VARIATIONS OF TIDAL RESPONSES IN A SEISMIC REGION: THE FRIULI-NE ITALY CASE

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Abstract

The relationship between tidal admittance and seismogenetic and seismotectonic effects have been studied in a particularly seismic area of the Alps (Friuli, in NE-Italy), analyzing 14 years of 3 sets of horizontal strainmeter observations. The rigidity and bulk surface moduli, effective crustal elastic parameters, reveal a doubling of their value in the years following the destructive earthquake of 1976. The ratio l/h of Love numbers, determined relative to three different azimuthal directions, indicates a high degree of anisotropy of the elastic structure, which reflects the strong directionality along Dinaric elements, defined by faults and overthrusts. An apparent periodicity of 2-3 years is observed in the ratio of l/h variations, as well as in those of the elastic shear parameter, the low l/h values corresponding to high values of shear.

Key Words: Earth tides, Seismicity, Strainmeters

Introduction

The region under study, the Friuli in NE-Italy, is one of the most seismic regions of the Alps. It's tectonic structure is characterized by the merging of E-W trending Alpine and NW-SE trending Dinaric elements (Fig.1). The last catastrophic seismic crisis occurred during 1976 with an earthquake sequence which included one M=6.4 event in May and one M=6.1 event in September (Slejko et al.(1987)). The succeeding years presented a seismicity with events of considerable magnitude being around M=4, with 2 to 4 years return period. The overall seismicity in the region has decreased considerably, as shown in Fig. 2, where local seismicity in 30 km distance from our strainmeter station is measured as number of earthquakes in 3 months time intervals. In the present study the temporal variations of the local elastic characteristics of the upper crust are examined with the aim of discovering the relationship between such variations and seismicity processes. This is accomplished by observation of the Earth tide admittance determined from the records of three horizontal wire strainmeters. In 1978 the 3-component strainmeter station Villanova (VI, Fig. 1) was set up in a natural cave (about 60 m depth below the surface, annual temperature variation of about 1°C)

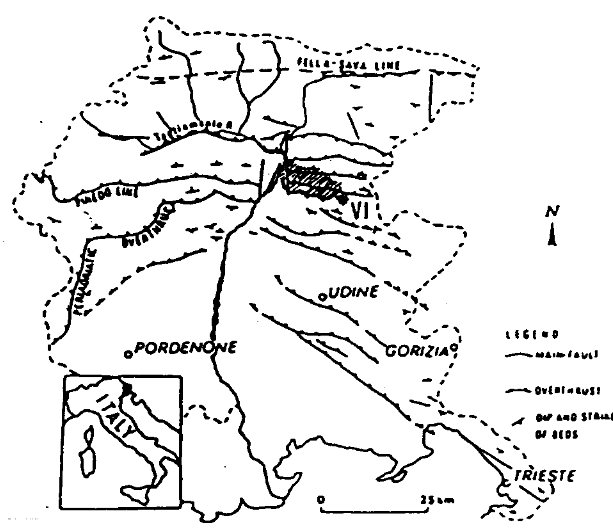

Fig. 1 - Map of the seismic Friuli region (modified from Slejko et al. (1987)). The position of the extensometric station VI is marked by an asterisk. The epicentral position of the destructive earthquakes of 1976 is shown shaded.

and has been operative since then, presenting thus to date a 14-year long deformational record. The three strainmeters (ST2, ST3, ST4) are of the Cambridge type in invar wire (length ST2-13.06m, ST3-12.63m and ST4-14.33m, for details see Mao et al., (1989)) and are oriented in the horizontal plane as follows: ST2-N128E, ST3-N27E and ST4-N68E. The registration, with a sensitivity of 10^{-7}, was analogical up to August 1989 and was successively changed to digital recording. The sampling rate is fixed to one sample per hour.

