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Pierre Briole, Giuseppe de Natale, Roland Gaulon, Folco Pingue, Roberto Scarpa. Inversion of geodetic data and seismicity associated with the Friuli earthquake sequence (1976-1977). *Annales Geophysicae*, 1986. hal-04270986

**HAL Id: hal-04270986**

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Submitted on 20 Nov 2024

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# Inversion of geodetic data and seismicity associated with the Friuli earthquake sequence (1976-1977)

P. BRIOLE <sup>(1)</sup>, G. DE NATALE <sup>(2)</sup>, R. GAULON <sup>(1)</sup>, F. PINGUE <sup>(2)</sup>, R. SCARPA <sup>(2)</sup>

<sup>(1)</sup> *Laboratoire de Sismologie (CNRS, LA 195), Institut de Physique du Globe, France.*

*4 place Jussieu, 75252 Paris Cedex 05, France.*

<sup>(2)</sup> *Osservatorio Vesuviano, 80056 Ercolano (NA), Italy.*

Received February, 1985; accepted October, 1985.

**ABSTRACT.** A faulting model for the Friuli earthquake sequence (1976-1977) is derived through the inversion of levelling data obtained by the Istituto Geografico Militare. The inversion of these data is performed using the elastic dislocation theory and a source model consisting of three rectangular faults, as suggested by seismological observations. Both the quasi-linear formalism with *a priori* information developed by Matsu'ura and Hirata (1982), and the non-linear inverse formalism by Tarantola and Valette (1982) are applied and show coincident results.

Location of the aftershocks from different networks operating in the epicentral area after the main events has been carried out in an homogeneous process to improve previous solutions.

The focal parameters derived from the inversion and from the aftershock distribution are consistent with those obtained from the analysis of far-field seismological data.

These results show that faulting along shallow dipping planes, involving underthrusting of the southernmost blocks beneath the Alps, is the predominant seismogenetic process in the Friuli region. These shallow faults (less than 10-12 km in depth) progressively ruptured during the 1976-1977 from E to W direction according to the seismological interpretation.

*Key words :* ground deformation, inversion, seismicity, Friuli.

*Annales Geophysicae*, 1986, 4, B, 4, 481-492.

## INTRODUCTION

The sequence of moderate events that shook the Friuli region in northern Italy in 1976 has been largely discussed and different focal mechanism solutions have been proposed which are not all in complete agreement. Therefore additional constraints have to be considered to improve the final solution.

The systematic analysis of geodetic data is one of the methods to study the rupture processes associated with earthquakes and their long term time behaviour (Fitch and Scholz, 1971; Scholz, 1972). Recently the faulting mechanisms of some large magnitude events (like the 1923 Kanto earthquake,  $M_s = 8.1$ ) have been modelled through the study of geodetic data (Ando, 1971; Scholz and Kato, 1978; Thatcher and Rundle, 1979). Up to present geodetic data have been used to model earthquakes having a magnitude larger than 7, with surface displacements of several meters (for instance Matsu'ura *et al.*, 1980; Ruegg *et al.*, 1982). This paper constitutes one of the first attempts to model displacements of the order of a few tens of centimeters, associated to the Friuli earthquake sequence.

On the other hand, a large amount of aftershock data was collected by different institutions after the events for variable periods of time. Homogeneous data processing is carried out in this paper in order to try to eliminate biases due to different network geometries and structural models used in aftershock location.

## Seismotectonic setting of the Friuli earthquakes

The Friuli region is an area of moderate seismic activity, but higher than other regions of the Alps. The earthquake sequence of 1976-77 occurred after a quiescence of larger events lasting some centuries; previously comparable-size earthquakes occurred in 1348 and 1511. This region lies in an area where a complex zone of northward dipping thrust faults exists (Carulli *et al.*, 1981; Martinis, 1977; Amato *et al.*, 1976). The main shock (May 6, 1976, 20 h 00 min,  $M_s = 6.5$ ) was preceded by a  $M_s = 4.5$  foreshock at 19 h 55 min and followed by a sequence of aftershocks. On September 11, 1976 at 16 h 31 min and 16 h 35 min two earthquakes having  $M_s = 5.5$  and 5.4 occurred.

Again on September 15, 1976, at 03 h 15 min and 09 h 21 min two other events having  $M_s = 6.0$  and  $5.9$  occurred. Then the seismic activity decayed in time until September 16, 1977, when a  $M_s = 5.1$  event was recorded. These features of the sequence, and the tectonic domain make the study of the Friuli region very interesting for the understanding of rupture processes in continental areas. The seismogenetic region has been located at depth less than 10-12 km. Cipar (1980, 1981) and Lyon-Caen (1980) studied the rupture process using synthetic seismogram calculations from long-period surface waves and from long- and short-period body waves, illustrating the complexity of the rupture propagation associated with shallow-dip thrusts, with a slow migration of the rupture zones, from E to W direction, during the sequence (fig. 1).

These faulting mechanisms discussed by Cipar (1980, 1981) are in agreement with isoseismal data (Giorgetti, 1976), strain contours (Livieratos, 1980) and the trend of the space distribution of the largest events (Lyon-Caen, 1980). Finetti *et al.* (1979) and Wittlinger (1980) suggested however a migration of September 1976 events toward North, interpreting this seismic activity as distributed along a shear zone, dipping about  $40^\circ$ , underthrusting below the Alps. This last interpretation has been based on the aftershock locations and their mechanisms. The absence of clear and unambiguous evidence of surface faulting further complicates the study of these earthquakes.

A geophysical interpretation of existing ground deformation data has been made by Ebblin *et al.* (1982), which suggested as a possible source of the observed ground displacements (Talamo *et al.*, 1978; IGM-RG, 1978) a change on the physical properties of the rocks under the tectonic loading stresses.

To check the consistency of the available geodetic data, when compared to other seismological and geophysical interpretations and to further contribute in reducing the existing ambiguities in evaluating the fault planes, we focused in the present paper on the analysis of ground deformations using elastic dislocation theory and a complex faulting geometry.

## METHODS OF ANALYSIS

The source model consists of one or several rectangular faults with two horizontal sides located in an homogeneous half-space. Each fault is characterized by 9 parameters (fig. 2). Empirical relationships (for instance Kanamori and Anderson, 1975) allow to relate some dislocation model parameters to seismological data and to compare the observed displacement field to sliding along the fault walls (Manshina and Smylie, 1971; Savage, 1980). The model parameters are estimated by inverting the data through linearized algebraic methods. In this paper we applied both the non-linear inverse formalism developed by Tarantola-Valette (1982), and the quasi-linear inverse formalism by Mats'ura and Hirata (1982) taking into account the errors of the data, model parameters and *a priori* information on the problem. The analytical relations between

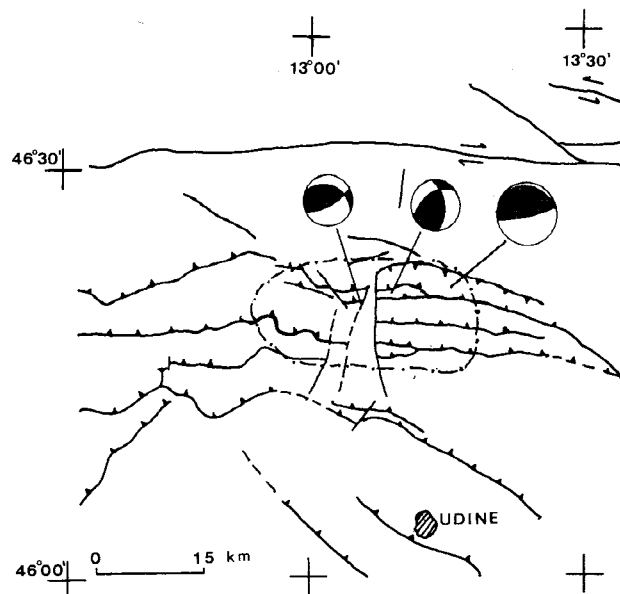


Figure 1  
Faulting mechanisms of the three largest Friuli events. The dashed line represents the limit of the aftershock region. Neotectonic linear elements are also illustrated after Amato *et al.*, (1976) and focal solutions drawn according Cipar (1980) results; circle size according to magnitude.

parameters and measured ground movements are linearized with respect to an initial model. This model is deduced from available geophysical and seismological information. The generalized least-squares criterion is used to find the solution.

