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Geodetic measurements at the northern border of the Adria plate

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Abstract

This work describes measurements and results relevant to crustal movements at the northern border of the Adria plate. The measurements taken into consideration are subsurface observations made with extensometers and tiltmeters and episodic and continuous GPS (CGPS) observations. The subsurface measurements cover a remarkably long period of 34 years, while the episodic GPS campaigns have been performed over a time period of 7 years. The CGPS observations are available since July 1996, and 3.5 years of data have been considered in this work. The main characteristics of each different type of measurement are illustrated, and a first approach is made to compare the results. It is shown that environmental effects are present both in subsurface and surface measurements. Methods to interpret and remove these signals are also proposed. The correlation between crustal deformation and seismic events is investigated, and some examples are presented. The long-term observations are discussed with respect to a well-known model of plate motion. The subsurface crustal long-term observations reveal inversions in the direction of deformation with time scales of 10 or more years, providing important boundary conditions for future geodynamic models of the northern Adria plate. The results show that the comparison between subsurface deformation and CGPS measurements, if made over a sufficiently long period of time, in the order of 10 years, can give important contributions to the understanding of the geodynamical and physical mechanisms related to the earthquake occurrence in this area. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The convergence of the African and Eurasian plates has been recognised as being responsible of the build-up of the Alpine, Dinaric, and Apenninic chains. The available geological and geophysical information has suggested a more complex plate interaction, with the presence of the Adria plate (or microplate), which is either defined as an independent unit, or as a promontory of the African plate. The temporal behaviour of the Adria plate in response to the convergence of the surrounding regions has been presumably more complex than a simple horizontal displacement. Most likely, it involved flexural bending processes, with a succession of vertical and horizontal displacements (Mantovani et al., 1997). The northern margin of the Adria plate is defined by the western Alps, southern Alps, Dinarides and by the Apennines. Concerning the anti-clockwise rotation of Adria with respect to Eurasia, several rotation poles of Adria have been proposed in the geological literature. For a discussion of the Adria plate we refer e.g. to the paper of Meletti et al. (2000) and citations therein.

The present work aims at describing the results of long-term measurements of crustal movements made both by means of subsurface geodetic instrumentation and the Global Positioning System (GPS) at the northern border of the Adria plate. It represents one of the first efforts to jointly discuss the GPS and subsurface deformation measurements, which is, however, hampered by several factors. In the case of GPS, the time variations of the station coordinates are measured with respect to a reference system. The differential movements of at least two GPS points are necessary to determine the extension or the tilt along a certain direction, which is the quantity comparable to the subsurface extension or tilt measurements. If the relative distance between two GPS points is achieved by means of episodic observations with an error in the order of 1 mm, a precision in deformation of 10^{-9} can be reached over a distance of 1000 km. This precision is typical of horizontal strain measurements. Yearly crustal deformation rates of the order of 10^{-7}/a can be detected over distances of the order of 10 km. GPS can give the average surface strain rate, which, however, can be rather different from the local strain rate measured with subsurface observations. Another problem is due to the different time resolution, which for subsurface measurements typically ranges from a few minutes to one hour, whereas repeated GPS measurements are made at few months or even a few years intervals. Only in recent times, with the advent of CGPS, time resolution is comparable. This fact broadens the spectrum of signals, which can be compared, such as Earth tides, ocean loading tides, and the effects due to atmospheric pressure, temperature and hydrology.

Next to tectonic signals related to the plate movements causing slow deformation, the Earth crust deforms due to a number of different effects. These are the Earth tides, the loading exerted by the ocean tides, the free oscillations of the Earth, the seismic waves, the movements along crustal faults (aseismic slip, coseismic slip) and environmental effects such as air pressure variations and the hydrological cycle. The full understanding of crustal movements implies that each one of these phenomena be correctly recognised, separated and modelled.

For decades, along the northern border of the Adria plate, subsurface measurements have been made by means of tiltmeters and strainmeters, providing a unique opportunity to study most, if not all, of the above phenomena. The first station was installed in 1958 near Trieste (Fig. 1), in the Grotta Gigante cave. The long-base tiltmeters (horizontal pendulums) of Zöllner type have been continuously working since then, with an interruption of a few years which allowed to

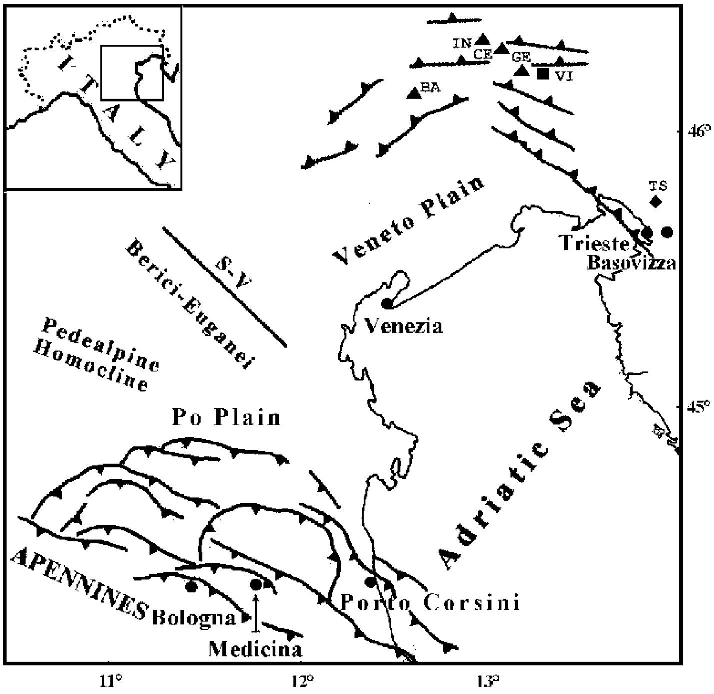

Fig. 1. Location of the stations and geological framework. Solid dots represent the GPS stations, triangles the stations equipped with short-base tiltmeters, a square the station with short-base tiltmeters and extensometers and the diamond the Grotta Gigante station with the long-base tiltmeters. (BA, Barcis; IN, Invillino; CE, Cesclans; GE, Gemona; VI, Villanova; TS, Grotta Gigante). Main tectonic features are indicated (see text for explanation; from Pieri and Groppi, 1981).

completely revise the instrumentation (Marussi, 1960, Braitenberg and Zadro, 1999). Later, in 1977, a network of five stations was installed about 100 km to the north, in Friuli, an area which is one of the most seismic along the Alpine belt (Zadro, 1978). All stations (Fig. 1) were equipped with a couple of short-base Marussi-tiltmeters and one with three additional horizontal invar-wire extensometers. These stations have been continuously recording until the end of 1997, when only the tilt-extensometric station was kept in operation. In order to compare the long-base tiltmeters with the tiltmeters installed in the Friuli area, in June 1999 a pair of Marussi-tiltmeters was installed in the Grotta Gigante cave, nearby the long-base tiltmeters. Details on the instrumentation can be found in Braitenberg (1999a). The measurements of the different phenomena are also influenced by site-effects and by the type of instrumentation used. The long-base tiltmeters differ in a fundamental point from traditional tiltmeters. In fact, traditional tiltmeters measure the tilting of the ground by measuring the differential height variation of two points on the floor; the long-base horizontal pendulums measure the differential horizontal movement of two reference points on the bottom and ceiling of the cave, about 100 m apart. This makes the latter instruments very stable and less prone to disturbances.

