Tilting variations and seismicity that preceded the strong Friuli earthquake of May 6th, 1976

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1. Introduction

1.1. – In a long 1970 work on the seismic and geodynamic characteristics of the Po Valley (to be understood in the broadest sense, that is, as including the Adriatic-Po, trough and all the beds and basins of the rivers emptying into the upper Adriatic as well as the mountains bordering it), Caloi *et al* observed, in commenting an the diagram of seismic energies in recent centuries up to 1969, with particular reference to the last century, that:

"It began with the strong earthquake of Santa Croce in 1875, which suddenly broke the relative seismic quiet that had endured throughout the broad zone since 1800. The disastrous seismic crisis of the Lake Santa Croce zone was followed that same year by strong seismic activity on the opposite side of the plain, at Cattolica near the sea, along the northern Appennine slopes. *It almost seems that these violent ruptures of the seismic equilibrium on the two sides of the plain were linked as cause and effect, and vice versa.* The same phenomenon occurred at other times during the past century: the strong Adriatic earthquake of 1934 (Caloi, 1937) [1], for example, was followed two years later by the very strong earthquake of Cansiglio (Caloi, 1938) [2].

"Since 1875, seismic activity on a reduced scale has been practically uninterrupted, manifesting itself in not very intense shocks,

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sometimes here, sometimes there, as if all the Po Valley were being disturbed by a unitary tectonic restlessness that revealed its presence especially on the northern and southern edges. This activity, which had been noticeably decreasing in the previous three decades, recorded an appreciable resumption with the strong earthquake (I = VIII) that occurred on December 30th, 1967. *It is not to be excluded that this 30-year truce will be further broken by other significant shocks, probably at the zone's edges*".

Was this a prediction? Naturally not, simply a logical observation suggested by the situation that had evolved. It is nonetheless to be noted that in 1971 strong seismic shocks repeatedly alarmed the people of the Modenese and Emilian Apennines in general. Then, in 1972, began the dramatic seismic crisis that struck Ancona and its surrounding areas so hard and so long.

Confirmation of the interdependence of the seismic activities in the two extremes zones had to be awaited. And that, unfortunately, was provided in due course by the disastrous seismic crisis in Friuli, that started on the night of May 6th, 1976.

1.2. – It is to be noted that the epicenter of the second shock in Friuli on May 6th, 1976 practically coincided with that of the October 11th, 1954 earthquake, which was located between Bordano and Osoppo. As is known, that of 1954 constituted the first surprised earthquake in its preparatory phase (Caloi, Spadea, 1955) [3]: it was possible, in fact, to follow the variation of the apparent vertical associated with it, at first slow, then very rapid, again slow, culminating 22 days later in the earthquake. The principal shock, moreover, was preceded by a long series of microshocks, which began some days prior thereto, and was followed by a long series of aftershocks, some of them violent.

1.3. – The pre-seismic variations observed in Italy have not been limited to the apparent vertical trend and to microseismicity only. In studies conducted since 1950 for the survey of the modulus of elasticity in the neighbourhood of large dams and related basins, Caloi noted that provoked microseismicity caused invariably a decay in the modulus of elasticity of the rock and, therefore, an attenuation in the propagation velocity of the seismic waves, with particular reference to the longitudinal waves. Caloi [4] reported these results in numerous works, in specific way, with studies of the phenomenon

of the anomalous dispersion in the field of the very high frequencies (Caloi, 1957) (4). After a re-examination in 1962 of the results obtained (Caloi, 1962) (5), Caloi in 1964 returned to the subject roughly in response to the disbelief, the evident indifference, if not hostility, of the directly interested researches towards the new discoveries concerning the behavior of the elastic field in the rocks by natural or provoked microseismicity and to the enormous interest in their extension to the study of seismic phenomena in general. Caloi wrote, among other things, that:

"*Once again attention is called to the interest (at times fundamental, even for practical purposes) of steady observation of variations in the elastic field in areas in which a semi-solid is subjected to unceasing strain variations, however caused. The harrowing action associated with tension variations expresses itself in a decay of the modulus of elasticity, evidenced by a more or less noticeable diminuition in the propagation velocity of elastic waves. Continuous observations of the elastic field in a seismic zone, combined with contemporaneous observation of the apparent vertical, can constitute a valid way of approach to the problem of forecasting earthquakes*".

We have deemed suitable to relate these references in order to demonstrate that in the 1950's research was being made in Italy, on a priority basis in the field of pre-seismic variations (naturally unbeknownst to ... Italians, those accustomed to looking always beyond the frontiers).

1.4. – Subsequently, such studies were also initiated abroad, particularly in Japan, where changes in the seismic waves velocity before major earthquakes had been observed — changes that were attributed to modifications in the elastic properties of the Earth's crust in the area where an earthquake was building up. That had induced Japanese researchers to introduce, in their broad program of studies aimed at forecasting earthquakes (Tsuboi, Wadati, Hagiwara 1962) (6), periodic determination of the seismic waves velocity, provoked by explosions, specially in selected areas of high seismicity.

Analogous research also occurred in other countries. In the USSR, variations in the $\frac{v_p}{v_s}$ ratio were observed in the Garm area before some earthquakes having magnitudes ranging from 4.2 to 5.4. In the United States, careful study of, in particular, the pre-seismic warnings that had preceded the destructive San Fernando

earthquake of February 9th, 1971 revealed a clear anomaly in the $\frac{v_p}{v_s}$ ratio. Other studies followed in Japan and in the U.S.. The phenomenon linked to variations in the $\frac{v_p}{v_s}$ ratio was explained in the U.S. by the dilatancy which occurred in the preparatory phase of an earthquake, although this was attributed to physically questionable events.

