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EXPERIMENTAL SEISMIC REFLECTION STUDY IN THE NORCIA AND GARGANO AREAS (CENTRAL-SOUTHERN ITALY)

CONTENTS

ABSTRACT

Under the auspices of the European Co-operation in the Field of Scientific and Technical Research, COST-Action 625 "3-D Monitoring of Active Tectonic Structures", a collaboration project was undertaken among researchers from the Universities of Aarhus with Italian partners of the CNR-Institute of Geosciences and Earth Resources (Florence) and of the University of Camerino (Macerata).

The objective of the project was to investigate faulted sedimentary sequences at shallow depths at selected sites with known active faults in the Norcia (Central Apennines), San Severo and Mattinata area (Gargano Promontory).

KEY WORDS: Seismic profiles, faulted sequences, active faults

1. INTRODUCTION

In Italy, the COST (European Co-operation in the Field of Scientific and Technical Research)-Action 625 "3 D Monitoring of Active Tectonic Structures" project is mainly focused at detecting strain variations and/or any phenomena that may precede future seismic events, in two selected areas (Fig. 1 and Fig. 2): (i) the Central Italy (Norcia seismic zone; CELLO *et alii*, 1997) and (ii) the Gargano area (PICCARDI, 1998, BORRE *et alii*, 2003).

For selecting the seismogenic structures to be monitored in Italy we first performed a structural and a morphological analysis of the faults exposed in the in two selected areas (CELLO *et alii*, 1997; PICCARDI, 1998, PICCARDI *et alii*, 1999; TONDI, 2000; PICCARDI, in press), aimed at characterizing their geometry, kinematics and activity in Holocene times, by recording specific indicators relating surface faulting phenomena to the geomorphic signature in the local landscape. Based on this information we selected a few sites for the execution of high-resolution seismic reflection profiles, designed with the aim of relating observed surface faults to deep structures, and to evaluate slip and displacement rates across imaged seismogenic faults.

In this paper we show the first results of the high-resolution seismic reflection profiles carried out in the Norcia and Gargano areas.

2. GEOLOGICAL FRAMEWORK OF STUDY AREAS

The areas selected for the study have suffered some of the strongest historical earthquakes recorded in Italy (BOSCHI *et alii*, 1997): i.e. that known as the Norcia earthquake (Fig. 1), which occurred on the 14^{th} of January 1703 (Imax=XI), and the S. Severo (Gargano) event (Fig. 2) of the 30^{th} of July 1627 (Imax=X).

From a structural point of view, the selected areas are part of two "homogeneous" domains in peninsular Italy: I) The Norcia area, located in the axial zones of the central Apennines (refer to Fig. 1), which is affected by two major NNW-SSE trending normal-transtensional faults border the Norcia basin, a tectonic depression filled with Pleistocene-Holocene fluvio-lacustrine sediments (CELLO *et alii*, 1997; TONDI, 2000; TONDI & CELLO, 2003), and ii) the Gargano promontory, which is part of the Apenninic foreland which includes the Adria microplate (refer to Fig 2), bordered to the south by an E-W trending active fault system, the Mattinata fault system (MFS; FUNICIELLO *et alii*, 1988; BOSELLINI *et alii*, 1993, PICCARDI, 1998, CHILOVI *et alii*, 2000), including several right lateral fault segments; some of them are known as: i) the San Marco in Lamis fault (SML), ii) the San Giovanni Rotondo fault (SGR), and iii) the Monte Sant'Angelo fault (MSA).

3. EXPERIMENTAL SEISMIC REFLECTION STUDY OF FAULTED SEQUENCES IN THE APENNINES

Based on experiences from investigations in Denmark, the quality of high-resolution reflection seismic images is strongly dependent on the mechanical properties of the surface-near layers. Implicitly, therefore, the methodological objective of the project was to investigate the applicability of the chosen method under the conditions met at the selected sites.

The seismic instrumentation provided by The Department of Earth Sciences, Aarhus, consisted of a 48-channel recording instrument (Geometrics Strataview R48) and a hydraulic auger drilling equipment (Knebel Drilling