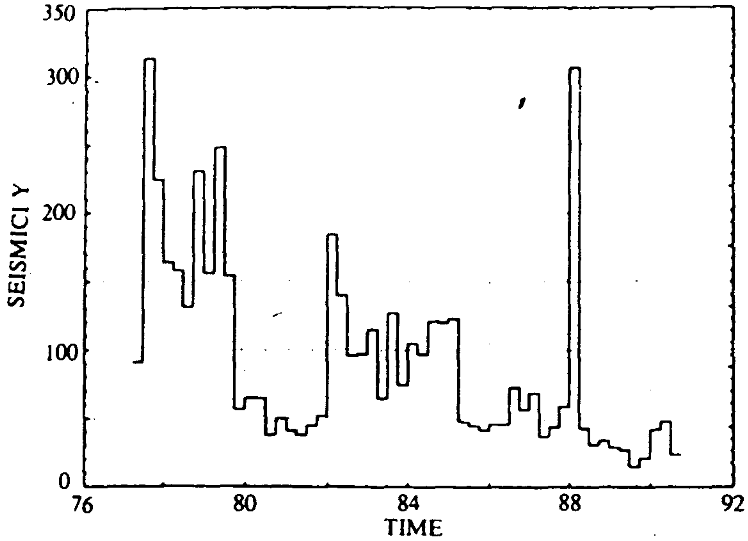

Fig. 2 - Time variation of the local seismicity, measured as number of earthquakes in 3 months, for events with epicentral distance less than 30 km from the extensometric station VI. Seismic data from OGS local telemetric seismic network.

The relationship between the tidal response and the mechanical crustal properties in seismic areas has been studied in the past theoretically (Beaumont & Berger, 1974), and experimentally in a number of seismically active regions, as Tanaka (1950), Latynina & Tikhomirov.(1992) and Yamauchi (1989), Linde, Gladwin & Johnston (1992). For the Friuli region first experimental evidences for variations of mechanical properties were reported by Mao, Ebblin & Zadro (1989).

Earth-tide strain observations

The deformational response of the Earth to the tidal forces are theoretically obtained by calculation of the tidal potential and taking into account the elastic yielding of the Earth (Melchior, 1978, Longman, 1963, Farrell, 1972, Wahr, 1981). Generally, discrepancies between the observed tidal deformation and the theoretical one are found, which must be ascribed to local effects, not accounted for in the Earth model. Among these most important are the loading effects due to the ocean tides, local crustal elastic properties and site effects as topographic and cavity effect.

For the station of VI the loading tides of the Adriatic sea (Bozzi Zadro, 1972) have been estimated by application of Boussinesq's solution to the calculation of the flexure of a flat Earth's crust due to the load of the water (Melchior, 1978). They result to amount to about 3% percent only of the tidal deformation, and have not been considered further in the analysis. The topography effect has been carried out by means of the finite element method, and has proved to be negligible. In any case, as the topographic and the cavity effect are stable in time, temporal variations of the tidal response have to be mainly ascribed to variation in the crustal elastic properties. Two different approaches are used to study the time variations of the elastic properties.

The ratio l/h of Shida number l and Love number h

With α the azimuth of the strainmeter, θ the colatitude of the observation site, β the phase lag between the observed and potential tidal phase, and l/h the ratio of Shida number l and Love number h, for the semidiurnal waves we have (Melchior & Ducarme, 1976)

$$\cot\text{an}\beta = \frac{(1 - 2l/h\ (1+\cos^2\alpha))\sin^2\theta + 2l/h\ \cos 2\alpha}{2l/h\ \cos\theta \sin 2\alpha} \qquad (1)$$

The ratio l/h is obtained resolving the above equations, except in the cases of 0 and 90 degree azimuths, when the denominator vanishes, and the above equations are not defined.

Both observed and potential tides are filtered with a pass-band ideal filter with 48 h lag and cut-off frequencies f=1/48 cph and f=1/4 cph. The spectral analysis is applied on a moving time window of 364 days length, which is shifted by 60 days in order to obtain bimonthly values of amplitude and phase for the 4 major semidiurnal and diurnal spectral components of tides: M2, S2, O1 and K1. The spectral analysis is carried out year by year for all three strainmeters ST2, ST3 and ST4, as well as for the theoretical tidal potential. An enhanced resolution of the spectral values of the tidal components is obtained applying a method based on the least squares (Zadro & Poretti, 1972), which has proved very reliable.

As an example for the analysis in Fig 3 the spectral amplitudes in 10^{-9} and the phases obtained for the years 1979-'92 for one of the three strain meters, ST4, and tidal components M2, S2, O1 and K1 are graphed.