First we have used an algorithm which utilizes the Tarantola-Valette (1982) formalism, taking into account the random errors on the data. The solution of the problem is obtained using the formula developed by Manshina-Smylie (1971). Partial derivatives of the displacements with respect to the fault parameters are evaluated numerically.

The choice of an initial model and the uncertainty on the parameters fully characterize the inversion procedure adopted. Some synthetic tests have shown that 4-6 iterations lead to a convergence toward a solution which minimizes the residuals between measured and calculated data, under the condition that the initial model does not strongly differ from the « true » model. If this is not the case, then instability is observed after the first inversion step. It is noteworthy that this procedure gives results comparable to the method by Mats'ura and Hirata (1982) applied to the same data set as in the following discussion and by Arca *et al.* (1985).

## APPLICATION TO THE FRIULI REGION

We applied the method described in the previous paragraph to the Friuli region, where levelling and triangulation measurements before and after the 1976-1977 earthquake sequence are available.

The experimental data are related to 103 levelling benchmarks and 19 triangulation points. The levelling data are distributed along 4 lines (fig. 3) :

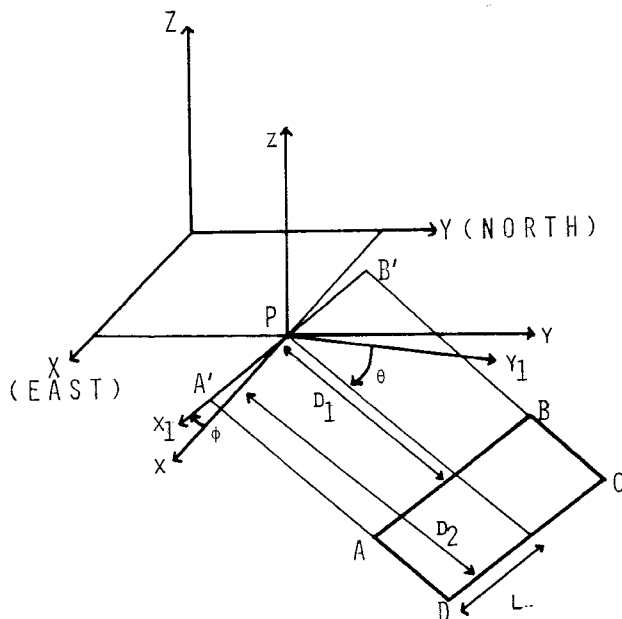


Figure 2

Parameter description of a rectangular fault model :

$P$  middle point center of the fault trace  $A'B'$

$X_p$  abscissa of the point  $P$

$Y_p$  ordinate of the point  $P$

$\phi$  angle of the trace  $A'B'$  measured from east counterclockwise

$\theta$  dip of the fault

$D_1$  distance between the trace and the upper limit of the fault

$D_2$  distance between the trace and the lower limit of the fault

$L$  half length of the fault

$b_1$  strike-slip component of the Burger's vector (a negative value indicates a dextral slip)

$b_2$  dip-slip component of the Burger's vector (a negative value for an inverse fault).

line 36 (Udine-Carnia) - line 37 (Carnia-Forni di Sotto)  
line Aa (Carnia-Coccau) - line CZT (Udine-Gemona).

These measurements were performed in 1952 and 1977, with the exception of the line CZT, measured in 1929 and 1977. These measurements were made according to the high precision levelling standards (Commissione Geodetica Italiana, 1974) and the observed dispersion in the data is in the range 1.5-2.0 cm (Talamo *et al.*, 1978).

The triangulation data (fig. 3) were measured in 1949 and 1977 (IGM-RG, 1978). Livieratos (1980) and Bencini *et al.* (1982) studied the strain pattern on the basis of these data. Some tests performed using these data in the inversion procedure have shown that they do not affect very much the solution. However, due to the large instrumental errors and problems concerning the network compensation, these triangulation data must be considered with care. Consequently in the

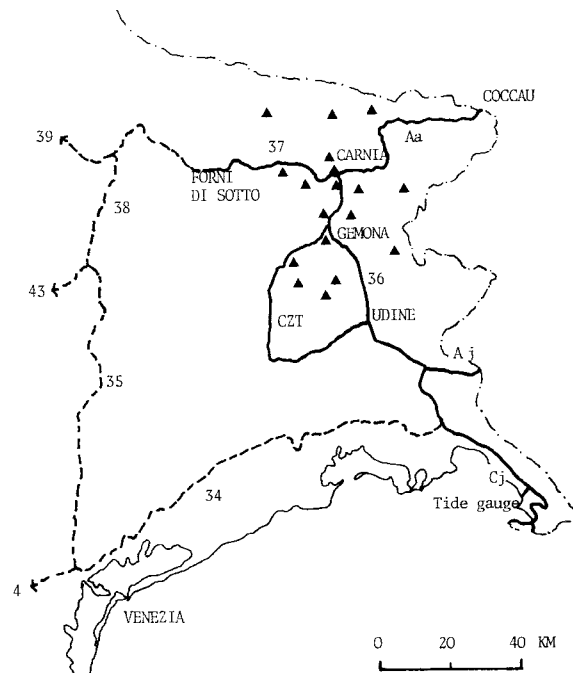


Figure 3

Levelling network in the Friuli region (after Talamo *et al.*, 1978).  
Triangles show the triangulation bench marks (after IGM-RG, 1978).

subsequent analysis here described in details, these data have been disregarded.

In the present paper we interpret deformations as being produced by seismic events, but because of the large time interval between measurement periods, we cannot exclude aseismic slip as reported by Dragoni *et al.* (1985).

The initial faulting model was taken from the source parameters obtained by Lyon-Caen (1980), from an analysis of the long period teleseismic body wave radiation. The hypocenters of the main-shocks of the sequence have been assumed to be located in the lower part of the faults. In the initial model, in order to take into account of the complexity of the variations of the observations along the lines we consider three faults possibly related to the three large earthquakes of the sequence that occurred on May 6, 1976 ( $M_s = 6.5$ ), September 15, 1976 3 h 15 min ( $M_s = 5.9$ ) and September 15, 1976 9 h 21 min ( $M_s = 6$ ). We will check later if these three events are really necessary.

Table 1 gives the initial values of the faulting model parameters and their uncertainties used for the inversion. According to this initial model, vertical displacements in the southernmost part of the line 36 are zero,

Table 1

Initial faulting model used for geodetic data inversion.

	$X_p$ (km)	$Y_p$ (km)	$\psi$ ( $^\circ$ )	$b_1$ (m)	$b_2$ (m)	$\theta$ ( $^\circ$ )	$D_1$ (km)	$D_2$ (km)	$L$ (km)
6 May	368,6	5113	10	0	- 0,5	12	10,5	23,5	6,5
15 September 3 h 15 min	363	5123	40	- 0,25	- 0,43	20	5,5	13,5	4
15 September 9 h 21 min	365,6	5110	24	0	- 0,5	15	18	27	4,5
Assumed variance	2	2	8	0,1	0,1	2	2	2	0,5

in agreement with the experimental data within the errors (less than 2 cm). Thus, data from these benchmarks, because of the large distance from the active zone, affect neither the solution nor its reliability. Consequently the first 18 bench-marks have not been used and only the significant and constraining part of the observed vertical displacements has been modelled. Vertical displacement data have been assumed to have a standard error of 1.5 cm.

In a first attempt the line CZT was not used because of the different reference periods. Two points, apparently anomalous, located on the lines 36 and 37 have been disregarded and 64 vertical displacements have been analyzed. After 5 iterations a good agreement was obtained between observed and calculated data.

A second inversion test has been performed adding data from the line CZT (83 points in total). Initially this line was referred to the bench-mark located in Udine, but the points 32, 33 and 34 of the line 36 are not consistent with the points 103 and 102 located at close distance. On the other hand an average uplift of the line CZT can be observed in its southernmost part. This leads to the choice of Gemona as a common reference between the line 36 and CZT. The remaining lines were also reajusted in order to reduce them at a zero level values, which corresponds to the average value of the bench-marks located away from the region with large displacements.