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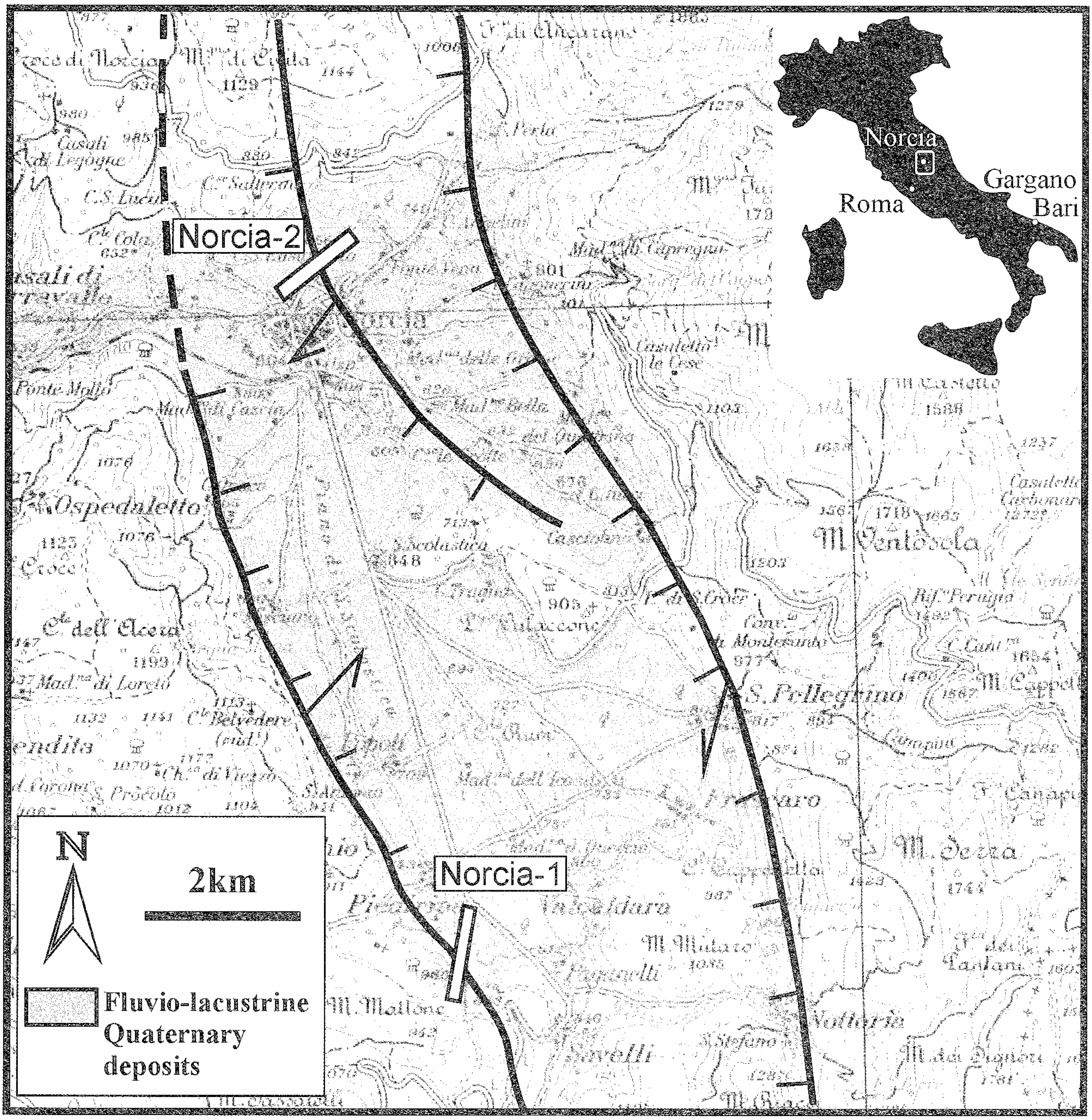


Fig. 1 - Norcia fault system, with location of the analyses performed.

Hy-Gr75). The recording instrument was installed in a van Cables, geophones and power supply was carried in a trailer. The auger drill was mounted on a trailer pulled by its own van.

A number of line-sites for the seismic profiles had been selected at places with active faults as known from geological studies near the following localities: Norcia (Fig. 1; Central Apennines), San Severo and Mattinata (Fig. 2; Gargano promontory). At all sites, except San Severo, the seismic profiles were located on the downthrown block close to the fault. In the San Severo site the seismic profile was crossing the assumed fault trend. Five seismic profiles with a total length of 3050 m were acquired in five days (Tab. 1). Small (25 or 50 g) dynamite charges were used as seismic sources. The charges were detonated at a depth of approximately 2 m. Receivers were 15-Hz geophones with one geophone at each of the 48 locations recorded per shot. The shots were fired partly along the geophone line at locations midway between or at the geophone locations, and partly at location at the front of the geophone line. In the latter case (end-on setup) the 48 geophones were moved forward in the same pace as the shots. This procedure was facilitated by the use of a roll-along-switch.

