriatic coastline, and may record slow Apennines thrust belt migration. In the northern Adriatic Sea, vertical tectonic motions result from opposite displacements in the Southern Alps, internal Dinarids and Northern Apennines, but flexure of the Adriatic (micro-) plate beneath the Northern Apennines appears the dominating contributor. Here, rate and spatial extent of displacements are steady over different time-scales, highlighting the control exercised by slab dynamics.

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Introduction

Although caught in between the steady-state relative convergence of the African and European continental landmasses, the Neogene history of Italy features smaller-scale orogenic segments where rapid thrust-belt motion, crustal thickening and back-arc thinning (Fig. 1) often overwhelmed the plate-scale signature (e.g. Carminati *et al.*, this issue). Depending on the timescale of observation and on the appropriate analytical tool, however, modes and rates of deformation in individual crustal segments can be established with variable accuracy and precision. Tectonic events occurring at the million-yr timescales have left their record in the geological archive of Italy, and rates of orogenic belt migration are relatively well established using syn-orogenic deposits (e.g. Patacca and Scandone, 2007) or ancient erosional and depositional surfaces (e.g. Ferranti and Oldow, 2005) as markers. Similarly, the pattern of contemporary deformation is well depicted by seismicity and geodetic (e.g. Fig. 2; Barba *et al.*, this issue; Devoti *et al.*, this issue) analysis. Unfortunately, geologic and modern motions are not always reconciled with ease, a pitfall occurring almost everywhere in the world.

This limitation particularly downgrades efforts seeking to compare rates and patterns of horizontal tectonic motion. Although the geological pattern can be compared to horizontal motions derived from GPS geodetic velocities (e.g. Oldow *et al.*, 2002; D’Agostino and Selvaggi, 2004; Serpelloni *et al.*, 2005; Ferranti *et al.*, 2008), the intervening time intervals from the 1 Myr to the present-day is left undisclosed, with fundamental drawbacks on understanding current geodynamic processes.

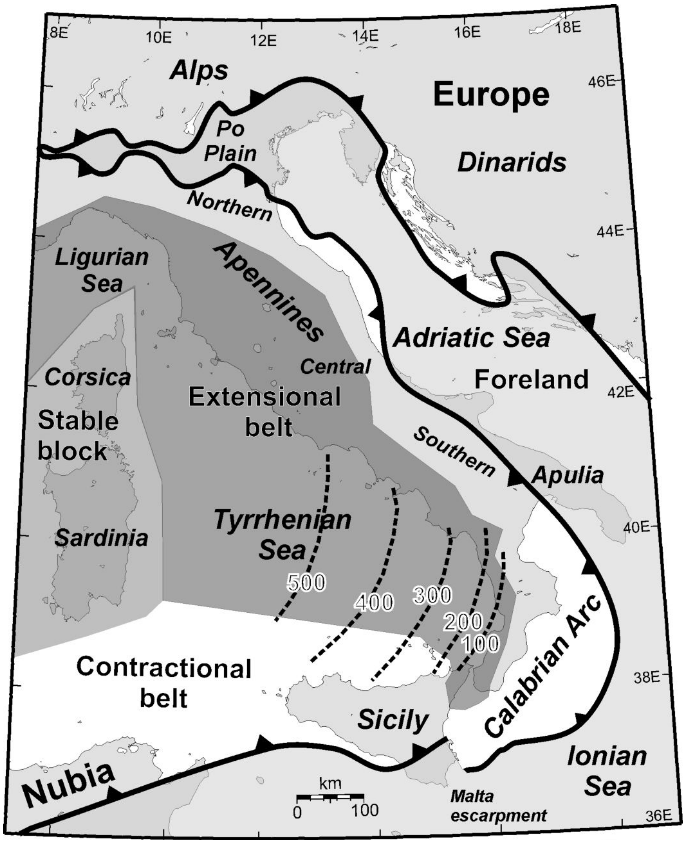
Fortunately, favourable outcrop conditions coupled to a long-lasting tradition of coastal studies in Italy has led to investigation of markers of ancient shorelines at several sites, covering the whole nation perimeter albeit with variable density. Appraisal of these paleo-geodetic markers occurrence in the context of the regional tectonic processes provides an unprecedented opportunity to assess and compare the extent, rate and duration of vertical tectonic displacements at what we may call the intermediate- (100 to 10 kyr BP) to short-term (10 to 1 kyr BP) timescales. In addition, the recent availability of high-quality geodetic data at costal sites (tide gauges and Global Positioning System, GPS, measurements) supplies a much needed snapshot on the contemporary pattern of deformation, provided that adequate corrections for non-tectonic effect are applied. Thus, information yielded from coastal tectonic analysis stands as vital in order to bridge the gap between events occurring at geologic (1 Myr) and contemporary timescales.

In this contribution, we deliver an overview of current vertical tectonic motions experienced by the nation coastline, mostly building upon studies carried by our group and by other researchers, to whom the reader is referred for detailed data analysis. Integration of morphotectonic, structural, geoarcheological and geodetic data is used to establish the appropriate spatial extent, rate and duration of vertical tectonic motion within individual crustal segments. What we are particularly interested in is to have clues on the timescale of rate changes by comparing intermediate and short-term rates in specific sectors. A second fundamental task is the search for different signals in the deformation pattern recorded by markers of past shorelines. Specifically, we are interested to establish whether the present position reached by these markers results from the aggregate contribution of processes operating at a regional or local scale (or both), and to stipulate the magnitude and spatial significance of each contribution. As a fundamental corollary, our analysis provides qualitative clues on the depth significance and driving mechanisms of deformation.

The paper is organized as follows. After a brief review of published studies on regional-scale relative sea-level (RLS) changes and coastal tectonics, we illustrate the intermediate and short-term pattern of deformation based on the Last Interglacial (Lig, 125 kyr BP) and Holocene (1-10 kyr BP) markers. Later on, we present instrumental (tide-gauge and GPS) approaches and observations on vertical displacement and RSL changes. These different datasets are blended together in the discussion chapter.

As this review will show, we found that regional tectonic processes are substantially halted in the central and northern Tyrrhenian Sea margins, but local mechanisms continue to operate. Differently, the pattern of displacement in the Calabrian arc highlights the contribution of both regional and local processes to deformation. The finding of recent changes in deformation rates in Calabria, which is possibly accommodated by a large part of the local structures mapped or inferred in the on-land territory and offshore, allows to understanding the appropriate time-scale of changes in stick-slip motion. A third instructive case history is represented by the northern Adriatic Sea margins, where no rate changes have occurred at the regional scale, suggesting that major geodynamic processes are controlling the deformation pattern.

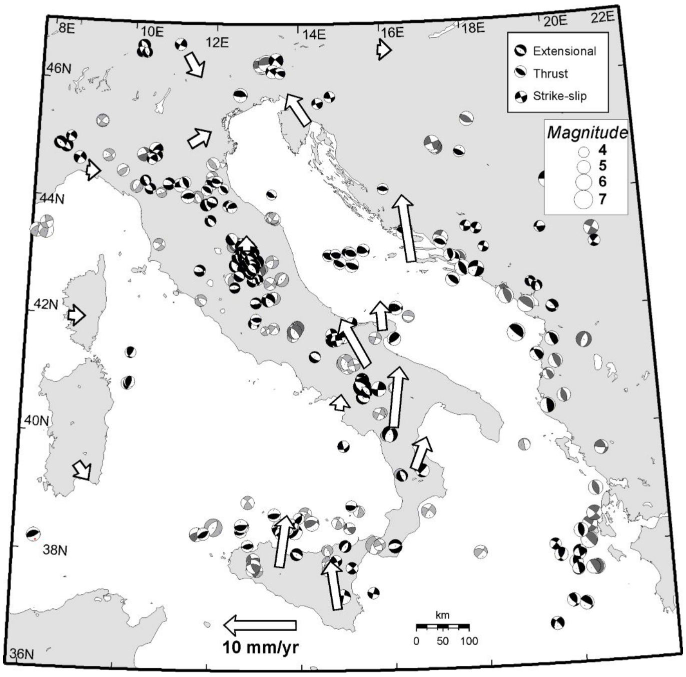
Figure 1. Major tectonic domains of Italy



Adriatic foreland, contractional and extensional belts, and stable block, indicated by light grey, white, dark grey and medium grey, respectively (slightly modified after Antonioli *et al.*, 2009). Dashed lines in southern Tyrrhenian sea indicates the depth (in km) of the Benioff zone (Giardini and Velonà, 1988; Selvaggi and Chiarabba, 1995).

It is not superfluous to note that accurate and precise determination of intermediate- and short-term markers of deformation is of paramount importance in active orogens with relatively low displacement rates, such as those encountered in the Central Mediterranean Sea (Devoti *et al.*, this issue). Although historic observations and instrumental data are of prime quality in Italy, they have still limited capability of capturing the entire extent of cyclic deformation processes such as seismicity. On the contrary, coastal tectonic analysis may provide vital information on the seismic cycle for particular areas or structures and the relative role of seismogenic versus regional processes, with profound implications on seismic potential determination.

Figure 2. Active deformation in Italy.



Beach-balls are focal solutions of M>4 earthquakes (black: 1976-2004 Harvard - http://www.seismology.harvard.edu/CMTsearch.html - and 1997-2004 Mednet - http://mednet.ingrm.it/ - CMT catalogues; light grey: Gasparini *et al.*, 1985; medium grey: Anderson and Jackson, 1987). Arrows are generalized GPS velocities with respect to stable Europe (Oldow *et al.*, 2002). Depth of the Ionian slab as in Fig. 1.

Regional studies on coastal tectonics in Italy

Existing studies of vertical displacements at the Italian coasts have used markers of different age, but two relatively well dated shorelines stands as the prominent benchmarks, namely the Last Interglacial (LIg) and the Holocene strandlines.

The LIg shoreline coincides with the Marine Isotope Sub-stage (MIS) 5.5, which occurred between 132 and 116 kyr (Shackleton *et al.*, 2003), and is thus representative of the intermediate-scale displacements. Along the coasts of the Italian peninsula and islands, the recognized altitude variability of the marker was attributed to tectonic processes, which resulted in differential displacements relative to the predicted eustatic position. Studies dating back to several decades have detailed this occurrence at numerous sites (see references quoted in Ferranti *et al.*, 2006). In the final decade of the last century, pioneering review studies [Cosentino and Gliozzi, (1988) and Bordoni and Valensise (1998), based on the LIg marker; Westaway (1993) and Miyauchi *et al.* (1994), using the LIg and Middle Pleistocene shorelines] outlined the tectonic displacements occurring at a regional scale in central-southern Italy, and particularly in the Calabrian arc (Fig. 1) where displacement rates are higher. The pattern of rapid uplift was attributed to isostatic or dynamic processes occurring in the lithospheric slab underlying this region (Fig. 1; Cosentino and Gliozzi, 1988; Westaway, 1993). Bordoni and Valensise (1998) in their review of the LIg displacement outlined the interplay between regional and local tectonics to explain the large variability in amplitude and wavelength of the elevation pattern in different parts of southern and central Italy.

Ferranti *et al.* (2006) provided an updated review of the LIg shoreline position to detect the vertical component of tectonic displacement along the whole coastline of Italy in the last 130 kyr. They used the shoreline displacement drawn from published and in few occurrences from new work, as a means to provide accurate displacement rates and verify existing tectonic models. Using a compilation of 246 sites, Ferranti *et al.* (2006) observed a significant alongshore difference in site elevation between +175 and –125 m respect to the present sea level, which they attributed to the combination of regional and local processes, including faulting and volcanic deformation. They found that whereas most of Sardinia and the northern Tyrrhenian Sea coasts are tectonically quiescent, the central Tyrrhenian Sea coasts display stable promontories, subsiding plains, and localized centres of weak uplift. Subsidence of the plains was related to extensional faulting locally enhanced by volcano-tectonic collapse, and weak uplift arises from magmatic unrest. Rapid uplift of southern Calabria, northeast Sicily and the Ionian sea coasts was viewed as a response to deep crustal delamination beneath the Calabria forearc terrane. The central Adriatic Sea was found to show weak thrust-related uplift, but foreland flexure in northern Adriatic resulted in locally intense regional subsidence. The rapidly uplifting regions were spatially correlated with the sectors of higher seismic release and surface horizontal motion documented by geodetic velocities, underlining the four-dimensional nature of deformation.

Other studies in the intervening time have detailed the position of the LIg shoreline at few more locales. New LIg data, mostly from the Venetian plain, were provided by Antonioli *et al.* (2009) in their recent analysis of Holocene relative sea-level changes along the Italian and Istrian coastlines. In the south, along the Ionian Sea coast of northern Calabria and Lucania, Westaway and Bridgland (2007), Santoro *et al.* (2009), Ferranti *et al.* (2009) and Caputo et al (2010) have provided new observations on Middle Pleistocene and LIg shoreline position. The works of Santoro *et al.* (2009) and Ferranti *et al.* (2009) have shown that a regional and a local component are embedded in the deformation profile of Middle-Late Pleistocene marine terraces in north-eastern Calabria. The magnitude of the regional component is almost four times greater than the local component, the latter being attributed to growing folds within a transpressive displacement field. Further to the north, different interpretation of the displacement pattern were published by Westaway and Bridgland (2007) and Caputo et al (2010) in eastern Lucania. Whereas the first authors highlighted the thermal response to sediment load in promoting crustal uplift through lower crustal flow directed beneath regions of prevailing erosion, the latter have stressed the contribution of deep crustal and lithospheric contraction versus shallow-crustal folds. Along the Tyrrhenian sea coast of Calabria, Cucci and Tertulliani (2006) have provided an updated review of Pleistocene coastal terraces at Capo Vaticano (following previous work by Miyauchi *et al.*, 1994 and by Tortorici *et al.*, 2003) and identified the contribution of a local extensional fault as being lower than regional uplift. New studies on coastal tectonics in Italy have recently appeared on a Special Issue of Quaternary International (Antonioli *et al.*, 2011).

Short-term markers of deformation are represented by Holocene shorelines and geoarcheological markers of sea-level changes. Pioneering works of synthesis on Holocene displacements in the Calabrian arc were carried by Pirazzoli *et al.* (1997), Lambeck *et al.* (2004), and Antonioli *et al.* (2006). The latter authors found average uplift rates during the Holocene were consistently higher (64 to 124%) than longer-term rates, but the location of sites having the fastest Late Pleistocene and Holocene uplift rates spatially coincide.

Lambeck *et al.* (2004) published a review of the last 12 kyr relative sea-level changes in Italy and used the elevation of the LIg marker as a benchmark to assess tectonic stability at individual coastal sites. Most of the 27 sites investigated by Lambeck *et al.* (2004) were located along tectonically stable coasts. A more comprehensive review of the Holocene displacement was provided by Antonioli *et al.* (2009), using more than 100 sites in stable, uplifting and subsiding regions. Antonioli *et al.* (2009) afforded a first comparison with intermediate-scale rates provided by published and new LIg markers, and with instrumental record provided by tide-gauges and levelling measurements in Calabria and NE Italy. A more updated compilation has been presented by Lambeck *et al.* (2011) using improved glacio-hydro isostatic model parameters. Differences between observed and predicted sea level changes were interpreted as reflecting Late Holocene vertical tectonic contributions at more than 456 sites (211 for the Holocene and 255 from the LIg).

These review works on Holocene displacement have estimated the averaged tectonic motion, but have not assessed whether different sources (e.g. due to regional or local processes) contribute to displacement. Only in few case-studies in the Calabrian arc (de Guidi *et al.*, 2003; Ferranti *et al.*, 2007; Scicchitano et al, 2011) it was possible to quantify the contribution of stick-slip, co-seismic displacements versus regional, steady displacement.