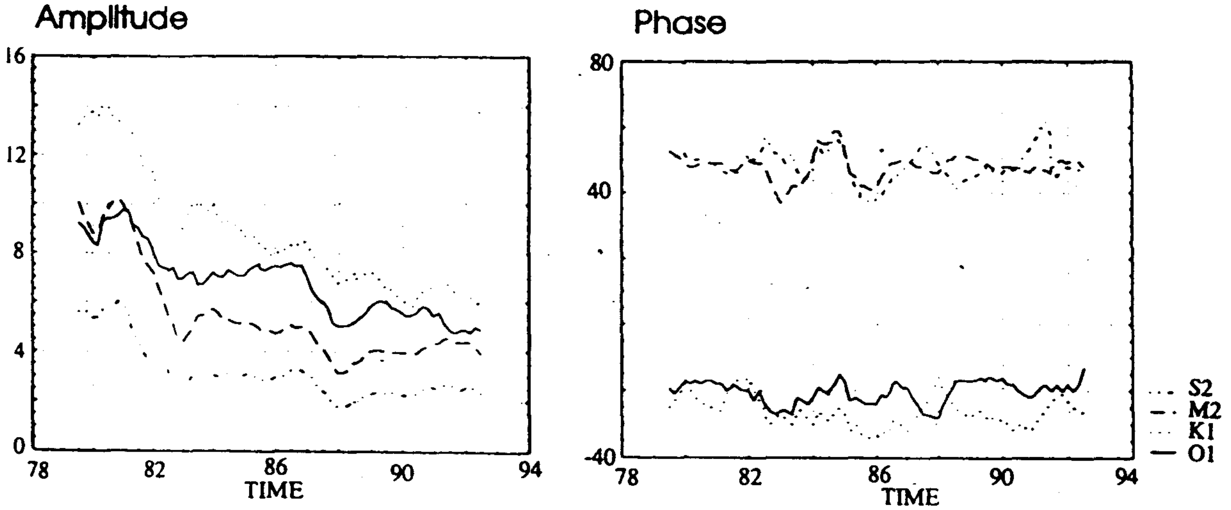

Fig.3 - Time variation of spectral amplitude and phase of the tidal components M2, S2, O1 and K1 for strainmeter ST4 (spectral amplitudes in 10^{-9} and phases in degrees)

In Fig. 4 the l/h ratios are represented for both the M2 and S2 waves, the most reliable tidal components. Their mean values are indicated by a horizontal line and may be compared to the theoretical value of l/h=0.140 (Earth model 1066A of Gilbert & Dziewonski, 1975).

Along the ST4 azimuth we have the best correspondence with the theoretical model (mean value is 0.14 for both M2, S2). Along the ST3 azimuth we find larger oscillations as well as higher mean values (0.14 for M2 and 0.15 for S2). For the ST2 azimuth we have fewer data, but it appears that high mean values of the l/h ratio have to be ascribed to this direction. Moreover a large discrepancy appears between the M2 and S2 waves, probably due to particular influences of atmospheric and/or thermoelastic effects.

The observed variations must be ascribed to the influence of inhomogeneities and anisotropies present in the Friuli which is a tectonically complicated, heavily fractured region: in fact such large variations of the ratio on model calculations of a homogeneous stratified earth, could not be obtained even for large (50%) variations of the crustal parameters.