The data was digitally recorded with a sample rate of 1 millisecond. Before sampling a band pass filter 10-300 Hz was applied. The recording length was 2 seconds.

	Length (m)	*Shot Separation (m)*	*Geophone separation (m)*	*Near offset (m)*	*Fold coverage*
Norcia-1	770	10	5	2.5/17.5 end-on	24/12
Norcia-2	510	10	5	2.5/17.5 end-on	24/12
San Severo-1	760	20	10	5/35 end-on	24/12
San Severo-2	760	20	10	5	24
Mattinata-1	250	10	5	5	24

Tab. 1 - Main characteristics of the six seismic profiles carried out at Norcia and Gargano areas.

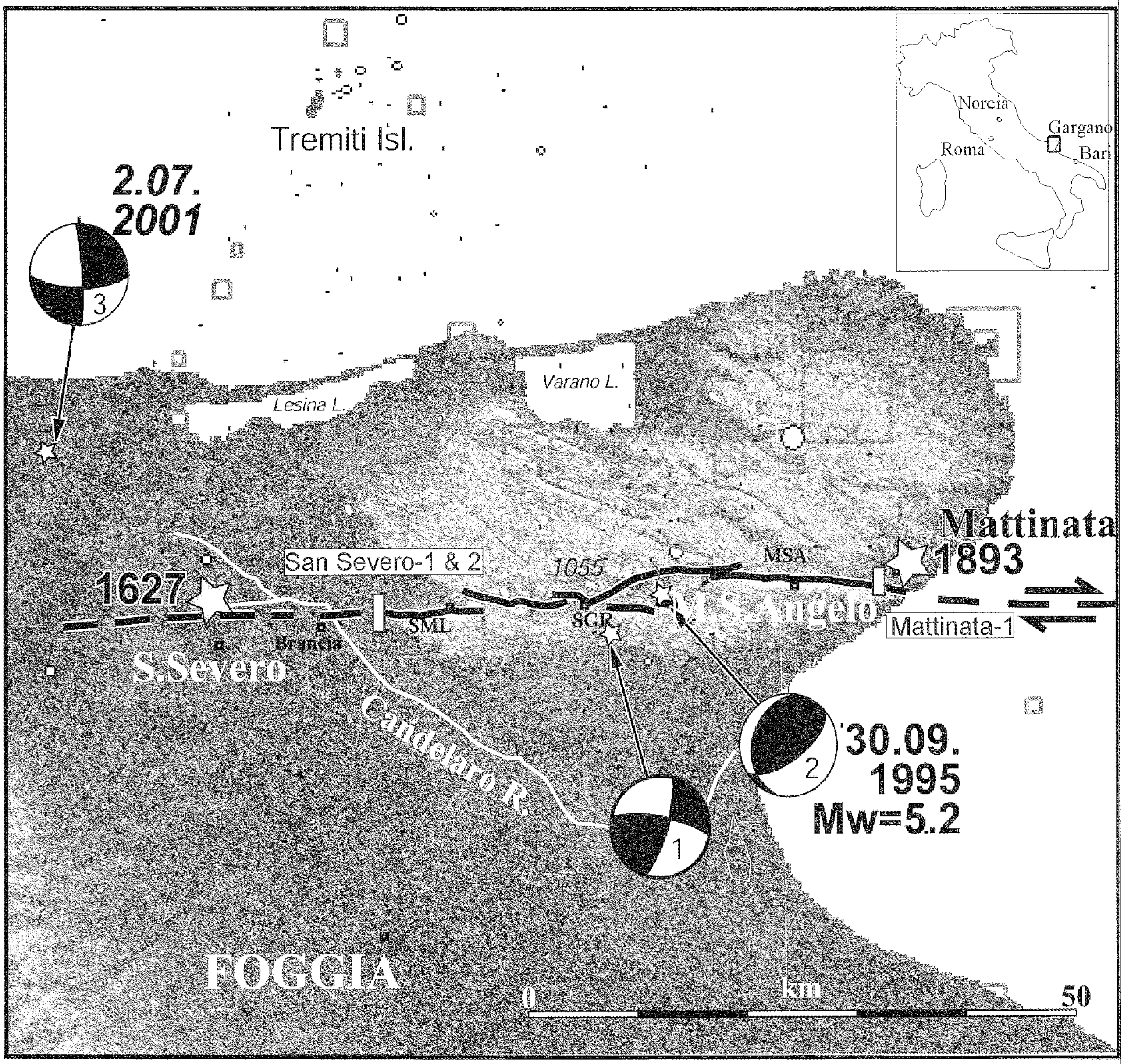


Fig. 2 - Seismotectonic map of the Gargano area with location of the analyses performed. Focal mechanisms from: 1) GASPARINI *et alii* (1985); 2) Catalogue of Harvard University Seismology Group (2001); 3) Catalogue of Swiss Seismological Service (2001); 4) INGV. On the map are show also the epicentral areas of the two major historical earthquake: the July 30, 1627 San Severo earthquake (I=X MCS, Me=6.7; LUCCHINO, 1630; BOSCHI *et alii*, 1997) and the August 10, 1893 earthquake (I=VIII MCS, Mk=5.4; BARATTA, 1893; C.P.T.I. (1999).