Regional tectonic setting

The central Mediterranean area marks the broad collisional boundary between the African and the Eurasian plates. The geodynamic characteristics of this region are driven by lithospheric blocks showing different structural and kinematic interaction, including subduction, back-arc spreading, and fold-and-thrust belt development (Fig. 1). The active dynamics of Italy is shown by the distribution of seismicity and GPS velocities fields, which outline the major deformation belts of the Alps and of the Apennines in peninsular Italy and Sicily (Fig. 2).

The transition between the Apennines and Western Alps occurs north of the Ligurian Sea (Fig. 1). In contrast, the Adriatic Sea and surrounding promontories represent the remaining part of the Adriatic lithospheric block caught between Europe and Africa and serving as the foreland domain of the Southern Alps, Dinarids and Apenninic thrust belts (Fig. 1; Royden *et al.*, 1987; Carminati *et al.*, this issue). Similarly, the Ionian Sea straddles the transition between the front of the Hellenids and Apennines across the Adriatic continental and Ionian transitional or oceanic lithosphere.

The Tyrrhenian back-arc basin opened and migrated eastward behind the Apennines in the wake of the retreating Adriatic–Ionian slab (Malinverno and Ryan, 1986). Today, seismic tomography and deep earthquakes beneath the south-eastern Tyrrhenian Sea identify the subducted Ionian slab (Fig. 1; Selvaggi and Chiarabba, 1995; Chiarabba et al., 2008). During Quaternary, the eastern and southern margin of the Tyrrhenian basin experienced extension, which was locally accompanied by volcanism (Conticelli *et al.*, this issue). Displacement along normal faults articulated the Tyrrhenian coast of mainland Italy and Sicily in a complex alternation of subsiding basins and uplifting rocky promontories (Mariani and Prato, 1992; Ferranti *et al.*, 2006; Acocella and Funiciello, 2006).

Calabria and north-eastern eastern Sicily form the Calabrian Arc, which represents a forearc terrane emplaced above the NW dipping-Ionian slab (Fig. 1). During Quaternary, the entire region experienced vigorous uplift (Westaway, 1993; Miyauchi *et al.*, 1994) accompanied by extensional faulting along the Tyrrhenian Sea margin and the chain axis (Ghisetti, 1992; Monaco and Tortorici, 2000). Seismogenic normal faulting is still acting today (Fig. 2). Uplift and attendant extension are interpreted as a response to stalling of slab retreat and consequent asthenospheric flow into the gap resulting from slab detachment (e.g. Westaway, 1993; Wortel and Spakman, 2000), as being supported by asthenosphere wedging beneath the decoupled crust (Gvirtzman and Nur, 2001), or as due to viscoelastic response to enhanced erosional flux from land to sea following the onset of glacial-interglacial cycles (Westaway and Bridgland, 2007). At the borders of the uplifting regions, recent shortening is recorded by morphotectonic, seismicity, and geodetic studies in northern Calabria-Basilicata (Ferranti *et al.*, 2009; Caputo *et al.*, 2010) and in northern Sicily (Pondrelli *et al.*, 2006; Hollenstain *et al.*, 2003; Argnani *et al.*, 2007; Ferranti *et al.*, 2008; Mattia *et al.*, 2009).

The islands of Sardinia and Corsica are a detached fragment of the Alpine foreland and orogenic belt (Patacca and Scandone, 2007). The western and eastern side of this block have been effected by extensional tectonics related to the Oligocene–Miocene Ligurian–Balearic and Miocene–Pliocene Tyrrhenian sea rifting, respectively (Fig. 1). Today, both islands appear tectonically stable as indicated by the negligible seismicity rate (Barba *et al.*, this issue). Regional geodetic networks show that the block is not moving with respect to Europe (Devoti *et al.*, this issue), although limited horizontal residual motions occur in southern Sardinia (Ferranti *et al.*, 2008) as a result of relative convergence with Sicily.

Methods

We use a compilation of data on RSL changes drawn from previously published papers, and specifically from Ferranti *et al.* (2006), Antonioli *et al.* (2009) and Lambeck *et al.* (in press) for Late Pleistocene and Holocene data. The nature, accuracy and precision of observational data have been discussed at length in the quoted papers, to which the reader is referred for a thorough discussion. These information are briefly summarized in the following.

Markers attributed to the LIg are represented by notches, marine terraces, beach deposits, speleothem concretions, boreholes of molluscs living in the spray zone of rocky cliffs and, for subsiding regions, wells to depths of 100 m or deeper. These same kind of markers are used for the Holocene, with the addition of barnacle rims and lagoonal layers in shallower wells.

The uncertainty of sea-level positioning is constrained by the precision of the measurement, the accuracy with which the position of the indicator with respect to the paleo-sea-level is determined (which depends on the type of marker, see Ferranti *et al.*, 2006; 2007), and the precision of the age of the indicator (the latter determined by radiometric, ecostratigraphic and geomorphologic techniques). Ecostratigraphy for the LIg terraced deposits relies on the index fossil Strombus bubonius and is less reliable when only barren ‘‘senegalaise fauna’’, which includes species still living today, occur. The accuracy of the paleo-sea level position is the most difficult to model and suffers of variable uncertainty. Scrutiny of the present occurrence of markers as well as the sea-floor topography helps in circumventing this problem. Also, errors in marker recognition can exist, as, for instance, inferred markers can be displaced above their coeval sea-level by processes other than tectonics. Fortunately, large tides and extreme storms are very infrequent in the central Mediterranean and were probably so in the Holocene.

For the Latest Holocene, a wealth of coastal archaeological indicators are available in Italy (fish-tanks, harbours, piers, and, with a greater uncertainty, quarries and tombs). The use of archaeological data for sea-level studies is afforded by definition of the "functional height" as the elevation of specific architectural parts of an archaeological structure with respect to an estimated mean sea level at the time of their construction. Antonioli *et al.* (2007; 2009) and Scicchitano *et al.* (2008), applied these observational constraints to estimate relative sea level changes and tectonics in Sardinia and eastern Sicily.

The vertical tectonic motion is stipulated as the residual between the observational data and the eustatic position predicted from global sea-level curves (e.g. Waelbroeck *et al.* 2002) and, for Holocene markers, from glacio-hydro-isostatic predicted sea-level curves specifically built for this region (Lambeck *et al.*, in press). At the Mediterranean coasts, the average level attained by the sea during the LIg is inferred to be 6±3 m relative to the present sea position (Lambeck *et al.*, 2004; Ferranti *et al.*, 2006). During the Holocene, the position of the sea at any time changed along the coast as a result of the Glacial Isostatic Adjustment (GIA) that accompanied and followed the melting of the Late Pleistocene ice sheets, which is a dominating component on global scale, and the response to the ocean floor loading by the melt water – the glacio-hydro-isostatic and eustatic contributions (Lambeck *et al.*, 2004; in press). Crustal loading during 120 m of eustatic sea-level variation is on the order of a few metres (e.g. Lambeck *et al.*, 2004). In this paper, the GIA contribution to Holocene observational data is subtracted using the Lambeck *et al.* (in press) model prediction. On the other hand, this correction is not applied to Lig data, because for the complete glacial-interglacial cycle, given the range of observed elevations of Lig markers up to over 100 m, the GIA contributes little to the total uncertainty.

In a later chapter, data from GPS and tide-gauges are used to snapshot some contemporary trends in vertical crustal motion that can be compared to geological and archaeological rates.

Analysis of intermediate to short-term displacement within individual crustal segments

The altitude of LIg and Holocene markers varies along the coastline of Italy, and this occurrence stems from different sources including regional and local tectonic processes, hydro-isostatic adjustments to deglaciation, sediment constipation, and, for the more recent times, from anthropogenic causes. In the following, the rates established on the elevation of the LIg and Holocene markers are outlined in specific sectors, which are selected on the basis of the known past and ongoing crustal deformation processes. Analysis of the spatial and temporal variability of displacement rates along these crustal sectors is carried with the aim of placing constraints on different tectonic contributions to coastline displacement. Because the present paper is intended as a national review, in the following paragraphs the primary straightforward interpretations for individual situations are illustrated along with data presentation, whose detailed discussion is presented in the quoted analytical publications. A short summary is attached at the end of each paragraph. In the later Discussion section, an interpretation of the emerging pattern is illustrated at a broader scale blending together geological and instrumental data.

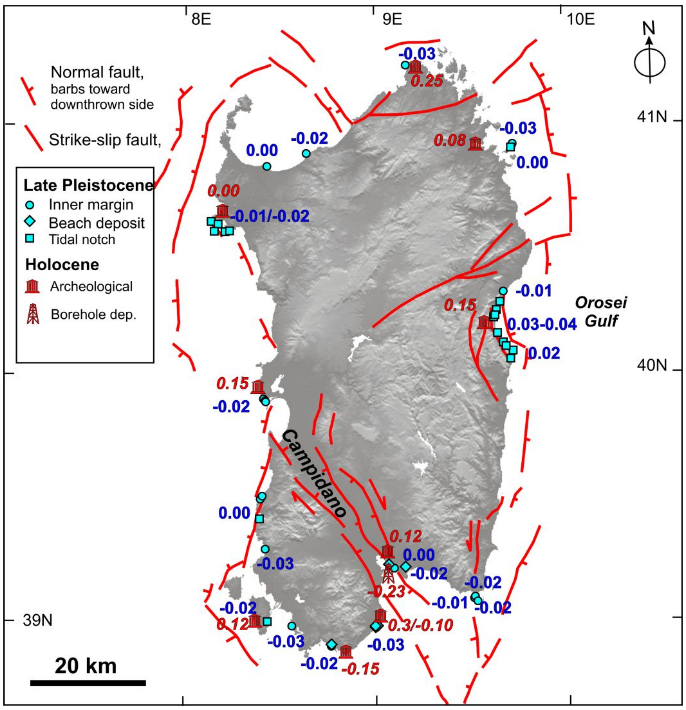
Sardinia margins.

From Sardinia, an extensive number (58) of LIg sites are known (Fig. 3), where the marker elevation has the lowest variability among the nation coastline of between 2-10 m, and therefore it was chosen as reference site for the LIg eustatic elevation (Ferranti *et al.*, 2006; Lambeck *et al.*, 2004; in press). Within this generally stable setting, minor but consistent patterns of vertical motions at metre scale were detected. Extremely slow subsidence occurs on the NW (Ferranti *et al.*, 2006), indicative of block motion possibly accommodated by fault creeping or sliding associated with the Ligurian continental margin. In the central segment of the eastern coast (Orosei Gulf, Fig. 3), uplift of the LIg marker at a comparably low rate forms a bulge which has been associated with upward welling of magma in the nearby offshore (Ferranti *et al.*, 2006; Mariani *et al.*, 2009).

Archaeological markers (numbering 12) of between 2.5 and 1.6 Kyr BP indicate Late Holocene stability or weak uplift (0.1–0.25 mm/yr) at several locations along the coast (Antonioli *et al.*, 2007). A core recovered near the town of Cagliari shows Holocene subsidence at an average rate of 0.23 mm/yr (Lambeck *et al.*, in press, and references therein), which, given the pattern of nearby sites (Fig. 3), is likely due to sediment compaction. In general, it appears that Holocene rates are slightly higher than LIg data and predominantly positive (Fig. 3), perhaps due to the larger uncertainty in estimating paleo-shoreline from archaeological markers.

All in all, LIg and Holocene data in Sardinia reveals a general stability with only localized coastal tectonic motions. Given the robust control provided by the LIg marker, it is possible to isolate the different, very localized contributions of block sliding (or fault creeping) in the north, sediment compaction in the south, and volcanic bulging in the east.

Figure 3. Vertical displacement rates in Sardinia.



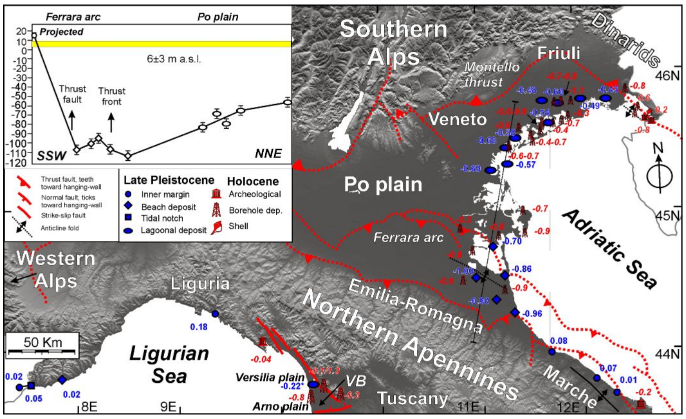
Vertical displacement rates (mm/yr) computed from the elevation of Late Pleistocene and Holocene markers plotted with main faults on a DEM of Sardinia (slightly modified after Ferranti *et al.*, 2006).

Ligurian Sea margin

The Liguria region margin features a rugged topography with coastal ranges limited by sheer cliffs (Fig. 4), but large recent displacements are not present. The little information (5 sites) available from the LIg marker indicates mild uplift of the eastern coast at ~0.2 mm/yr (Federici and Pappalardo, 2006), and an almost stable western coast (Roveri *et al.*, in press). Likewise, a geoarcheological indicator in eastern Liguria suggests almost negligible subsidence at 0.04 mm/yr (Antonioli *et al.*, 2009).

It is known that the eastern Liguria Apennines experienced Quaternary surface uplift at 1 mm/yr (Bernini and Papani, 2002), and seismicity documents that extension is still active in the east (Fig. 2). However, coastal markers indicate that the margin to the west is quiet.

Figure 4. Vertical displacement rates in northern Italy.



Vertical displacement rates (mm/yr) computed from the elevation of Late Pleistocene and Holocene markers plotted with main thrust faults and folds on a DEM of northern Italy. Rate value with asterisk in Tuscany is established on pre-Lig strata in borehole. VB=Viareggio basin. Inset shows section of Lig marker elevation across the front and foredeep of the Northern Apennines (trace indicated by thin solid line) (slightly modified after Ferranti *et al.*, 2006).

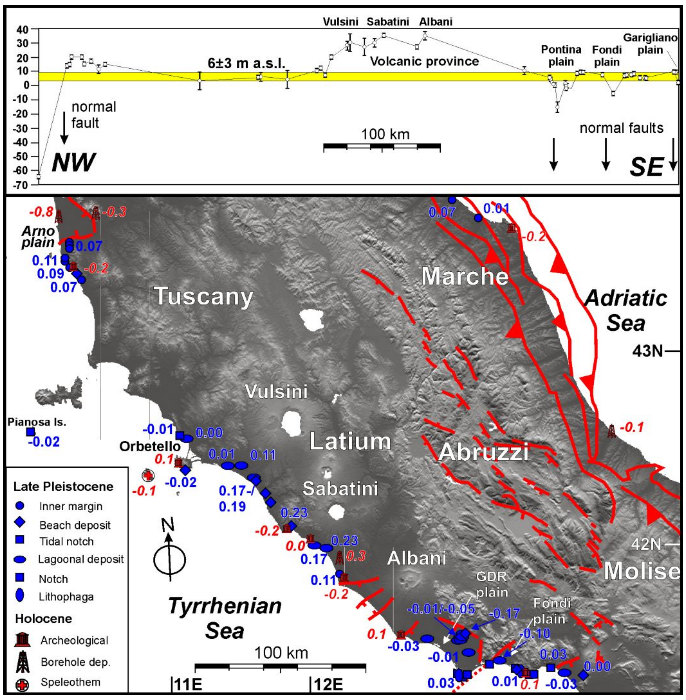
Eastern Tyrrhenian Sea margin, northern sector.

The Tyrrhenian Sea margin stretching from the administrative regions of Tuscany in the north and northern Calabria in the south, is characterized by the the alternation of coastal promontories and plains, shaped by extensional faults that have caused horizontal displacements both orthogonal and parallel to the margin (Mariani and Prato, 1988; Ferranti et al 1996; Acocella and Funiciello, 2006).

