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The 1976 Friuli (NE Italy) Thrust Faulting Earthquake: A Reappraisal 23 Years Later

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Abstract. We revisit the 1976 Friuli earthquake sequence by combining hypocenters relocation, long period surface wave inversion, field geology and strong motion modelling. We show that fault-related folding is the main active deformation by which the seismic energy was released during the main shock (Ms=6.5) and that some of the surface effects reported in 1976 correspond to widespread bedding planes displacements induced by flexural-slip folding. The fault evolved from blind to semi-blind along strike showing the control of the inherited structural geology on the fault surface break and rupture arrest. Our fault model produces waveforms that fit the accelerograms recorded in the area.

Introduction

The May 6, 1976 Friuli earthquake (Ms = 6.5) is the largest so far recorded event in Northern Italy. It took place in the Southern Alps within the active collision zone between Eurasia and Adria that undergoes 4 to 5 mm/year of crustal shortening [*Anderson and Jackson*, 1987; *De Mets et al.*, 1990].

The Friuli main shock was preceded by a M 4.5 foreshock, and followed by a strong aftershock sequence. The largest aftershocks occurred in September 15th, 1976, at 03:15 (Ms=6.0) and 09:21 GMT (Ms=6.1). The area has therefore sustained a high seismic strain, which if released simultaneously, could have produced quite a large earthquake. This peculiar earthquake sequence has been the subject of several studies [*Ambraseys*, 1976; *Amato et al.*, 1976; *Finetti et al.*, 1976; *Lyon-Caen*, 1980; *Cipar*, 1980], but the causative geological structure and related fault-rupture process remained unknown.

In this paper, we relocate the main shock and strongest aftershocks. We invert the surface waves of the main shock and two strongest aftershocks to retrieve their mechanism and depth. We perform quantitative landform analysis and field investigations supplemented by the analysis of pre and post earthquake aerial photos to assess the nature and patterns of Quaternary deformation in the epicentral area. Merging together our new results with the reported 1976 field observations we propose a fault-rupture model for the 1976 Friuli earthquake and simulate the related acceleration field for frequencies lower than 1 Hz. Data analysis and other relevant details are in *Aoudia* [1998].

Earthquake Relocation

The main shock and strongest aftershocks were well recorded by several WWSSN stations. We use JHD and modified single-event methods [*Dewey*, 1971] to relocate the epicenters of 34 earthquakes (M>4.2) of the Friuli earthquake sequence that occurred in 1976 and 1977. The M>5.2 events produced good quality P-wave readings, while for the others good Pg and Lg readings are available. To test the stability of our results we use two different calibration events located by IPGS and OGS local networks and widely recorded by WWSSN stations. Station corrections and their variances were estimated for 210 station-phase pairs for phases at regional, near teleseismic, and far-teleseismic distances. The relocated 34 events along with other aftershock data located by a local network and reported in *Granet and Hoang* [1980] are plotted in Fig. 1. The aftershocks cover a surface 25 km long and 15 km wide, a region comparable to the expected fault surface implied by the source mechanism. All the aftershocks are distributed to the west of the main shock (Fig. 1). This pattern suggests a unilateral and westward rupture propagation. The maximum depth extent of the aftershocks is approximately 14 km, most of them being at 5 km.

Source parameters

To retrieve the source parameters of the main shock and two largest aftershocks, we use the joint inversion method of long-period surface wave spectra described by *Bukchin et al.* [1994]. We make use of the recently recalibrated HGLP digital data [*Ekstrom and Nettles*, 1997] together with long-period data from the early Seismic Research Observatory (SRO) of the GDSN. The estimation of moment tensor and source depth in the instantaneous point source approximation is done by inverting Love and Rayleigh fundamental mode spectra.

The mechanism and scalar seismic moment we obtain for the main shock (strike=288°, dip=29°, slip=112°, and $M_0 = 0.57 * 10^{19} Nm$) are very similar to the recently computed Harvard source parameters [*Ekstrom and Nettles*, 1997]. Our solution is also similar to the mechanism computed by *Cipar* [1980], but rather different from the one estimated by *Lyon Caen* [1980] from P-wave first arrival polarities. Varying the possible depth of the source, we calculate the residuals between observed and synthetic spectra for every trial value of depth. The residuals reaches its minimum value between 4 and 6 km of centroid depth.