Studies were then extended to pre-seismic variations associated with crustal movements, with electrical resistivity, with the magnetic field, with radon emission, etc. The results of these studies were recently published by one of us (Caloi, 1976) (8).

On the basis of the results thus far achieved in the USSR and in the U.S., a diagram has been drawn that gives the interval of the premonitory period (expressed in days, on the logarithmic scale) as a function of magnitude. The premonitory interval of the 1954 earthquake, magnitude 4.4, the first studied from this point of view, agrees with it very well (see Figure 4).

2. Pre-seismic variations related to the Friuli earthquake of May 6th, 1976

2.1. – The epicenter of the disastrous earthquake of May 6th, 1976 was determined (if only provisionally) by utilizing the five closest ENEL (Italian National Electric Power Agency) stations: Ambiesta (Tolmezzo), La Maina (Sauris), Pieve di Cadore, Vajont and Mis (Belluno).

The data furnished by the international centers are almost always approximative, particularly as regards depth, for crustal earthquakes especially. The reasons are evident and involve mainly the widespread non-homogeneity and variations in the crust's thickness in different directions. Whoever concerns himself with these problems knows this well and has learned to one's cost, to have no faith in the results obtained by using stations too far removed from the epicenters and to limit his investigations of hypocentral coordinates by using times registered at nearby stations.

The epicentral coordinates for the second Friuli shock of 6 May 1976 were $\varphi = 46^\circ\ 16.5'$N, $\lambda = 13^\circ\ 06.0'$E. The depth was not less than 15 kilometers and the original time $H = 20.00.15.5$. Others

have obtained the most disparate values for these data, especially as regards the original time, which has even been reported as being seven seconds before that given. If that were the case, since the time of the second shock at Ambiesta — 15 kms from the epicenter — was for the *Pg* of 20.00.18.5 ($\pm$ 0.2 seconds), the *Pg* waves would have taken 10 seconds to travel about 20 kms, which is manifestly absurd. For the magnitude, a value of between 6.3 and 6.5 was chosen.

For the present, we will leave aside the problem of the mechanism of the earthquake at the hypocenter, which others have treated, quite incorrectly, on the basis of the aftershocks. We promise, however, to return to the subject when we can utilize the original recordings of a large number of seismic stations located throughout the world. We will limit ourselves here to reporting the pre-seismic variations observed in the Ambiesta area.

2.2. – We area dealing, of course, with an *a posteriori* study. The operating tiltmeters closest to ENEL dams have the task of controlling their entire respective localities, with particular attention to the stability of the dam and of the rock cradle supporting the water basin. Not all of the tilmeter stations are appropriate for recording phenomena of a tectonic nature. However, those located at the Ambiesta dam are suitable for that purpose, particularly the one on the left bank, on the edge of an active fault. The latter station is particularly sensitive to local seismic manifestations, so that the variations of the apparent vertical occurring there very rarely fail to be registered.

The activity tilting at Ambiesta during 1971 was rather remarkable, associated as it was with a series of low intensity seismic shocks that occurred in the area. On the contrary, 1972 was a relatively quiet year, without local seismic activity: the smooth and disordered movements observed were attributable to the disturbing action of transitory baric depressions. With 1973, something new occurred. The apparent vertical in the southeastern sector bent decidely and recorded, albeit slowly, a broad contrasting volute until December 6th. Beginning from that date, the vertical variation turned decidedly toward the south-southeast and proceeded rapidly in that direction for almost all of 1974. The remarkable deviation observed in the last two months, which was complicated by a loop, provided grounds for forecasting a tectonic movement in progress. This, in fact, began to manifest itself with an initial shock on March 7th, 1975 and with alternative intensity, turned particularly strong between March 24th and June 8th,

1975, the latter being the date on which the zone was hit by a shock of a magnitude 3.6 ab. The tectonic restlessness then appeared to lessen, to exhaust itself on December 25th, 1975 with a local microshocks. Figure 3 summarizes the trend of the shocks magnitudes during this period. In the meantime, the apparent vertical variation was becoming ever less and practically ceased toward the end of April 1976. On the evening of May 6th, 1976, the rupture of the elastic field occurred, violently.

The close analogy with the vertical variation occurred in relation to the 1954 Friuli earthquake has to be emphasized: in that case, there was a slow variation at the beginning, a slow variation in the final phase and a rapid variation in the middle phase, while the behavior that preceded the May 6th, 1976 strongest earthquake was similar, except proportions. As regards the foreshocks, its duration was conditioned by the magnitude of the coming earthquake: 22 days in the first case (magnitude 4.4 ab.), about three years in the second case (magnitude between 6.3 and 6.5). Moreover, even the foreshocks occurred in comparable succession. In the earthquake of October 1954, the microshocks occurred close to the second phase of slackening, while the pre-seismic phase of the May 6th, 1976 strong earthquake preceded the definitive slackening of the tilting variation, with the only difference that — this time — the shocks were real, felt by the people. Moreover this is the trend observed for the velocity variations highest in the middle phase of the pre-seismic anomaly.

At this point, we must ask ourselves if, having been able to follow step by step the trend of the pre-seismic disturbances, we have be able to forecast, some margin of safety, what was developing. In all conscience, the answer is in the negative. There are still too many elements of uncertainty that condition the development of such phenomena; the former have been mentioned in a recent work written by one of us ([8]).