In northern Tuscany, the Viareggio half-graben basin (Argnani *et al.*, 1997) and ancillary basins in the interior (Fig. 4) are bordered by normal faults whose activity shifted in space during Late Neogene, and also tuned the Quaternary subsidence pattern (Aguzzi *et al.*, 2007). Geophysical explorations indicate that the recent-most activity was segregated along the southern border of the basin, which is limited by a NE-SW striking fault (Cantini *et al.*, 2001) (Fig. 4).

A very mild subsidence (0.25 mm/yr; Fig. 4) of the northern part of the basin (Versilia coastal plain) during the last 200 kyr is documented from borehole data (Antonioli *et al.*, 2009), and thus LIg to Holocene stability was supposed at the same location (Lambeck *et al.*, 2004; in press). In the south (Arno river plain: Aguzzi *et al.*, 2007), borehole data analysis (Fig. 4; Lambeck *et al.*, in press) yields Holocene subsidence at rates ranging from ~0.2-0.3 (core CC, in the interior) to ~0.8 mm/yr (core M1, near the coastline), the latter being comparable to the long-term value in the same core (Antonioli *et al.*, 2009).

Figure 5. Vertical displacement rates in central Italy.



Vertical displacement rates (mm/yr) computed from the elevation of Late Pleistocene and Holocene markers plotted with main faults on a DEM of central Italy. GDR=Giuliano di Roma. Inset shows coast-parallel section of Lig marker elevation on the Tyrrhenian coast (slightly modified after Ferranti *et al.*, 2006).

It is thus reassessed that recent subsidence in the south may stem from focused activity on the border fault outlined by gravity anomalies and alignment of moderate-size earthquake epicenters (Cantini *et al.*, 2001). Post-100 kyr BP activity of this fault was previously supposed based on the elevation of the LIg marker just to the south of the basin, where it was uplifted to 15-20 m a.s.l. before tailing to a background value further to the south (Fig. 5). Uplift at up to ~0.1 mm/yr was related to flexural unloading in the footwall of the bordering fault (Ferranti *et al.*, 2006). Flexural models (King *et al.*, 1988) predict that the subsidence-to-uplift ratio along normal faults, although locally varying as a function of integrated co- and post-seismic slips, and of the thickness and thermo-mechanical behaviour of the brittle layer and lower crustal flow induced by sediment load redistribution, is typically in the order of 3. Thus, a ~0.3 mm/yr subsidence in the Arno plain could have been predicted on the basis of the tectonic displacement experienced by the footwall crest. Based on this, it is further inferred that the site having this subsidence value (core CC) shows a true tectonic signal, whereas the core with higher subsidence (M1) may reflect an additional component, likely deriving by its estuarine, constipation-prone location (Fig. 5).

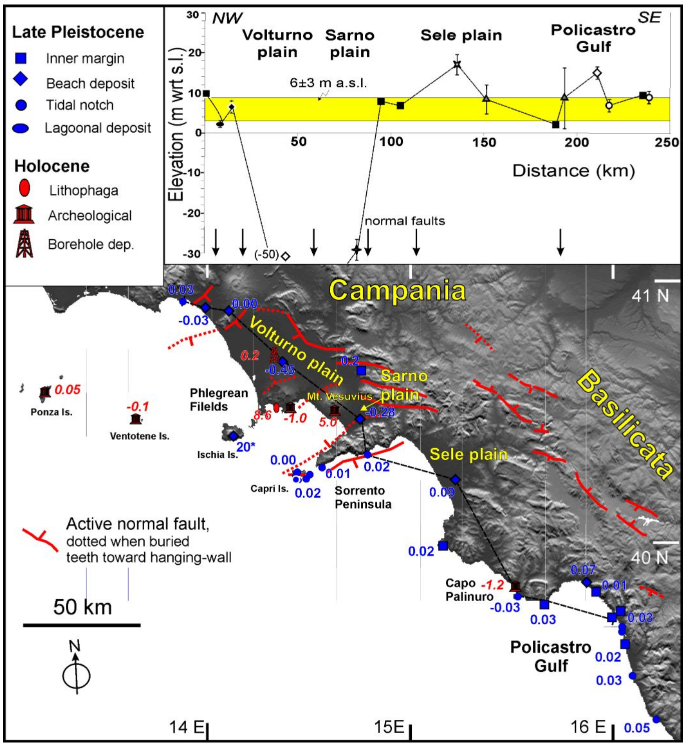
The central part of the margin between central Latium and Campania regions is characterized by a Quaternary volcanic province whose activity has been progressively shifting southward in time (Barberi *et al.*, 1994). Appraisal of the marker elevation (Bordoni and Valensise, 1998; Ferranti *et al.*, 2006) is consistent with the volcanological observation. Specifically, whereas in southern Tuscany and northern Latium (near the Orbetello promontory and at Pianosa island, Fig. 5) intermediate- and short-term markers suggest stability or a extremely slow subsidence, from the Sabatini to the Albani volcanic complex the LIg marker forms a 150 km-wavelength bulge at 0.1-0.2 mm/yr related to magmatic injection beneath the 420 kyr vents (Bordoni and Valensise, 1998; Karner *et al.*, 2001; Nisi *et al.*, 2003), and with spikes deriving by the interference between the different volcanic complexes (section in Fig. 5). The Holocene marker provides contrasting results (Fig. 5). Archaeological markers show slow subsidence, and this would be consistent with cessation of significant volcanic activity by ~20 kyr (Barberi *et al.*, 1994). On the other hand, borehole analysis from the Tiber river mouth provides mild uplift at ~0.3 mm/yr, in a manner consistent with the Lig trend.

South of the volcanoes, between southern Latium and northern Campania, the pattern of subsidence in the plains and stability on the rocky promontories typical of the eastern Tyrrhenian coast is evidenced by the LIg (Nisi *et al.*, 2003; Ferranti *et al.*, 2006) and Holocene (Lambeck *et al.*, 2004; in press) markers, and is consistent with the assessment that the faults bordering the promontories are not considered to be active (GNDT, 2000). Perhaps, only the fault bordering the Giuliano di Roma and Fondi plains (Fig. 5), in light of the higher long-term subsidence (0.10-0.17 mm/yr) recorded in the plains, have a tectonic component of displacement (see also Acocella and Funiciello, 2006). Elsewhere, the mild subsidence at between 0.01-0.03 mm/yr in the plains probably results from sediment constipation.

Eastern Tyrrhenian Sea margin, southern sector.

The LIg marker indicates that the pattern of stability in the promontories and subsidence of the plains exists also in the southern part of the margin accompanied, as in the north, by significant volcano-tectonic deformation in central Campania region (Fig. 6). Unlike Latium region, however, where volcanic uplift prevails, the pattern occurring in Campania is generally of subsidence induced by faults and secondarily by magma chambers withdrawal and soil compaction, with localized exceptional uplift driven by volcanic processes.

Figure 6. Vertical displacement rates westen southern Italy.



Vertical displacement rates (mm/yr) computed from the elevation of Late Pleistocene and Holocene markers plotted on a DEM of of Campania and Tyrrhenian Basilicata. Rate value with asterisk at Ischia is established on 33 Kyr deposits. Inset shows coast-parallel section of Lig marker elevation (slightly modified after Ferranti *et al.*, 2006).

In the wide Volturno coastal plain north of Naples (Fig. 6), the LIg marker retrieved in borehole provides an average subsidence rate of ~0.5 mm/yr between ~125-40 kyr BP. The depth at which younger (inferred MIS 3, Romano *et al.*, 1994) marine deposits are found in the same core suggests a half subsidence rate (0.2–0.3 mm/yr) for the last ~40 kyr. On the ridges bordering the plain to the east, the LIg marker was reportedly found above eustatic prediction (Ietto and Sgrosso, 1963; Romano et al., 1994), yielding a ~0.3 mm/yr uplift rate. Because ridges and plains are limited by extensional faults (Fig. 6), these might be active. It is possible, however, that the recentmost subsidence might have been fostered by volcano-tectonic collapse following emplacement of the Campanian Ignimbrite from a complex fissural center located in the Phlegrean Field volcanic district around 37 kyr ago (De Vivo *et al.*, 2001). The slowing down-subsidence trend is confirmed by dated wood fragments in lagoon deposits (Barra *et al.*, 1996), which indicate tectonic stability or even weak uplift at ~0.2 mm/yr during the last 5 kyr (Fig. 6).

Within or very near to the Phlegrean Field caldera centre, dramatic uplift is associated to local volcanic processes. Uplift of the Ischia island at over 20 mm/yr during the last 33 kyr (Barra *et al.*, 1992) is attributed to block resurgence inside a pre-existing caldera (Orsi *et al.*, 1991). Today, large subsidence at Ischia is indicated by SAR and terrestrial levelling data (Manzo *et al.*, 2006), with a lower bound value related to fault activity and/or de-pressurization of the hydrothermal system. Historical uplift at the famous site of Pozzuoli was investigated since Lyell (1830) times and interplayed with subsidence as a result of shallow magma injection and withdrawal, at an average uplift rate of ~9 mm/yr (Morhange *et al.*, 2006). Conversely, stability or slow subsidence is found at the Ponza and Ventotene islands further offshore (Fig. 6).

In the east, at Mt. Vesuvius volcano a ground uplift event of ~30 m is documented in the last 6 kyr, at an average rate of ~5 mm/yr (Marturano *et al.*, 2009). In between the two uplift patches of Phlegrean Field and Vesuvius, the city of Naples experienced Late Holocene subsidence at ~1 mm/yr (Fig. 6; Cinque *et al.*, in press). Subsidence since the LIg is found in borehole within the Sarno plain, south of Mt. Vesuvius volcano (Barra *et al.*, 1991), at a rate (0.28 mm/yr) comparable to the Volturno plain in the north. South of there, in the Sorrento peninsula, the LIg marker indicates stability (Fig. 6), although very slow fault motion or creep is evidenced at Capri (Ferranti and Antonioli, 2008). The pattern evidenced at Capri and in the Sorrento peninsula is of minimal tilt to the NW, consistent with the geological structure (Fig. 6).

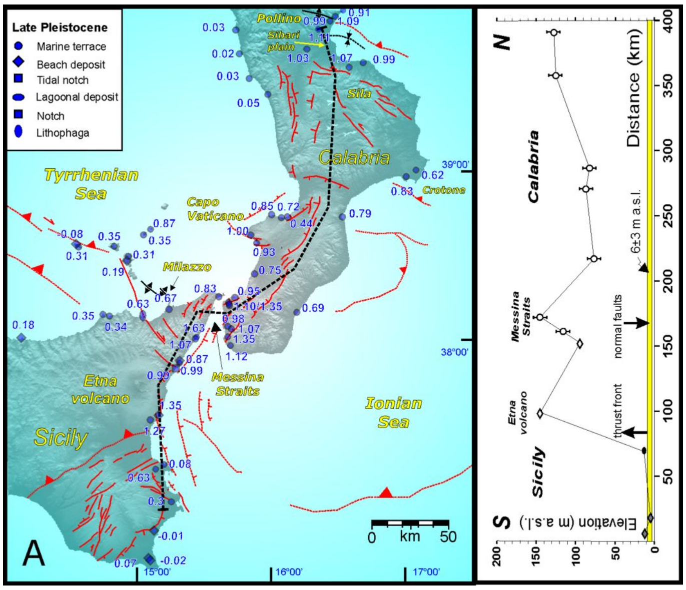
In summary, the elevation pattern of the LIg and younger markers indicates long-term subsidence in the plains at 0.3-0.5 mm/yr (with a slowing-down trend in the north), stability but possibly retailing of the promontories, and dramatic uplift followed by moderate subsidence in the volcanic areas.

A different history of vertical displacement is found in southern Campania, where the Late Pleistocene strandlines indicate generally weak uplift at up ~0.1 mm/yr and only locally subsidence (Ferranti *et al.*, 2006; and references therein). Due to the very low rate, no information is provided by the Holocene marker, although local subsidence is inferred at Capo Palinuro based on archaeological data (Lambeck *et al.*, in press), in a manner consistent with the Lig marker (Fig. 6).

Calabrian Arc

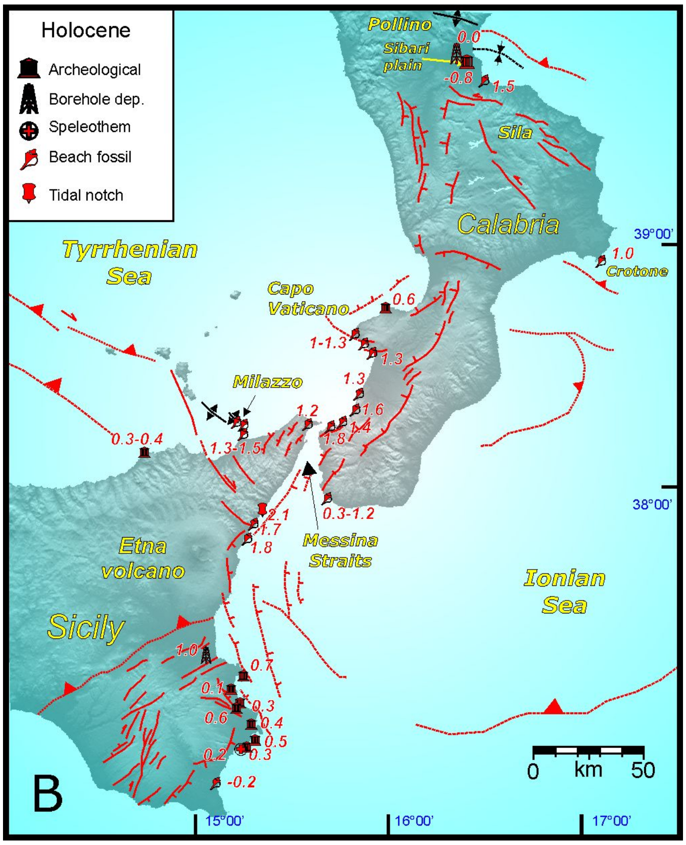
On the Tyrrhenian Sea side of Calabria (Fig. 7a), the LIg marker elevation (Ferranti *et al.*, 2006, and references therein) provides average uplift rates which peak abruptly at Capo Vaticano (~0.6-1.2 mm/yr, and up to 2 mm/yr according to Tortorici *et al.* 2003) and again to the south in the Messina Straits (~1.0-1.4 mm/yr) between Calabria and Sicily. Along the eastern Sicily coast, rate decreases steadily south of the Messina Strait and attains a quasi-eustatic elevation at the southern tip of the island (Antonioli *et al.*, 2006).

Figure 7a. Vertical displacement rates in the Calabrian Arc.



The uplift pattern in this province of active extensional faulting (Fig. 7a) has been related to the interplay between regional and local (i.e. fault related) components of vertical displacement. Much of the so-called regional uplift is associated with the subducted Ionian slab (see Fig. 1; Cosentino and Gliozzi,1988; Miyauchi *et al.*, 1994; Bordoni and Valensise, 1998), and a smaller fraction, estimated from offset terraces across the main faults, to upper crustal rebound in the footwall of extensional faults (Westaway, 1993; Tortorici *et al.*, 2003; Catalano *et al.*, 2003; Ferranti *et al.*, 2007; 2008b). During the last 125 kyr, whereas regional uplift is estimated at 1 mm/yr, footwall uplift for individual faults was typically ~0.2 mm/yr on average (Westaway, 1993; Catalano *et al.*, 2003), but might have peaked to 1 mm/yr during limited time intervals of clustered slip (Ferranti *et al.*, 2007; Tortorici *et al.*, 2003).

Figure 7b. Vertical displacement rates in the Calabrian Arc.



Vertical displacement rates (mm/yr) computed from the elevation of Late Pleistocene (a) and Holocene (b) markers plotted with main structures on a DEM of Calabria and eastern Sicily. Main structures from Monaco and Tortorici 2000, Catalano *et al.*, 2003, Del Ben *et al.* (2007), Billi *et al.*, (2007), Argnani *et al.* (2007) and Ferranti *et al.* (2009).