For the September 15th aftershocks, we could not retrieve a reasonable estimate of depth. We fix the depth at 8 km, the average of the different values proposed in the lit-

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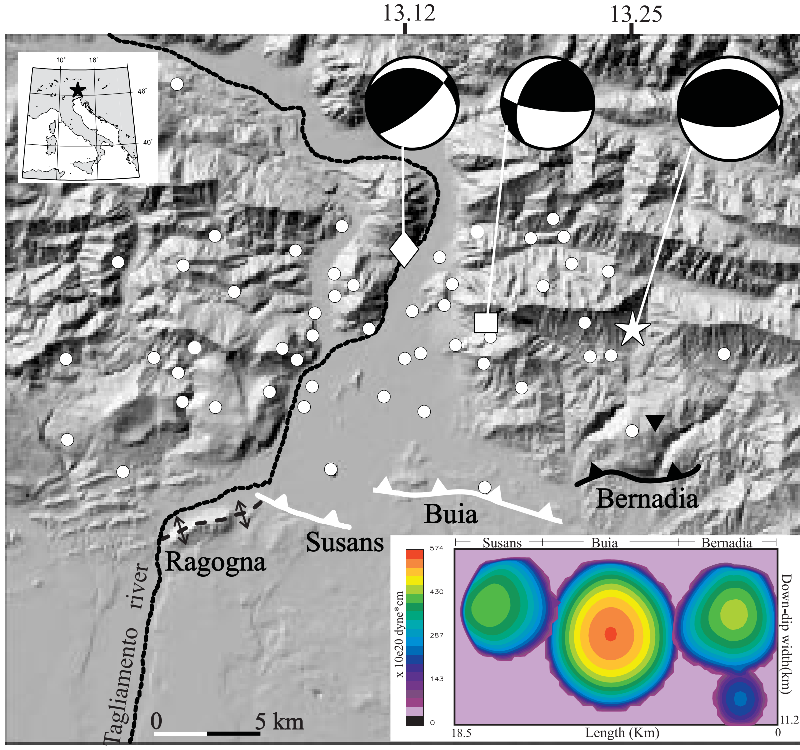

Figure 1. Fault model of the 1976 Friuli earthquake and moment release history used to compute the synthetic strong motions. The white barbed lines are the vertical projection of the top of the blind thrusts while the black line corresponds to an emergent thrust. The fault plane solutions for the main shock (star) and the September 15th aftershocks 3:15 (square) and 9:21 GMT (diamond) are also shown. The triangle refers to the AGIP oil well.

erature. For the 03:15 aftershock the computed mechanism shows a large strike-slip component (strike=204°, dip=36°, slip=21°, and $M_0 = 0.87 * 10^{18} Nm$) when compared to the Harvard CMT solution. The second aftershock solution (strike=288°, dip=28°, slip=144°, and $M_0 = 0.98 * 10^{18} Nm$) is very close to the solutions estimated by *Cipar* [1980], *Lyon Caen* [1980] and *Anderson and Jackson* [1987].

Earthquake Geology

To orient our field investigations, we couple JHD and long-period seismology results with high-resolution digital elevation models (DEM) and GIS surface analysis in an area with a dense vegetation cover. We focus on the most relevant surface effects reported by *Martinis and Cavallin* [1976] and *Ambraseys* [1976]. Those reported by *Bosi et al.* [1976] are located almost at the same latitude as the epicenter, and the field investigations and DEM surface analysis [*Aoudia*, 1998] revealed that the crack locations outlines the contact between Eocene Flysch and Mesozoic limestones representing the uppermost limit of a large paleolandslide.

The Bernadia structure is the only prominent geological structure located 10 km to the south of the epicenter (Fig. 1). It is a basement fault-bend fold covered unconformably by fluvial and fluvio-glacial deposits. The steep south limb and gentle north-dipping back limb require a north-dipping thrust and constrain the dip of the fault to a range of 30-45° (Fig. 2). Figure 2 shows the most striking geomorphic landforms apparent in the front limbs of the fold. The terrace T1 with no apparent tilt or folding sits 50 meters above the modern main Torre river and exhibits the same slope as the Torre. Other terraces appear in the front of T1 and are deformed and back-tilted by a set of N075 to E-W high-angle reverse ramps. This suggests a flat geometry of the frontal thrust. The investigation of pre and post earthquake aerial photos did not reveal any surface faulting of the ramps.