The calculation of noise spectra is a good means to estimate the quality of a station or instrument. In Fig. 2 the noise spectra of the long-base and traditional tiltmeters, both from the station Grotta Gigante are shown. The spectra of the long-base pendulums were calculated by means of

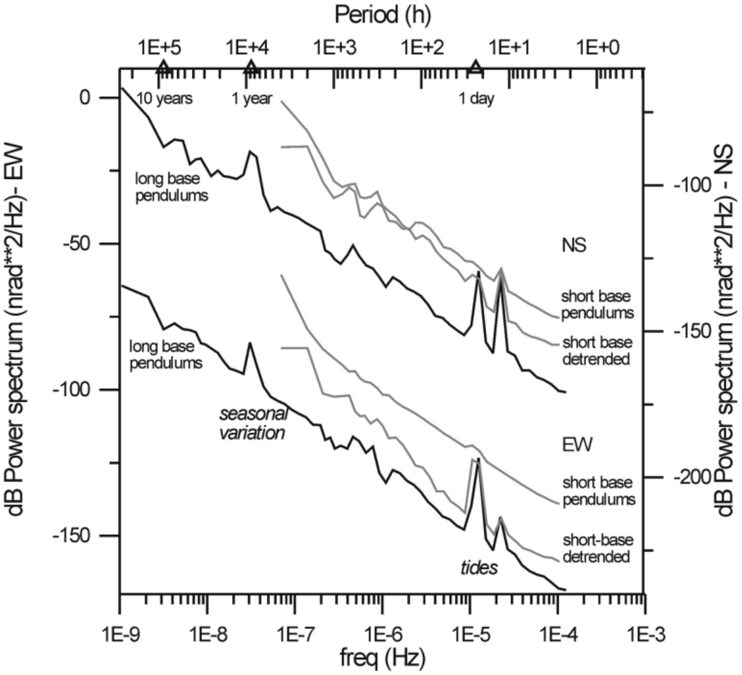

Fig. 2. Noise spectra of the long-base pendulums (black) and of the short-base Marussi-pendulums (grey), both installed in the Grotta Gigante. The spectra of the short-base pendulums pertain to the original and the detrended data, respectively.

30 years of data (1967–1997) in the low frequency range, and by means of six years of data (1991–1996) for the high frequency range (2.10^{-7}–10^{-4} Hz). The spectra of the short-base pendulums are limited by the data availability and were calculated over 19 months of data (June 1999–December 2000). The short-base pendulums are affected by a drift, not present in the long-base pendulums. The effect of the drift on the noise spectrum is an upward shift of the curve, as can be verified by comparison with the noise curve of the data detrended with a fourth order polynome. It can be seen that the noise level is altogether lower for the long-base instrumentation, although some portion of the noise in the short-base pendulums may be due to the initial period of instrumental settlement. It is important for crustal movement studies to have low noise level and high precision instrumentation, due to the fact that the tectonic signals that are sought for are very small (Zadro and Braitenberg, 1999). The fact of having long data series allows the quantification of the order of magnitudes of the different contributions to the deformation signal. In Table 1 the contributions due to long-period drift, annual variation, pressure variations, hydrologic effect, and Earth tides are summarised. The long-period drift rates are maximum values calculated over several years in which the drift direction remains constant. The amplitude of the annual variation is calculated over 20 years of records.

The initial GPS observations started with episodic campaigns in 1993 at Medicina, Venice, Trieste and Basovizza (Fig. 1) within the framework of the European Union SELF Project (Zerbini et al, 1996). At Medicina, a well-known fiducial station of the space geodesy network, the

Table 1
Quantification of the contribution of different signals measured by deformation instrumentation (VI, Villanova; GG, Grotta Gigante)

	Long-term drift	Annual variation[a]	Tidal signal[a]	Hydrologic signal	Pressure signal
Extensometers VI	$0.7\ 10^{-6}$/a	$1.2\ 10^{-6}$	$40\ 10^{-9}$	$400\ 10^{-9}$	$30\ 10^{-9}$
Tiltmeters VI	730 ms/a	1000 ms	25 ms	100 ms	Nearly absent
Long-base tiltmeters GG	13 ms/a	100 ms	25 ms	100 ms	Absent

[a] Peak to peak amplitude.

GPS benchmark was installed on the main pillar of the mobile satellite laser ranging (SLR) pad, in Venice the benchmark is located at Punta della Salute close to the tide gauge housing. In Trieste, the GPS benchmark is in the harbour, on the balcony of the Adriaco Yacht Club on the Sartorio pier, while at Basovizza the benchmark is on the main pillar of the mobile SLR pad in the area of the Astronomical Observatory. Measurements were repeated in these stations during 1996 in the course of the SELF II Project (Becker et al., 2000) and in Trieste also during 1998. Continuous GPS (CGPS) observations started within the activities of the SELF II Project in mid 1996 at Medicina and Porto Corsini (see Fig. 1). At Porto Corsini the GPS antenna benchmark is on the roof of a building close to the tide gauge housing. Continuous GPS observations started in Bologna in May 1999 (the antenna is located on the roof of the new building of the Department of Physics) while in Trieste CGPS observations started in March 2000.

The GPS technique plays nowadays a fundamental role in the definition of high precision station velocities, both horizontal and vertical. It is therefore a key tool to be used in crustal deformation studies. Horizontal station velocities can be determined by means of repeated episodic campaigns to the few mm/a level of accuracy, while vertical rates are more difficult to determine to the sub-centimetre level because of the several possible error sources affecting the height determination. Among these, the tropospheric signal propagation error is one of the most relevant. CGPS observations provide the capability to estimate horizontal velocities to the fraction of millimetre level; in the case of height changes, the few mm/a level of accuracy can be reached if sufficiently long time series are available, and provided that the installation and equipment has not changed. Long-time series allow the identification of seasonal signals, which need to be understood and modelled since they can contribute a few mm/a to the long-term linear trends.