All these readjustments are low and comparable to the estimated measurement errors :

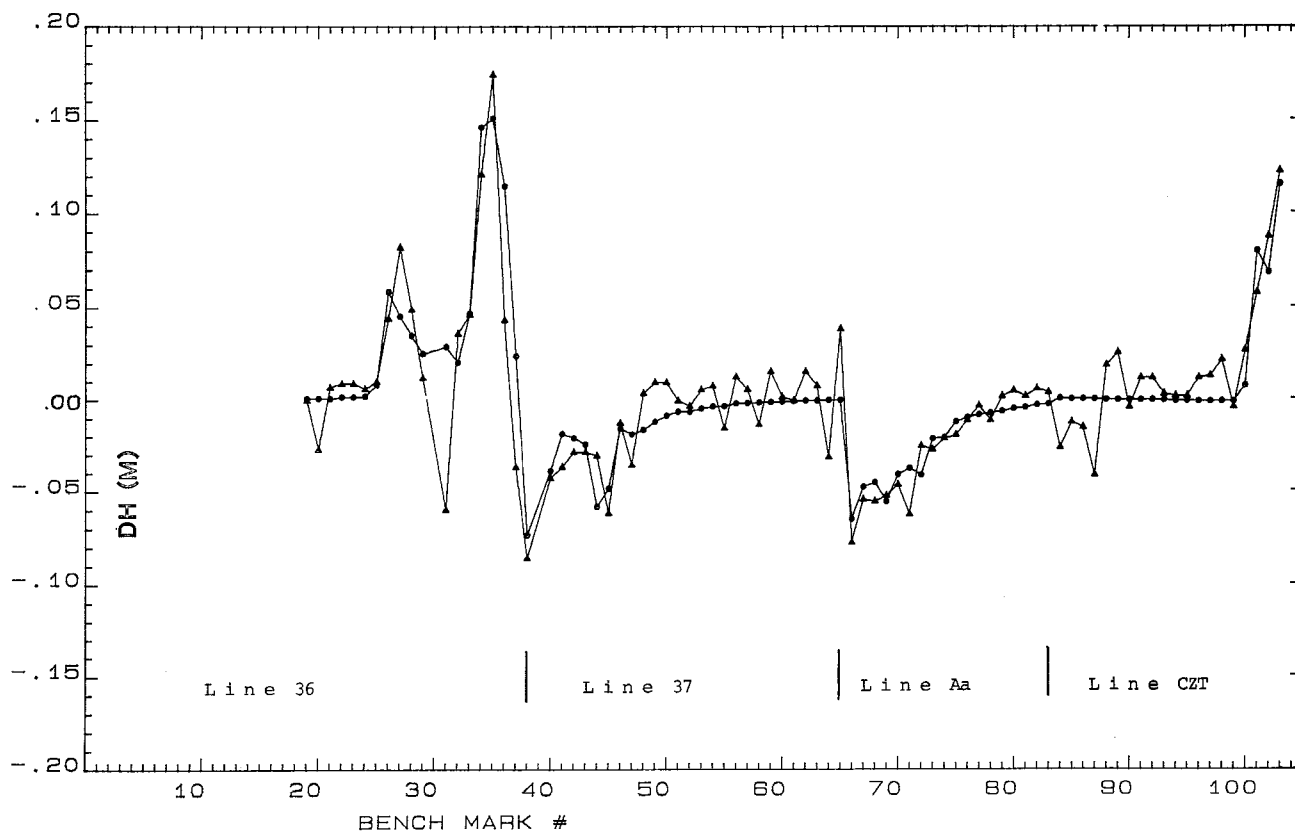


Figure 4  
Comparison between observed (triangles) and modelled (circles) vertical displacements, taking into account data from lines 36, Aa, 37 and CZT.

Table 2  
Optimum fault parameters of the Friuli earthquakes.

	$X_p$ (km)	$Y_p$ (km)	$\psi$ ( $^\circ$ )	$b_1$ (m)	$b_2$ (m)	$\theta$ ( $^\circ$ )	$D_1$ (km)	$D_2$ (km)	$L$ (km)
6 May	370,8	5111,0	18,2	0	- 0,52	11,8	11,2	24,9	6,5
Variance	1	1	5	0,07	0,09	1,9	1,7	1,4	0,4
15 September 3 h 15 min	358,4	5130,8	54,9	- 0,34	- 0,41	18,93	3,2	11,5	2,45
Variance	1	1	6	0,08	0,08	1,8	1,1	1,2	0,4
15 September 9 h 21 min	361,4	5111,9	18,8	0,2	- 0,66	7,8	19,5	25,3	4,2
Variance	1	1	4	0,09	0,09	1,4	1,2	1,3	0,4

line 36 : + 1 cm    line 37 : - 0.5 cm  
 line Aa : + 1 cm    line CZT : - 4.8 cm .

When comparing to the previous inversion it is observed a faster convergence to obtain a good fit with the experimental data (fig. 4). Table 2 gives the final model parameters and table 3 a comparison between some values of seismological interest before and after the inversion. Figure 5 shows the surface projection of the three faults. The dislocation surface of the event of May, 6 is poorly constrained in absence of lines to the East. Figure 6 shows the contribution of each one of the three dislocations to the total vertical displacement observed along lines 36, 37, Aa and CZT. It can be seen that the three faults are really needed in order to match the complex observed data.

The same data set has been also interpreted with the inversion algorithm of Matsu'ura (1977), later modified by Matsu'ura and Hirata (1982). The algorithm performs a quasi-linear inversion with *a priori* informations, using the singular value decomposition technique and allowing to find optimum fault parameters for data with random noise, including the effect of systematic errors. Partial derivatives with respect to fault parameters are evaluated analytically and possible displacements of the reference bench-marks are considered as extra parameters and estimated from the data.

The Matsu'ura and Hirata (1982) procedure was applied to Friuli displacements data, by using the initial model of faulting discussed before. All the vertical displacements data, but those from the line CZT were used for the inversion, without any preliminar adjustment

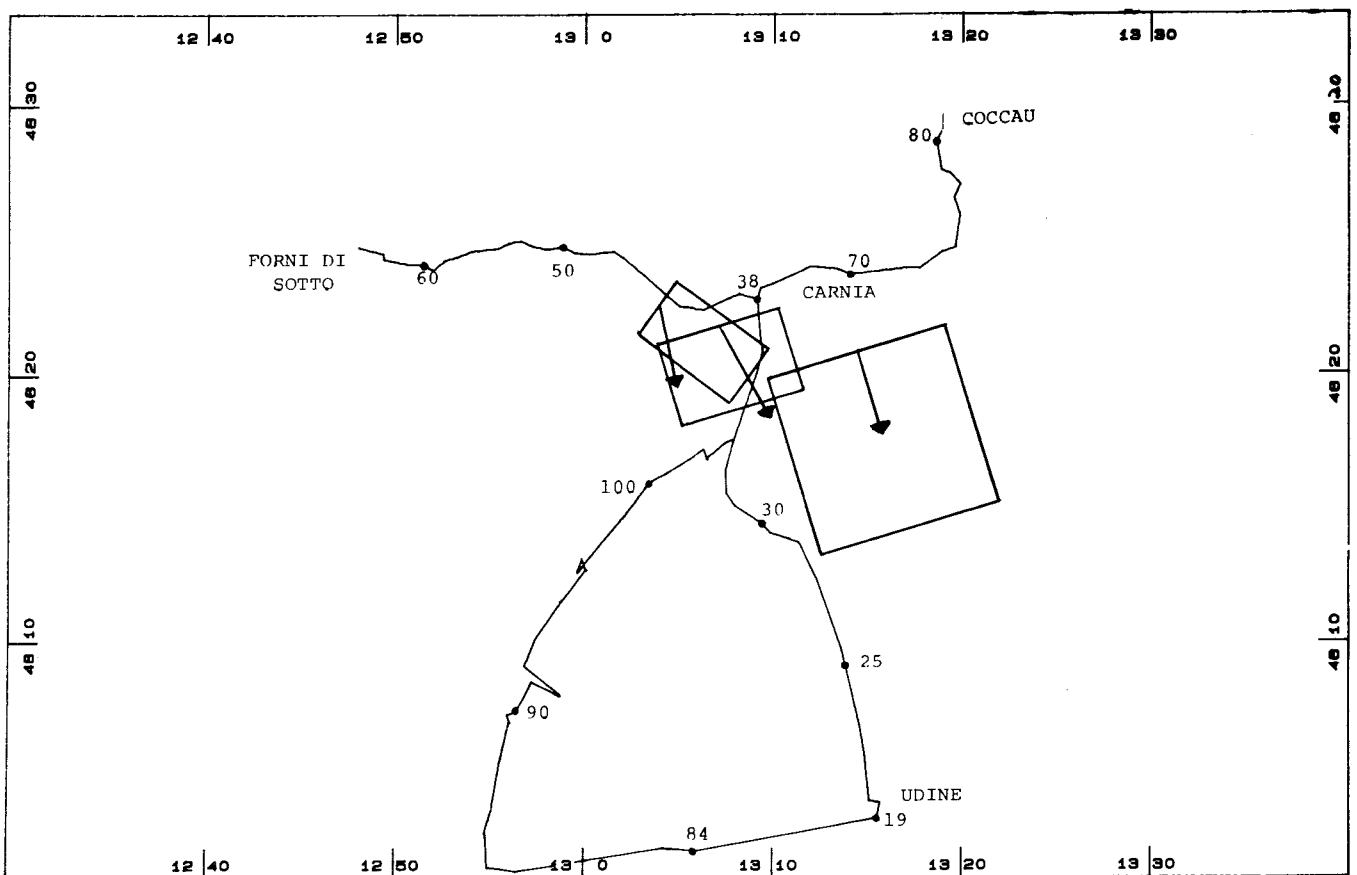


Figure 5

Surface projection of the three faults. This solution corresponds to data of figure 4. The levelling lines 36, 37, A and CZT are also illustrated. Arrow indicates the surface projection of the hanging wall displacement relatively to the footwall one (arbitrary scale).