3.1 **Data quality**

The quality of the collected data is strongly varying from site to site, and it appears that the data quality is correlated with the properties of the soil.

Two different soil types were encountered along the seismic profiles: gravely and stony material was met along all profiles except along the two San Severo profiles where the soil consisted of clay-rich material. The data collected in the two different soil materials are drastically different as demonstrated in figure 3. In terms of field operation conditions were very different in the two soil types. Drilling with the auger equipment was extremely cumbersome and time consuming in the coarse materials but very easy in the clay materials in the San Severo profiles. The planting of the geophones was somewhat hampered in the coarse materials, and the acoustic coupling was often far from ideal in these materials. Acoustic coupling conditions were much better along the San Severo profiles and the drilling operation was easily carried out here.

3.2. **Processing**

The seismic data was processed by Promax software at the Department of Earth Sciences in Aarhus.

Only the profiles Norcia-2 (Fig. 4) and San Severo-

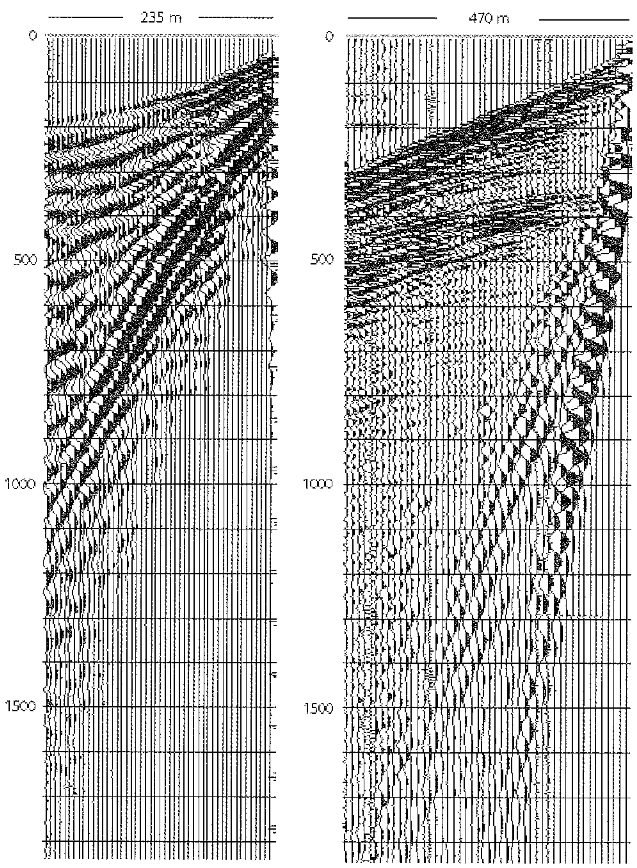


Fig. 3 - Field recordings (shot gathers) from Norcia-1 (left) and San Severo-1 (right).
Note the different horizontal scales. In the San Severo-1 shot reflections are clearly visible as well defined hyperbolas with short-period signals. In the Norcia-1 shot reflections are concealed under long-period linear noise-signals.