2. Geological setting

All the stations considered in the present study are distributed around the northern edge of the Adria plate, which is almost entirely surrounded by thrust belts (see Fig. 1). Bologna and Medicina are located in the southern Po Plain, close to the Pede–Apenninic margin (Boccaletti et al., 1985), which represents a main structural boundary, repeatedly active during the Pleistocene, between uplifting (to the south) and subsiding (towards the Plain) crustal sectors. In the subsurface of the Po Valley, north-east verging Apenninic fronts, in the form of buried arcuate belts of asymmetric folds, overthrust onto the Pedealpine Homocline and are sealed by Upper Pliocene to

Quaternary alluvial sediments (Pieri and Groppi, 1981). The eastern arch is formed by the internal (Romagna) imbricate thrusts and the external (Ferrara and Adriatic) folded features (Boccaletti et al., 1985). Porto Corsini lies on the easternmost coastal Plain on the Adriatic Sea, where the natural, long-term subsidence has been greatly enhanced, in the second half of 1900, by anthropogenic factors, connected to overpumping of water and gas from the underground.

East of the Berici–Euganei alignment, the main Adria plate is considered to be de-coupled from its Padanian sector by a shear zone, whose northernmost segment should correspond to the Schio–Vicenza line (Mantovani et al., 1997). In correspondence of the Veneto Plain, the Adriatic foreland shows poor internal deformation; in this area, in fact, the subsurface slopes with uniform gradient from the foot of the Pre-Alps to the south and meets the buried front of the Dinarid folds in the Friuli Plain (Pieri and Groppi, 1981). The sector as a whole is characterised by moderate subsidence (Boccaletti et al., 1985). In the northern part of the Friuli pre-alpine zone, in which the tilt-strainmeters are located (Fig. 1), the Alpine EW overthrusts collide with the NW–SE Dinaric strike-slip structures. At the northeastern edge of the Adriatic foreland are located Trieste and Basovizza, lying on a sector tectonically deformed mainly along NW–SE oriented folds.

3. Environmental effects

Table 1 shows that the environmental effects in the underground deformation measurements cannot be neglected, if a full understanding of the deformational records is to be achieved. This is equally significant for the CGPS observations, which show relevant seasonal fluctuations, particularly in the vertical component. These signals must be considered when aiming at a proper interpretation of the records, since they must not be interpreted as purely tectonic effects. The most important environmental parameters are temperature, barometric pressure and rainfall. In some cases it can be of use to consider the water table variations as well because the underground water flow can influence the measurements.

3.1. Air pressure loading

The air pressure loading has the greatest effects on the extensometric measurements. Correlation studies (Dal Moro and Zadro, 1998) have shown that the extensometric signal is correlated with pressure, with correlation coefficients up to 0.7 considering the frequency range of 1/15–1/2 cpd. The regression coefficient resulted to be $1.5\ 10^{-9}$/mbar. The variation of pressure being in the range of ± 20 mbar gives a maximum induced signal of about $30\ 10^{-9}$. As regards tiltmeters, no significant correlation with air pressure has been identified. In fact, it has been reported that the spatial gradient influences tilt measurements, rather than the local pressure variations (Weise et al., 1999). Regarding the Italian stations, this hypothesis is still to be studied. Model studies using the Finite Element Method (FEM) can explain the observations in terms of loading of a topographic surface, in which a cave is embedded. The results are sensitive to the slope of the topographic surface and to the presence of the cavity, the latter producing a threefold amplification of the induced signal with respect to a solid model. The order of magnitude of the induced signal can be estimated by means of the FEM (Dal Moro et al., 2001).

The effects of air pressure loading on the Earth's crust have been studied in the CGPS height time series of the Medicina and Porto Corsini stations (Zerbini et al., 2001a,b). They appear to be relevant. At both stations, significant seasonal (annual) height variations induced by air pressure atmospheric loading have been identified. The vertical surface displacements were estimated by means of the Rabbel and Zschau (1985) model using regional (NCEP, NOAA-CIRES, Boulder, Colorado) and local air pressure data. This seasonal effect was represented by means of best fitting annual waves with maxima in mid July and amplitudes of 1.4 mm and 1.3 mm for Medicina and Porto Corsini respectively.

3.2. *Temperature effect*

The variation of the external temperature is transmitted to depth by heat conduction of the rocks. This is governed by the heat conduction equation, which depends on the frequency of the temperature variation and the thermal conductivity of the rocks. This results in an exponentially attenuated temperature curve at depth, phase shifted by a certain amount (Lowrie, 1997, p. 189). The attenuation coefficient and the phase shift depend on frequency, conduction coefficient and depth. In the case of measurements made in caves, as in the Friuli area, the heat conduction equation underestimates the temperature variation and results in an overestimated phase shift, most likely due to air currents along the different arms of the cave. The temperature variation gives rise to a thermoelastic crustal deformation, recorded by all instruments. The peak-to-peak annual deformation values are given in Table 1. In the different Friuli stations, it was found, from regression analysis (Garavaglia et al., 2000), that the tiltmeters have regression coefficients equal to 25 ms/°C to 50 ms/°C for the annual variation. Only in one case (CE), a surface station located on a conglomerate hill, was found to have much higher coefficients, with strong differences in the NS and EW tilt component, 200 ms/°C and 700 ms/°C, respectively. The time evolution of the yearly deformation is generally a regular sinusoidal curve. However, it has been observed that, in some stations, the regular variation is disturbed by another signal, most likely due to hydrologic-induced effects and/or snow melting.

3.3. *Hydrologic induced effect*

The rainfall and water table variations have a significant influence on deformation measurements. The typical rainfall-induced deformation signal is a step-like deformation, with near to exponential recovery. The signal is stable for each station: the extensometers record a compressional signal, with relatively stable direction of the principal axis of deformation. Similarly for tilts, the induced signal is characterised by a station-dependent typical direction. The direction may change to some extent, according to the amount of rainfall (Dal Moro and Zadro, 1998). There have been some efforts to model the hydrologic-induced signal by describing the process in terms of poro-elasticity (Kümpel, 1986). For the Friuli stations, a statistical approach has been applied, which makes use of linear predictive filtering methods (Braitenberg, 1999b; Braitenberg and Zadro, 2001). It has been found that the statistical approach allows the modelling of the induced signal quite well. The study of the hydrologic-induced signal is important because this could be misinterpreted as a tectonic signal, if not correctly identified. Further, in connection with the induced seismicity, the hydrologic-induced signals are of interest, as they may help to explain the triggering phenomenon observed at dams. Concerning the seismicity of Friuli, it has been shown that the microseismicity is not random, but contains a small, however significant, close to annual periodicity. The hypothesis has been made that this observation could be related to the local hydrology (Braitenberg, 2000).