The Buia ridge (Fig. 1) is the only relief that outcrops in the middle of the Tagliamento morainic amphitheatre.

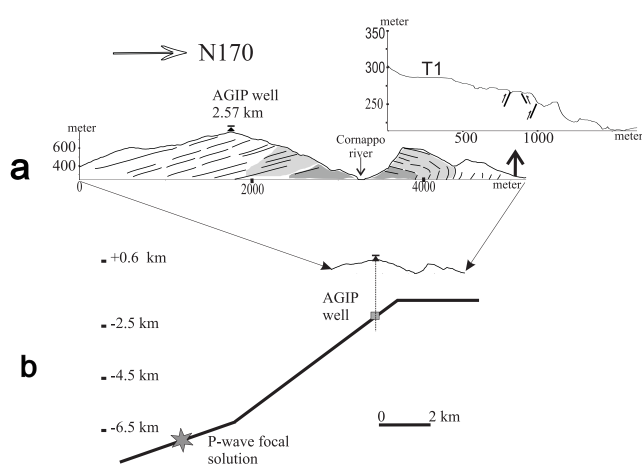

Figure 2. (a) Bernadia field cross-section (see AGIP oil well in Fig. 1 for location) and 5 meter DEM topographic profile at the front of the fold. (b) The integration of the P-wave solution (depth 7 km, dip 19°, strike 260°), the 2.57 km deep oil well *(AGIP, 1959)*, the basement geology along with the surface geology and geomorphology allow us to outline the geometry of the Bernadia thrust.

The denudation of its morainic cover has been attributed by *Carraro et al.* [1982] to vertical deformation. In the field, a thrust places Flysch deposits on top of vertical conglomerates that exhibit slip along their beddings. The Buia structure is probably the surface expression of the anticline that runs W-NW imaged on seismic profiles [*Amato et al.*, 1976] which is related to a fault that is illuminated by the aftershocks in *Finetti et al.* [1976]. The aerial photos did not reveal any surface faulting. The surface projection of the Buia thrust corresponds to the maximum isoseismal of *Giorgetti* [1976].

The N120 Susans ridge (Fig. 1) is made of fluvio-glacial deposits and south-dipping N120 striking conglomerates and sands. *Ambraseys* [1976] described cracks north of Susans ridge and parallel to its strike over a length of 500 meters. The origin was defined as non tectonic. In the field numerous bedding-plane are experiencing widespread flexural slip consistent with a north-dipping blind thrust (Fig. 3). A south dipping high-angle reverse fault offseting the Miocene sand is well exposed at the northern flank of the ridge (Fig. 3). Its location is in good agreement with the surface breaks reported by *Ambraseys* [1976]. The fault acts probably as a backthrust above the main north-dipping blind thrust and the recent activity is highlighted by the presence of wind gaps associated with the Tagliamento river at the western tip of the fold, where tilted alluvial terraces are exposed.

To the west, the N120 trending Susans structure terminates in a pure alpine NE-SW trending system (Fig. 1), represented by the Ragogna ridge. It is a Neogene flexural-slip anticline that extends 18 km along the range front. It is made of marls and clay units interstratified with stiff conglomerates. Widespread NE-SW ground cracks were mapped and well described by *Martinis and Cavallin* [1976] along the bedding-planes of the first 4 km of Ragogna structure towards Susans. The cracks did not show any reactivation during the September aftershocks and were attributed to gravity effects although the authors description suggests a tectonic origin. Our field investigations reveals that these cracks are expressions of slips on bedding-planes distributed over a wide zone. Where Martinis and Cavallin described the most spectacular cracks (20 cm of offset), we found an