Holocene uplift rates in the region were found to be nearly 50% higher than late Pleistocene rates (Pirazzoli *et al.*, 1997; de Guidi *et al.*, 2003; Antonioli *et al.*, 2006; 2009; Ferranti *et al.*, 2007), peaking at ~2 mm/yr in the Messina Strait and north-eastern Sicily (Figs. 7a; 7b). Higher Holocene rates have been attributed to clustered fault activity which equals regional displacements (Ferranti *et al.*, 2007). Both at the ~100 and the ~1 kyr BP scale, the uplift pattern in the Strait is asymmetric, with larger motion on the eastern (Calabria) side in the north and on the western side (Sicily) in the south, respectively. This occurrence may reflect the location of major faults and folds, albeit a contribution from the Etna volcano in the south is conceivable (Figs. 7a, 7b). Further south, along the SE Sicily coast, Holocene uplift rates decrease from 0.7-1 mm/yr between Catania-Siracusa and to 0.2–0.5 mm/yr and then to almost null south of Siracusa (Fig. 7b). The southward decreasing Holocene uplift pattern broadly mirrors the spatial trend evidenced by the LIg marker (Fig. 7a). These data are consistent with a general southward decrease of both the regional uplift and the remote effect of active faults, either located in the Ionian offshore (Bianca *et al.*, 1999) or in the Hyblean block (Fig. 7).

Along the northern shore of Sicily, both the long- and short-term markers documents that the large uplift province of the Calabrian arc grades westward to quasi-eustatic values. In the Milazzo headland, cumulative Holocene uplift occurred at 1.3-1.5 (locally up to 2.1) mm/yr, with ~0.65 mm/yr attributed to regional, steady processes, and the rest to co-seismic events (Scicchitano *et al.*, in press). The Holocene regional uplift there is equal to the cumulative Late Pleistocene rate, and thus co-seismic structures are either very recent or have a limited long-term slip rate. Unlike the Messina Straits, the local sources responsible for co-seismic effects in this area are seek in an NNW–SSE striking transpressive belt, known as Aeolian-Tindari fault, that has caused the growth of Middle Pleistocene folds beneath the sea-bottom (Figs. 7a, 7b Argnani *et al.*, 2007). Current contractional strain is also evidenced by dense geodetic network observations in the nearby southern Aeolian islands (Mattia *et al.*, 2008). Further west along the Sicily shore, an abrupt decrease in both the Pleistocene and Holocene uplift rate is observed just west of the fault belt (Figs. 7a, 7b), point to its contribution to coastal deformation. In the Aeolian Islands, the LIg marker is generally uplifted at 0.2-0.3 mm/yr, but geoarcheological and GPS data document high Late Holocene uplift (1.9 mm/yr) and current (Fig. 18a) subsidence.

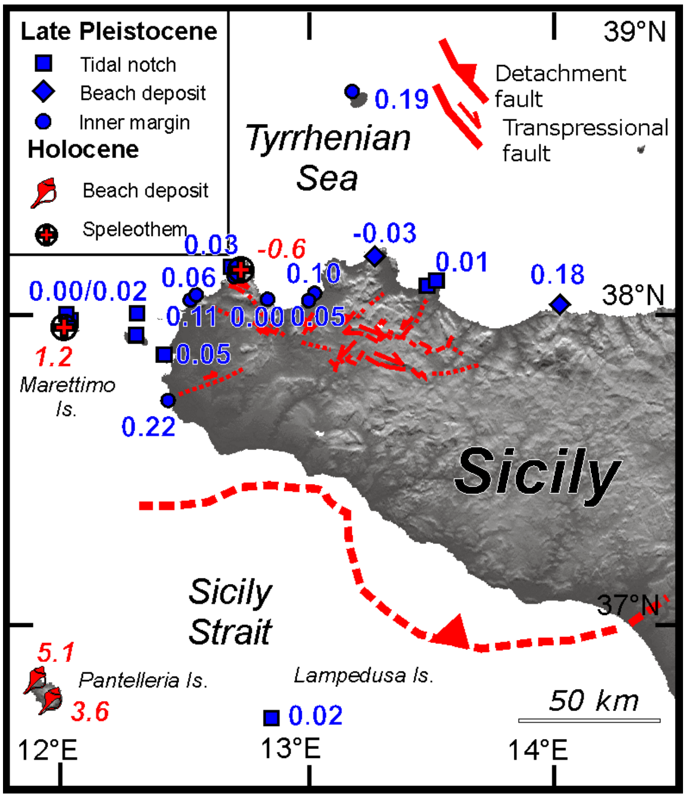
On the Ionian Sea side of Calabria, uplift rates recorded by the LIg terrace are slightly weaker (0.6-0.8 mm/yr) along a 300 km stretch of coast till the border with the Basilicata region (Fig. 7a). In these sector, no major faults are mapped at the coast and large earthquakes are not recorded, and so vertical displacement might chiefly embeds the regional component. Along the coasts of Sila and Pollino mountain ranges in northern Calabria, however, the LIg terrace indicates again uplift rates of magnitude similar to southern Calabria (Fig. 7a). Unlike the Tyrrhenian side of Calabria, however, uplift was attributed to the combination of regional uplift and growth of crustal transpressional folds, as indicated by on-land and marine morphotectonic data (Ferranti *et al.*, 2009; Santoro *et al.*, 2009).

Similarly, Holocene rates are only established in the Crotone promontory and approach 1 mm/yr (Fig. 7b). Further north, borehole data from the Sybaris archaeological area point to intense subsidence (Pagliarulo, 2006 and references therein), that, however, was limited to a ~2 kyr interval during the Mid-Holocene climax and only affected the ancient Sybaris (Ferranti *et al.*, in press). Elsewhere around, either weak subsidence or uplift occurred throughout the Holocene (Fig. 7b), reflecting the prevailing role of local folds over the regional process in the short term (Ferranti *et al.*, in press).

Western Sicily

Along the coast of western Sicily, the LIg marker lies generally only a few metres above the predicted eustatic elevation (Fig. 8). In northern Sicily, local differences particularly along small promontories standing out from the main coastline run are explained by displacement on faults which in few cases cut through the LIg terrace (Antonioli *et al.*, 2006). Most of these faults are transpressional, and are possibly reflected in the pattern of GPS velocities (Ferranti *et al.*, 2008). Thus, weak coastal uplift and subsidence may locally occur along restraining and releasing bends, respectively, of faults. In southwestern Sicily, the occurrence of the LIg terrace is poorly constrained, although it is locally suspected to lie above its eustatic elevation as a result of active thrust uplift.

Figure 8. Vertical displacement rates in western Sicily.



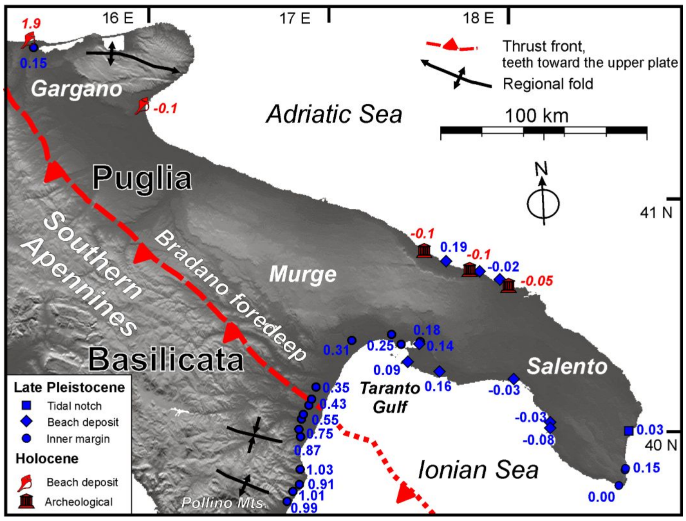
Vertical displacement rates (mm/yr) computed from the elevation of Late Pleistocene and Holocene markers plotted on a DEM of of western Sicily.

In the whole region, the Holocene marker is only found in the most north-western part of Sicily (Fig. 8), where it provides 1.2 mm/yr uplift in the Egadi island and weak subsidence at S. Vito Lo Capo west of Palermo (Lambeck *et al.*, in press). Large uplift (4-5 mm/yr) in the last kyr or so is only documented at Pantelleria island in the Sicily Channel (Fig. 8) as a result of episodic inflation processes related to magmatic intrusion along feeding fissures (de Guidi and Monaco, 2009).

Northern Ionian Sea margin

Like in Sicily, the elevation of the LIg terrace decreases steadily to the NE along the former foredeep basin of the Southern Apennines thrust belt, to a minimum at the northern and eastern shore of the Taranto Gulf (Fig. 9). No significant jump in the regional uplift pattern is observed crossing the front of the Southern Apennines (Fig. 9), supporting the notion that thrust displacement had vanished by the onset of the Middle Pleistocene (Patacca and Scandone, 2007), although according to Caputo *et al.* (2010) a break does exist and higher cumulative rates are encountered. Be as it may, large-wavelength uplift tapering to the north is consistent with the longer-term history of the region, characterized by uplift since the middle Pleistocene (Westaway, 1993; Westaway and Bridgland, 2007; Caputo *et al.*, 2010). On the other hand, no information exists for the short-term vertical deformation pattern.

Figure 9. Vertical displacement rates in southeastern Italy.



Vertical displacement rates (mm/yr) computed from the elevation of the Late Pleistocene and Holocene markers plotted with main structures on a DEM of Basilicata and Puglia (slightly modified after Ferranti *et al.*, 2006).

South-central Adriatic margin

This coastline straddles the partly deformed foreland of the Apennines and is morphologically split in uplifted bedrock blocks (Gargano, Murge, and Salento) in the Apulia region in the south, and terraced coastal plains in the north (Figs. 4, 5, 9).

In the south, the LIg marker has a quasi-eustatic elevation along the Salento shores of Puglia region, but a limited accuracy surrounds its definition (Ferranti *et al.*, 2006). Similarly, poor constraints are available in Gargano and Murge further north (Fig. 9), and along the central Adriatic coastline from Molise to Emilia-Romagna region (Fig. 5).

Significant Holocene uplift is reported on the northern Gargano shore at a rate (~2 mm/yr) which is unmatched by the nearby LIg marker (~0.2 mm/yr; Fig. 9), a fact attributed to a current high-release seismic cycle (Mastronuzzi and Sansò, 2003). This tectonic block is characterized by ongoing seismological transpression (Fig. 2), and thus the invoked model might be feasible. Along the southern shore, however, lesser Holocene uplift is recorded by geoarcheological markers (Fig. 9; Antonioli *et al.*, 2009), and thus the block might be pushing and tilting northward. Along the Salento shore, geoarcheological markers (Antonioli *et al.*, 2009) suggest weak subsidence up to 0.1 mm/yr, in agreement with the long-term pattern.

Unlike Apulia, the central Adriatic coastline runs parallel to the foothills of the thrust belt, which is still tectonically active beneath the coastal region and the Adriatic Sea (Lavecchia *et al.*, 1994; Pondrelli *et al.*, 2006). Along the Marche and southern Emilia coastline, the LIg terrace shows weak uplift (Fig. 5) with a few km wavelength, suggestive of segmented fold growth (Vannoli *et al.*, 2004). Conversely, mild subsidence is evidenced by few Holocene data (either boreholes or geoarcheological markers) at the Marche and Abruzzi regions coastline (Fig. 5).

Northern Adriatic margin

The northern Adriatic region straddles the transition from the Adriatic foreland and Dinarids belt in Slovenia and Croatia to the east, the southern Alps to the north, and the northern Apennines to the southwest (Fig. 2). During the Neogene, progressive convergence of these orogens shrunk the Adriatic foreland plate now submerged beneath the Adriatic sea and covered in the northwest by the Po plain sediments. Current shortening occurs at the Alps and Apennines front, and transpression is recorded inland of the Dinaric coast (Fig. 2; Pondrelli *et al.*, 2006; Devoti *et al.*, this issue).

In the south, a Neogene south-westward thickening (up to 2 km) foredeep wedge (Carminati *et al.*, 2003) was deposited in front of the advancing Apennines thrust belt, and is today reflected in the modern Po River Plain. Asymmetric subsidence continued after Late Pleistocene as documented by the depth and geometry pattern of the LIg deposits reconstructed by borehole analysis (Amorosi *et al.*, 2004; Ferranti *et al.*, 2006; Antonioli *et al.*, 2009). As a matter of fact, high subsidence rates (~0.9-1 mm/yr) are found in the Romagna region in front of the Apennines mountains and just above a deep thrust belt (the Ferrara arc, Fig. 4). This buried arc is seismically active (Fig. 2), and thus regional subsidence interplaying with imbrication of the LIg marker is feasible. Sites located further north display decreasing subsidence from 0.6-0.7 to 0.5-0.6 mm/yr in the Veneto and in the Friuli coastal plains, respectively (Fig. 4), consistent with a northward-tapering flexure model. South of the locus of maximum subsidence in Romagna, the projected position of the coastal Marche site (section in Fig. 5) is consistent with this model.

Holocene data partially mimic the long-term pattern (Fig. 4). Several borehole markers show subsidence of ~0.3-0.9 mm/yr along the whole coast from Emilia to Friuli (Antonioli *et al.*, 2009). The sites with larger Holocene subsidence (1 mm/yr) are located both in front of the Apennines and, unlike the old markers, of the Alps. The northern sites with highest Holocene subsidence are closer to the active thrust front of the Southern Alps (Montello thrust, Fig. 4), and thus a component of loading from the Alps may not be neglected.

In the eastern part of northern Adriatic (Trieste Gulf and Istrian coastline), sparse evidence from the LIg exists, but a wealth of Holocene archaeological and geomorphological indicators are available (Antonioli *et al.*, 2009). It appears that vertical displacement in the Trieste Gulf (Fig. 4) changes southward from uplift to to ~0.8 mm/yr subsidence at the northern border of the Istria promontory. Similarly, an opposite pattern of northward increase in subsidence is observed moving north from Trieste along the shore of the Gulf from weak uplift to -0.8 mm/yr downlift (Furlani *et al.*, 2011). This pattern may also be reflected by a contemporary tilt to the northwest between Trieste and the Friulian plain detected by long-base tiltmeters data (Braitenberg *et al.*, 2005). Weak uplift has been detected also in cores drilled offshore Trieste, an occurrence interpreted as reflecting active growth of an NW–SE trending anticline which is imaged in seismic reflection profiles (Antonioli *et al.*, 2007). In summary, although the locus of seismological deformation in this region is shifted inland and is expressed by strike-slip motion along the Idrija fault (Burrato *et al.*, 2008), the differential pattern of Holocene subsidence and uplift along the north-eastern Adriatic coast is attributed to active shortening of the frontal Dinarids (Antonioli *et al.*, 2007; Furlani *et al.*, 2011).

Analysis of secular and contemporary displacement

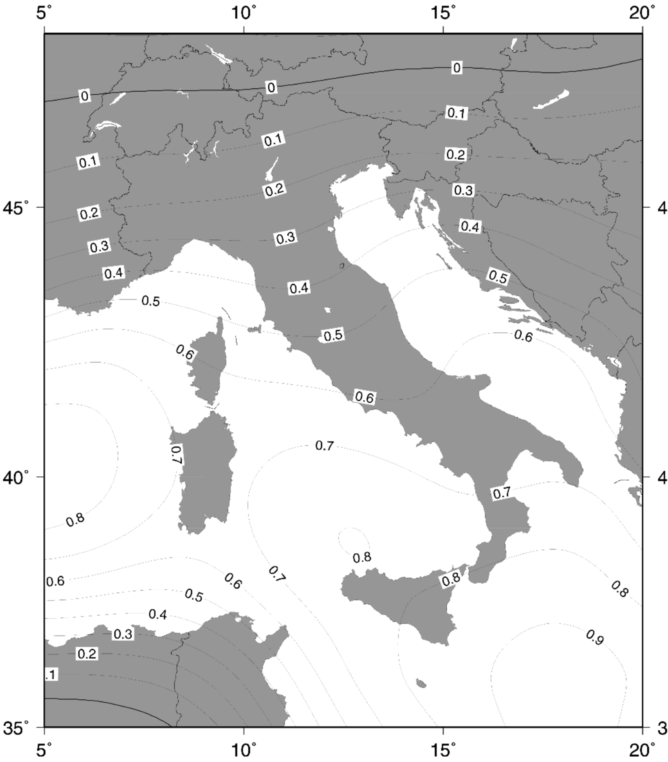
Tide gauge observations

Tide gauges provide very short to secular records of the elevation of the free surface of the oceans, approximately corresponding to the geoid, relative to the solid surface of the Earth. Relative sea level variations, defined by the offset between these two surfaces, are evolving according to a wide spectrum of spatio-temporal scales. Due to the memory effects of mantle minerals, GIA is still operating today in form of slow crustal deformations and gravity field variations, whose combination result in a smooth, long-wavelength pattern of relative sea level change. Conversely to the GIA signal, long- to short-term tectonics-related vertical movements of the crust result in regional to local scale spatially heterogeneous relative sea level changes. Separating these two distinct signals from the tide gauges record demands an accurate modelling of GIA and long enough time series (> 50 years) in order to filter out the short term sea level oscillations related to waves, currents and tides (climatology, oceanography and astronomical forcing).