As in the case of the air pressure, vertical crustal displacements can be induced by loading effects due to the hydrological cycle. CGPS measurements at Medicina and Porto Corsini have allowed the study of the contribution of hydrological loading effects on the observed height variations (Zerbini et al., 2001a,b) by means of a simplified climatic hydrological balance for the two areas. A seasonal signal has been identified, and modelled by using an admittance factor between the hydrological balance series and the GPS height series. The resulting annual waves describing the vertical displacements, have maxima occurring in mid September and amplitudes of 2.1 mm for Medicina and 1.4 mm for Porto Corsini respectively.

4. Earth tides

The Grotta Gigante long-base tiltmeters were installed in 1958 in the frame of an international program promoting a world-wide campaign for Earth tide measurements, the principal task was a better determination of the rheological behaviour of crust and upper mantle. The Earth tides indeed are the only one case of forced oscillations which involve the whole Earth's body and for which the input is very well known, outputs being the deformations recorded in the stations around the world. Since the early times, several perturbations in the measurements were recognised, as those due to the atmospheric and hydrological agents discussed in Section 3. The loading effect of the oceanic tides was also found to be a strong perturbation factor, especially for stations near the oceanic coasts. Thereafter, a good knowledge of the oceanic co-tidal and co-range lines both for diurnal and semidiurnal waves, as well as of the elastic model of the Earth permitted to calculate, with good approximation, the Newtonian and elastic loading response of the gravity and deformational perturbations inside continental areas. Such computations are useful for inland stations, where the perturbation is weak, however, for stations near to the coasts, the local behaviour of the sea tide must be more carefully evaluated. Stations near closed or partially open basins are mostly influenced by the inner sea tides, so that the effect has to be calculated according to the knowledge of the corresponding co-tidal and co-range lines and the local structure of the crust. This is the case of the Grotta Gigante station, located at only 2.5 km distance from the coast, at the northern edge of the Adriatic Basin which is a semi-enclosed basin. The tidal excursion recorded at the Trieste harbour reaches about 1m and is the highest recorded on the Adriatic coasts. The Grotta Gigante tilt loading response is of the same order of magnitude as the Earth tide effect and, due to the particular local situation, is in phase with the sea tide recorded at the Trieste harbour (Zadro, 1972). The order of magnitude is about 0.25 ms/cm towards West for the E–W component, and about 0.30 ms/cm towards South for the N–S component (for increasing sea level variations).

The tides of the Adriatic Basin were already known (Polli, 1959) at the time of the installation of the Grotta Gigante long-base tiltmeters, and those of the Mediterranean Basin were computed by integrating the hydrodynamical equations, taking into account the Mediterranean harbour tidal data (Zadro and Chiaruttini, 1975; Chiaruttini, 1976). The loading effect was computed for the GG station, as well as for some additional sites in Italy. In Fig. 3 the co-tidal and co-range lines are shown for the M2 tide. A summary of the results described above regarding the amplitude and phase for the two main diurnal and semidiurnal tides (K1 and M2) and the GG station is given in Table 2. The table reports amplitudes and phases of the two tidal constituents for the tide gauge of the Trieste harbour, the long-base pendulums of GG, and the astronomical tide referred to a rigid Earth. Taking into account the Love-numbers, the theoretical tilt tide is 70% of the astronomical tide. The above results demonstrate how loading effects can influence geodetic measurements, especially for stations near to the coast.

The Friuli tilt-strain stations have been installed for the purpose of detecting seismotectonic deformations. Only after 1990, the stations were digitised thus providing an appropriate signal to detect also the Earth tides. However, the three strainmeters operative at VI were equipped from the beginning (1979) with an analog recording system suitable to detect also the Earth tides. In

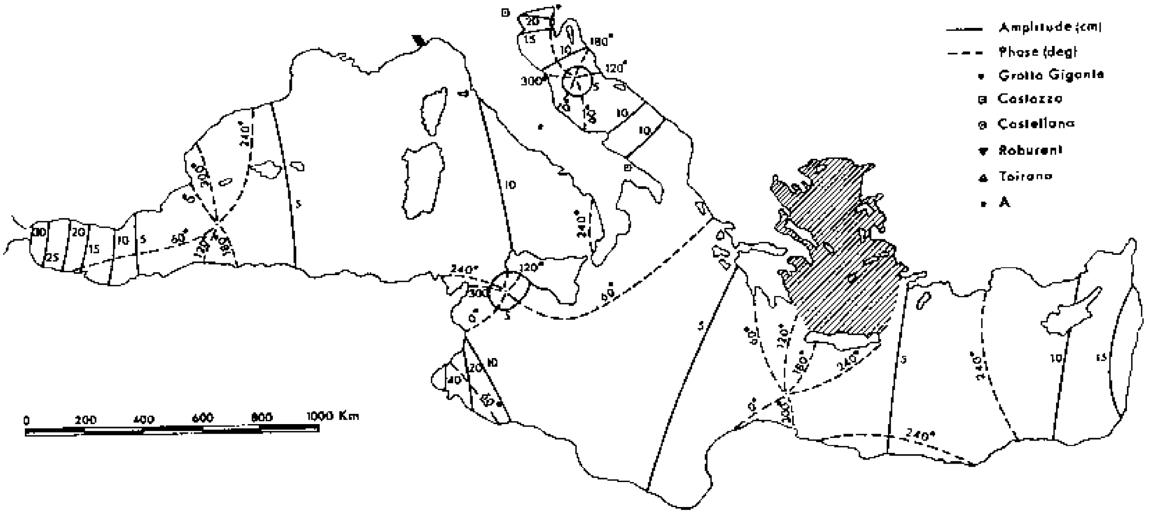

Fig. 3. Co-tidal maps of the Mediterranean Sea for M2-tide. Shaded area was not considered in the calculations.

Table 2
Amplitude and phase of main diurnal (K1) and semidiurnal (M2) tidal constituents for the tide gauge of Trieste harbour, the astronomical tide referred to a rigid Earth, and the long base pendulums of Grotta Gigante

	Trieste tide gauge		EW astr. (ms)	Observed tides GG station		EW sea effect (ms)	EW sea effect (°)
	(cm)	phase (°)		EW (ms)	EW phase (°)		
K1	17.2	69	6.7	9.2	84	4.3	73
M2	26.8	276	10.9	1.2	86	6.6	273
			NS astr(ms)	NS (ms)	NS phase (°)	NS sea effect (ms)	NS sea effect (°)
K1	17.2	69	0.2	4.0	67	4.4	73
M2	26.8	276	7.8	6.6	313	4.9	275

the VI station the loading effect is negligible and the length of the records has allowed a long-term analysis on possible local variations of the admittance of the tidal response caused by variations in the elastic properties of the crustal layers. The areal strain factor (Mao et al., 1989) shows that its time variation is significant. The modifications of mechanical properties, estimated in terms of the local shear and bulk modulus variations, were calculated and compared with the simultaneous inversion of the arrival time data of the local seismometric network, thus showing comparable changes. A major change, both in seismic velocities and the elastic parameters, started in March 1982, which was about 11 months before an earthquake of magnitude 4.1, the largest event from 1979 to 1986, which occurred within the seismic network on 10 February 1983.