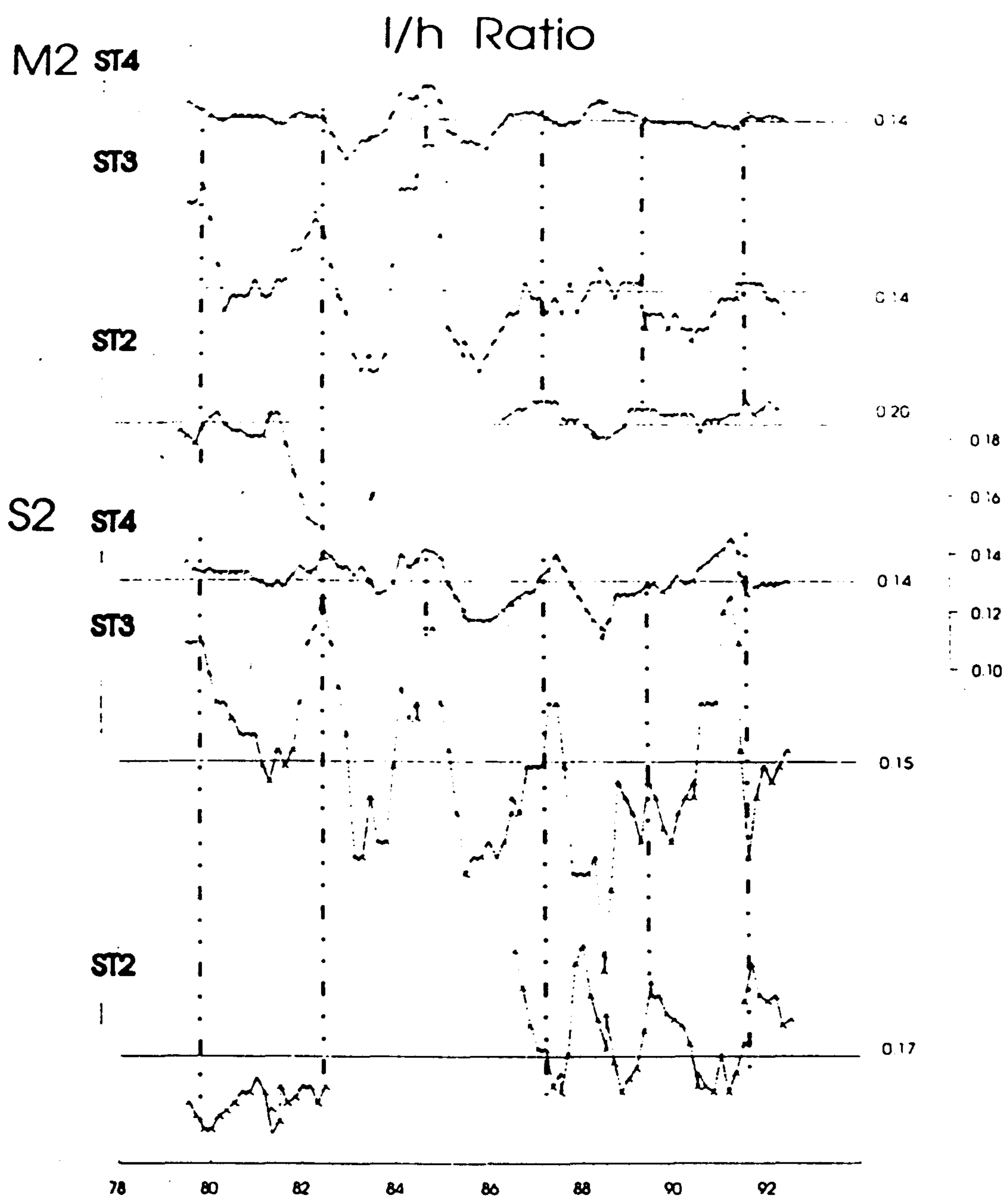

Fig.4 - Temporal variation of the ratio l/h of Love and Shida numbers in Friuli for the period 1979-1992. The ratio was obtained from the tidal phases of the semidiurnal M2 and S2 waves for the three strainmeters ST4 (N68E), ST3 (N27E) and ST2 (N128E). Error bars correspond to a maximal error of 3° of phase determination. Apart from azimuthal anisotropy effects, one observes and oscillation of the ratio about the mean value (horizontal line), with periodicity near to 2 years.

Mean values of the l/h ratio apart, it seems interesting to evidence the temporal variations of the ratio l/h itself. From Fig. 4 it appears that the effective l/h ratio is changing synchroneously along the three azimuths with a periodicity of about 2-3 years, to which some longer periodicity effect seems added.

Elastic shear and incompressibility moduli variations

The results concerning the l/h ratio depending entirely on the phase of the tidal spectral components of each strainmeter, the second analysis requires the complete horizontal plane deformation tensor, which is obtained from the contemporary records of the three strainmeters.

Assuming a homogeneous quasi-static elastic plane model of the crust, the tidal stresses may be calculated from the theoretical as well as the observed tidal strains. From the condition that the stresses thus calculated be equal, the following relations for the observed bulk K^o and shear μ^o modulus, related to constant, but unknown reference values K^r, μ^r, are obtained (Mao et al., 1989):

$$\mu^o / \mu^r = \frac{e^t_{11} - e^t_{22}}{e^o_{11} - e^o_{22}} \tag{2}$$

$$K^o / K^r = \frac{(e^t_{11} + e^t_{22}) 4/3}{(e^o_{11} + e^o_{22})(\lambda^r / \mu^r + 2) - \dfrac{e^o_{11} - e^o_{22}}{e^t_{11} - e^t_{22}}(e^t_{11} + e^t_{22})(\lambda^r / \mu^r + 2/3)} \tag{3}$$

where e^t_{11}, e^o_{11} and e^t_{22}, e^o_{22} are respectively the theoretical and observed strain values along the axes of the reference frame. The Lame' parameters of the superficial elastic model are set equal to λ^r= 342 kbar, μ^r= 265 kbar, which correspond to the velocity model used by the local seismic observatory OGS (OGS, 1987).