Table 3

Comparison between some initial and final fault parameters of the Friuli earthquake

	Initial model			Solution		
	6 May	15 September		6 May	15 September	
		3 h 15 min	9 h 21 min		3 h 15 min	9 h 21 min
$S$ (km) <sup>2</sup>	169	64	81	178	41	49
Dislocation (m)	0,5	0,5	0,5	0,52	0,53	0,69
Depth (km) of the lower limit of the fault	4,9	4,6	7	5,1	3,7	3,4

(84 points). Convergence to an optimum solution was obtained after few iterations and was found not to be very strongly dependent on the initial parameters that were allowed to vary within 5 km for the spatial coordinates of the faults and  $10^{\circ}$ - $20^{\circ}$  for the orientation of the Burger's vector. Also in this case we noted the decreasing quality of the fit between observed and modelled displacements when including the vertical displacements along the line CZT. Anyway, the computed solution did not vary significantly due to the fact that most of this line is located away from the active zone and does not influence a « local » solution. By using only the measurements along the lines 36, 37 and Aa we obtained an excellent fit between theoretical and observed displacements shown in figure 7. The computed parameters are practically coincident with those previously estimated. The space location of the observed faults is illustrated in figure 8, indicating an optimum agreement with the results obtained using the Tarantola-Valette (1982) inversion scheme. It is also noteworthy that the computed displacement of the reference bench-mark 19 (Udine) was practically insignificant (1 mm) as compared to the random errors ( $\sim 1.5$  cm). This indicates the absence of evident systematic errors in the data.

### INTERPRETATION OF THE SEISMOLOGICAL DATA

The fault-plane solution of the May 6, 1976 event ( $M_s = 6.5$ ) obtained from the long-period *P*-wave

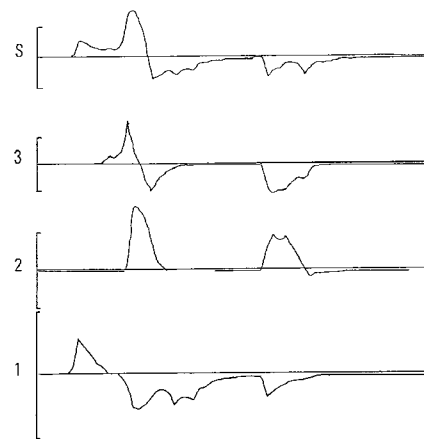


Figure 6  
Vertical displacements computed along the different profiles for each dislocation considered independently (1 to 3) and final solution obtained by adding the three amplitudes (*S*). Vertical bars correspond to a displacement equal to 10 cm.

first motions and *S*-wave polarization indicates thrust faulting with nodal planes dipping to the South-Southeast at an angle of  $77^{\circ}$  and to the North-Northwest at a shallow angle ( $16^{\circ}$ ) respectively (Müller, 1977). Comparable results have been obtained by Cipar (1980) and Lyon-Caen (1980) by also using synthetic seismograms of body and surface waves. They also obtained similar solutions, but with different strike and dip, for the large shocks of September 15 which are characterized by a minor component of dextral transcurrent motion.

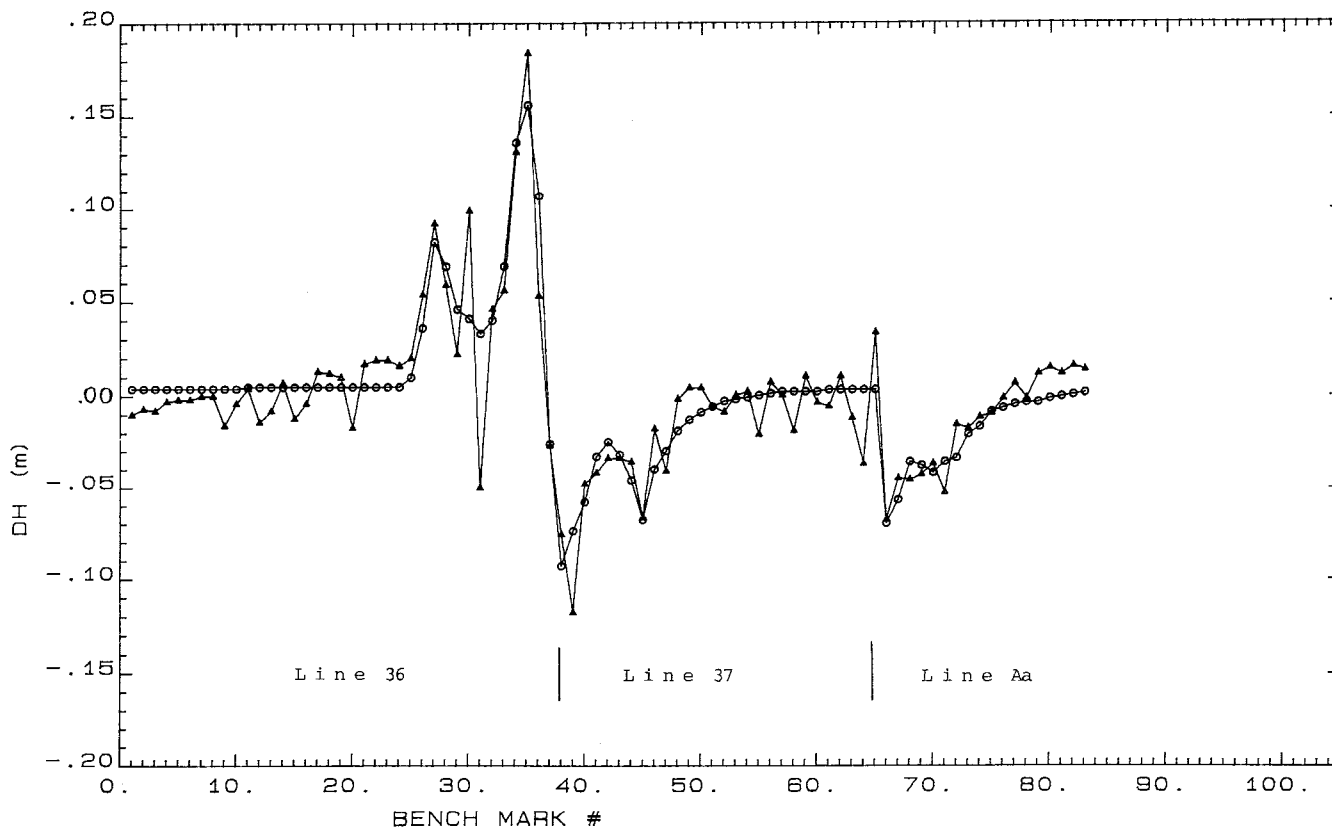


Figure 7  
Comparison between observed (triangles) and modelled (circles) vertical displacements with the exclusion of line CZT by using the Matsuura and Hirata (1982) algorithm.

