The area of the fault, the dislocation, the stress drop and the seismic moment of the Friuli earthquake of May 6th, 1976

M. CAPUTO *

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SUMMARY. — With different approximate methods are estimated the values of the area of the fault, of the dislocation, of the stress drop and of the seismic moment of the Friuli earthquake of May 6th, 1976. Some considerations follow on the possibility to forecast the earthquake and on its relation to the subsequent event of September 11th.

RIASSUNTO. — Con vari metodi approssimati si stimano i valori dell'area della faglia, della dislocazione, del rilassamento di sforzo e del momento sismico relativi al terremoto del Friuli del 6 Maggio 1976.
I valori determinati coi vari metodi vengono poi confrontati ed analizzati. Se ne deducono alcune interessanti conclusioni riguardo al terremoto.

Among other parameters characterizing earthquakes the stress drop is of great importance because of its relation to the surface deformation which may have preceded the earthquakes. The application of static elastic dislocation theory and of linear elasticity theory to the study of surface deformation pryor to faulting and accompaniyng faulting can be associated to observations of surface deformations of the crust pryor to the earthquake and after the earthquakes and give important information on the mechanics of faulting. These studies can also contribute to the studies of earthquake precursors in both

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* Istituto Nazionale di Geofisica, Roma; Istituto di Geofisica, Università di Bologna.

giving the precursor and the estimate of the nature of the expected earthquake.

In the case of the Friuli May 6th, 1976 earthquake, since measurements of deformation of the crust have not been made pryor to the earthquake, by means of an estimate of the parameters carachterizing the earthquake, we can only check whether a precursor as deformation of the crust was available. This can be done by using the area of the fault, the stress drop, the depth of the hypocenter, and the fault plane solution.

The first two of these parameters are usually obtained by considering the seismic moment.

The techniques for the computation of the seismic moment are varied, they range from sophysticated analysis of the free modes of the Earth and of the surface waves, to the analysis of near focus seismic records or accelerograms. When near focus seismic records or accelerograms are not available, and one wants to avoid the cumbersome analysis of the surface waves and of the free modes, one may use approximate techniques which give the area of the fault which caused the earthquake which in turn gives the stress drop or directly the stress drop.

The area of the fault which generated the May 6th, 1976 earthquake in Friuli can be estimated in three ways. From the area covered by the distribution of the aftershocks (Benioff 1954) (1), from a relation obtained in a model recently proposed by Caputo (7), and from an empirical formula which can be obtained for the italian seismic region relating the magnitude to the size of the isoseismals of various degree. Methods (I) and (III) sometimes overestimate the size of the fault and give an underestimated value of the stress drop.

In cases where no other data was available, the area of the fault which caused an earthquake was estimated to be about that containing the epicenters of the aftershocks. The “ Bollettino sismico ” issued by I.N.G. (1976) (12) gives the distribution of the hypocenters of the aftershocks of the earthquake of May 6th, 1976 in Friuli. The epicenters fill almost homogeneously an area of about 600 kmsq centered between Trasaghis and Gemona. Using this data we could therefore induce that the radius of the fault (assumed to be circular) which generated the earthquake is about 14 kms.

For the second method of estimating the area of the fault generating the earthquakes we must recall a formula relating it to the magnitude, the elastic parameter μ (assumed $3 \cdot 10^{11}$ for the italian regions) and the angle ϑ between the direction of the fault and that of the major tectonic force; in case of circular fault of radius R the formula can be written (Caputo) (7)

$$2 \cdot 10^{\beta+\gamma M} = \frac{16\,\eta\,R^3}{7\,\mu}\left(\frac{f_a}{\dfrac{\sin 2\vartheta}{2} - f_c \cos^2\vartheta}\right)^2 \qquad [1]$$

η is the seismic efficiency, μ the rigidity and f_a the cohesive force on the sides of the fault. The stress drop p and the dislocation s are

$$p = \frac{f_a}{\dfrac{\sin 2\vartheta}{2} - f_c \cos^2\vartheta} \qquad [2]$$

$$s = \frac{16\,R\,f_a}{7\,\pi\,\mu\left(\dfrac{\sin 2\vartheta}{2} - f_c \cos^2\vartheta\right)} \qquad [3]$$

$\beta = 12.24$, $\gamma = 1.44$ (Bath, 1973); also for the italian region it has been estimated $f_a = 10^{5.61}$ (Caputo, 1976 c) (6).