5. Long-term observations

5.1. Underground measurements

The multi-decades continuous extensometric and clinometric observations provide a good picture of the long-period deformations. In Fig. 4 the entire data set of the stations Villanova and Grotta Gigante, reduced from the original hourly to daily sampling, is shown. The most stable records come from the long-base Grotta Gigante pendulums. All instruments reveal a multi-annual drift, with time changes in the drift rate, as well as in drift direction. The Grotta Gigante records have changes in drift direction around 1980 and 1995. The drift behaviour of the Villanova station is more complicated, with an inversion around 1988. In the case of long-period observations the danger exists that a drift is due to material deterioration, more than being a tectonic effect. However, the observation that the drift rate changes in direction is not compatible with a purely instrumental effect, and this can thus be attributed to a tectonic effect. Comparisons of the records at Grotta Gigante with those of the VI and CE Friuli (see Fig. 1) stations have revealed a significant correlation between the observed deformations. This has been interpreted as being due to two crustal long-period travelling waves of 3–4 and 7–8 years period (Rossi and Zadro, 1996). A direct correlation of the long-term drift rates and the time evolution of local seismicity has not been found up to now.

5.2. Continuous and episodic GPS

The observed absolute topocentric motion vectors for the Bologna, Medicina and Porto Corsini stations together with, for comparison purposes, those estimated by means of the NNR NUVEL-1 model (Argus and Gordon, 1991) are presented in Fig. 5. The results of the Trieste station are not discussed here because the time series is still too short (only a few months) to provide reliable information on the station velocities. As a matter of fact, it shall be pointed out that the horizontal velocity vector for the Bologna station has been derived by means of only the first six months of observations (May–December 1999). It appears to differ from the model predictions, both in magnitude and direction, by an amount significantly larger than those of the other two stations for which 3.5 years of continuous observations are used. This might be due to the fact that a marked seasonal signal seems to be present in the available year of data, thus affecting the determination of a long-term trend (Zerbini et al., 2001a,b; Negusini et al., 2000).

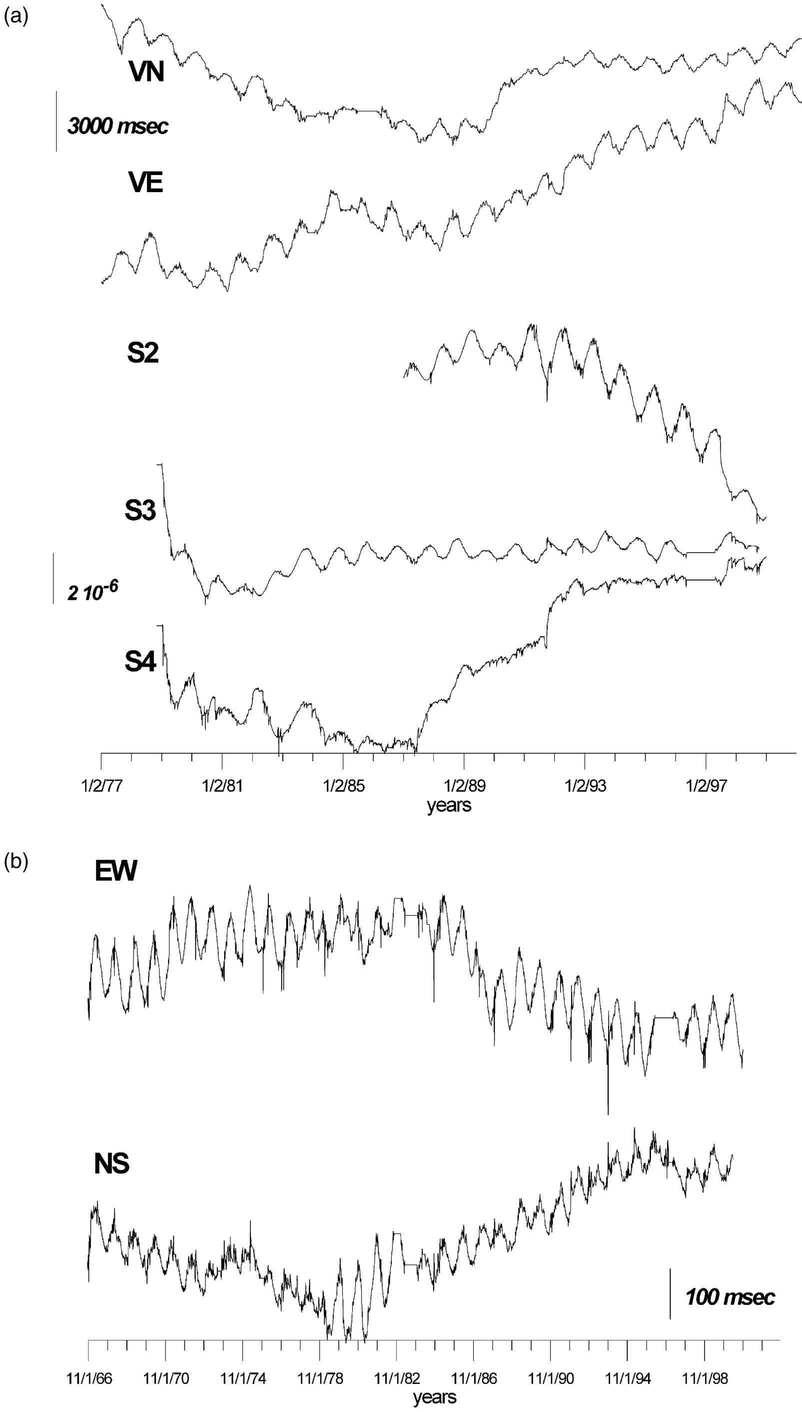

Fig. 4. Graph of the tilt-strain observations. Daily sampling. (a) Villanova S2, S3, S4 the three strainmeters, VN, VE, the tiltmeters in NS and EW direction, respectively; (b) Grotta Gigante station, EW and NS components of long base

Fig. 6 shows the residual vectors (NNR NUVEL-1 model subtracted, motions are relative to the Eurasian plate) for the three stations. The Bologna and Medicina residual vectors have the same northward direction, however different magnitudes for the reason described above. The Porto Corsini residual velocity vector is clearly more northeastern oriented.