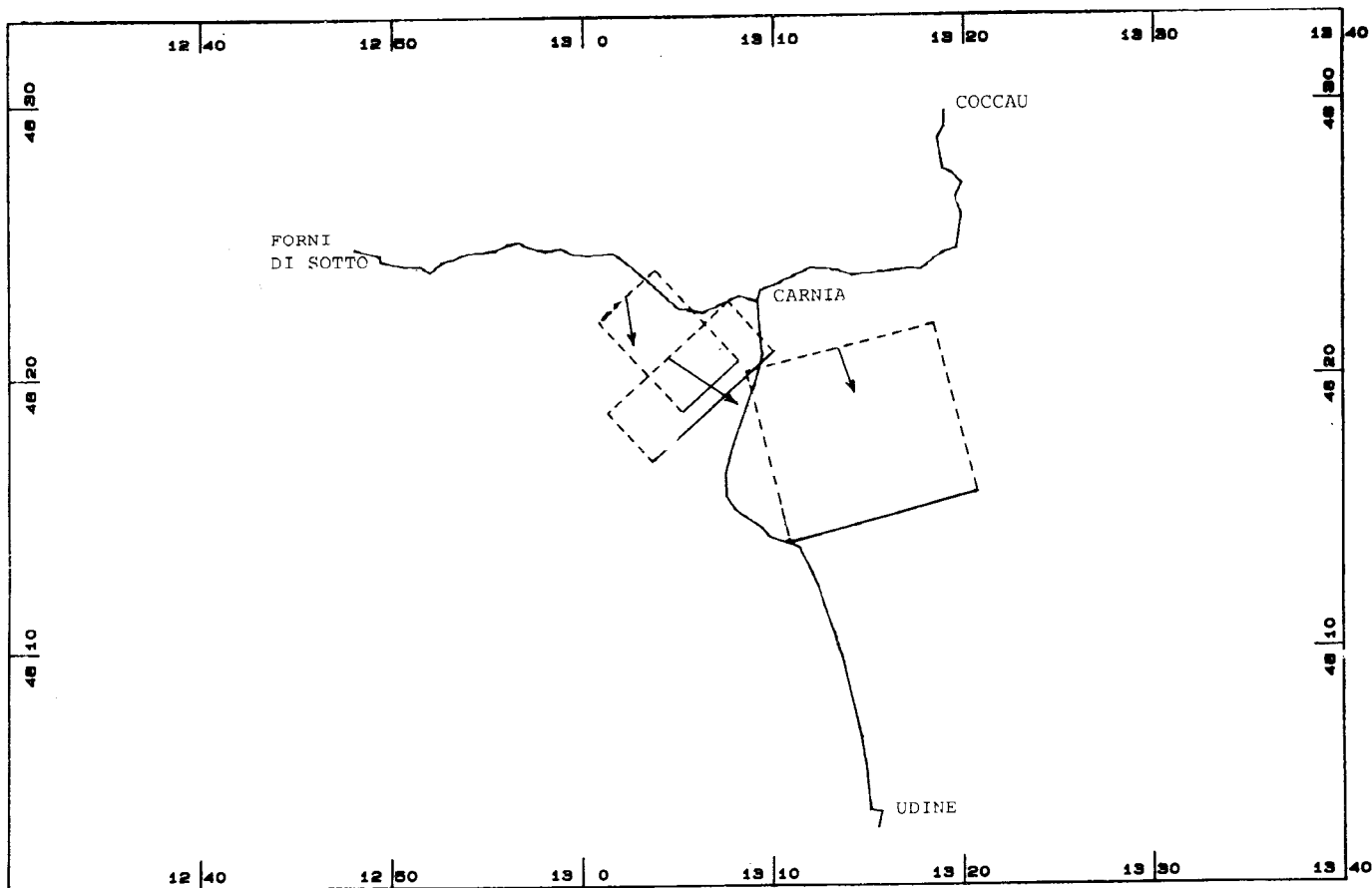


Figure 8  
 Surface projection of the three faults corresponding to the solution shown in figure 6. This figure also shows the levelling lines 36, 37 and Aa. Symbols as in figure 5.