The analysis is operated in time space, though applying spectral techniques to the data. The semidiurnal wave band only is considered, as it gives the most reliable spectral results. Both observed and theoretical data are pass-band filtered (see preceding section) with cut-off frequencies f=1/11 cph and f=1/13 cph. We calculate separately the envelopes of the numerator and denominator in the right hand sides of Eqs. (2) and (3). The analysis is limited to the maximal points of the envelopes, which correspond to sizigial tides when the tidal amplitude is maximum and thus the observational error and the perturbing effects are least.

In Fig. 5 the ratios K^o/K^r and in Fig. 6 the ratios μ^o/μ^r are shown. Due to ill functioning of strainmeter ST2 during the time from '82 to '86 an observational gap occurs, as the calculation of the deformational tensor requires data from all three instruments. We observe a mean increase of the ratios over the full 14-year period. Considering the large amount of the increase of both the ratios, it may be concluded that the elastic parameters obtained represent the effective elastic material properties as a whole, governed by microfractures and inhomogeneities, rather than the mean elastic properties of a homogeneous rock representing the upper layer of the crust. In this case, an increase in the elastic parameters should indicate a major compaction of the crustal material. The shear modulus presents an oscillating variation, superposed to the increasing trend, which is found to correlate well with the variations observed for the l/h ratio. Infact comparison of the occurrence times of the maxima of the observed l/h ratio, added as vertical lines in the Fig. 6, are seen to correspond to minima of the shear modulus.

Conclusions

The relationships between tidal admittance and seismogenetic and seismotectonic effects have been studied in a particularly seismic area of the Alps (Friuli, N-E Italy), analyzing 14 years of strainmeter observations. The area is characterized by the convergence of two tectonic structures, the Alpine (E-W oriented) and the Dinaric (NW-SE oriented), both tied to the compressive stresses acting on the N-E Adriatic plate.

The ratio l/h of Love numbers indicates a high degree of anisotropy of the structure.

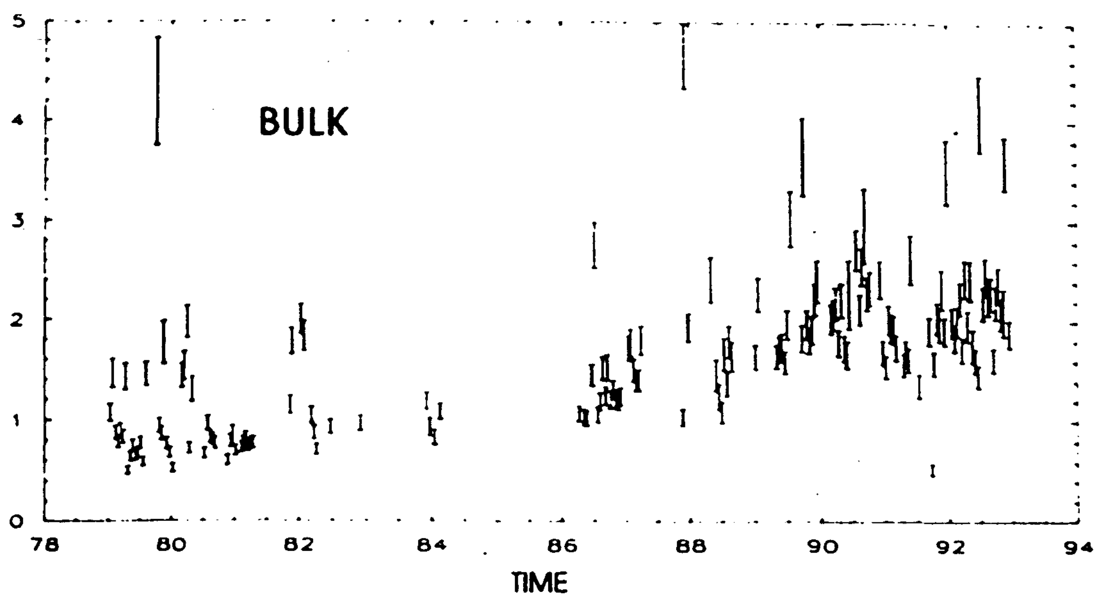

Fig. 5 - Temporal variation of the ratio of observed and reference bulk modulus. Error bars indicate +- 1 standard deviation.