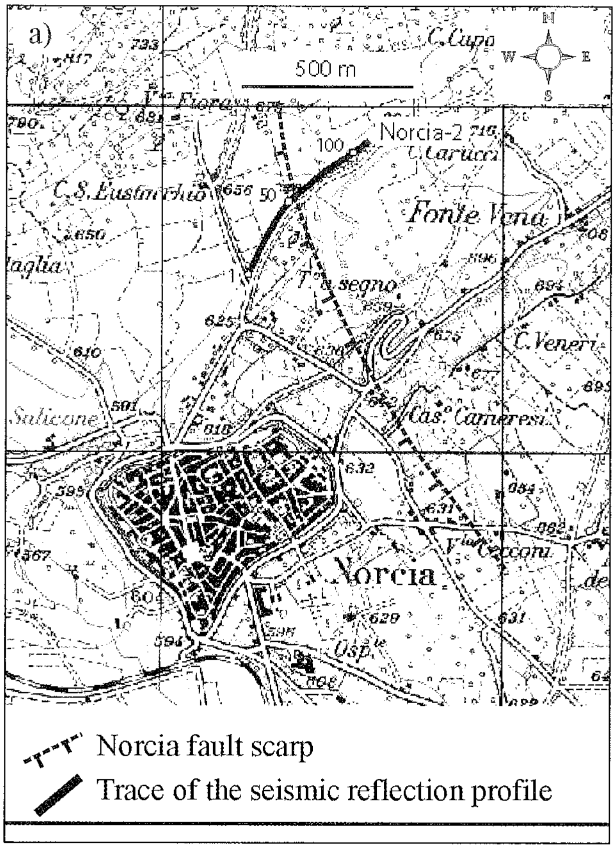
1 and -2 (Fig. 5) resulted in stacked sections permitting reliable geological interpretation. The processing of the Norcia-2 profile afforded many difficulties related to the fact that potential reflections were drowned in trains of linear noise. After severe muting and band-pass filtering coherent events appeared that are believed to represent reflections in the stacked section (Fig. 4b). As can be seen from the seismic image of the fault, the bedrock units underlying the Late-Pleistocene alluvial fan deposits of Monte Patino are displaced by ca. 30 metres. This offset is of the same order of magnitude of that measured on the fault scarp at the surface, hence corroborating that the Norcia fault is a newly formed structure (post 700 ky) characterized by slip rates of about 0.5 mm/yr (CELLO *et alii*, 1997).

The processing of the San Severo profiles was straight forward due to the excellent signal-to-noise ratio in the field data (Fig. 5b). The two San Severo profiles have been spliced to one coherent profile. The gap between the lines in the field (Fig. 5a) has been partly filled in the migration process. The seismic image in the gap sector is not apt for interpretation. The presence of a fault with the footwall to the south is clearly documented. If the suggested correlation of reflections across the fault zone is correct the fault has the characteristics of a growth fault developing in the period corresponding to the interval between the two stippled reflections. The difference of thickness across the fault amounts to about 50 msec (Two Way Time). Assuming a velocity of 2000 m/s this corresponds with an accumulated, differential, vertical movement on the fault plane of about 50 m. The correlation of the shallowest reflections across the fault zone may be questioned due to the fact that the simple pattern recognition applied may not be valid across a growth fault. But as a first approximation it seems likely that the sequence is faulted right to the surface. The San Severo profiles image a cross section of the major wrench fault termed the South Gargano Line in BORRE *et alii* (2003). The wrench component can not be deduced from one single seismic profile, but a closer study of the fault system in three dimensions may be possible by acquisition of 3-D reflection seismic data - an enterprise that can be highly facilitated if the dynamite is replaced by a vibrator source.

CONCLUSIONS

In this paper we illustrated the first results of part of the European Co-operation in the Field of Scientific and Technical Research, Cost-Action 625 "3-D Monitoring of Active Tectonic Structures" carried out in two known seismic areas in the Italian peninsula: i) the Gargano promontory (southern Italy) and ii) the Norcia basin (central Italy).