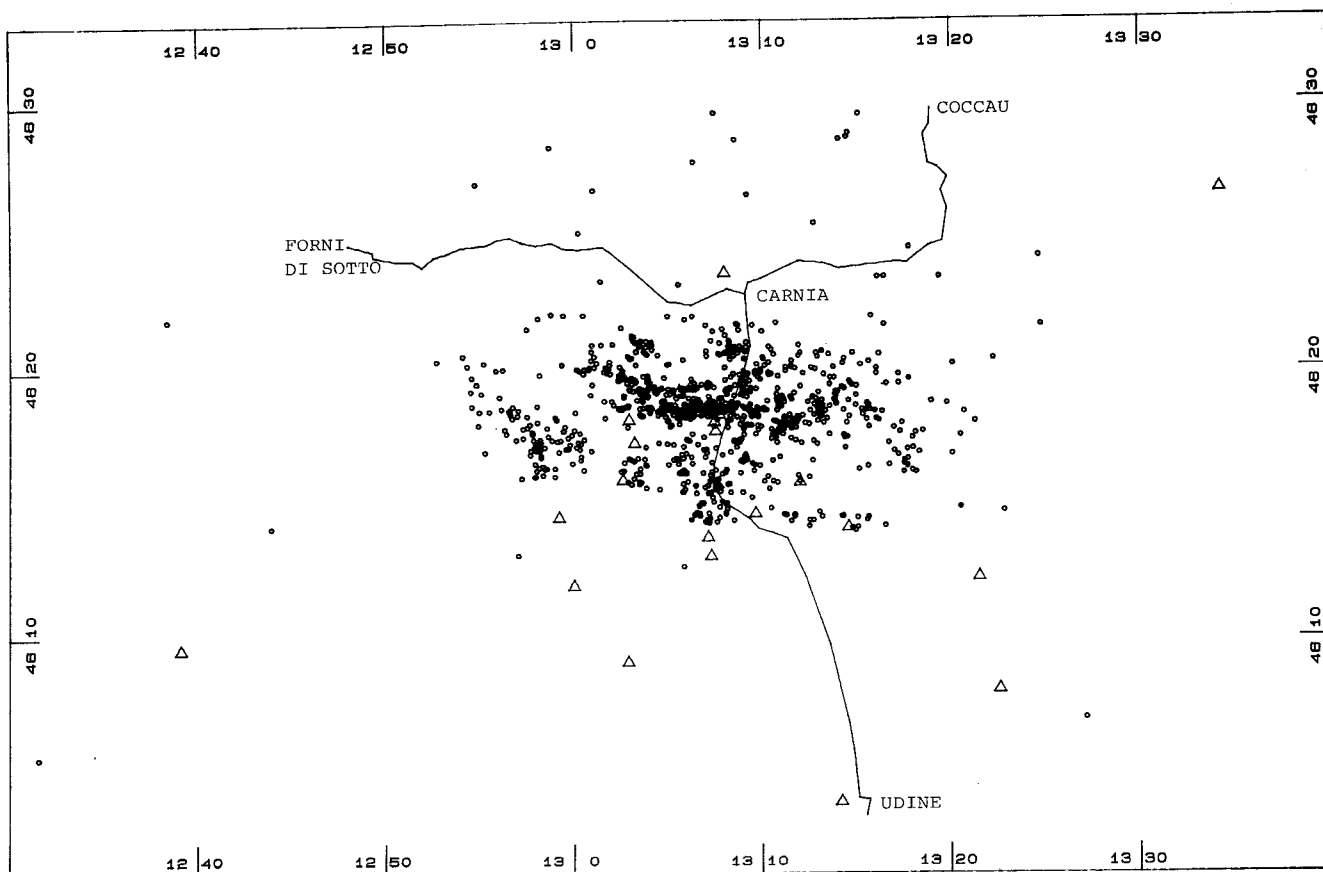
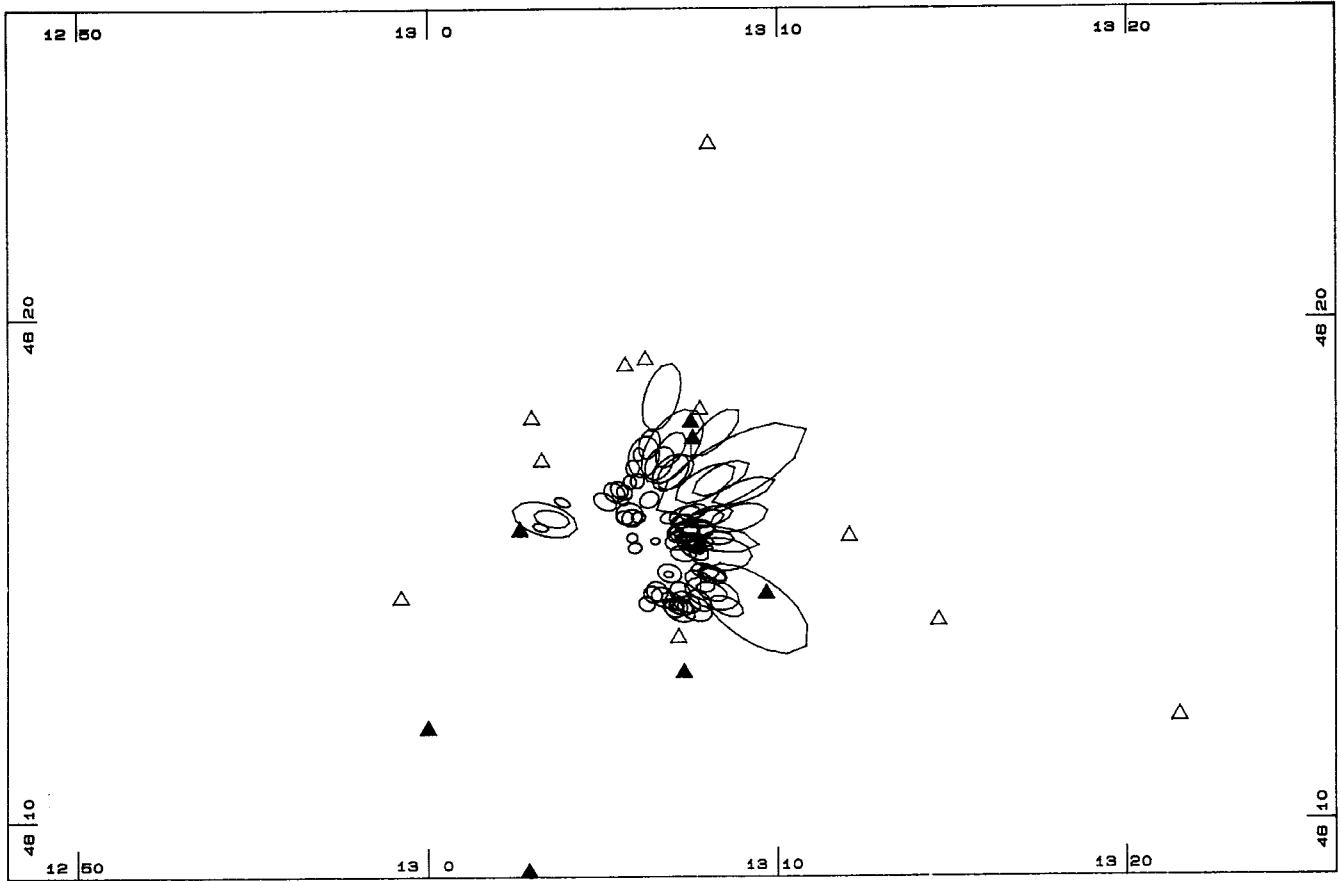
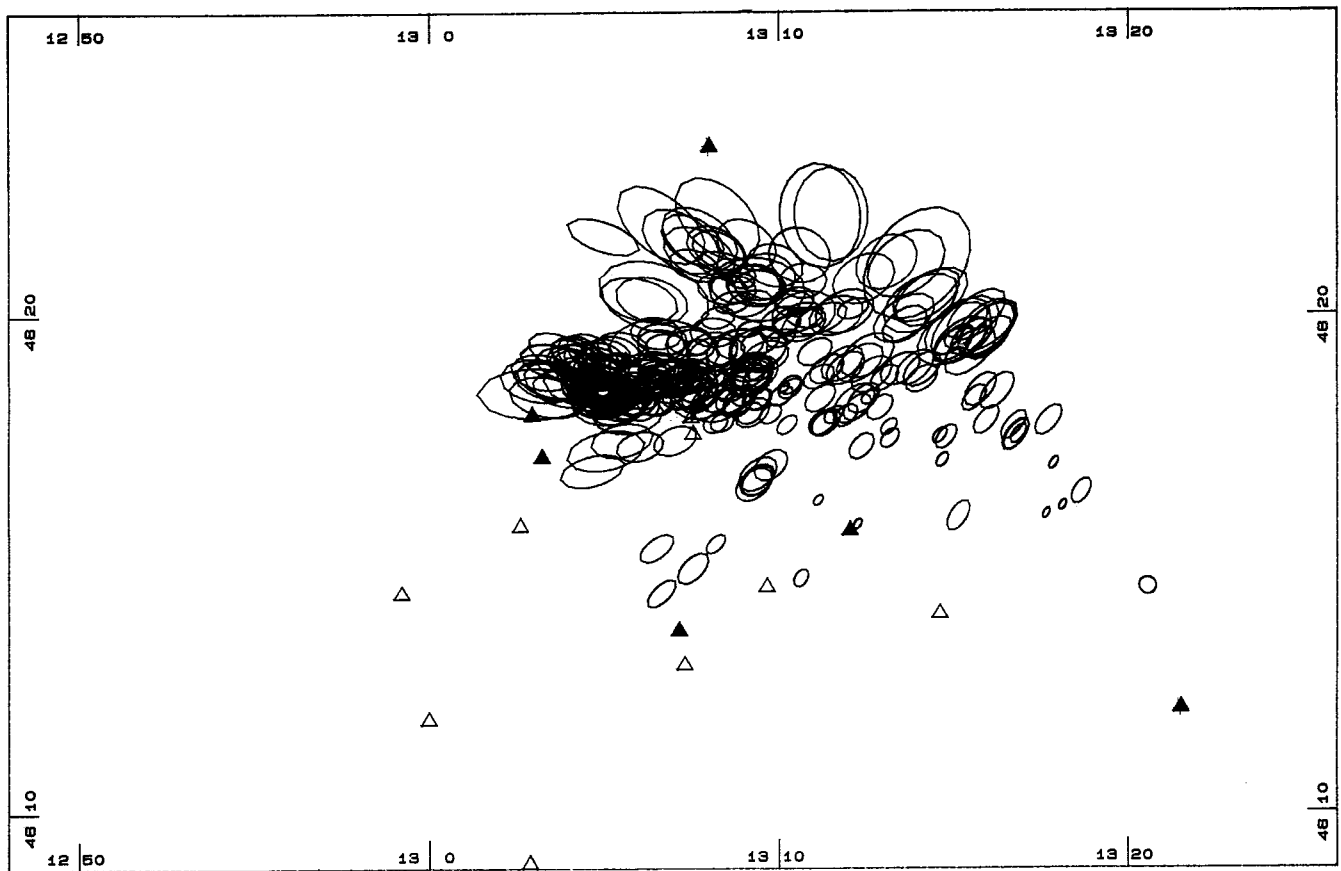


Figure 9  
 Epicenter distribution of the Friuli events in the period 1976-1980. Triangles are all the seismic stations installed. Only the events recorded at a minimum number of stations 6, and r.m.s. residual less than 0.3 s are represented. The figure also shows the levelling lines 36, 37 and Aa.



