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The very-broad-band long-base tiltmeters of Grotta Gigante (Trieste, Italy): Secular term tilting and the great Sumatra-Andaman islands earthquake of December 26, 2004

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Abstract

The horizontal pendulums of the Grotta Gigante (Giant Cave) in the Trieste Karst, are long-base tiltmeters with Zöllner type suspension. The instruments have been continuously recording tilt and shear in the Grotta Gigante since the date of their installation by Prof. Antonio Marussi in 1966. Their setup has been completely overhauled several times since installation, restricting the interruptions of the measurements though to a minimum. The continuous recordings, apart from some interruptions, cover thus almost 40 years of measurements, producing a very noticeable long-term tiltmeter record of crustal deformation. The original recording system, still in function, was photographic with a mechanical timing and paper-advancing system, which has never given any problems at all, as it is very stable and not vulnerable by external factors as high humidity, problems in power supply, lightning or similar. In December 2003 a new recording system was installed, based on a solid-state acquisition system intercepting a laser light reflected from a mirror mounted on the horizontal pendulum beam. The sampling rate is 30 Hz, which turns the long-base instrument to a very-broad-band tiltmeter, apt to record the tilt signal on a broad-band of frequencies, ranging from secular deformation rate through the earth tides to seismic waves. Here we describe the acquisition system and present two endline members of the instrumental observation, the up to date long-term recording, and the observation of the great Sumatra-Andaman Islands earthquake of December 26, 2004, seismic moment magnitude $M_w = 9.1–9.3$ [Lay, T., Kanamori, H., Ammon, C.J., Nettles, M., Ward, S.N., Aster, R.C., Beck, S.L., Bilek, S.L., Brudzinski, M.L., Butler, R., DeShon, H.R., Ekström, G., Satake, K., Sipkin, S., 2005. The Great Sumatra-Andaman Earthquake of 26 December 2004. Science. 308, 1127–1133.]. The secular-term observations indicate an average tilting over the last four decades towards NW of 23.4 nrad/year. We find evidences that this tilting is regional and has been going on since at least 125 ka. The recent earthquake of December 26, 2004 was well recorded by the pendulums. We show that the free oscillation modes were activated, including the lowest modes as e.g. ${}_0T_2$, ${}_0T_3$, ${}_0T_4$, ${}_0T_5$ and ${}_2S_1$, ${}_0S_3$, ${}_0S_4$, ${}_1S_2$.

Keywords: Geodetic underground measurements; Secular crustal deformation; Free oscillations; Ultra-broad-band tiltmeter; Sumatra-Andaman 2004 earthquake

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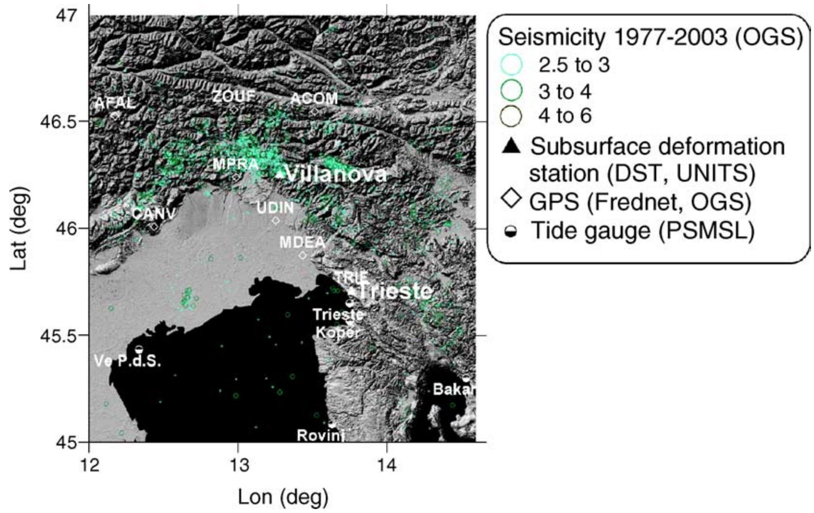

Fig. 1. Topographic map of the investigated area, with the locations of the long-base pendulum Grotta Gigante station (Trieste, Italy) and the tilt-strain observatory Villanova (Italy). Also shown are the tide-gauge stations of the PSMSL database (PSMSL, 2004) and the local seismicity (OGS, 2004).

1. Introduction

The Grotta Gigante (giant cave) situated in the Trieste Karst (latitude 45.7083°N and longitude 13.7633°E) bears the Guinness Award of greatest cave in the world, as it has an ellipsoidal shape of 130 m length, 65 m width and 107 m height. The geographical location of the station is seen in Fig. 1 (Trieste), where the topography (SRTM, 2004) of the studied area is shown. The other deformation station (Villanova) refers to a tilt-strain meter observatory we operate north of Trieste (Braitenberg, 1999b). Prof. Marussi (1959) had the brilliant idea to use the height of the cave to build a couple of long-base tiltmeters of the horizontal pendulum type with Zöllner suspension. After this date, the design of the mechanical part of the instruments was completely overhauled and the present instrumentation was installed in 1966. The horizontal pendulums consist of a sub-horizontal pendulum arm suspended by an upper wire fixed at the vault of the cave and a lower wire fixed to the ground of the cave. The distance between upper and lower mountings is 95 m. The total weight of the pendulum (including wires) is 18.7 kg, the horizontal beam has a length of 1.4 m and the period of oscillation of the pendulum in the horizontal plane is of 6 min (Marussi, 1959; Braitenberg, 1999b; Braitenberg and Zadro, 1999). A horizontal shift of the upper relative to the lower mounting of the pendulum (shear), a tilt of the cave or the inclination of the vertical are recorded as a rotation of the beam in the horizontal plane about the rotation axis, which lies on the line connecting the upper and lower mounting points of the pendulum. The static amplification factor for tilt (ratio of the angle of rotation of the beam in the horizontal plane with the tilting-angle of the line connecting upper and lower mountings) is about 24,000. The original recording system was optical on photographic paper, with an amplification of 4.4 nrad/mm. This system is very reliable and has been recording without greater problems since the time of the installation. The pendulums have been overhauled in 1982/1983 and in 1997, and some parts as the polyethylene tubes protecting the wires have been exchanged. Recently, in December 2003, a new digital acquisition system was installed, which is supposed to replace the photographic recording in the future, once its reliability has been ascertained. The advantages given by the digital acquisition system are the automatic readout, a drastically increased time and signal resolution, wherefore the instruments acquire the characteristics of a very broad-band tiltmeter.