The pole of the first nodal plane found by Console (1976) (9) has azimuth 168° and dip angle 75.5°.

In this solution the Northern Alps would have sinked with respect to the South Eastern Alps; this mechanism is unlikely because lateral compression forces could not cause the slip with such an angle (Caputo 1976 b) (6) while vertical lift caused by isostatic adjustment would cause an earthquake by lifting the Northern Alps.

The pole of the second nodal plane has azimuth of 350° and dip of 14.5°. This solution in which the Eastern Alps would have thrusted under the Northern Alps is more acceptable.

We should note that for value of ϑ between 75° and 90° the stress drop and the radius obtained from [2] and [1] are very sensitive to small variations of ϑ. Therefore this method will be used to infer the value of ϑ from the data obtained with the other methods.

The third method of estimating the area of the fault which generated the earthquake consists in the assumptions that the area the isoseismal of IX degree is roughly equal to that of the fault. The area of IX degree isoseismal has been obtained by Gasparini (1976) (10); it amounts to about 1100 kmsq from which we obtain a radius of 19 kms.

Nearly the same value for the area Q of the isoseismal of IX degree could have been obtained immediately from the paper of Caputo et al. (1973) (3) which gives for the italian region

$$\log Q = 0.79\,M + 8.07 \qquad [4]$$

which is valid in the range $5.5 < M < 7$; for the magnitude $M = 6.2$ we obtain $R = 17$ kms.

From the value of R one may obtain the stress drop p occurred during the earthquake by using the formula of Keilis Borok (1959) (^{11})

$$p = \left(\frac{7\, E\, \mu}{8\, \eta} \right)^{1/2} R^{-3/2} \qquad [5]$$

from which follows for the dislocation

$$s = \frac{16\, R\, p}{7\, \pi\, \mu} \qquad [6]$$

where E is the elastic energy excited by the earthquake (Båth 1973)

$$E = 10^{12.24 + 1.44 M} = 10^{\beta + \gamma M} \qquad [7]$$

and $\mu = 3 \cdot 10^{11}$ is the rigidity.

In this note we assumed for the magnitude of the May 6th, 1976 earthquake in Friuli the value 6.2 obtained at the Osservatorio of Monte Porzio Catone (Roma) of the Istituto Nazionale di Geofisica and also the value 6.4 which is the maximum observed in other observatories. In the table are reported the values of R obtained with the two methods and the two values of M; in the same table the value of the stress drop, of the dislocations and of the seismic moment M_0 are listed.

It may be noted that the value of the stress drop is consistent with what one may expect for the italian region; the same value would be very common in California.

According to the empirical law [4] one would also obtain in general for the italian region

$$R = 10^{3.786 + 0.395 M} \qquad [8]$$

which implies for the average stress drop as function of the magnitude using the relation [5]

$$p = 10^{6.15 - 1/2 \log \eta + 0.1275 M} \qquad [9]$$

From the approximate empirical formula used one may also obtain the average dislocation for the italian regions

$$s = 10^{-1.68 - 1/2 \log \eta + 0.52 M} \qquad [10]$$

The seismic moment M_0 would follow immediately as function of M

$$M_o = 10^{17.87 - {}^1/_2 \log \eta + 1.31 M} \qquad [11]$$

Finally, we can find the frequency distribution of the seismic moment which would follow from the frequency distribution of the magnitude. Let $\bar{n}_o\,(M_o)\,\mathrm{d}M_o$ and $\bar{n}\,(M)\,\mathrm{d}M$ be the number of earthquakes with moment and magnitude in the ranges M_o, $M_o + \Delta M_o$ and M, $M + \Delta M$.