Recent GIA modelling results have shown that the GIA signal in the Mediterranean sea is mainly driven by the melt-water loading which results in a subsidence localized in the bulk of the basin (Ionian Sea, western Tyrrhenian Sea) and radially decreasing towards the coastlines (Lambeck *et al.*, 2004; 2011; Stocchi and Spada, 2009). Fig. 10 show the predicted GIA-related rate of relative sea level change according to a refined version of the Stocchi and Spada (2009) model. Different predictions are achieved using the Lambeck *et al.* (2011) model; analysis of the different input observations and parameters, as well as prediction results of the two models, are beyond the scope of the present paper. Besides the original papers, the reader is referred to Antonioli *et al.* (2009) for a comparison of the models.

Inspection of Fig. 10 shows that the coasts of France and northern Italy (Liguria and northern Adriatic) are affected by the subsidence driven by the collapse of the forebulge related to the Fennoscandian ice sheet. To a lesser extent the coasts of Liguria and northern Adriatic may experience the response to the melting of the Würm Alpine ice cap which results in a weak land uplift counteracting the subsidence induced by the meltwater from the far field ice sheets (Stocchi *et al.*, 2005; Spada *et al.*, 2009). In this context the Italian peninsula, given its geographical position and elongated shape, is affected by a GIA-related rate of relative sea level rise which increases with decreasing latitudes (Fig. 10), reaching its maximum values in southern Calabria and around Sicily and Sardinia islands (Lambeck *et al.*, 2004; 2011; Stocchi *et al.*, 2009).

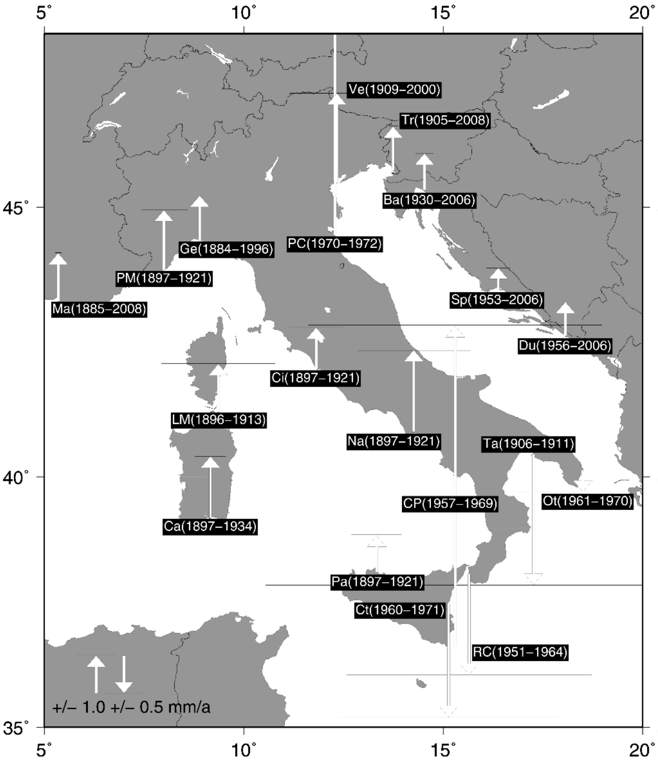
Figure 10. Predicted GIA-related rate of RSL change.



Predicted GIA-related rate of relative sea level change.

In the ideal case of a dense coastal coverage of tide gauges recording secular time-series, the comparison between a reasonable GIA model and the observed rates of relative sea level change would be a straightforward method to detect the tectonics-related signal along the coasts of Italy. The freely available time series for the Italian coastlines are provided by the Permanent Service for the Mean Sea Level (http://www.pol.ac.uk/psmsl). Figure 11 shows the stations and their rates of relative sea level change considered in this study. The rates have been derived from the Revised Local Reference (RLR) annual means time series. Unfortunately only the tide gauges of Genova, Venezia and Trieste have recorded time series longer than 70 years. These three Italian stations, combined with the French tide gauge of Marseille, which has recorded the longest time series in the Mediterranean (108 years), are only representative of the relatively small longitudinal area from the northern Tyrrhenian sea to the northern Adriatic sea. While Marseille, Genova and Trieste share the same rate of RSL change of +1.2 mm/yr, Venezia is affected by a stronger local subsidence which results in a 2.4 mm/yr rate of relative sea level rise. Such a higher rate testifies a very localized combination of natural and anthropogenic forcing (Antonioli *et al.*, 2009; Buble *et al.*, 2010).

Figure 11. Tide gauges and rates.



Tide gauges location and rates (RLR) from PSMSL record (http://www.pol.ac.uk/psmsl).

The remaining Italian tide gauges have not recorded continuous time series longer than 30 years and make therefore necessary a type of approach based on the analysis of differential rates of relative sea level change for common time spans. However, by benchmarking the RSL recorded at different stations for a common period to a station located on a geologically stable block, we can derive reasonably accurate quantitative estimates of crustal deformation at these sites.

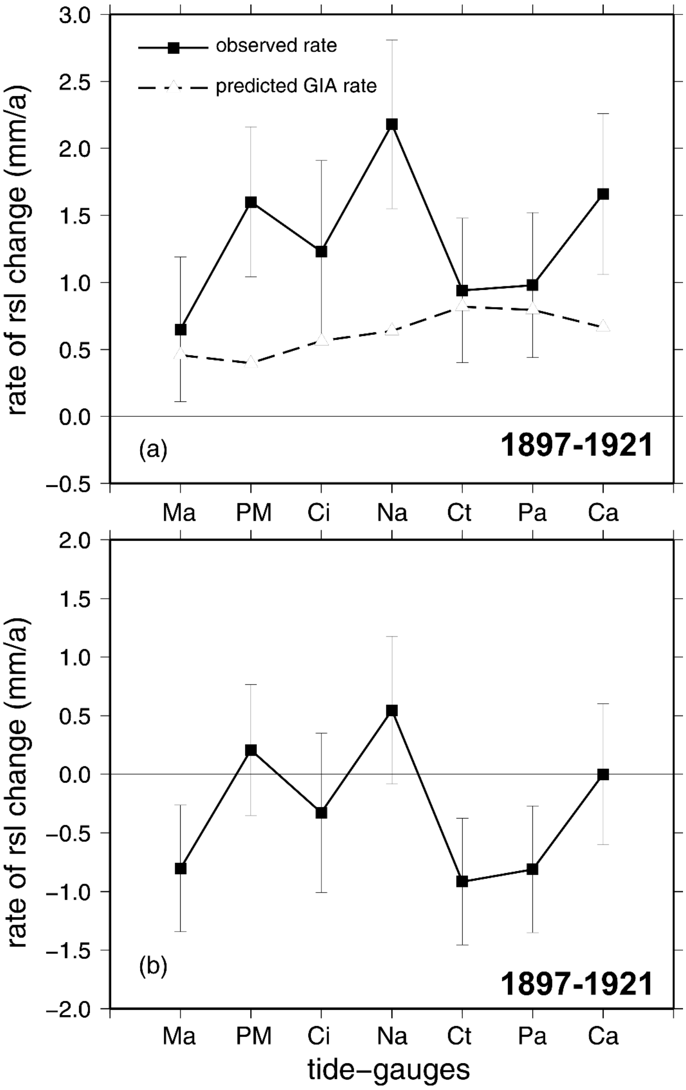
1897-1921 time interval data.

The first time interval considered for analysis of differential rates of RSL change for common time spans is 1897-1921 and is only representative of the Tyrrhenian and Ligurian Sea. Figure 12a shows the observed rates of relative sea level change (black squares and solid line) and the predicted GIA-related rates (white triangles and dashed line) lined clockwise from Marseille (Ma) to Cagliari (Ca), and piercing through Porto Maurizio (PM) in Liguria, Civitavecchia (Ci) and Naples (Na) in the eastern Tyrrhenian margin, Palermo (Pa) in the southern Tyrrhenian margin and Catania (Ct) in the Ionian Sea. For the tide gauge of Catania, the rate has been derived from the available metric time series. The increase of subsidence from the North (Marseille) to the South (Catania and Palermo) predicted by the GIA model is also broadly observed by the tide gauges which all share positive values of RSL change. Tide gauge data, however, are significantly scattered in space when compared to the smooth GIA signal. It is noticeable the opposite trend among the observed and predicted rates along the baseline from Naples (Na) to Cagliari (Ca). In particular the stations of Catania (Ct) and Palermo (Pa), where the GIA subsidence is expected to be the highest (Fig. 12a), show comparable rates of relative sea level rise (+ 0.9 mm/yr), and lower than Civitavecchia (Ci). As pointed out by Antonioli *et al.* (2009), Palermo and Catania are therefore well correlated.

By removing the GIA signal from the observed rates and then by referring each station to Cagliari (reference station), it is possible to better appreciate the local contribution to vertical coastal motion affecting the tide gauges (Fig. 12b). Cagliari, as analysis of intermediate- to short term markers indicates (see section 5.1), lies on the tectonically stable block of southern Sardinia, and therefore differential rates to this station, once skimmed of the GIA component, can be taken as reliable estimates of absolute vertical motion along individual baselines.

The differential rate of -0.8 mm/yr obtained at Marseille (Ma), especially when compared to the slightly positive value obtained at Porto Maurizio (PM), indicates mild uplift. The -0.32 mm/yr differential rate found at Civitavecchia (Ci) appears in striking agreement with the ~0.2 mm/yr uplift rate suggested by the LIg marker (see section 5.3; Fig. 5). Likewise, the positive differential rate of 0.55 mm/yr computed at Naples is consistent, within uncertainty, with the ~1 mm/yr Holocene subsidence rate (see section 5.4; Fig. 6). The differential rates of -0.92 mm/yr and -0.81 mm/yr found respectively at Catania and Palermo testify current uplift affecting Sicily (see section 5.5; Fig. 7).

Figure 12. Tide-gauge data, 1897-1921.

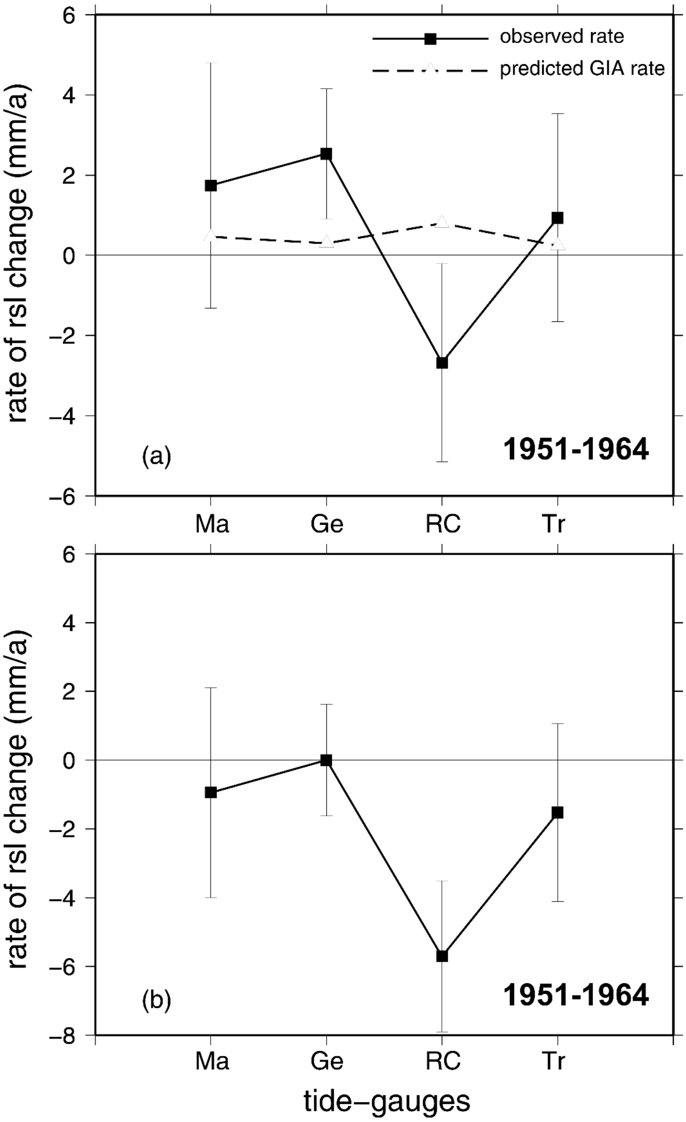


Tide-gauge data for time interval 1897-1921: (a) Observed vs GIA; (b) GIA-detrended data IA referenced to Cagliari (Ca).

1951-1964 time interval data.

A similar analysis is performed for the time interval 1951-1964 for fewer stations (Fig. 13) spanning from the Ligurian Sea (Marseille, Ma; and Genova, Ge) directly south to the Messina Strait (station Reggio Calabria, RC) and up to the Adriatic Sea (Trieste, Tr). For this time interval, a rate of RSL change of -2.7 mm/yr is recorded at Reggio Calabria (RC), while positive values of +2.53, +1.74, and +0.94 mm/yr are observed respectively at the reference station of Genova (Ge), Marseille (Ma) and Trieste (Tr), as shown in Figures 13a and 13b. For the analyzed cluster, we fix the station Genova (Ge). Although LIg and Holocene data are not available at this site, it rests on a region of very weak geological motion, if any (Fig. 4). Note, however, that the RSL rate at Ge for this time interval is twofold the long-trend (+1.2 mm/yr) rate, and thus differential rates computed for the 1951-1964 time interval results higher. When the GIA component is removed, we observe uplift of Marseille (Ma) at 1.25 mm/yr, a finding comparable to the 1897-1921 dataset within uncertainty. Whereas large uplift of up to ~6 mm/yr is found at RC, Trieste has a lesser uplift.

Figure 13. Tide-gauge data, 1951-1964.