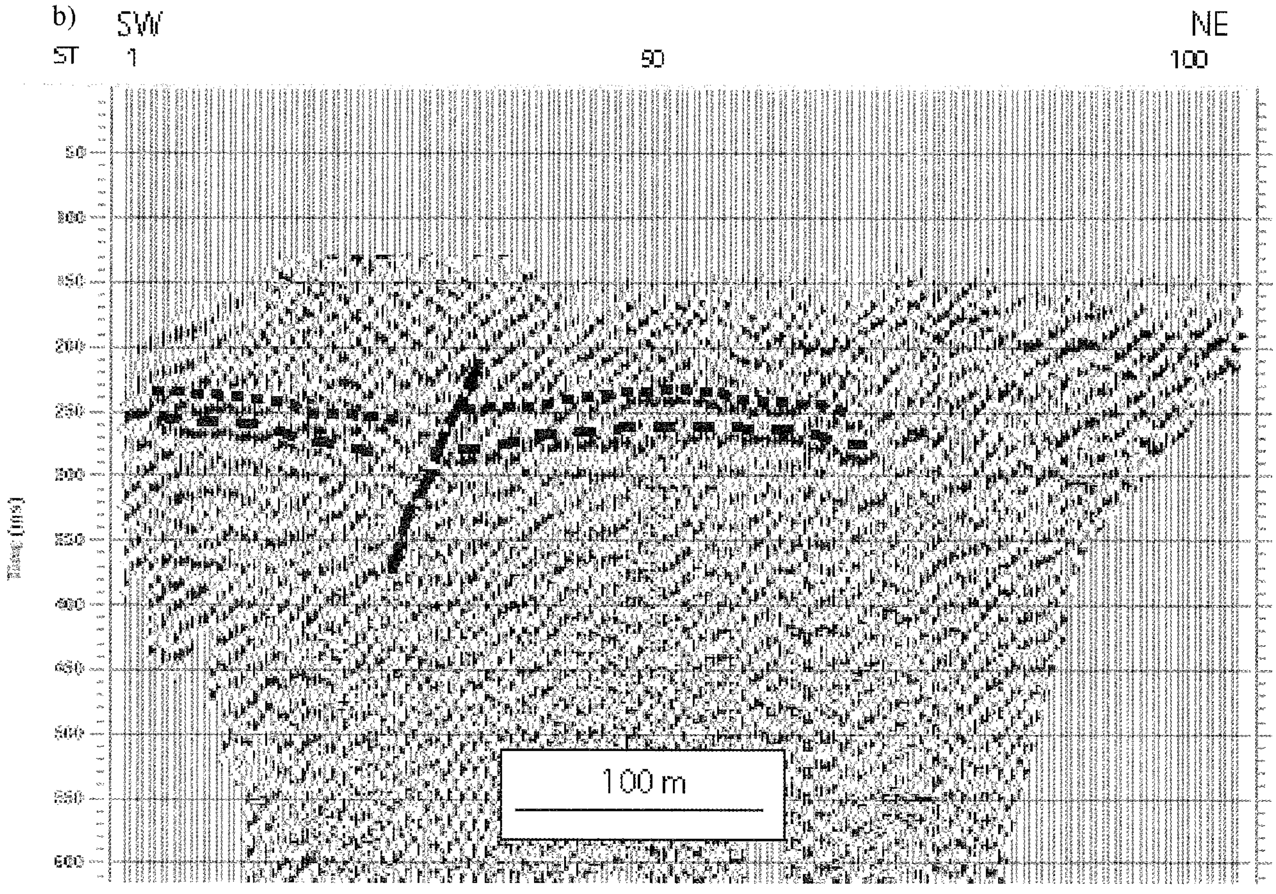
The processing of seismic reflection profiles in all sites, except for the San Severo site, afforded many difficulties related to the fact that potential reflections were drowned in trains of linear noise. Due to the excellent signal-to-noise ratio in the field data, in the San Severo profiles the presence of a fault with the footwall to the south is clearly documented. If the suggested correlation of



a)

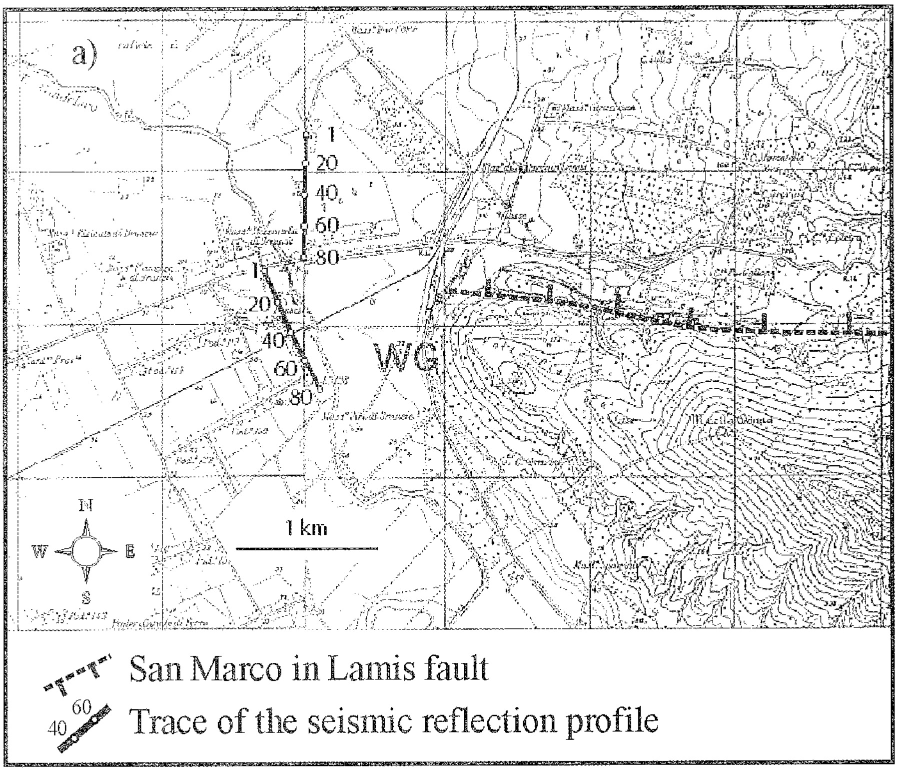
Fig. 4 - a) Location of reflection seismic profile Norcia-2. Station numbers annotated along the line.