Assuming (Caputo), (8)

$$\log \bar{n}_o = \bar{A}_{o2} + \bar{B}_{o2} \log M_o$$

$$\log \bar{n} = \bar{A}_2 + \bar{B}_2\, M \qquad [12]$$

we obtain

$$\bar{A}_{o2} = \bar{A}_2 + \frac{\nu - 1}{3} \log \frac{2\ \mu\, 10\beta}{\eta\, p_2} - \log\left(\frac{\gamma}{2} \ln 10)\right)$$

$$\bar{B}_{o2} = \frac{\bar{B}_2}{\gamma} - 1 = - \frac{\nu + 2}{3}$$

For the Italian Alps (see Caputo et al., 1973 (2), area N) we obtain, for moments in the range $25 < \log M_o < 27$ and per year and 1000 kmsq

$$\log \bar{n}_o\,(M_o) = -1.68 \log M_o + 18.58 - 0.68 \log \eta\, p_2 \qquad [13]$$

where p_2 is the maximum stress drop. Also we may note that the distribution of faults in this region ($R^{-\nu}$) is inversely proportional to the volume where the stress drop occurs because $\nu \simeq 3$.

Of all the parameters obtained in this note the most interesting for our purpose is the stress drop. From this value we may deduct two important conclusions, on the possibility to forecast the earthquake of May 6th, on the consequences of such stress drop at the focal depth of the earthquake which was estimated about 26 kms or less (I.N.G. 1976) (12) and on the dip angle of a supposed Benioff plane of that area.

We shall first proceed to determine the angle of the dominating tectonic force with the horizontal plane. To obtain this we shall use the determined average values of p presented in the table and formula [2] in which we consider ϑ as unknown. For $p = 8$ bar we obtain $\vartheta = 87^\circ$. Assuming that there is a Benioff plane in the area of the earthquake its dip angle in that area is approximately 11.5°.

The average value of the stress drop of this earthquake is 8 bars; this implies that pryor to the earthquake there was a stress field. If this was shear it would have implied a deformation on the crust, in turn this would have caused a displacement of about 50 cm on a distance of 20 kms. If the stress was a compression the displacement would have been of about 20 cms.

The detectability of these displacements depends on two factors. The first is the effect of the surface layers of the crust and of the sediments in transmitting the phoenomenon of the lower layers to the surface. The second is the time needed for the accumulation of the stress. Although these two factors could put limitations on the possibility to detect the surface effect, the possibility cannot be excluded that precursory phoenomena were detectable on the surface pryor to the earthquake.

Another consequence of the average stress drop of about 8 bars at the depth of 26 kms (or less) is the large elastic unbalance created in the upper part of the crust in the vicinity of the fault. This unbalance is generally eliminated by means of the sequence of the aftershocks; in this particular case, when there are faults which are transverse to the one which generated the earthquake, it is very reasonable that in a relatively short period of time another earthquake, of almost the same magnitude of the first, occurs in the transverse fault and nearer to the surface as it was the case of the Friuli sequence.

TABLE I

Method	M	R km	p bar	s cm	Log M_0	Reference for R
I	6.2	14	8	27	25.7	ING 1976 (12)
III a	6.2	19	5	23	25.9	Gasparini 1976 (10)
III b	6.2	17	6	25	25.8	Caputo et al. 1973 (3)
Average		17	6	25	25.8	
I	6.4	14	11	37	25.8	
III a	6.4	19	7	32	26.0	
III b	6.4	21	9	37	26.0	
Average		18	9	35	25.9	

M = Magnitude, R = radius of the fault, p = stress drop (assuming stress drop to zero), s = displacement, M_0 = seismic moment (with $\eta = 0.2$) for the Friuli event of May 6th, 1976.

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