In the framework of the European Union SELF I and II projects (Zerbini et al., 1996; Becker et al, 2001), repeated GPS observations were performed at tide gauges in the Mediterranean area. Among the stations involved, there were the five stations in the northern Adriatic presented in Fig. 7, where the observed absolute motion vectors as well as the NNR NUVEL-1 model predictions are depicted. Medicina and Porto Corsini were observed during four and three campaigns respectively. The last two ones at Medicina and the last one at Porto Corsini lasted more than one week. Trieste was observed during three campaigns, the first two lasting only 48 h each, while the last one took place over an entire week. Basovizza and Venice were observed only

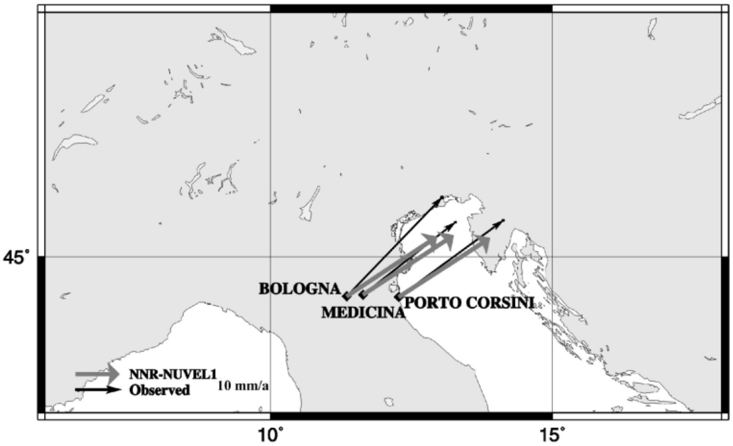

Fig. 5. Absolute topocentric motion vectors from continuous GPS observations (bold arrows) and model (NNR NUVEL-1) predictions (grey arrows).

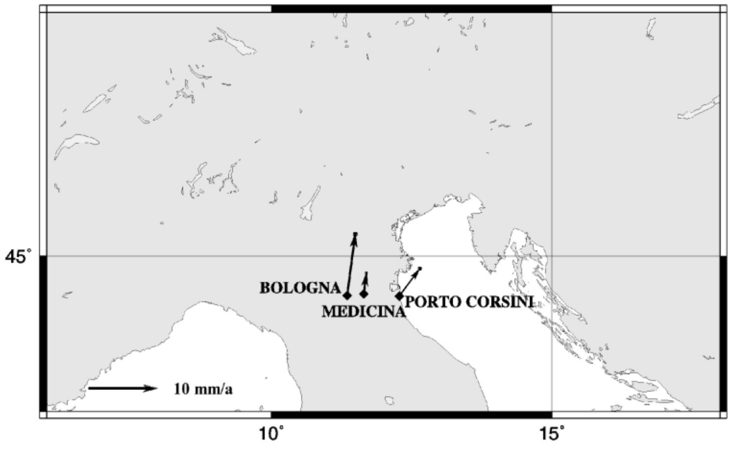

Fig. 6. Residual (model subtracted) velocity vectors. Motions are relative to the Eurasian plate.

during two campaigns, each lasting 48 h. In Venice problems were encountered with the GPS signal reception (Zerbini et al., 1996). A detailed description of the results of the SELF I and II GPS campaigns can be found in Becker et al. (2001).

The residual motion vectors are described in Fig. 8. The error ellipses, obtained by multiplying by a factor 15 the formal errors, reflect, on the one hand, problems associated with the stations (see Venice, as mentioned above) and the fact that these are episodic observations (versus the CGPS information available for the permanent sites). For the Medicina and Porto Corsini stations, a comparison is possible with the results obtained by continuous observations (see Fig. 6). The motion vectors, though not dramatically different from those obtained from CGPS observations, however, show discrepancies both in magnitude and direction. The vector magnitudes are larger for the results of the episodic campaigns, and directions appear to be more easterly oriented. The results of the episodic observations are obtained from the adjustment of a denser

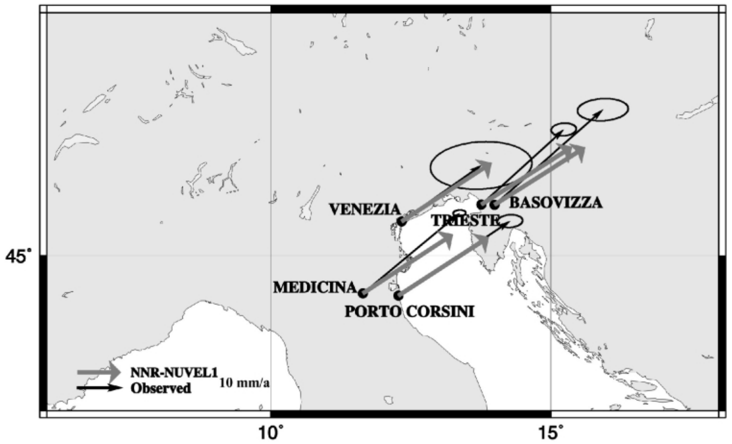

Fig. 7. Absolute topocentric motion vectors from episodic GPS campaigns (bold arrows) and model (NNR NUVEL-1) predictions (grey arrows).

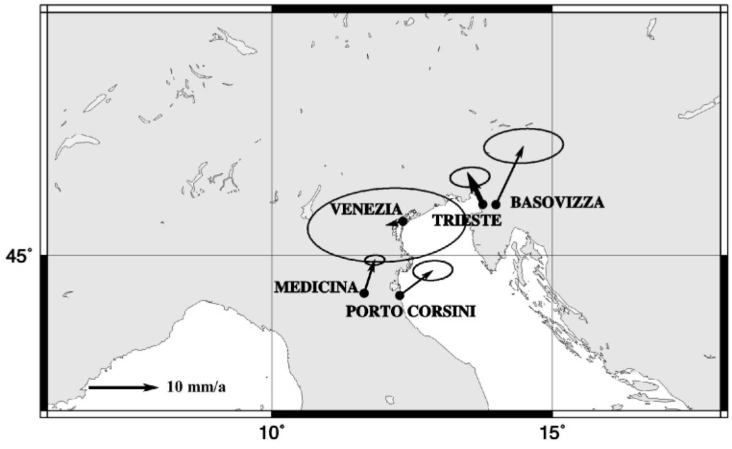

Fig. 8. Residual (model subtracted) velocity vectors. Motions are relative to the Eurasian plate.

and larger network of stations involving the entire Mediterranean area. It is likely that the adjustment of the solutions of the episodic campaigns may benefit from the higher density of stations (acting as constraints in the solution) with respect to those available (smaller network of stations, see, for example, Zerbini et al., 2001b) when considering the CGPS observations.