In the sequel we give a short description of the acqusition system and show the secular tilt over the full observation period and the observation of the Sumatra-Andaman Islands $M = 9$ seismic event of December 26, 2004.

2. The new acquisition system

The new acqusition system records the position of a laser light reflected by a mirror mounted on the horizontal pendulum beam in correspondence of the rotation axis. The sensor is an analogical position sensitive detector (PSD)

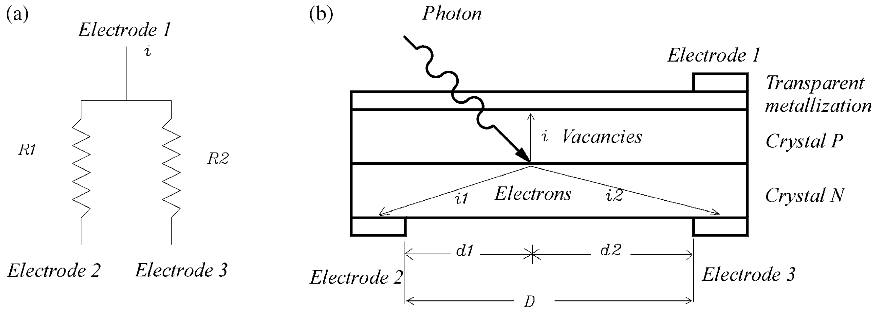

Fig. 2. Functioning of the PSD acquisition system. (a) Electronic circuit, (b) the interaction of the incoming light with the P–N junction creates a current, from which the position of the laser light can be determined.

made of a long P–N junction, which can be illuminated across a transparent metallization surface (Fig. 2b). The laser-light generates charge carriers that form the current i. The current that flows in the P-crystal is collected by the metallization, the current that flows in the crystal N is collected by the two electrodes located at the two extremes of the crystal, through which the currents i_1 and i_2 (with $i_1 + i_2 = i$) flow, respectively. The conduction, away from the junction, obeys Ohm's law and therefore depends on the distance of the electrodes and the conductivity of the crystal. The position of the luminous point of the laser beam on the surface of the sensor can thus be expressed as a function of the ratios of the currents on the electrodes.

With ρ the resistivity of the crystal N, for the resistances R_1, R_2 and the currents i_1, i_2 of the circuit shown in Fig. 2a, the following relation holds:

$$R_1 = \rho d_1$$
$$R_2 = \rho d_2$$
$$R_1 + R_2 = \rho D$$

The following equation shows how from the currents across the electrodes 2 and 3, the position of the luminous point can be obtained. V is the voltage applied to the circuit, d_1, d_2 and D are seen in Fig. 2b:

$$\frac{i_1 - i_2}{i_1 + i_2} = \frac{V/R_1 - V/R_2}{V/R_1 + V/R_2} = \frac{R_2 - R_1}{R_2 + R_1} = \frac{\rho d_2 - \rho d_1}{\rho D} = \frac{d_2 - d_1}{D} = \frac{2d_2 - D}{D}$$

from which it follows that the position d_2 is given by:

$$d_2 = \frac{D}{2}\left(1 + \frac{i_1 - i_2}{i_1 + i_2}\right)$$

The currents, which are output from the PSD are transformed into voltage, enter the A/D converter and are fed into the microprocessor for the arithmetical operations of sum and multiplication. The digital data are transferred to the serial port of the PC, and the data are saved on hourly files of 109,600 samples by the acquisition software. The PSD sensor has a length of 7 cm, which is read with 16 bit. This resolution is tied to the intrinsic PSD noise. The read out numbers are saved as decimal numbers with five significant digits. One unit corresponds to 8×10^{-11} rad of recorded tilt. The PC, running Linux, is accessible via ethernet, so the data are available in real time.