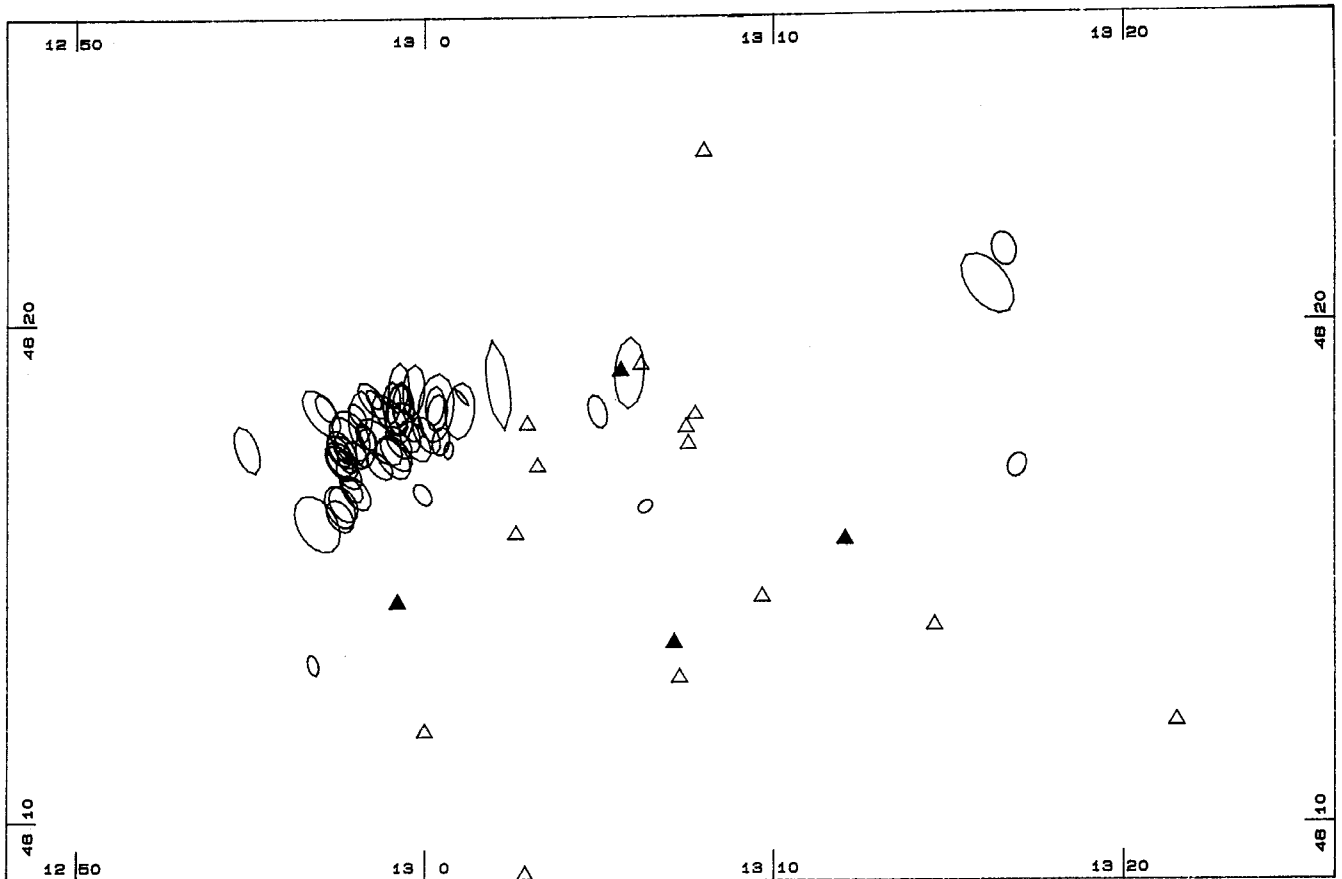


a



b

Figure 10  
 Error ellipses of some events in the periods : a) 10-14 May 1976 ; b) 18 September-31 December 1976 ; c) (right page) September 1977-December 1980. Triangles correspond to seismic stations ; closed symbols indicate those operating during each sequence.



c

Lyon-Caen (1980) applied the master event technique to relocate the largest shocks of the sequence, by using as a reference event an aftershock located by the local network of the Osservatorio Geofisico Sperimentale (OGS) installed during 1977. It has been found an east-west alignment of these large events, with a progressive migration toward the west, while Finetti *et al.* (1979) and Wittlinger (1980) suggested instead a migration to the North.

A basic problem for the reliable interpretation of these aftershock data is due to the small number of seismic stations, the location procedures and the network geometry which varied with time and consequently it is almost impossible to obtain a good resolution on the space-time distribution of the events. To minimize this bias we have collected all existing *P* and *S* first arrival readings from the Institut de Physique du Globe of Strasbourg network operating on the period 10-14 May 1976, 15 September-31 December 1976 and the OGS network in the period May 1977-December 1980. The velocity model used was derived by inverting travel-times of a set of 40 earthquakes recorded by the OGS network in 1977-1980 for velocities under a parameterization in plane homogeneous parallel layers following the Crosson (1976) method. The results indicate that the velocity structure is reasonably approximated by a layer 3-4 km thick with a *P*-wave velocity around 4 km/s overlying another layer that extends up to 10-12 km depth (i.e. the maximum depth reached by these events) and with a *P*-wave velocity of 6 km/s. This result is consistent with those obtained by other researchers by using passive and active seismic techniques

(Italian Explosion Seismology Group, 1981; Angenheister *et al.*, 1972; Gebrande *et al.*, 1976).

All the aftershocks have been relocated using the computer program LQUAKE (Crosson, 1981). Figure 9 shows some events in the period 1976-1980, located by using at least six stations, and r.m.s. residual less than 0.3 s. A quiescence zone is clearly defined in the westernmost part (near 13° E and 46° 18' N) between the area active in 1976 and the locations of another moderately event in September 16, 1977 ( $M_s = 5.2$ ) and its aftershocks.

The space distribution of these events allows to distinguish at least three regions, which may be associated to the largest seismic events of the sequence. The error ellipsoids associated to the best recorded events indicate average standard errors on the epicenters around 1-2 km and 2 to 4 km in depth (fig. 10). All these events are quite shallow, characterized by depths in the range 1-2 to 10-12 km, as can be seen from the figure 11, showing a section aligned N10W. This figure does not show any clear pattern. However, by extracting the locations of the aftershocks following the 6 May, 1976, magnitude 6.5 earthquake (fig. 12), it is possible to note an alignment at a low dipping angle of the bottom of the epicenter distribution. The number and location of events recorded during May 1976 are, however, strongly conditioned by the network geometry and the adopted selection criteria reduce by a factor 8 the available data set. Apparently the sequence that occurred in September 1976 is displaced NW with respect to the aftershocks recorded during May, in agreement with the relocation by Lyon-Caen (1980).

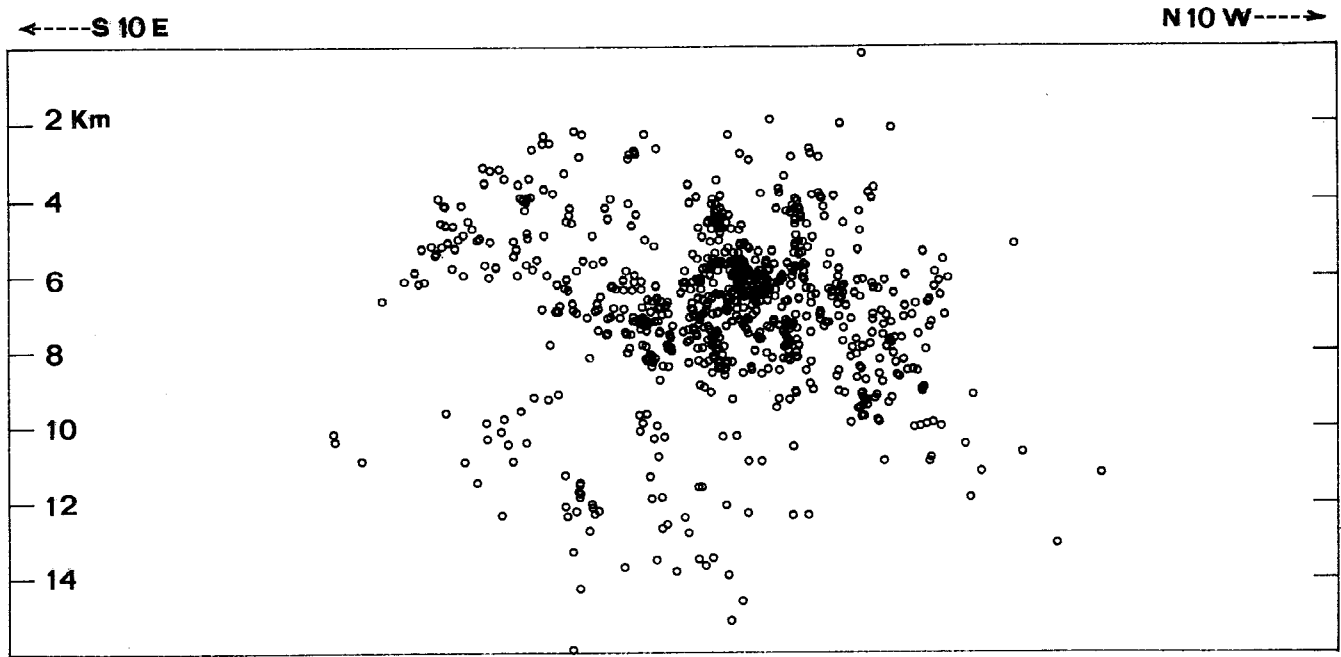


Figure 11  
 Vertical section of hypocenters in the period 1976-1980 centered at 46° 18' north latitude and 13° 10' east longitude. The horizontal scale is the same as the vertical one.