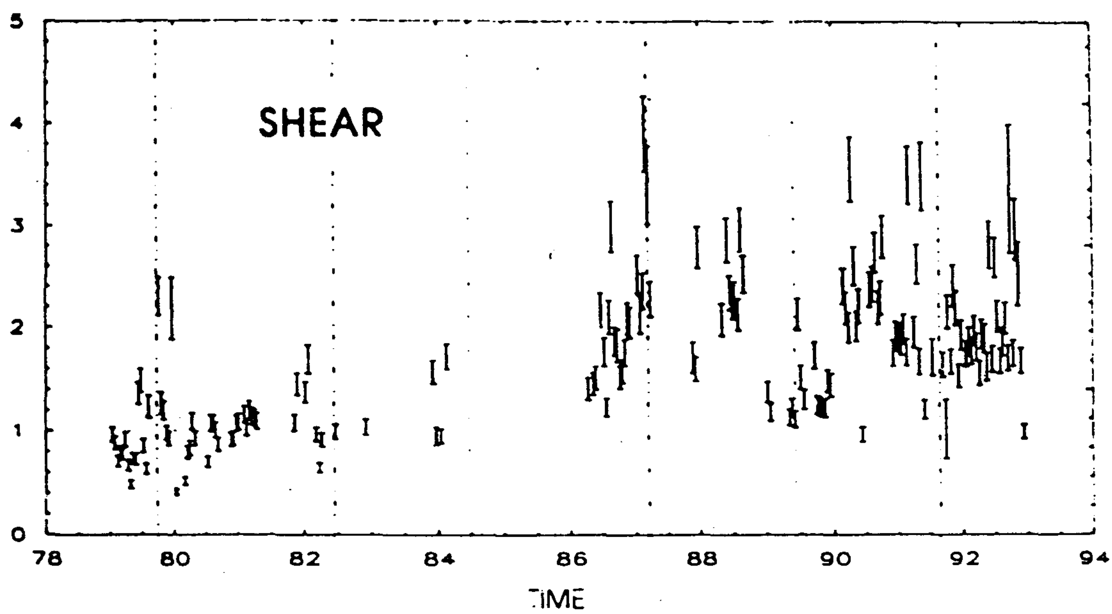

Fig.6 - Temporal variation of the ratio of observed and reference shear modulus. Error bars indicate +- 1 standard deviation. Dashed vertical lines indicate maxima of the l/h ratio variation.

Both mean values and simultaneous oscillations found for the three strainmeters, demonstrate the ST4 strainmeter direction as the one nearest to one of the axes of anisotropy. Considering the strainmeter orientations, this shows that the major anisotropy occurs along the Dinaric lineaments, due to fracturation and inhomogeneity caused by material intruded in faults and overthrustings.

Both the shear and bulk effective surface moduli result to have doubled over a time interval of 14 years following the strong '76 seismic event, as has been inferred from the observed horizontal deformation. This increase, although related to local upper layers, highly fractured and inhomogeneous, evidences a general postseismic consolidation phase.

According to the theory of a solid with the presence of microfractures modelled as flat cracks (O'Connell & Budiansky, 1974), an increase of both shear and bulk moduli is obtained for closing of cracks A decrease in the shear modulus, accompanied by no or small variation of bulk modulus, as seen in our observations in the years '88-'89, occurs in the case of opening of cracks, accompanied by fluid injection. We regard this as a tentative explanation to our observations, well aware that in a region with strong regional directionalities, the theory of variation of elastic properties due to dilatant cracks should be modified in order to include larger scale rock-fractures and inhomogeneities as well.

Acknowledgements: This work has been partially supported by MURST 40% R.91 Cod.978 and by Regione Autonoma Friuli-Venezia Giulia convention N°:DRPC/2846/SRP.7 dd 21.11.1990

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