3. Secular crustal deformation for the years 1966–2004

The long period continuous observations by means of tiltmeters, which cover the remarkable time interval of nearly 40 years, are shown in Fig. 3a. The original data-sampling rate of the photographic readout is 1 h, which has been reduced to the rate of 1 day after application of a low-pass anti-alias filter. One evident feature of the observations is the regular yearly oscillation, seen in all crustal deformation stations of good quality, and mainly due to the thermal influence of 1 year period on the deformation; to some extent it is also due to the yearly variation of the subsurface waters, which though do not have such a regular oscillation (e.g. Zadro and Braitenberg, 1999; Braitenberg et al., 2001). By band-pass filtering the records with a cosine-tapered frequency filter (corner-periods equal to 300 and 400 days) we have isolated the yearly variation. Fig. 3b shows the tilt-vector for the yearly variation for the entire observed time

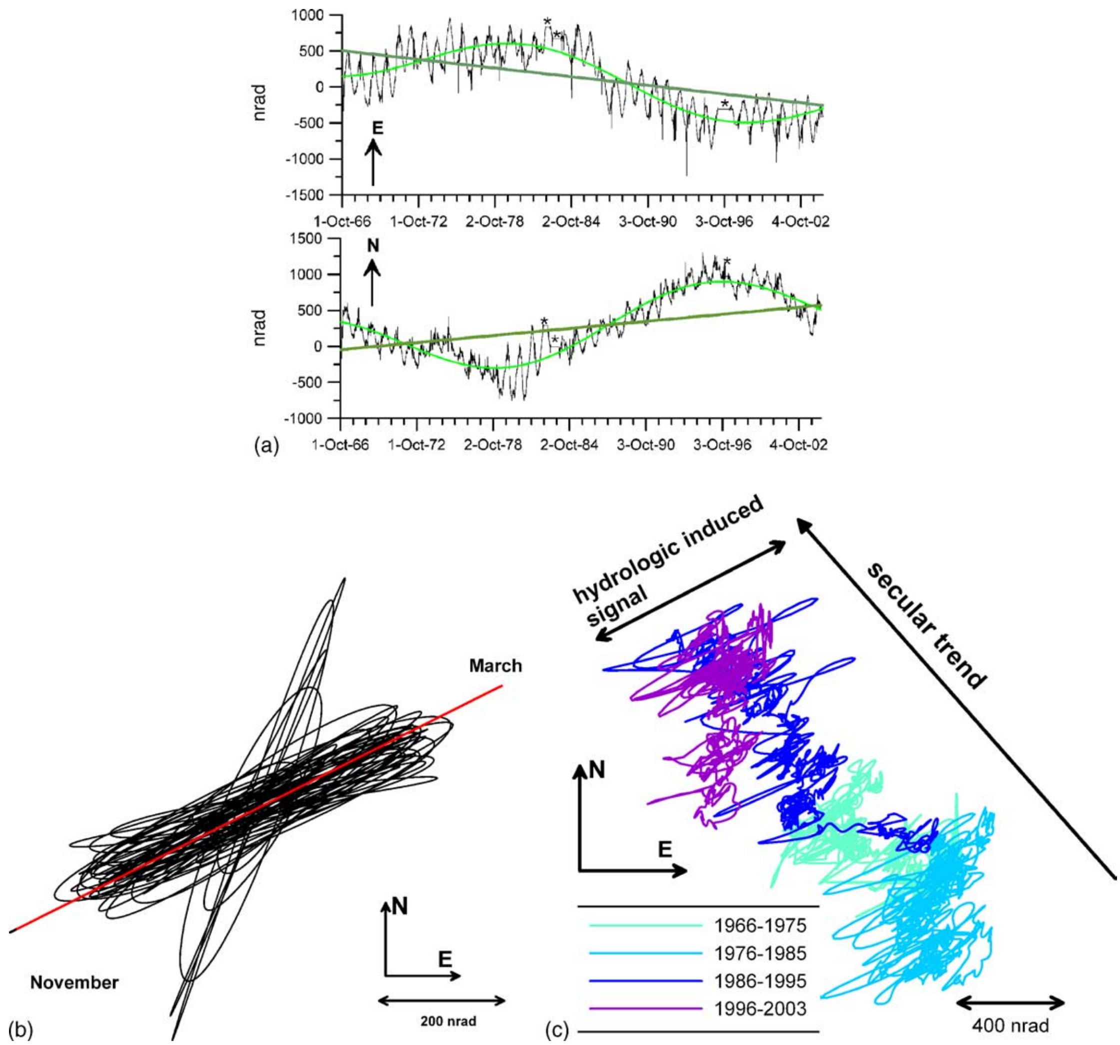

Fig. 3. The secular deformation of the cave as recorded by the long-base tiltmeters from October 13, 1966 to June 22, 2004. (a) Time-series of the NS and EW components: PE and PN refer to the EW and NS component, respectively. Interruptions longer than 75 days are denoted by an asterisk. Shown is the data curve (continuous line and the interpolation with a sinusoidal oscillation (light green line) and the interpolated linear variation (dark green line). The linear variation amounts to 23.4 nrad/year towards NW. (b) Hodograph of the tilt-vector showing the periodic yearly variation; the yearly variation has been extracted from the observations by band-pass filtering. The yearly variation is polarised along a NE-SW orientation (red line, linear regression), except for some exceptional years. The yearly variation is ascribed to temperature and hydrologic effects. Inversions of the tilting direction occur in November and March. (c) Tilt-hodograph, which shows the secular variation of the tilt-vector. The colour coding refers to different time windows. The original records with daily sampling have been cleaned from the yearly variation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

interval. The yearly tilt variation is polarized along the azimuth N64E, with the maximum tilting excursions towards NEE in March and towards SWW in November. The secular tilting is obtained from fitting the data to a linear trend and an oscillation of several decade-period. The length of the data-series does not allow to definitively identify this long-term secular variation, so we have tentatively isolated an assumed linear trend, which represents the net mean tilting in one definite direction and the possible oscillation. Fig. 3c shows the hodograph of the residual tilt-vector, cleaned from the yearly variation. The mean secular trend towards NE is visible, with inversions in the rate-directions in 1979/1981 and 1995/1997 (see Fig. 3a). We determine the optimal oscillation period by calculating the squared sum of errors between the observations and the model curve for oscillation periods between 20 and 60 years, with a step of 1 year. The root mean square of the model error on both components varies between 370 and 284 nrad for the periodicities between 20 and 60 years, respectively, and has the value of 270 nrad for the minimizing periodicity of 32