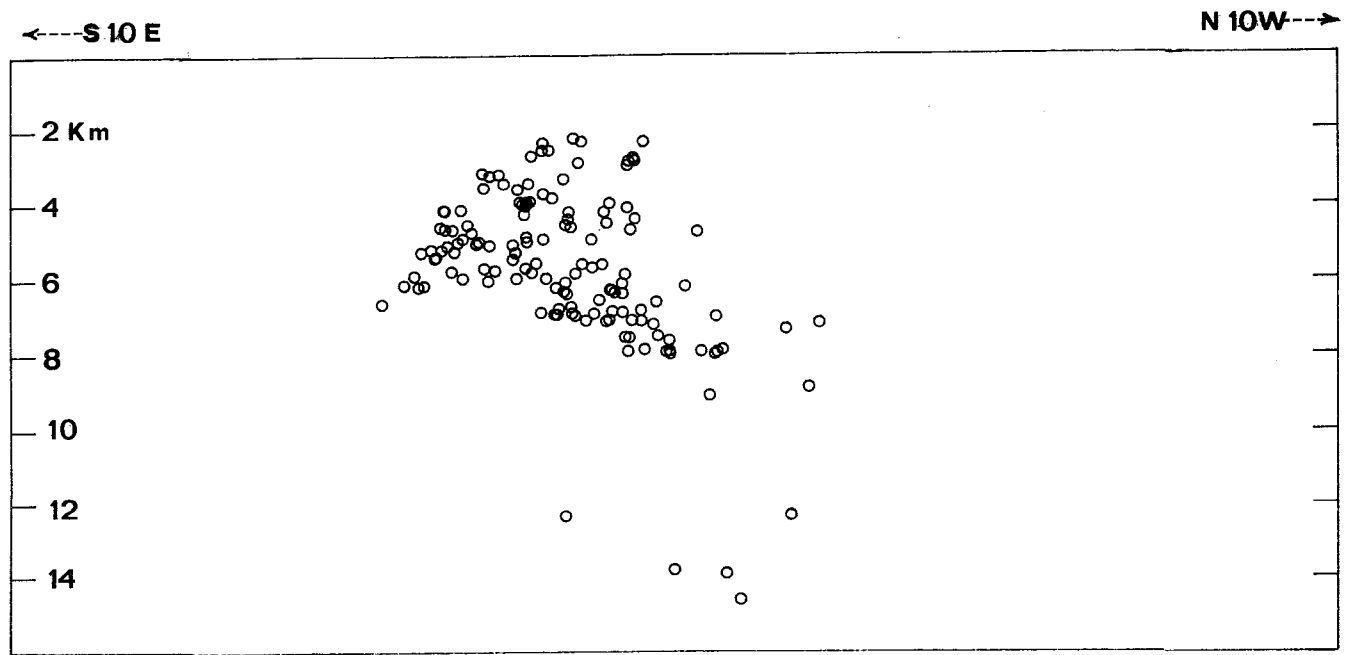


Figure 12  
 Same as is the figure 9, but for events in the period 10-14 May 1976.

## DISCUSSION

Although several papers have reported studies of the faulting mechanism of the Friuli using seismological data (Cipar, 1980, 1981; Ebblin, 1980; Lyon-Caen, 1980; Müller, 1977; Stoll, 1980), on the space time distribution of the aftershocks (Chiaruttini *et al.*, 1980; Finetti *et al.*, 1979; Wittlinger, 1980), and the strong motion data (Console and Rovelli, 1981; Rovelli, 1983), the ground deformation data were never studied in detail.

Livieratos (1980) interpreted the triangulation data obtained by the Istituto Geografico Militare (IGMRG, 1978) showing that the shear strain reached maximum values in the range  $5-16 \times 10^{-5}$ , with an elliptical space distribution, oriented EW, in good agreement with the aftershock distribution, the trend of one of the nodal planes derived from long-period body wave data and the apparent E to W epicenter migration of the largest shocks suggested by Lyon-Caen (1980). Bencini *et al.* (1982) confirmed this spatial pattern of strain using collocation techniques and

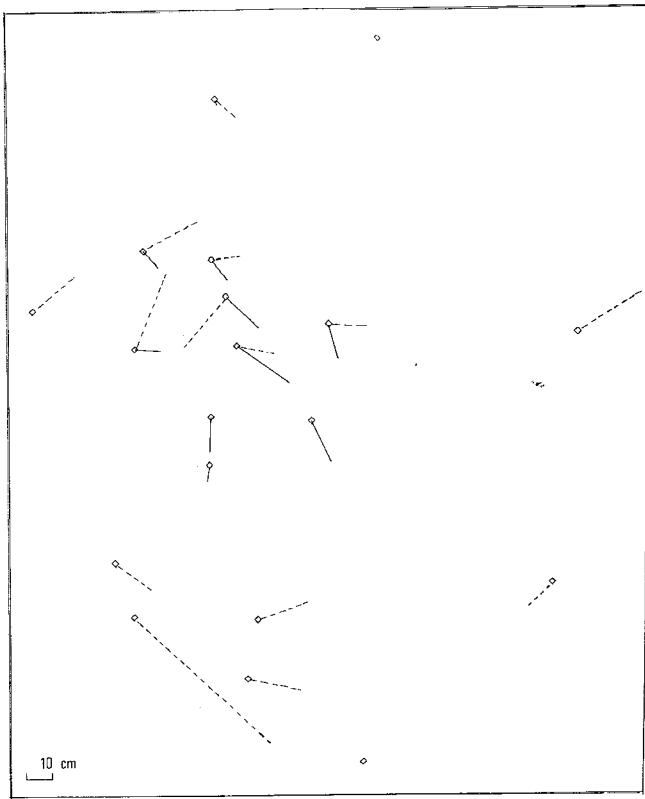


Figure 13  
Horizontal displacements computed according to the inversion model deduced from the levelling data (solid lines) compared with the field observations (dashed lines).

bidimensional filters. We have computed the horizontal displacements produced by our dislocation model for the triangulation bench-marks. Figure 13 shows these displacements compared to the observed values reduced by fixing two northernmost and southernmost points (IGM-RG, 1978). Our solution is not compatible with these data and this discrepancy may be due either to large measurement errors or to the reduction process. Both reasons led us to disregard this data set. Ebblin *et al.* (1982) suggested that the variation of mechanical properties of rocks, arising from tectonic loading stresses, may produce vertical displacements of the order of tens of centimeters explaining the ground movements observed in the Friuli region. Although this last interpretation may be not totally excluded in the case of the Friuli displacements, the present paper shows that the elastic dislocation theory, using a source model formed by three rectangular faults, fits well most of the observed vertical displacements.

Again these faults dip at a shallow angle to the North indicating a northward underthrusting of the southernmost blocks beneath the Alps. One of the two faults located on the western side has a component of dextral transcurrent motion : this is also in agreement with the fault plane solutions deduced from seismological data. The location of these faults is at shallow depth, which is consistent with the most reliable depth locations of the main shocks and aftershocks. These have been relocated by using an homogeneous procedure and velocity model, but are strongly conditioned by the station geometry. The depth resolution of the whole data set is quite poor and does not identify possible depth migration of hypocenters. From these data only a spatial migration of the rupture zones associated with the aftershocks from E to W direction is clear. As it can be seen on figures 5, 7 et 8, the surface projections of the faults derived from displacement data inversion and from the aftershock distribution almost overlap. A shallow dip angle trend of aftershocks can be seen for the May 1976 sequence. This is in agreement with the result found by Siro and Slejko (1982) for the 1977-1980 sequence, although the hypocenters may be systematically biased by the possible presence of lateral inhomogeneities and by the weak constraints due to the poor geometry of the network.

In conclusion the results obtained in the present paper further confirm the importance of geodetic studies and the relevance of applied inverse formalism to understand the physical processes and the rupture geometry associated to moderate size earthquakes. The multiple faulting model discussed in this paper and homogeneous careful aftershock relocation are consistent with the interpretation derived from most other seismological data, confirming the peculiar characteristics of the complex faulting processes at the origin of the Friuli earthquakes : shallow thrusting faults dipping to the NNW progressively ruptured from East to West during the long duration sequence.

#### Acknowledgements

This work was partially supported by the Institut National d'Astronomie et de Géophysique (INAG) through the ATP « Sismogenèse » and the CNR, Rome. The authors are grateful to H. Haessler and G. Wittlinger for providing data on the aftershocks and H. Lyon-Caen and R. Madariaga for many valuable discussions on the problem. M. Matsu'ura is acknowledged for providing valuable material on the geodetic data inversion.

Contribution IPG n° 842.

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