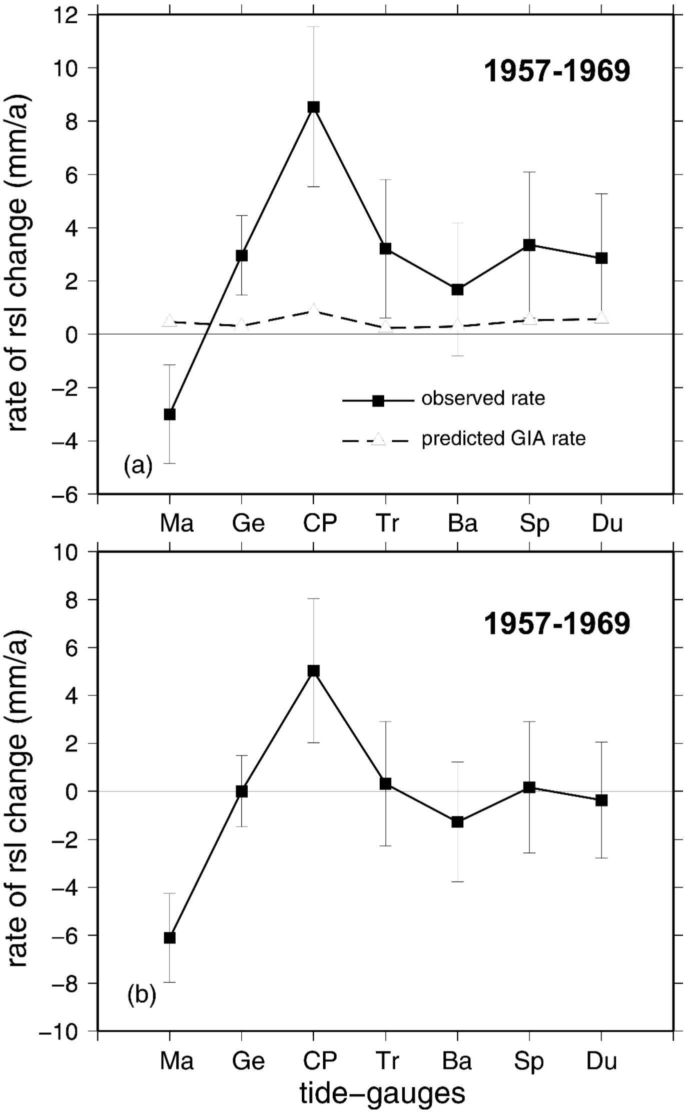


Tide-gauge data for time interval 1951-1964: (a) Observed vs GIA; (b) GIA-detrended data referenced to Genova (Ge).

1957-1969 and 1960-1971 time interval data.

The third time interval considered in this study is 1957-1969, for which the tide gauge of Capo Passero (SE Sicily) shows a surprisingly high rate sea level rise of +8.54 mm/yr (Fig. 14). Also in this case the station of Genova is chosen as reference (Fig. 14a, b). Once purified from the GIA contribution and referenced to Genova, the Adriatic tide gauges of Trieste, Split and Dubrovnik show a good correlation, which suggests a relative tectonic stability. Bakar (Ba) instead could be affected by a localized uplift. Marseille and Capo Passero show two opposite differential rates of -6.0 mm/yr and +6.0 mm/yr respectively, which indicate localized uplift and subsidence, although the magnitude appears severely biased by unknown processes.

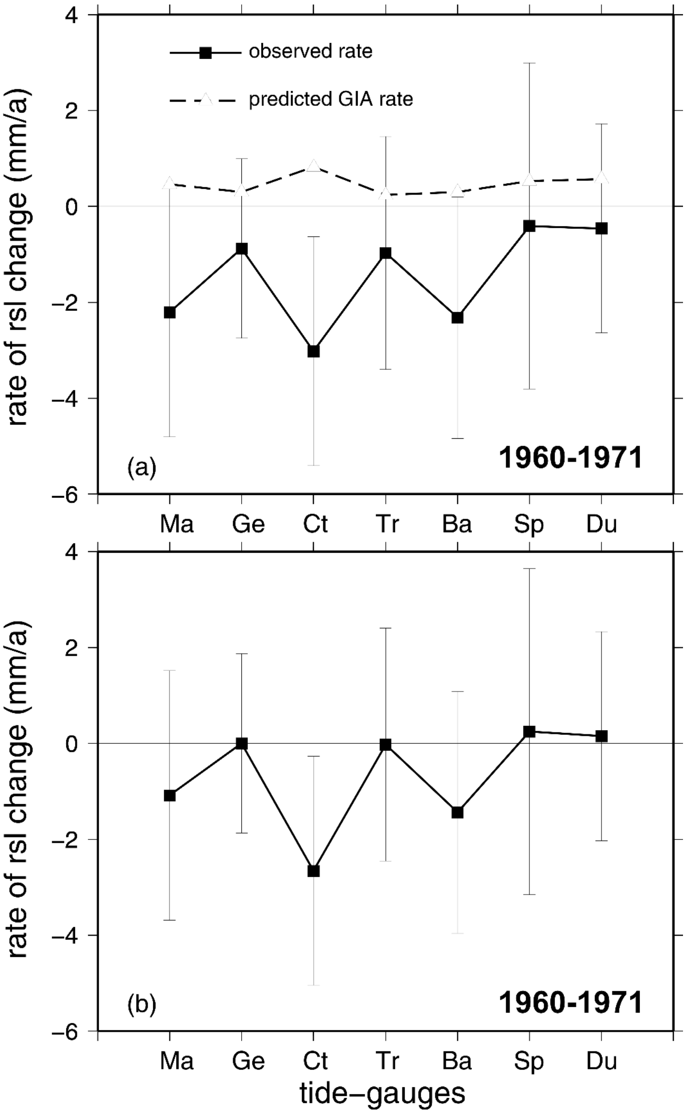
Figure 14. Tide-gauge data, 1957-1969.



Tide-gauge data for time interval 1957-1969: (a) Observed vs GIA; (b) GIA-detrended data referenced to Genova (Ge)

The time interval 1960-1971 is characterized by negative rates of RSL change at all the tide gauges taken into account (Fig. 15a). A maximum value of sea level fall of -3.0 mm/yr is observed at Catania (Ct). By referencing the GIA-filtered rates to the station of Genova, both the stability of Trieste, Split and Dubrovnik, and the uplift at Bakar, Marseille and Catania are confirmed. The latter is well correlated with the apparent uplift found for the time interval 1897-1921, when the tide gauge of Cagliari has been used as reference station.

Figure 15. Tide-gauge data, 1960-1971.

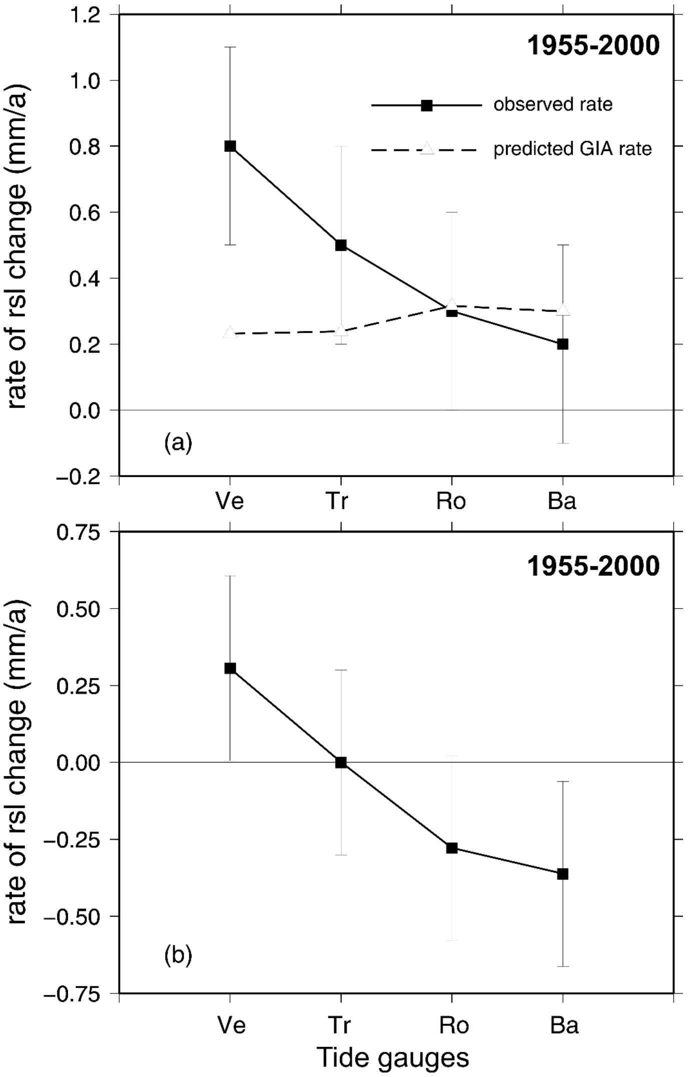


Tide-gauge data for time interval 1960-1971: (a) Observed vs GIA; b) GIA-detrended data referenced to Genova (Ge)

1955-2000 time interval data.

We comment here on the data presented by Antonioli *et al.* (2009) for Northern Adriatic stations Trieste (Tr), Venice (Ve) in Italy and Rovinj (Ro) and Bakar (Ba) in Slovenia for a common time span between 1955 and 2006 (Fig. 16). Venice has a greater sea-level rise (0.8±0.3 mm/yr) with respect to Trieste (0.5±0.3 mm/yr), indicative of its recent subsidence. The latter shows a slightly higher rate relative to Rovinj (0.3±0.3 mm/yr) and Bakar (0.2±0.3 mm/yr) stations.

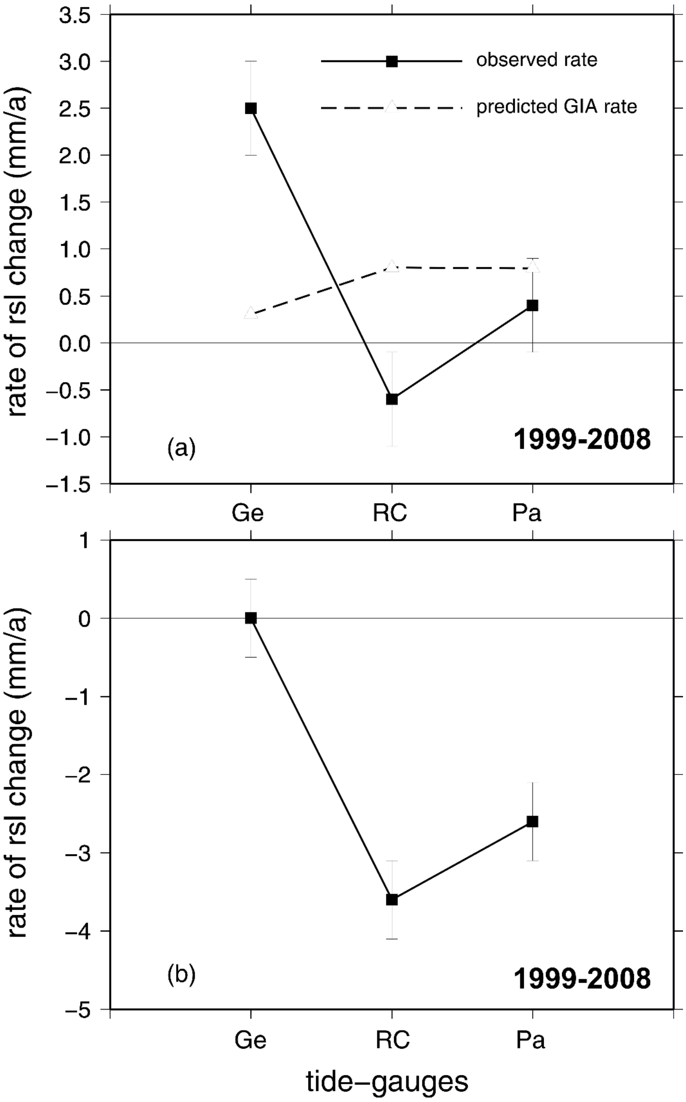
Figure 16. Tide-gauge data, 1955-2000.



Tide-gauge data for time interval 1955-2000: (a) Observed vs GIA; b) GIA-detrended data referenced to Trieste (Tr)

1999-2008 time interval data.

Figure 17. Tide-gauge data, 1999-2008.



Tide-gauge data for time interval 1999-2008 (ISPRA record, http://www.apat.gov.it/site/it-IT): (a) Observed vs GIA; b) GIA-detrended data referenced to Genova (Ge).

Antonioli *et al.* (2009), using the 1999-2008 mareographic records provided by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, http://www.apat.gov.it/site/it-IT), show a rate of RSL change of -0.6±0.5 mm/yr at Reggio Calabria, while positive values of 0.4±0.5 mm/yr and 2.5±0.5 mm/yr are found at Palermo and Genova, respectively (Fig. 17). By combining the 1999-2008 and the 1951-1964 time intervals it is apparent that the sea level fall recorded at Reggio Calabria is driven by a long-term uplift reasonably related to tectonics. The differential rate across baseline RC-Ge in the 1999-2008 data (detrended form the GIA component) is ~3.6 mm/yr, probably a more accurate estimate of the tectonic rate than the 1951-1964 dataset.

Uplift reasonably influences the tide gauge at Palermo (western Sicily), which, for both 1897-1921 (Fig. 12) and 1999-2008 (Fig. 17) time intervals, shows a positive rate well below those measured respectively at the reference stations of Cagliari and Genova. In the 1999-2008 data, the differential rate between Pa and Ge is 2.1 mm/yr, and when the GIA component is removed, relative uplift of Pa to Ge is up to 2.6 mm/yr. Furthermore, because the GIA component is broadly equal at RC and Pa (Fig. 10), their differential rate of ~1 mm/yr in the 1999-2008 dataset is more accurately indicative of the tectonic rate gradient across the Messina Strait and Sicily.

Summary.

Tide-gauges measurements for stations with a sufficiently long time series to allow at least computations of differential rates, once the GIA component is removed, indicate consistent pattern of tectonic motion due to regional or local processes. The western Liguria sea margin in southern France (Marseille, Me) appears uplifting relative to the Italian sector (Porto Maurizio and Genova stations) at an average rate of ~1 mm/yr, a finding in agreement with the localized uplift found by Bennett and Hreisendóttir (2007) relative to a local reference frame.

In the eastern Tyrrhenian margin, relative to the stable Cagliari station, Civitavecchia (Ci) and Naples (Na) are uplifting and subsiding, respectively (1897-1921), at rates strikingly similar to the LIg and Holocene rates (Figs. 5, 6).

In southern Calabria and eastern Sicily, stations show uplift relative to quasi-stable Cagliari which is large at Reggio Calabria and lesser (~0.9 mm/yr, 1897-1921 interval) at Catania, the latter in noticeable agreement with the computed 1 mm/yr Holocene rate (Fig. 8a). Northern Sicily (Pa) is uplifting relative to Sardinia (Ca) and Liguria (Ge) at 0.8 mm/yr (1897-1921 dataset) and ~2.6 mm/yr (1999-2008 ISPRA dataset), respectively (Figs. 12, 17). Similarly, uplift of Catania relative to Genova is 2.7 mm/yr (1960-1971), whereas in the ISPRA 1999-2008 dataset, the integrated uplift of baseline RC to Ge is ~3.6 mm/yr. These data are consistent with largest uplift segregated in the Messina Strait (RC), and with a gradient of ~1 mm/yr relative to both Sicilian stations Catania and Palermo.

Whereas secular uplift at Catania and Reggio Calabria are no surprise as manifestation of the ongoing Calabrian Arc dynamics (see section 5.5), the uplift observed at Palermo merits further investigation in light of the quasi-stability or weak uplift afforded at nearby locations by LIg data (Fig. 7). Although few Holocene data exist for north-western Sicily, the close proximity of station Pa to the uplifting site of Marettimo (1.2 mm/yr), and the relatively short baseline between Palermo and the benchmark site of Cagliari (1897-1921 dataset), might indicate a recent, significant uplift of northwest Sicily.

Uplift might also be recorded in the Ionian Sea tide gauge data. Albeit quantitative calculations are not possible due to the short time record and the lack of a common time span, we note that stations Taranto (Ta) and Otranto (Ot) in Apulia region have recorded negative rates of RSL change during their operation life (Fig. 11), in a manner reminiscent of the uplift recorded by LIg markers (Fig. 9).