b) Norcia-2 stacked section. ST: stations numbers. Upper part of the section has been removed from shot gathers as noise by muting. Two closely spaced reflections (black stippled lines) appear in the south western part of the section at about 250 ms Two Way Time. The offset of the reflector was interpreted to be the top of bedrock units underlying the Late-Pleistocene alluvial fan deposits of Monte Patino. The displacement is in the order of 30 metres.



b)

a)



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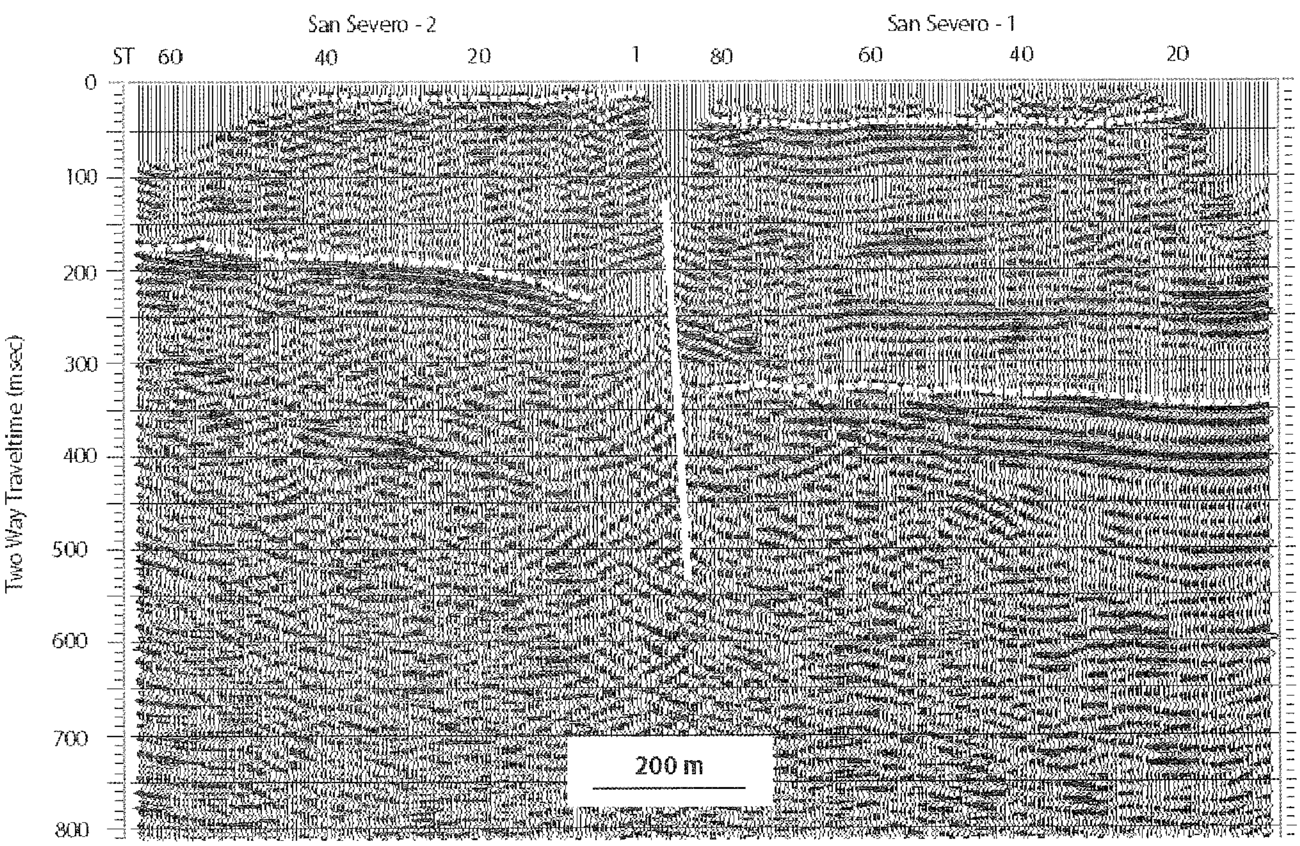

b)

Fig. 5 - a) Location of reflection seismic profiles San Severo-1 (north) and San Severo-2 (south). Station numbers are annotated along the lines.