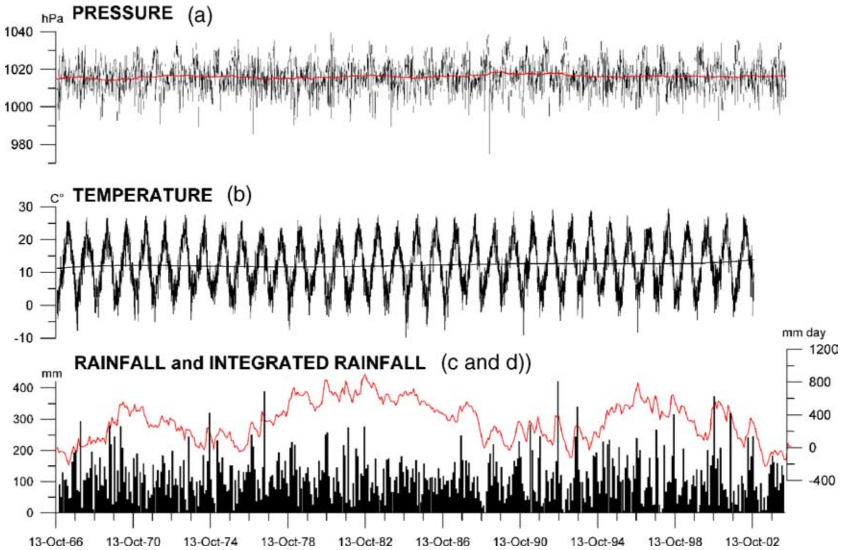

Fig. 4. Long-term observation of local ambient factors at station Borgo Grotta: (a) atmospheric pressure, (b) external temperature, (c) rainfall and (d) detrended integral of rainfall.

years. Taken each component separately, the minimizing period results to be of 31 and 34 years, for the NS and EW component, respectively, showing that there is consistency in the oscillation period for the two components. Adopting the 32 years periodicity, the linear trend is equal to 23.4 nrad/year in the tilting direction N45W over the time interval of 37 years. We have investigated whether the observed secular trend and the rate-inversions may be caused by long-term changes of environmental agents, which are temperature, atmospheric pressure, rainfall and ocean loading.

Long-term recording of daily atmospheric pressure is also available at a station above the cave. Fig. 4 shows the original daily records, and (red) the low pass filtered recording (365 days running mean) free from the yearly variation. In the years 1961–2004 the average pressure is 1016.05 ± 0.058 hPa, with the minimum value of 972.76 hPa, and the maximum value of 1041.01 hPa, and a standard deviation from the mean of 7.39 hPa. The long-term trend is near to zero. These values agree with a statistical study on 30 years of data recorded in a station situated in the town of Trieste, at 6 km distance. These pressure observations (1960–1990) have shown that the yearly average was limited within the bounds of 1018 and 1014 hPa (Stravisi, 1994). We have carried out a statistical analysis of the influence of atmospheric pressure variations on the pendulum records by regression analysis. For this purpose 2 years of pressure and tilt records were band-pass filtered with a cosine taper filter with cut-off periods of 30 and 720 h, in order to free the data from the tidal band and limit the variations to variations of 1 month. These periods were chosen, as the influence on the tidal band was calculated separately introducing also the tidal earth response, and because the tilt variations for periods longer than a month are influenced by the seasonal signal, present to a much less extent in the pressure data. It is found that the response to pressure from the tidal band to the band of 1 month is very small and equal to 0.97 nrad/hPa (Pagot, 2001). This shows that the influence of pressure on the secular term tilting is insignificant, as its contribution is less than 4 nrad (1018–1014 hPa multiplied by 0.97 nrad/hPa) over the entire observation interval.

The continuous long-term measurements of temperature inside the cave are unavailable, but measurements over the years have been made. Between 1969 and 1973 the yearly average temperature in the cave varied between 11.61 and 11.56 °C, with annual average variations between 0.3 and 0.65 °C (Tommasini, 1974). The long-term daily measurements of external temperature above the cave, between the years 1967 and 2002 are available (Fig. 4). The yearly average temperature is 12.25 ± 0.064 °C. Extremal values were −9.8 and 30.5 °C, with a standard deviation of 7.28 °C. The incremental coefficient of the regression line resulted to 0.038 °C/year, which amounts to an increase of 1.33 °C in the 35 years since 1967. Considering the yearly signal of tilting and temperature variation, we compare the standard deviation of 7.28 °C for temperature with the amplitude of 183 nrad of yearly tilting with azimuth N64E. In the case that the yearly tilting variation be entirely temperature induced, the tilt responds at the most with an amplitude of 183 nrad/7.28 °C, equal to 25 nrad/°C. With a mean temperature increase of 1.33 °C in 35 years, this would amount to a maximal effect of 25 nrad/°C × 1.33 °C, equal to 33 nrad, which is very small compared to the observed long-term