In contrast to the south of Italy, no significant difference is observed between sites located along the Croatian coast and Trieste between 1957-69 and 1960-1971 (although Bakar has a little uplift of few mm/yr relative to Trieste both in the above time spans and, together with Rovinij, in the 1955-2000 dataset). This findings is consistent with the observation that current seismological deformation is accommodated inland along the Dinarid axis (Fig. 2). The north-western Adriatic shore (Venice) has a weak (0.3 mm/yr) subsidence relative to Trieste during 1955-2000 (Fig. 16), but over the longer time span of between 1905-1970, differential subsidence increases to 1.8 mm/yr. As observed by Antonioli *et al.* (2009), the longer dataset records anthropogenic effects, which were reduced or halted after 1970; thus the 1955-2000 rate can be taken as truly tectonics, in light of the good agreement with the 0.4-0.7 mm/yr Holocene rates (see section 5.9; Fig. 4).

GPS observations

Determination of the vertical component of Earth's current crustal velocity field using the Global Positioning System (GPS) is a challenging goal for the estimation of the vertical tectonic rates. This is important for the study of seismic and volcanic regions but it becomes crucial for coastal application. Since the beginning, GPS has revealed its uncertainty in the height component and this is an important issue in studying RSL changes, when GPS height of the benchmark is used for defining an absolute sea level datum. Some international initiatives have aimed to co-locate GPS and tide gauges to cope with these geodetic topics and measure sea level and land motion through these integrated stations (Schöne *et al.*, 2009; http://adsc.gfz-potsdam.de/tiga/index_TIGA.html). Vertical crustal motion is difficult to measure using satellite geodesy for several reasons. Among the others, the main important are technical (accuracy of the satellites orbits, phase center of GPS antennas, multipath, etc.), site effects (i.e. geological or monument instability, soil compaction, etc.), physical (i.e. atmospheric and ionosphere delay), and geodetic (i.e. stability of the chosen reference frame, center of mass of the Earth, etc.). The amount of these signals can result in vertical positioning bias. Additionally, the contribution of scale change to vertical error is an important source of uncertainty compared with tectonic rates which can be of order 1 mm/yr or less. Hence, tectonic interpretation of space geodetic measurements of vertical movements requires careful attention, especially along the coasts when tide gauge data are compared with GPS data, as the former instruments provide a continuous measure of the sea level with respect to the "fixed" land to which are anchored.

The central Mediterranean region has been recently investigated for the existent relationships between vertical crustal motion and sea level change (Bennett and Hreinsdóttir, 2007; Stocchi *et al.*, 2007; Buble at al., 2010) using the long-record tie gauges (see above chapter), and continuously recording GPS (CGPS) stations. These stations are part of networks in operation since five or more years belonging to different agencies (Réseau National GPS, RENAG; RING network managed by the Italian INGV; GPS Network of the Italian Space Agency; EUREF Permanent GPS Network - EPN, and/or International GNSS Service (IGS), and are sometimes located along the coastal regions. The available long GPS time series for these stations allows for precise determination of vertical rates with respect to the geocentric reference frame with typical theoretical (i.e., "formal") rate uncertainty of $\leq$0.1 mm/yr.

Data analysis centers generally use different software (see Devoti *et al.*, this volume), to process data from hundreds of stations located in the Euro-Mediterranean and African area and combine regional and global solutions from SOPAC (http://sopac.ucsd.edu). The final positions are computed in the IGS reference frames and velocities are estimated from the time series after removing jumps due to stations equipment changes (or co-seismic offsets) and the seasonal signals (with annual and semi-annual period). Uncertainties are estimated and reduced adopting noise models (as white+colored error noise model), to produce a self-consistent and homogeneous three-dimensional velocity field and estimates of vertical land movements. Notwithstanding, the GPS reference frame stability still remains un unresolved issue. To mitigate this problem, Altamimi *et al.* (2007) proposed a correction to the vertical rate of 1.8 sin(latitude) mm/year.

Bennett and Hreinsdóttir (2007) assessed the precision of GPS-determined vertical rate estimates for the central Mediterranean area, using at least 5 yr of GPS data, compared with independent constraints derived from the altitudes of Holocene and late Pleistocene shorelines, tide gauge records, and sea level changes measured by satellite altimetry. They found an average formal uncertainties of 0.08 mm/yr, thus 3 to 5 times smaller than the precision they determined through comparison of GPS with independent measures of surface uplift. They found in the GPS data uplift at several sites along the southern French coast, with short-wavelength spatial variation possibly related to GIA. They conclude that some of the observed difference was certainly associated with errors in rate estimates determined from shoreline data (imperfect corrections for the effects of glacial isostatic adjustment) and un-modeled variation of crustal motion through time.

Buble *et al.* (2010) have used observations from tide gauges and co-located continuous GPS (CGPS) stations to investigate the relationships between crustal deformation and sea level changes along the eastern margin of the Adriatic Sea. They tentatively separated the signal pertaining to absolute sea level and crustal motions with respect to a local Central Mediterranean–fixed GPS-defined reference frame. The tide gauge data indicated a consistent, mean sea level rise of 0.84 ± 0.04 mm/yr, 2-4 times lower than the global average. Conversely, they found a variable rate of the vertical motion of the land, as determined by CGPS, from -1.7 ± 0.4 to 0.0 ± 0.4 mm/yr in southern and northern Adria, respectively. They attributed this difference in crustal motion to an active thrust fault, which in the south accommodates the convergence of the Adria microplate with Europe (Fig. 1). The combination of tide gauge and CGPS measurements shows that absolute sea level relative to the GPS-determined reference frame varies of ~1.8 mm/yr along the Croatian coast producing a roughly constant sea level in this region. This result is in agreement with Antonioli *et al.* (2007) who point out the tectonic contribution to the relative sea level changes estimated for the northeastern Adriatic sea, based on archaeological and geological observations and modeling analysis.

Stocchi *et al.* (2009) compared for the Italian Region the tide gauge and GPS signals and tentatively defined the upper and lower bounds of the effects of the glacial isostatic adjustment (GIA) on current sea level variations and vertical movements along the coasts of Italy. At specific sites, where tide gauges and GPS stations are operating, the analyses found an agreement between the two data set: where land is down-lifting, local relative sea level is rising.

Anyway, as estimated in Bennett and Hreinsdóttir (2007), Buble *et al.* (2010) and Devoti *et al.* (this volume), the vertical rates of crustal motion as determined by CGPS in Italy are small, and their estimate is dependent by the duration of the recordings. Instrumental noise, local monument and ground instabilities and the geological environment on which the geodetic stations are situated can induce additional disturbance that conceal the geophysical signal. For the above reasons, the vertical component of the crustal motion is the most difficult to achieve for the limitation of the technique. Hence, a careful site selection and long enough time series (generally >5 years) of geodetic observations are required to provide significant data, with estimates above the accuracies of the uncertainties of the technique and the chosen reference frames.

Latest results on the vertical trends of deformation for the Italian region, as depicted by data analysis of the CGPS stations (Devoti *et al.*, this issue), show the first order vertical movements as a broad uplift of 1-5 mm/yr along the Alpine and Apennine mountain chains, diffuse subsidence in the Po river plain at up to 15 mm/yr, and near null movements for the Sardinia-Corsica block, but all with uncertainties often larger than these values. The few CGPS stations located near the coast, show null or minor movements along the vertical component (with the exception of those stations located in unstable areas, such as on the Ionian coasts near Crotone, with rapid motion at -2.70 mm/yr; or in the volcanic arc of the Aeolian islands, where they are subsiding at ~ -6 mm/yr). Notwithstanding, stations in the Calabrian Arc show uplift well above uncertainty (Devoti *et al.*, this issue) which are in agreement with geological and secular estimates made in the present paper.

Figs. 18a and 18b show two examples of time series recordings along the vertical component at a discrete (PANA) and a continuous (TRIE) GPS station, respectively. Data from these stations show the different tectonic behavior in these two crustal segments. PANA is placed in the volcanic arc of the Aeolian islands (southern Italy), characterized by mild long-term uplift (0.35 mm/yr; Fig. 8a), but the contemporary record is both of subsidence and uplift. On the opposite, TRIE rests on the north Adriatic foreland plate (northern Italy), with low strain rates (Figs. 2, 4, 11). The UP velocity at TRIE is 0.26±0.07 mm/yr (Eurasia reference frame, see Devoti *et al.*, this volume), and is strikingly consistent with the Holocene rate (Fig. 4). Similarly, the co-located tide gauge, which is continuously operating since the beginning of 19th century, provides a sea level trend of ~1.2 mm/yr, and common time-span estimate of stability or uplift relative to other site in northern Italy (see the previous chapter).

Figure 18a. GPS time series examples.

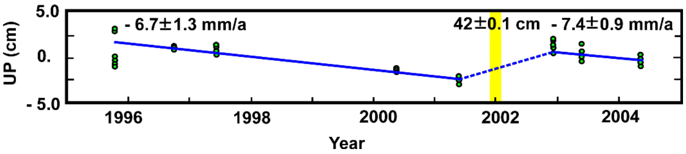
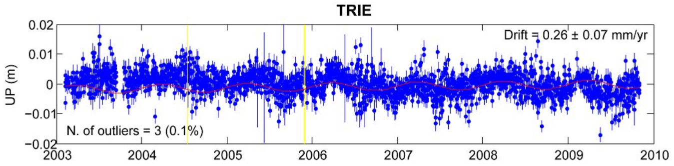


Figure 18b. GPS time series examples.



Two examples of GPS time series recordings along the vertical component: a) the discrete GPS station of Panarea (PANA) (modified from Esposito *et al.*, 2010) and b) the GPS station of Trieste (TRIE, daily solutions). The yellow vertical lines are outliers, the red line are the average positions.

Discussion

The appreciable length of Italy coastline and the coexistence of different geodynamic processes acting in close proximity, along with a rich suite of observational data spanning from the 100 kyr to the contemporary scale, allows to single out a variety of vertical tectonic behaviours in spatially adjacent regions. In addition, the existing dataase highlights, for individual sectors the contributions ensuing from processes acting at different depths and bearing different wavelength and amplitude signals, and the temporal scale of changes for these processes. In the followings, three main segments of the nation coastline are taken as representative of as many different tectonic behaviours and serve to illustrate the interplay between regional and local deformation.

Regional stability and local tectonic and volcanic displacement: western Italy.

The Sardinia, Liguria and northern Tyrrhenian Sea margins emerge from coastal analysis as sectors of stability at regional scale, with only sub-regional or local activity due to fault motion and volcanic processes. This behaviour is revealed by the LIg marker and is confirmed by Holocene (mainly archaeological markers) and by instrumental data (Figs. 3 to 6 and 12 to 15). Weak and very localized subsidence (e.g. promontories of Sardinia; small coastal plains of Campania and Latium) or uplift (e.g. Liguria and Toscana cliffs adjacent to plains) provided by LIg data occurs in regions of modest or null seismicity and thus might reflect creep and/or isostatic motion. This low-rate pattern can be rarely assessed by the Holocene markers. Higher subsidence, where a tectonic contribution seems viable, is locally encountered within larger coastal plains bounded by ostensibly active faults. This situation has been encountered in the Arno plain in Tuscany, where it was possible to isolate the contribution of footwall uplift, hanging-wall subsidence and sediment constipation on the southern border fault (see section 5.3.), resulting in a 0.3-0.5 mm/yr vertical slip rate in the last 125 kyr; or within the GDR and Fondi plains in southern Latium (Fig. 5); and the Volturno plain in Campania, where plain subsidence and mountain flank uplift points to active fault displacement (Fig. 6). In Campania, similar results with uplift in the Apennines and rapid subsidence in the plains is documented by radar interferometry (PS-Insar) data published by Vilardo et al (2008), who infer active motion along ~NW-SE to NNW-SSE striking faults bordering the chain.

A characteristic feature of the western Italian margin evidenced by its effects on coastal markers is represented by volcanic processes. Typically, these processes are signalled by a smooth and laterally limited (10 to 100 km) uplift profile of the LIg marker, and are attributed to the construction of small explosive edifices or to the emplacement of lava flows (eastern Sardinia and Latium). Where the Holocene marker is used, such as in the case of the Phlegrean Fields and Mt. Vesuvius in Campania (Fig. 6), it was possible to single out extremely rapid (1-2 cm/yr) but transient (<<100 kyr) episodes of magmatic unrest. It is worth to note that in the case of Latium volcanic province, where activity is not as dramatic as in Campania, Holocene borehole and tide gauge (Ci) data locally provide a ~0.2-0.3 mm/yr uplift of the same magnitude of that provided by LIg markers (although Holocene archaeological data show weak subsidence; Fig. 5). Remarkably, a ~0.2-0.3 mm/yr uplift rate was also sustained in the Latium volcanic area since the Early Pleistocene (Mancini *et al.*, 2007). Integration of all these observations might suggest that at the Latium coast a regional component of (deep?) magmatic deformation has occurred at almost steady rates, and transient effects are no longer detectable.

Major volcanic processes caused not only uplift, but also subsidence of coastal markers. A contribution arising from magma chamber withdrawal and volcano-tectonic collapse related to past exceptional eruptions (e.g. 37 and 15 kyr BP events) is probably embedded in the subsidence recorded in Campania (Fig. 6). Whereas subsidence in the plains may have slowed down or stopped during the Holocene, it is still occurring in the city of Naples as documented by Holocene (-1 mm/yr) and tide gauge (-0.6 mm/yr; Fig. 12) data, although anthropogenic effects are probably folded within these estimates.

Apart the localized and episodic volcanic deformations or fault-related subsidence in large coastal plains, analysis of coastal displacement markers lend to the conclusion that the continental margins of western Italy have reached a mature and thermally cooled stadium. This finding is consistent with seismicity, horizontal GPS velocities, and geologic reconstructions that place the locus of active deformation along the axis of the Apennines and not west of it, where regional tectonics has ceased (Figs. 1, 2).

Interplay between regional and local tectonic displacements: southern Italy.