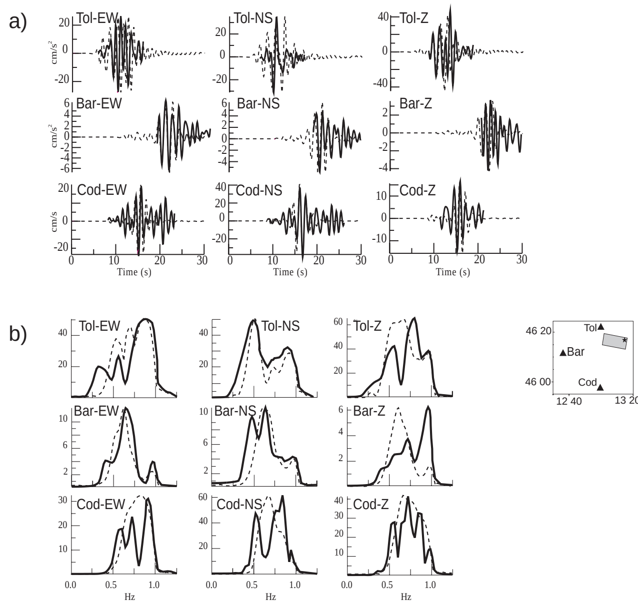

Figure 4. Comparison between three-component (a) real (solid line) and synthetic (dashed line) accelerograms; (b) real and synthetic spectra. The stations used are plotted on the map.

offset man-made wall, with a maximum slip of 50 cm, which coincides with a 6 meter cumulative bedding plane fault scarp exposed on a river terrace. We suggest that the 50 cm slip has been generated by coseismic folding during the 1976 main shock.

Conclusions: Fault Model and Strong Motion Modelling

Our data show that the Friuli earthquake rupture is related to a 19 km fault-related folding evolving from blind faulting beneath the Bernadia and Buia basement-involved structures to semi-blind faulting beneath the Neogene Susans structure (Fig. 1). The rupture ended up in Ragogna fold. The geometry of this fold relative to the N120 structure (interlimb angle of 130°) and the large slip it sustained are consistent with the flexural-slip process and a model where the surface sediments buckle at the end of a propagating rupture. The gravity field shows that the Bernadia is seen as an E-W to NE-SW trending -60 mGal low [*Amato et al.*, 1976] in agreement with the surface geology and the P-wave focal solution. The gravity low steps southwestward and continues uninterrupted across the plain, beneath Buia and Susans, on a N120 strike in agreement with our centroid solution. The above data and interpretation suggest a relatively shallower slip depth extent westward along the fault consistent with the westward shifted course of the Tagliamento river when nearing the N120 fold system (Fig. 1).

Using our fault model and the method of multimodal summation [*Panza*, 1985] for extended sources [*Panza and Suhadolc*, 1987; *Saraò et al.*, 1998], we compute synthetic accelerograms for three analogic strong motion stations that recorded the main shock. The quality of the available data is rather poor: lack of origin time and sometimes high level of noise make source studies by waveform inversion impos-

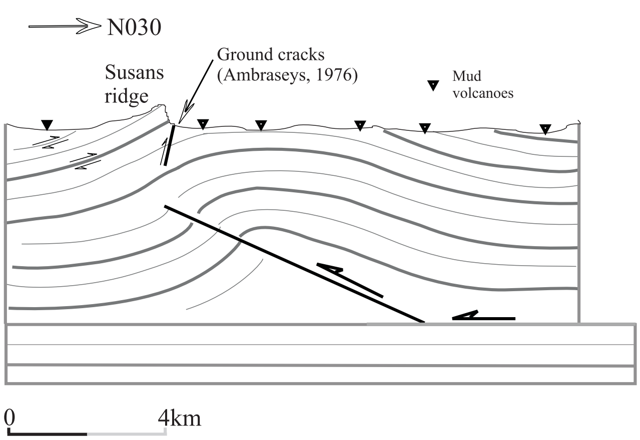

Figure 3. Interpretative cross-section through Susans. Susans ridge is probably the surface expression of a fault-propagation fold associated with a blind thrust ramp. Folding induces flexural-slip on bedding-planes. Depth countours are derived from seismic reflection studies *(AGIP, 1959; Amato et al., 1976).*

sible. Nevertheless, we use some real data for a qualitative comparison with synthetics generated by forward modelling. In our deterministic approach the extended source is a rectangular plane discretized into a grid of point sources. The rupture propagates at a constant speed of 70% of the shear-wave velocity of the medium. We use a fault rupture area of 18.5 km length by 11.2 km width (Fig. 1). The top of the fault is at a depth of 1.5 km and the nucleation point is 7 km deep. We place patches of high energy release in the location of the three fault segments and we smooth the slip distribution at the edges of the fault by a 2-D cosine tapering function. To image these segments seismic waves at least with frequencies up to 1 Hz (corresponding to wavelengths of about 3 km) should be considered. The comparison (Fig. 4) between real and synthetic accelerograms and spectra shows that, in the computed frequency range 0.25-1.00 Hz using a one-dimension structural model the proposed fault model reproduces the strong motion observations. We suggest that the lack of slip at the surface can be explained by flexural-slip folding.