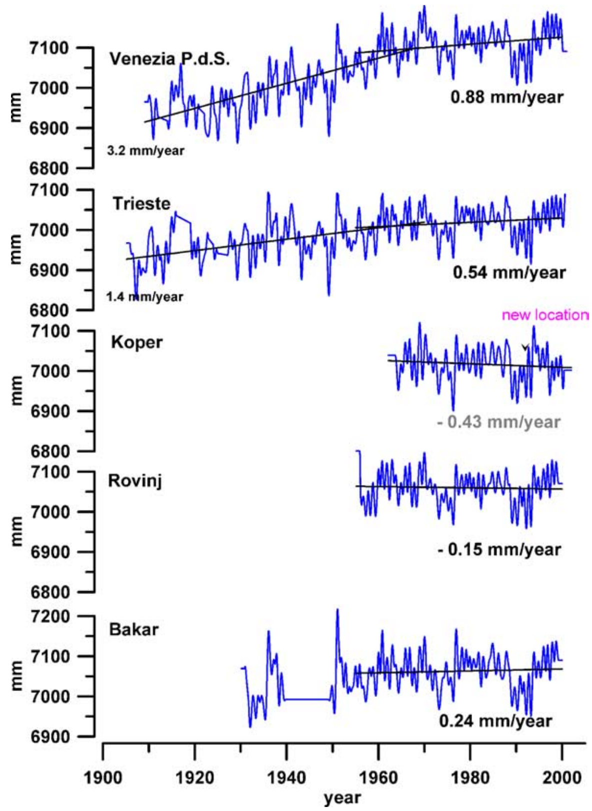

Fig. 5. Monthly record of tide gauge measurement of sea level in the upper Adriatic, including the locations Venezia Punta della Salute, Trieste, Koper, Rovinj and Bakar. The regression lines are calculated on the common time interval of years 1955–2000. For Trieste and Venice, furthermore the mean sea level rise has also been calculated for the years 1905–1970 and 1907–1970, respectively.

tilting of above 820 nrad. We may conclude that the long-term increase of temperature cannot be considered to have a significant effect on the long-term deformation.

The rainfall is available for the years 1967–2004 as monthly amount of rain (mm), measured above the cave. The average amount of monthly rain is 11.5 ± 3.3 mm, with extremal values of 0.2 and 420.6 mm and standard deviaton from the mean of 69.6 mm. For the purpose of comparison with the tiltmeters, we also calculate the time integral of rainfall and subtract the mean average increase. This corresponds to a bucket with a constant outlet and has been shown to be an appropriate first order means to evaluate the hydrologic effect in deformation measurements (e.g. Braitenberg, 1999a,c). The detrended rainfall integral (Fig. 4) shows a long-period variation, with maxima in the years 1970.4, 1982.9, 1997 and minima in 1976.4, 1993.5, 2003.6. The periodicity of this variation is much shorter than the one found in the tilt-meters (half-period of near to 16 years), and can thus be excluded to be responsible for the observed long-term observation.

The relative variation of sea level, as measured by the tide gauge of Trieste is available for the years 1905–2002, with monthly sampling. The data, shown in Fig. 5 are taken from the PSMSL database (2004), and have been low-pass filtered in order to reduce the high-amplitude yearly variation. The low-pass filter is a Hamming-filter with cut-off period of 12 months. The mean relative sea level has increased between 1906 and 2002 by an average rate of 1.1 mm/year, leading to a net relative increase of 11 cm. Presently, the exact calculation of the loading effect of the sea level rise on the tilt at Grotta Gigante is in progress and shall be presented in a following paper. Therefore, we may now estimate the order of magnitude of the contribution of sea level rise on tilt, by considering the loading effects of the semidiurnal and diurnal tides, which have been calculated precisely. Theoretical calculations (Zadro and Chiaruttini, 1975) have shown that ocean loading of the Adriatic on the pendulums is near to linearly proportional to the sea level in the gulf of Trieste, linear coefficients being −0.92 and −0.87 nrad/cm for the NS and EW components for the diurnal tides and −0.68 and −0.92 nrad/cm for the NS and EW components for the semidiurnal tides, for an increase in sea level (N and

E directions both positive). We can use these coefficients to estimate the order of magnitude of the loading due to the sea-level rise in the Trieste gulf. By using the greater of the coefficients (0.92 nrad/cm), the overall loading effect due to a sea level rise of 11 cm over the entire time interval is of 10 nrad. Also allowing this factor to be underestimated by 100%, which it is unlikely to be, the effect is negligible with respect to the observed secular tilting of 866 nrad over the same time interval.

We have analysed the tide gauge data of Trieste also with the aim of detecting a differential relative sea level change with respect to other PSMSL stations of the northern Adriatic Sea. The locations available in the database for our purpose are Venezia, Koper, Luka Koper, Rovinj and Bakar (Fig. 1). Among the different stations available for Venice, we choose the station Venezia Punta della Salute, as it has the longest observed time interval. Koper and Luka Koper refer to the same town, but the station Koper was moved to a new location in 1992 and given the new name Luka Koper. All data were processed in the same manner as described before for the Trieste station. We determined the relative sea level rise by linear regression analysis over a time interval common to the different stations, which extends from 1955 to 2000. Fig. 5 shows the different stations, the linear interpolation and the value of the interpolated sea level change. The evident change in sea level rate in Venice is a known fact and is ascribed to the ceasing of subsurface anthropogenic water-withdrawal up to 1970 (Tiezzi and Marchettini, 1997). The cause of the change in the rate at the Trieste station at approximately the same time is of unknown origin. The presence of a correlated oscillation of decadal period is observed in all stations. It has been shown, that the interval of 45 years is on the lower limit of determining average sea level trends (Douglas, 2001), due to the decadal variability of sea level curves. Nonetheless in our case the relative trend difference estimates are reliable, as they refer to the same time interval and because the decadal variation is highly correlated in all stations. We find that the Venice station has the highest sea level rate (0.88 mm/year), followed by the Trieste station (0.55 mm/s). The station Koper cannot be considered, as there seem to be some problems after the shift to the new station position, as the decadal variations is no longer correlated with the other stations. The station Bakar has a lower trend of 0.24 mm/year, wheras the station Rovinj, seated on the Istria promontory shows a lowering of the sea level by 0.15 mm/year. The differential rate between Trieste and Rovinj is thus 0.7 mm/s, which we will see further down is compatible with the observations of submerged tidal notches.