- b) San Severo -1 and -2 stacked and migrated section. Station numbers are annotated on top of the profile. Reflections marked with white stippled lines, which was interpreted to be the top of bedrock units underlying the Pleistocene continental deposits, indicate the presence of a growth fault with vertical offsets of about 75 msec at 250 msec (Two Way Time) and reduced to about 25 msec closely below the surface.

reflections across the fault zone is correct the fault has the characteristics of a growth fault developing in the period corresponding to the interval between the two stippled reflections.

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REFERENCES

BORRE K., CACON S., CELLO G., KONTNY B., KOSTAK B., LYKKE-ANDERSEN H., MORATTI G., PICCARDI L., STEMBERK J., TONDI E., VILIMEK V. (2003) - *The COST project in Italy: analysis and monitoring of seismogenic faults in the Gargano and Norcia areas (central-southern Apennines, Italy)*. Journal of Geodynamics, **36**, 3-18.

BARATTA M. (1893) - *Intorno ai fenomeni sismici avvenuti nella penisola Garganica durante il 1893*. Annali dell'Ufficio Centrale di Meteorologia, **XV/I**, 297-315.

BOSCHI E., GUIDOBONI E., FERRARI G., VALENSISE G., GASPERINI P. (1997) - *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1990*. ING-SGA Eds., Bologna, 1997, 644 pp.

BOSELLINI A., NERI C., LUCIANI V. (1993) - *Guida ai carbonati Cretaceo-Eocenici di scarpata e bacino del Gargano (Italia meridionale)*. Annali dell'Università di Ferrara (nuova serie), Sez. Scienze della Terra, suppl. to vol. 4, Bologna, 77 pp.

CELLO G., MAZZOLI S., TONDI E., TURCO E. (1997) - *Active tectonics in the Central Apennines and possible implications for seismic hazard analysis in peninsular Italy*. Tectonophysics, **272**, 43-68.

CHILOVI C., DE FEYTER A.J., POMPUCCI A. (2000) - Wrench zone reactivation in the Adriatic block: the example of the Mattinata fault system (SE Italy). Boll. Soc. Geol. It, **119**, 3-8.

C.P.T.I. GRUPPO DI LAVORO (1999) - *Catalogo Parametrico dei Terremoti Italiani*. ING, GNDT, SGA, SSN, Bologna, 92 pp.

FUNICIELLO R., MONTONE P., SALVINI F., TOZZI M. (1988). *Caratteri strutturali del Promontorio del Gargano*. Mem. Soc. Geol. It., **41**, 1235-1243.

GASPARINI C., IANNACCONE G., SCARPA R. (1985) - *Fault plane solutions and seismicity of the Italian Peninsula*. Tectonophysics, **117**, 59-78.

HARVARD UNIVERSITY SEISMOLOGY GROUP (2001) - *Catalogue of CMT solutions of large events (M>5.0) of the period 1977-1996*. http://www.seismology.harvard.edu/data.

LUCCHINO A. (1630) - *Del Terremoto che addì 30 luglio 1627 ruinò la città di San Severo e terre contigue*. Foggia, 1930, 52 pp.

PICCARDI L. (1998) - *Cinematica attuale, comportamento sismico e sismologia storica della faglia attiva di Monte Sant'Angelo (Gargano): la possibile rottura superficiale del 'leggendario' terremoto del 493 d.C.* Geografia Fisica e Dinamica Quaternaria, **21**, 155-166.

PICCARDI L., GAUDEMER Y., TAPPONNIER P., BOCCALETTI M. (1999) - *Active oblique extension in the central Apennines (Italy): evidence from the Fucino basin*. Geophisical Journal International, **139**, 2, 499-530.

PICCARDI L., (in press) - *Paleoseismic evidence of legendary earthquakes: the apparition of Archangel Michael at Monte Sant'Angelo (Gargano, Italy)*. Tectonophysics.

TONDI E., (2000) - *Geological analysis and seismic hazard in the Central Apennines*. In: Cello, G.& Tondi, E. (Eds.), The resolution of geological analysis and models for earthquake faulting studies. Journal of Geodynamics, **29 (3-5)**, 517-534.

TONDI E. & CELLO G. (2003) - *Spatiotemporal Evolution of the Central Apennines Fault System (Italy)*. In: Cello, G. & Kostak, B. (Eds.), Active faults: analysis, processes and monitoring. Journal of Geodynamics, **36**, 113-128.