The 1976 Friuli earthquake fault rupture model and related geological structures reflect a transfer of strain from the right-lateral Dinaric fault system to the convergent Alpine system.

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References

AGIP MINERARIA, *Microfacies Italiane,* S.Donato Milanese, Milan, 1959.

Amato, A., P. F. Barnaba, I. Finetti, G. Groppi, B. Martinis, and A. Muzzin, Geodynamic outline and seismicity of the Friuli Venezia Julia region, *Boll. Geofis. Teor. Appl., 19,* 217-256, 1976.

Ambraseys, N., The Gemona di Friuli Earthquake of 6 May 1976, *UNESCO Technical Report, RP/1975-76/2.222.3,* Paris, 1976.

Anderson, H., and J. Jackson, Active tectonics of Adriatic region, *Geophys. J. R. Astr. Soc., 91,* 937-983, 1987.

Aoudia, A., Active faulting and seismological studies for earthquake hazard assessment, Ph.D. thesis, 153 pp., Univ. of Trieste, October 1998.

Bosi, C., B. Camponeschi, and G. Giglio, Indizi di possibili movimenti lungo faglie in occasione del terremoto del Friuli del 6 maggio 1976, *Boll. Soc. Geol. It., 94,* 187-206, 1976.

Bukchin, B. G., A.L. Levshin, L.I. Ratnikova, B. Dost, and G. Nolet, Estimation of spatio-temporal source parameters for the 1988 Spitak, Armenia Earthquake, *Computational Seismology and Geodynamics, Am. Geophys. Union (eds),* 156-161, 1994.

Carraro, F., and F. Petrucci, Tentative assessment of the deformation of a morainic amphitheatre: the Tagliamento amphitheatre (Italy),*Z. Geomorph. N. F., 26,* 331-341, 1982.

Cipar, J., Teleseismic observations of the 1976 Friuli, Italy, earthquake sequence, *Bull. Seismol. Soc. Am., 70,* 963-983, 1980.

De Mets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int., 101,* 425-478, 1990.

Dewey, J. W., Seismicity studies with the method of joint hypocenter determination, Ph.D. thesis, 163 pp., Univ. Calif., Berkeley, 1971.

Ekstrom, G., and M. Nettles, Calibration of HGLP seismograph network and centroid-moment tensor analysis of significant earthquakes of 1976, *Phys. Earth Planet. Inter., 101,* 219-243, 1997.

Finetti, I., F. Giorgetti, H. Haessler, H. T. P. Hoang, D. Slejko, and G. Wittlinger, Time-space epicenter and hypocenter distribution and focal mechanism of 1976 Friuli earthquakes, *Boll. Geofis. Teor. Appl., 19,* 637-655, 1976.

Giorgetti, F., Isoseismal map of the May 6, 1976 Friuli earthquake, *Boll. Geofis. Teor. Appl., 19,* 707-714, 1976.

Granet, M., and T. P. Hoang, Some medium properties at Friuli (Italy) from amplitude spectrum analysis: a possible change in time or in space, *Tectonophysics, 68,* 167-182, 1980.

Lyon-Caen, H., Seismes du Frioul (1976): modeles de source a l'aide des sismogrammes synthetiques d'onde de volume, Ph.D. thesis, Univ. Paris VII., 1980.

Martinis, B., and A. Cavallin, The Friuli earthquake May 6, 1976: Ground cracks and sand mounds, *Boll. Geofis. Teor. Appl., 19,* 792-808, 1976.

Panza G. F., Synthetic Seismograms: the Rayleigh Waves Modal Summation, *J. Geophys., 58,* 125-145, 1985.

Panza, G.F., and P. Suhadolc, Complete strong motion synthetics, in *Seismic Strong Motion Synthetics, Computational Tecniques,* edited by B. A. Bolt, pp. 153-204, Academic Press, Orlando, 1987.

Saraò, A., Das, S., and P. Suhadolc, Effect of non-uniform station coverage on the inversion for earthquake rupture history for a Haskell-type source model, *J. Seism., 2,* 1-25, 1998.

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