The NW secular term tilting observed by the pendulum and the differential sea level change of the North Adriatic PSMSL stations are very interesting, as these observations are in agreement with geological–geomorphological evidences of a Plio-Quaternary tilting of the Karst-Plateau. The NW tilting of the Karst has been proposed by Carulli et al. (1980) and recently by Antonioli et al. (2004) on the basis of the following observation. A karstic cave at the depth of −180 m has been found 30 km northwest of Trieste by drilling a borehole (Albrecht and Mosetti, 1987). The cave must have formed above sea level, as subsurface water erosion was responsible for its formation. Another observation was that of a sequence of submerged marine terraces in the gulf of Trieste. The uppermost terrace at the level of −20 m was attributed (Antonioli et al., 2004) to the marine isotope stage (MIS 5.5, about 125 ka). This marine terrace was correlated by Albrecht and Mosetti (1987) to a sediment horizon of the drill-log seated at the depth of 75 m. If the timing of those features is correct, this observation would imply a NW tilt of the coast by the amount of 15 nrad/year (55 m depth difference on a distance of 30 km in 125,000 years). Another piece of evidence comes from the presence of a topographic palaeo-surface separated by a visible scarp due to a lithological discontinuity (Flysch-limestone) highlighting the tilting of the Karst area by 60–70 m over a stretch of 50 km in SE–NW direction (Antonioli et al., 2004). Furthermore the depth of marine notches along the coast, ranging from north of Trieste to the Croatian Coast was studied. North of Trieste a submerged notch was found at the depth of −1.7 m (Antonioli et al., 2004), whereas along the nearby Istria Peninsula the notch was found at the shallower depth of −0.6 m (Fouache et al., 2000). According to Fouache et al. (2000) this notch corresponds to the sea level of Roman antiquity, i.e. at 2000 years. This last observation translates into a differential vertical movement rate of 0.5 mm/year, between Trieste and the Istria Peninsula, which is on the same order of magnitude of what we found for the differential movement of the tide gauges (0.7 mm/year).

4. Observations at seismic frequencies—the Sumatra-Andaman Islands event 2004

The increase in the signal and time resolution of the new digital acquisition system makes it possible to record the horizontal ground movement due to the passage of seismic waves with the long-base pendulums. The instrumental response function of the pendulums is that of a damped oscillator with damping factor of 0.85 and a reduced pendulum length of 134.32 cm. The eigenfrequency of the pendulums is of 360 s. For illustration we have selected the recent seismic event off the western coast of northern Sumatra, the main shock of which occurred on December 26, 2004, with

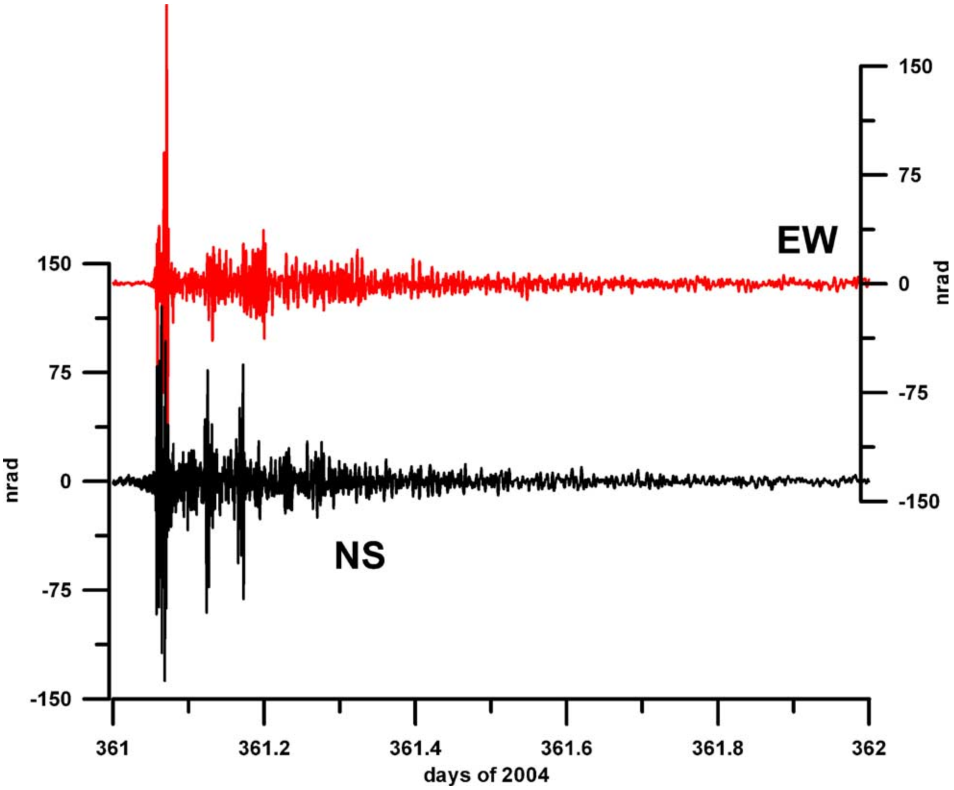

Fig. 6. Example of the recording of a seismic event: Sumatra-Andaman Islands, December 26, 2004. (M = 9.0, depth = 30 km). The detrended, band pass filtered data are shown.