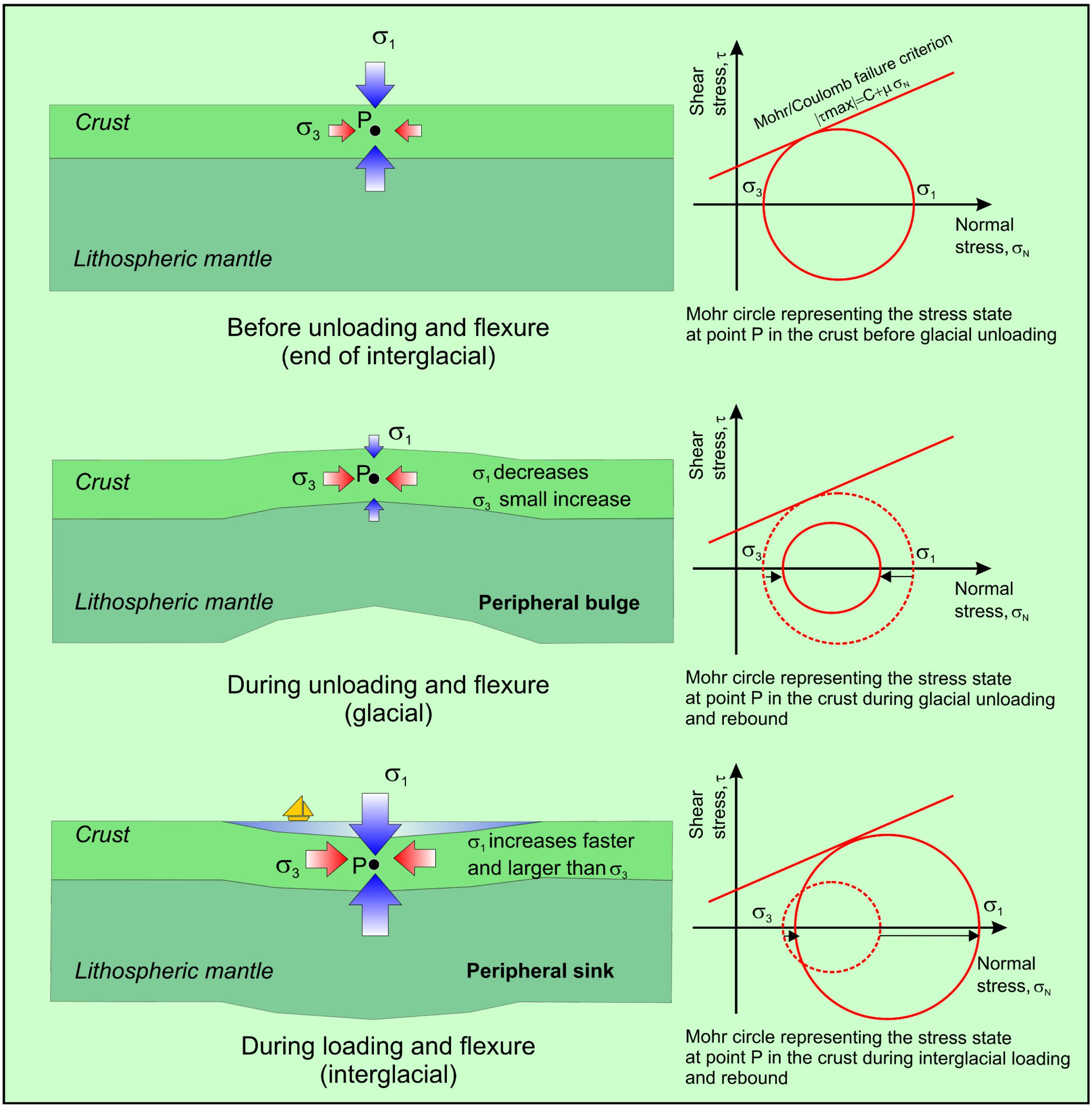
A difference in vertical tectonic behaviour between western and southern Italy coastlines is manifest. Since the middle Pleistocene, eastern Sicily, Calabria, and eastern Basilicata have experienced rapid and coherent uplift, documented by flights of marine terraces (Dumas *et al.*, 1987; Westaway, 1993; Miyauchi *et al.*, 1994). Uplift rates documented by the LIg and older markers form a bulge elongated for ~350 km in a NE-SW direction, and with a minimum ~100 km width between the Tyrrhenian and Ionian Sea coasts. The bulge exhibits two peaks centered in the NE (north-eastern Calabria) and in the SW between the Messina Straits and the Etna volcano in central eastern Sicily (Fig. 7a). Whereas the peaks record 125 kyr uplift rates of >1.2 mm/yr, the elongated saddle between them has a background uplift value of ~0.8 mm/yr. Outside the peaks, uplift rates decrease sharply to the NE in Basilicata and Apulia, to the W in northern Sicily and to the S in southern Sicily, where they drop off to null within a ~50 km stretch (Figs. 7a, 8, 9).

An interesting conundrum presented in this study, which was not assessed in our recent papers (Lambeck *et al.*, 2004; 2011; Ferranti *et al.*, 2006; Antonioli *et al.*, 2009) regards the possibility that the southern margin of the Tyrrhenian Sea in north-western Sicily may began to be involved in regional deformation. As a matter of fact, tide-gauge (Palermo) and Holocene (Marettimo Island) data suggest significant uplift at these sites at a rate which is not recorded by LIg markers (Fig. 8). Although this evidence is local and thus must be taken cautiously, it might pose the question whether north-western Sicily is witnessing a very recent inception of uplift, possibly in response to a relative convergence with Sardinia which is currently recorded by geodetic and seismicity data (Fig. 2; Serpelloni *et al.*, 2005; Pondrelli *et al.*, 2006; Ferranti *et al.*, 2008). Further studies on the Holocene markers in western Sicily are needed to address this point.

On a more general issue, there is a general consensus that post 0.8 Myr surface uplift of Calabria embeds components from two different sources, one regional and the other operating at a local scale (Valensise and Pantosti, 1992; Westaway, 1993). Because of the spatial alignment between the uplift bulge and the strike of a seismically active, NW-dipping lithospheric slab (Fig. 1), the regional contribution to uplift has been interpreted to arise from a deep-seated source (e.g. Westaway, 1993; Wortel & Spakman, 2000; Gvirtzman & Nur, 2001). Geodynamic reconstructions have paid less attention to the causes of local uplifts and on the tuning between deep and shallow sources at different timescales, and we further explore these issues in the following.

Although located within a plate convergence zone, much of Calabria topography was acquired during extension (Monaco & Tortorici, 2000), and a substantial fraction of uplift was attributed to slip on active normal faults (Westaway, 1993; Catalano *et al.*, 2003). Conversely, on the eastern (Ionian) side of the Calabrian arc, a mounting body of evidence points to whole crustal and possibly lithospheric shortening as driving a significant amount of uplift (Ferranti *et al.*, 2009; Caputo *et al.* (2010). Similarly, crustal shortening and transpression may be contributing to uplift of the western part of the arc in northern Sicily (Figs. 7a).

Figure 19. State of stress changes due to GIA.



State of stress before, during, and after glacial loading and flexure in a region of active extension, where the maximum principal stress is vertical (adapted from Hampel & Hetzel, 2006).

Study of displaced Holocene shorelines around the Calabrian arc coastline indicates average uplift rates consistently higher than longer-term rates, but the location of sites having the fastest Late Pleistocene and Holocene uplift rates spatially coincide (compare Figures 7a and 7b; Antonioli *et al.*, 2006). Inspection of short-term (Holocene), secular, and present-day displacement estimates, the latter two provided by archaeo-geodetic markers and tide-gauges, respectively, suggests that the pattern established in the Holocene continues today. Archaeological and instrumental data, however, do not have the capability of partitioning between regional and local sources, but they do suggest significant (elastic?) strain accumulation.

Detailed work along the Messina Straits shore has shown that the Holocene increase in uplift rate is related to temporal clustering of slip, possibly accommodated on offshore normal faults (Ferranti *et al.*, 2007; 2008). On the contrary, regional uplift progressed during the Holocene at a rate of ~1 mm/yr, similar to the long term estimation (Westaway, 1993), pointing to a time-interval larger than 100 kyr as appropriate for major geodynamic changes. Appraisal of the present elevation attained by a suite of 125 kyr and younger marine terraces has shown that rapid vertical displacement of coastal terraces across faults also occurred during the Lig highstand (125-80 kyr). Comparable results, with enhanced fault slip/fold growth rates during the LIg and the Holocene, can be documented elsewhere in the Calabrian Arc both in the extensional hinterland (e.g., Messina Strait, Catalano *et al.*, 2003; Taormina, de Guidi *et al.*, 2003; Capo Vaticano, Tortorici *et al.*, 2003; Cucci and Tertulliani, 2006) and in the transpressional foreland (e.g. north-east Calabria Ferranti *et al.*, 2009; Santoro *et al.*, 2009). The observation that the temporal variations in slip rate are maintained both in the extensional hinterland and in the transpressional foreland, strongly points to an external forcing of fault slip clustering. This mechanisms might be operating at the border of the uplifting bulge, where rates are 30% greater than the background value at the locations where local structures approach the coastline or penetrate in the land interior (Figs. 7a, 7b).

The fact that efficient seismic (or aseismic) strain release appears clustered in intervals of 10-20 ka during interglacial stages along many coastal or offshore local structures requires further inquire. We suggest that simultaneous clustered activity of local structures during interglacial highstands may record increased hydrostatic load and peripheral bulge collapse triggered by isostatic adjustment to mantle flow (Fig. 19). By contrast, fault rupture was inhibited by the concurrent reduction in vertical load and in pore pressure during glacial hydrostatic unloading and growth of the peripheral Mediterranean bulge to the continental ice. The episodic contribution of interglacial displacements over the steady back-ground uplift has led, in the long-term, to a prevailing regional signal (Fig. 19).

Dominance of regional tectonic displacements: eastern Italy.

Unlike the western Italy margin, the signature of regional deformation is still detected on the eastern side of the nation along the Adriatic Sea shore, where vertical displacement of coastal markers occurs in a province of contractional and transpressional tectonics. In the southern Adriatic and northern Ionian Sea coasts, deeper shortening and strike-slip faulting occurs mostly offshore within the Apulia foreland block, but its effects are also recorded on-land by long- and short-term markers (Fig. 9). Vertical displacement, particularly of the Holocene marker, is higher at the Gargano block (Mastronuzzi and Sansò, 2002), consistent with the geological history of the foreland, where Neogene mid-plate deformation was stronger and more prolonged than further south (Ferranti and Oldow, 2006).

Similarly, Late Pleistocene and Holocene markers testify of localized slow coastal uplift or subsidence in the northern section of the central Apennines, and confirms geological and present-day contractional motion along the front of the belt. Weak uplift rates (< 0.1 mm/kyr) of the LIg terrace in the Marche region are related to low-amplitude folds growing underneath the coast (Vannoli *et al.*, 2004). This situation occurs behind the active offshore frontal thrust and in the hanging-wall of an inner thrust which borders the mountainous topography of the northern Apennines (Figs. 4, 5). Thus, along the Adriatic shore, the transition from mid-plate deformation in the south to frontal thrust belt motion in the north occurs north of Gargano, in agreement with geodetic and seismological information (Fig. 2).

Further to the north, recorded displacement changes along the coast from weak uplift to strong subsidence (Fig. 4). Tectonic downlift in Romagna region happens at a rate of ~1 mm/yr both at the 100 and at the 10 kyr scale behind the buried frontal thrust of the Apennines (Ferrara

Arc), and in the footwall of the inner thrust which forms the chain escarpment. The subsidence pattern is explained with a flexure situated in front of the Apennines, and involving the foreland plate subjacent the frontal detachment of the orogen. Minor imbrication occurs above the inner thrust as recorded by the weakly uplifted Marche sites (Fig. 4). Lateral continuity of the active inner thrust front is supported by seismological data (Fig. 2) and by analysis of geologic and fluvial geomorphologic data (Picotti and Pazzaglia, 2008). However, the minimal vertical uplift rates (0.1 mm/yr) caused by thrust imbrications are ten times lower than the regional subsidence. Prevailing regional subsidence over secondary thrust imbrication documented by the LIg terrace is consistent with models of frontal accretion in rapidly retreating slabs, as it is thought to happen in the western Adriatic context (Doglioni *et al.*, 1999). Today, this pattern is confirmed by integration of gravity, interferometry and GPS observations, which show foredeep subsidence at ~3.3 mm/yr and uplift of the Romagna Apennines at ~1 mm/yr (Zerbini *et al.*, 2007). The larger instrumental rates when compared to geologic rates profoundly incorporates the anthropogenic effects.

Foreland subsidence decreases towards the fronts of the southern Alps and Dinarids, in a manner consistent with a northward-tapering flexure, and mirrors the long-term (106 yr scale) foredeep geometry. Although the northern sites are closer to the active thrust front of the Alps, it appears that both at the intermediate- and short-term (100-10 kyr) time interval, the effect of thrust loading from the Alps is minor compared to the down-to-southwest flexure of the Adriatic plate beneath the Apennines experienced by the Romagna sites. The process underlined by the Late Pleistocene-Holocene coastal markers supports the model of asymmetric slab retreat for the two oppositely verging thrust belts (Doglioni *et al.*, 1999; Mariotti and Doglioni, 2000).

There may be however, hints of active thrust loading from the Alps, too. Holocene sites with large (1 mm/yr) subsidence are not only located in front of the northern Apennines, but also near to the Alps in the north (Fig. 4). Although uncertainty in borehole data interpretation is large due to possible sediment constipation, there appears to be for the northern sites a coincidence between largest subsidence and highest proximity to the Alpine front. This advanced part of the Alpine chain overlies one of the most active strands of the segmented south-alpine frontal thrust (the Montello thrust, Fig. 4; Benedetti *et al.*, 2000; Burrato *et al.*, 2008). The sites with larger Holocene subsidence are located in the thrust footwall and within ~40 km from the thrust tip-line. Although direct coseismic subsidence is unlikely (Carminati *et al.*, 2003), when the thrust nucleation depth and flexural rigidity of the Adriatic plate are taken into account, subsidence induced by interseismic thrust loading might be substantial, instead (e.g. King *et al.*, 1988). We cautiously suggest that a fraction (in the order of ~0.5 mm/yr, consistent with simple calculations of viscoelastic flexure) of Holocene subsidence north of the Venice lagoon might be caused by loading related to the current seismic cycle. This occurrence should not be recorded in the long-term data, which average over many cycles of quiescence and co-seismic slip. As a matter of fact, average subsidence rates for this sector are ~0.4 mm/yr for the last 600 kyr (Kent *et al.*, 2002), and ~0.5 mm/yr for the last 125 kyr (Ferranti *et al.*, 2006). Pleistocene rates cannot be readily compared to the short-term rates, which may witness a phase of rapid tectonic subsidence coupled to un unknown amount of constipation. East of Venice, Holocene lagoonal sediments older than 6 kyr show tectonic rates of 0.6 mm/yr or lower (Antonioli *et al.*, 2009), similar to the long-term subsidence after an initial compaction. Thus, ~0.5 mm/yr may be taken as the regional subsidence rate in this area, and an equal component of thrust loading and constipation add to the remaining.

The more general conclusion drawn from appraisal of the northern Adriatic data relates to the constancy of deformation rates. Unlike the Calabrian arc, where short-term displacement rates are consistently higher than rates established using the LIg data, in the coastal Po plain rate and spatial extent of displacements are steady over the different time-scales considered here (Fig. 4), including perhaps the tectonic component of tide-gauge record at Venice station (1955-2000). We argue that, unlike the south, local structures have a less important role at this coast, and the more substantial contribution to deformation comes from flexure of the Adriatic (micro)-plate which, at the temporal scale under scrutiny, is constant. The secondary role of local structures may derive both from their higher distance from the coast and their more limited size relative to what happens in the south. Only locally it is possible that the effects of local structures are recorded by coastal markers, as it is argued here for the higher subsidence of Veneto sites close to the active

Montello-Conegliano thrust, which may be affected by a non-elastic component of footwall displacement (see section 5.9).

Concluding remarks

This review illustrates how the use of various analytical tools in the study of coastal tectonics in Italy may provide information on specific time intervals and acting processes, with variable accuracy and precision. We recognize that uplift rates computed from the LIg marker are average estimates since 125 kyr BP, and do not show the temporal variability that might have occurred during individual earthquake cycles, which act at the 1-10 kyr interval, or, in the case of volcanic deformation, during episodes of magmatic unrest. In addition, long-term markers do not establish whether a particular site is currently experiencing tectonic stability or deformation. This alternative occurrence must be checked using younger markers (i.e. Holocene geomorphological and geoarcheological markers), or instrumental data. However, determination of Holocene displacement is difficult for most sites in Italy because of observational limitations imposed by the low displacement accrued since. Thus, the LIg markers remains for most of the Italian coastline an unsurpassed tool for reconstruction of the recent vertical tectonic motion.

On the other hand, when favourable conditions ensue, it is only the Holocene markers that provide insights into the current (1-10 kyr) earthquake cycle or, in the case of volcanic deformation (e.g. Campania), into transient processes such as magma injection, withdrawal, and depressurization. Unfortunately, the occurrence of ancient coseismic events using Holocene geomorphological data has to date been proved only for an handful of sites in southern Italy and Sicily (Mastronuzzi and Sansò, 2002; de Guidi *et al.*, 2003; Ferranti *et al.*, 2007; Scicchitano *et al.*, 2011). Everywhere else, studies of Holocene coastal displacements have solely provided average displacement rates. Compared to the 100 kyr scale indicators, Holocene markers yield a higher precision (inherent in recognition and measurement of markers), but suffer of less accuracy. This stems from the concurrence of other, non-tectonic processes (sediment compaction, non-modelled GIA effects, and so on) in the displacement budget, which, on the contrary, are averaged out when the LIg data are used.

Finally, instrumental data, both CGPS and tide-gauges, provide the most positive evidence of active deformation, but are fewer and have so far lesser accuracy than Holocene data, a pitfall which will be surpassed as time series grow. Data mass enlargement will also permit to model more adequately transient processes (e.g. oceanographic perturbations for tide gauges and silent slips for GPS data) which in many cases are still embedded in the presently available signal.

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