The results indicate that, from a limited number of episodic campaigns, reliable information on the station movements can hardly be obtained. The presence of relevant seasonal signals in the station coordinates has been identified (Zerbini et al., 2001a,b) and needs to be further investigated. This, in fact, can corrupt the determination of the long-term tectonic trends in the station velocities.

6. Deformation and seismicity

6.1. Underground measurements

The relation between short-period variation in deformation and local seismicity has given several interesting results, discussed in the following. The observations include preseismic, postseismic and coseismic signals, concerning the Friuli stations and the Grotta Gigante pendulums. The most spectacular observations were obtained with the long-base pendulums of the Grotta Gigante in the years preceding the great $M=6.4$ event of Friuli which occurred on 6 May 1976. Starting from 1973, the pendulums recorded disturbing signals of a few minutes period (Zadro, 1978) lasting several hours. In the following months the appearance of the disturbances, as well as the relevant duration, increased. Firstly it was believed that the anomalies were due to some disturbing factor, then the wires of the pendulums were changed, and finally a plastic protection was made around the sustaining wires of each pendulum. These actions did not reduce the observed phenomena that continued to increase in intensity. The disturbances ceased suddenly with the advent of the main shock in 1976. During the following months, the duration and intensity of the anomalies decreased, and they disappeared since then. One theoretical explanation was proposed attributing the signals to silent earthquakes, generated by a slow movement along the fault (Bonafede et al., 1983; Dragoni et al., 1984/5). Theoretical relations regarding the expected coseismic (Wyatt, 1988) or preseismic (Dobrovolsky et al., 1979) deformation have been applied to screen the data for significant short-period deformations related to the local seismicity. The theoretical considerations provide magnitude-distance relations according to which, given the instrumental sensitivity level, a coseismic or precursory deformation associated to an earthquake of a given magnitude should be seen at the observation station. Furthermore, the empirical relation of Takemoto (1991) for precursory deformation was also tested. The crude seismic catalogue as well as the aftershock depleted catalogue was used, and both epicentral distances (Dal Moro and Zadro, 1999) and hypocentral distances (Braitenberg, 1999a) were applied. Regarding the precursory effects, two seismic events obeyed the above theoretical considerations and resulted to have generated anomalous deformation signals, even if very different in nature (Dal Moro and Zadro, 1999). Both events, of comparable magnitude near to $M=4$, occurred at small epicentral distances from the stations (a few km). The first event, in February 1988, was preceded by an anomalous drift, which started two to three months prior to the event. The coseismic deformation was well observed and it was compatible with a dislocation model of the fault. The second event, in October 1991, was preceded a few days before by an extremely intensive rainfall. Two of the strainmeters, usually having a compressional rain induced signal, measured a strong extension, and the tiltmeters in a second station recorded a steplike signal not followed by the typical exponential recovery. Regarding the coseismic steps, five events out of the eight being in a favourable magnitude–distance relationship, allowed to detect significant deformation. Dislocation models explain the observations reasonably well (Braitenberg, 1999a).

6.2. CGPS horizontal rates

The North and East components for the Medicina, Porto Corsini and Bologna stations are shown in Figs. 9 and 10, respectively. It shall be pointed out that the time period over which the horizontal rates for the Bologna station are computed is significantly different from that relevant to the other two stations. In fact, the GPS system was installed in Bologna only at the beginning of May 1999. This time difference, of course, is responsible for larger associated errors. However, also uncertainties in the determination of the linear trends of both coordinates could be present.

The baseline length between the stations of Medicina and Porto Corsini (the ones having a relatively long data set) is presented in Fig. 11. A linear trend equal to +2.5±0.1 mm/a is identified (Fig. 11a). After removing the linear trend (Fig. 11b), the baseline length residuals are shown together with two different linear trends identified prior and after the end of 1997. In the first period the rate is 1.9±0.2 mm/a, while in the second one it is 1.0±0.1 mm/a.

At the end of 1997, a sharp drop in the baseline rate of change is observed, mainly in conjunction with the inversion of sign in the differences of both the East and vertical components of the two stations. The sharp drop in the baseline length occurs within a few days (30 November–4 December 1997 with the main drop occurring between 1 and 2 December) at the end of an anomalous period of a few months during which the Central Italy (Umbria) seismic crisis took place. The first main shocks occurred on 26 September and the earthquake sequence lasted until the beginning of December 1997. Concurrently, the Medicina vertical component shows a clear

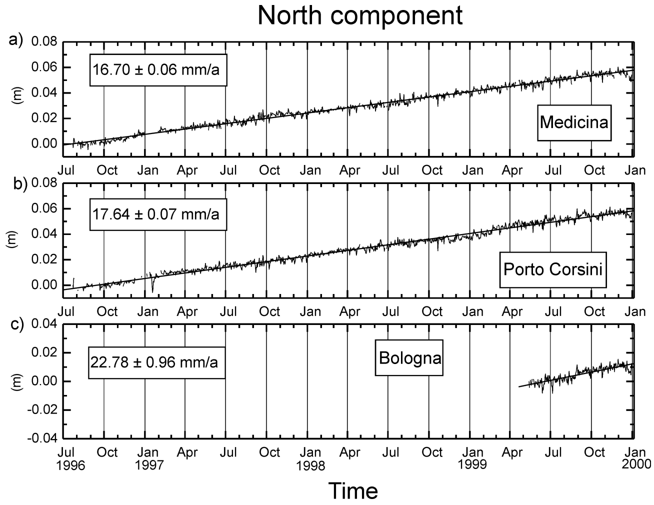

Fig. 9. North component for the Medicina, Porto Corsini and Bologna stations.

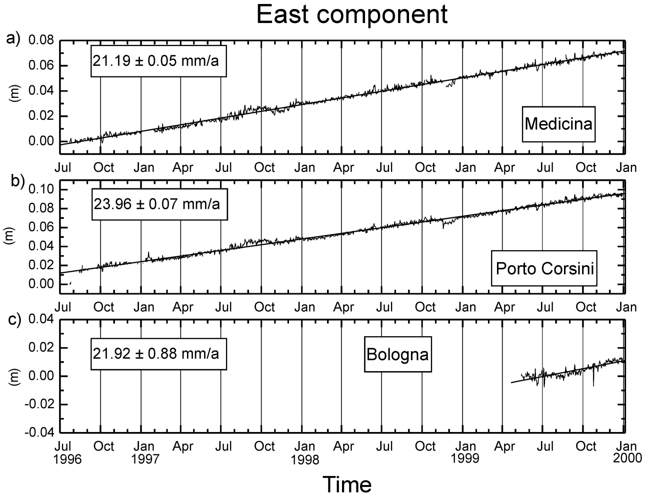

Fig. 10. East component for the Medicina, Porto Corsini and Bologna stations.