magnitude $M_w = 9.1–9.3$, at depth of about 30 km. The rupture began at latitude 3.3°N, longitude 96.0°E at 00:58:53 GMT. The Harvard centroid–moment–tensor (CMT) solution indicates predominantly thrust faulting on a shallowly (8°) dipping plane with a strike of 329°. The rake (110°) indicates a slip direction ∼20° closer to the trench-normal direction than to the interpolate convergence direction (Lay et al., 2005). In order to isolate the observation of the seismic event, the original data are first detrended by least-squares fitting of a polynomial curve of second order, then a band-pass filter is applied, with passing band from 5000 to 300 s period. In Fig. 6 the detrended and filtered data sequence is shown. In Fig. 7 the squared amplitude spectrum of the time series following the seismic event is shown. Spectral leaking in the spectra has been reduced by applying a Blackman Tukey window. We present two groups of spectra, the first with a constant window length shifted in time (Park et al., 2005), the second with an increasing window length, for enhanced spectral resolution. The first group is apt to evaluate the higher frequencies (e.g. above 1.4 mHz) modes, which decay quicker in time and do not necessitate maximum spectral resolution. We have used two time windows of 24 h length, shifted by 24 h. The first one starts at day 361.25 of 2004, after the greatest amplitude shocks of the earthquake. In Fig. 7a the two spectra are shown, together with the frequencies of the torsional (${}_{n}T_{l}$) and spheroidal (${}_{n}S_{l}$) free oscillations of fundamental mode $n = 0$ and variable degree “l”. The horizontal broken line shows the 95% confidence level of a spectral peak to be significant. This level was obtained by calculating the statistical distribution of the spectral energies in the frequency range from 0 to 5 mHz, and determining the level above which only 5% of the energies fall. If all spectral energies were distributed randomly, a spectral energy above this level would have 5% probability to be observed. This translates to the fact that all spectral peaks ranging above this level are significant to the 95% level. The upper limit of 7 mHz was chosen applying the criteria that energies above this range are practically nonexistent. The decay of the spectral energy of the higher frequency modes in the frequency range 1–3.5 mHz can be seen from the observation that the spectral density decays from one spectrum to the next. In the lower frequency band (below 1.4 mHz), where a higher frequency resolution is necessary, we have calculated the spectra for increasing time windows, using time windows of 65 and 113 h. The results are graphed in Fig. 7b, where the persistence of several spectral peaks can be seen. As before, the 95% significance limit is shown