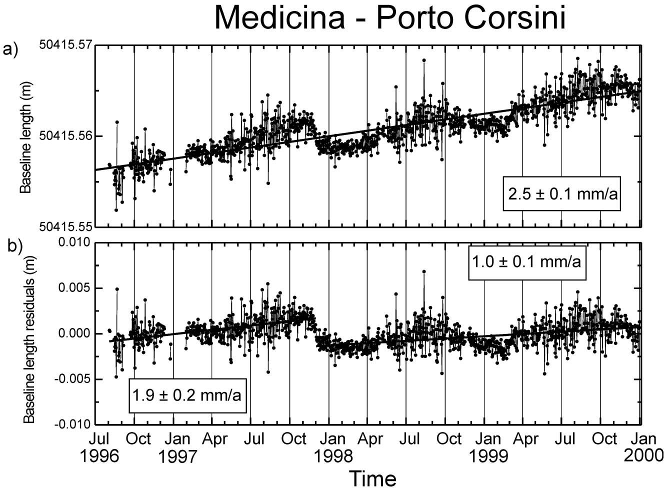

Fig. 11. (a) Medicina-Porto Corsini baseline length and linear trend; (b) baseline length residuals and different linear trends.

increase of about 5 mm during the month of September, reaching its maximum on 25 September (Zerbini et al., 2001b) the day prior to the first major shock. The observed drop in the baseline length is representative of a real change in the stations coordinates. In fact, at Medicina since October 1996 a superconducting gravimeter is also available. The gravity data series shows a sudden and major tilt of the pillar on which the superconducting gravimeter is located on 1 December 1997 (Zerbini et al., 2001a,b).

The baseline length behaviour mainly reflects the difference between the East components of the two stations, the correlation coefficient being 0.98. The height difference between the two stations also provides a significant correlation coefficient 0.70, while the difference of the North components does not show any such relevant correspondence.

The baseline length shows also a clear seasonal signal: during the summer periods the baseline rate of change is larger compared to the long-term trends (Zerbini et al., 2001b). Also the rms scatter of the baseline length residuals has a different seasonal behaviour, higher in the June–September time frame than it is in the October–May period. The higher scatter observed in the summer season might be attributed to atmospheric scintillation effects.

7. Conclusions and perspectives for the future

A picture of the experimental efforts and of the main results regarding geodetic monitoring of crustal movements along the northern border of the Adria plate has been provided. The observations included subsurface measurements of linear deformation and tilt of crustal rocks (extensometers and tiltmeters), and space-geodetic methods to determine time variations of ground station coordinates (episodic and continuous GPS). Both types of measurements aim at observing the deformation of the Earth's crust driven by plate-tectonic movements. The measurement techniques are quite different, as GPS allows the detection of movements of a point on the surface relative to an Earth reference frame, while tilt and extensometric measurements each give one component of the deformation tensor at a given depth. To directly compare the results of the different observational techniques in terms of surface strain components, a network of GPS points should be located above the subsurface measurement sites. Differences shall be expected, as the GPS-derived strain tensor is an average quantity depending upon the distances between the GPS points, whereas the subsurface measurements give a punctual local value of the strain tensor components. The comparison of different types of measurements is always profitable because it can provide independent estimates of the same observables and better insights for each technique. A proper interpretation of both GPS and subsurface measurements need the understanding and modelling of environmental effects. These effects, such as the thermoelastic deformation, the hydrologic, or the atmospheric pressure induced signal are commonly identified and modelled in subsurface measurements. In the case of GPS, only the most recent development of CGPS observations has started to allow the identification and monitoring of these signals. GPS data can presently be processed with sophisticated software packages allowing removal of Earth tides and ocean loading effects (see, for example, Rothacher and Mervart, 1996). Environmental effects such as those induced by temperature, humidity and air pressure variations and by the hydrological cycle need to be carefully investigated.

Regarding the long-term underground deformations, the major problem in the records is the reliability of the instrumentation that can suffer from material deterioration effects possibly inducing a drift component. The data recorded in the Friuli network and in Trieste (Grotta Gigante) have provided time series of up to 34 years length exhibiting long-term variations. The fact that the drifts do not maintain the same direction, but they invert the tendency after several years, has given confidence to the reliability of the measurements. In fact, it is not possible that a material deterioration process can invert the tendency without any external (natural or man-made) intervention.

Both types of measurement techniques should be collocated at the same stations and work in parallel for several years in order to collect time series capable of providing reliable information on crustal deformation processes taking place in the area.

Presently, at the border of the Adria plate, such a direct comparison of CGPS and subsurface measurements is not yet possible, since a GPS network covering the location of the long-period subsurface measurements does not exist. Hopefully, in the near future, an integrated network could be established. This would broaden the chance of a joint interpretation of space-geodetic and subsurface crustal movement observations. Good examples are the Japanese CGPS network, where several hundreds CGPS stations have been installed throughout the country (Kato et al., 1998), and the Californian Permanent GPS geodetic array (Bock et al., 1997) covering the area of the extensometric and tiltmeter observation stations.

The results presented in this paper indicate that horizontal crustal deformations can be reliably identified by means of GPS observations. CGPS provides more confidence in the estimates of the rates. For the Medicina and Porto Corsini stations, horizontal velocity vectors have been estimated from CGPS observations. They were compared to those derived by episodic campaigns and to the vectors provided by the NNR NUVEL-1 tectonic model. The observed directions of the horizontal motion vectors appear in agreement with an anticlockwise rotation of the Adria plate considering a rotation pole located further west, as suggested by Meletti et al. (2000). A possible influence on the horizontal as well as vertical coordinates behaviour of the two stations due to seismic activity (central Italy, Umbria seismic crisis, at the end of 1997) has been indicated.

Concerning the long-period variations of tilt observed in the Grotta Gigante and VI stations, which reveals a near to oscillating character with a period of more than ten years, future measurements will show whether this is a time persistent phenomenon. It shall be investigated whether the same phenomenon can also be identified in other subsurface stations located e.g. in Japan, the Confederation of Independent States, or in California, where continuous records over sufficiently long periods of time are available, and in the future, with long-term collocated CGPS observations.

A future goal shall be that of providing the science community with time series of different observational data (collocated instruments) characterised by high accuracy, homogeneity and continuity. This observational capacity will allow the clear identification of anomalous deformation signals having, possibly, similar characters to those observed prior to the occurrence of the seismic events mentioned above.

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