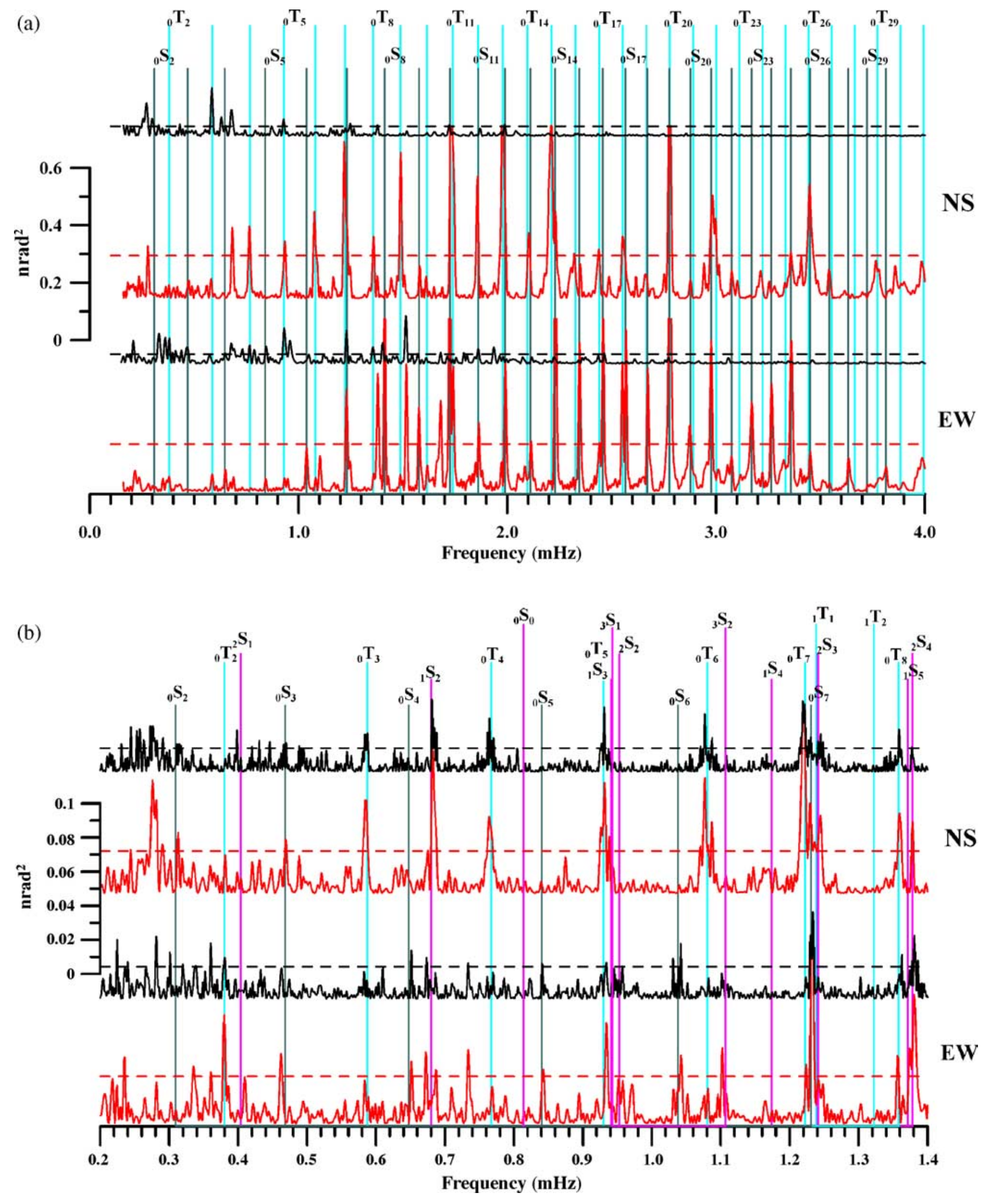

Fig. 7. Spectral analysis of the Sumatra-Andaman Islands event. (a) The spectral analysis is carried out on two sliding time-windows of 24 each, shifted by 12 h. The red and black line pertain to the windows starting at days 361.25 and 361.75 of 2004, respectively. The broken line indicates the 95% confidence level that a spectral peak be significant. The vertical lines show the frequencies of the fundamental spheroidal (grey) and torsional (light blue) modes of the free oscillations of the earth (Masters and Widmer, 1995); every fourth mode is labelled. (b) The spectral analysis is carried out on 2 time-windows of increasing length. The red and black lines pertain to the windows starting at day 361.25 and ending at days 363.9 and 365.9 of 2004, respectively. The broken line indicates the 95% confidence level that a spectral peak be significant. The vertical lines show the frequencies of all the published spheroidal (pink) and torsional light blue) modes of the free oscillations of the earth for this frequency range (Masters and Widmer, 1995). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

as a horizontal broken line. Nearly all the lower frequency modes are present in the spectra, as e.g. ${}_0T_2$, ${}_0T_3$, ${}_0T_4$, ${}_0T_5$ and ${}_2S_1$, ${}_0S_3$, ${}_0S_4$, ${}_1S_2$. We find significant spectral peaks at frequencies lower than the free oscillations, which could be caused by noise of atmospheric origin and the loading of the Adriatic. We also find peaks at frequencies intermediate to the published free oscillations, the nature of which requires further study. They could be due to overtones, coupled modes or noise. It cannot be totally excluded that they are due to an instrumental effect. In any case they had been observed also for the great 1960 Chile earthquake and interpreted at that time as nonlinear interaction of torsional and spherical modes (Bozzi Zadro, 1971) as the frequencies were explained as sums and differences of the modes.

5. Conclusions

The Grotta Gigante (Giant Cave) in the Trieste Karst (Italy) has housed for almost 40 years a couple of long-base tiltmeters, which have given a unique continuous record of long-term crustal deformation. As explained in previous studies (Braitenberg and Zadro, 1999; Zadro and Braitenberg, 1999; Braitenberg et al., 2001), the comparison with the noise-spectra of traditional short-base tiltmeters operative in the same cave since 1999, showed that the long-base pendulums have lower noise level and are less sensitive to ambient factors as hydrologic effects and atmospheric pressure loading. This applies also to the tidal spectral band, where the earth tides and the loading tides due to the near Adriatic Sea are measured with high signal to noise ratio. The instruments have been recently greatly improved by the installation of a new digital acquisition system, which has made it possible to record the signal also in the frequency band of seismic waves and which has brought a further increase in the resolution of the signal. Apart from the instrumental, ambient and electronic noise level, the resolution of the digital acquisition is of 8×10^{-11} rad. The availability of the digital recording system has transformed the long-base tiltmeters into a couple of very-broad-band tiltmeters, with which the deformation signal can be recorded on a large range of periodicities, from quasi static deformations to the passage of seismic waves.

We present two aspects of the recordings, the first regarding the secular deformation, the second the recordings of the recent destructive Indonesian event of Boxing Day 2004. The secular deformation indicates a NW tilting of the cave, which seems to be a regional signal that can be extrapolated to the Karst block into which the cave has been cut. The observed tilting is in agreement with geomorphological observations and differential relative sea level changes observed along the coastline. The NW tilting rates have had an acceleration and slowdown, with minimal tilting rates in the years 1979–1981 and 1995–1997. The observed long-term tilting and the rate changes cannot be explained by atmospheric effects as temperature, pressure or hydrologic system changes or either sea loading effects. Although the records are influenced by these agents, the agents do not present the secular term signals we find in the records of the pendulums. It must be concluded that the observed secular term deformations are of tectonic origin.

The new data acquisition system has produced a good quality recording of the Sumatra-Andaman Islands event of December 26, 2004. The event excited a broad spectrum of free oscillations of the earth in the frequency range 0.3–4 mHz, including the lower frequency modes, which are rarely observed (e.g. Masters and Widmer, 1995).

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