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Neotectonic setting of the Benevento area: comparison with the epicentral zone of the Irpinia earthquake

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Abstract
A neotectonic study of the Benevento area, Southern Italy, indicates the Quaternary tectonic activity for faults with the «Apennine» (ESE-WNW) and E-W trends. In some cases, movement postdates Recent Quaternary deposits. A morphological comparison with the neighbouring epicentral area of the 1980 Irpinia earthquake, especially the earthquake fault that is quite similar to many other Quaternary faults, indicates an apparently low rate of activity that contradicts the high rate of palaeo-seismicity in the area. This indicates that seismicity in the southern Apennines must be attributed to many faults with relatively low seismic activity, rather than to few faults with a very short recurrence frequency of less than 2000 years.

1. Introduction

As part of the CEC project for microzonation of Benevento (Lopez-Arroyo *et al.*, 1988; Marcellini *et al.*, 1991), the neotectonic study covered a rectangle of 70 by 55 km around this town (Bousquet *et al.*, 1990). The aim was to identify faults that were active in Quaternary times, to define the seismic hazard of the site. Structural, geomorphological and microtectonic observations led to the revision of known (Aprile *et al.*, 1979, 1980; Ambrosetti *et al.*, 1983; Lippmann-Provansal, 1987) neotectonic indicators.

We looked for new indicators, especially in recent Quaternary deposits, and studied the nearby epicentral area of the Irpinia earthquake as well, to see which lessons might be learned for the Benevento area.

The main indicators for recent deformation of the area, presented as map and table, can serve as guides for other Benevento microzonation works (interpretation of historical seismic data and results of precision surveying, installation of seismic network, definition of «source areas»).

2. Neotectonics of the Benevento region (fig. 1)

2.1 *Geological setting*

Neotectonics must be understood within the complex geological setting of the southern Apennines. Suffice it to say that the limestones, which form the highest points (Mt. Avella, Taburno, Matese and Camposauro), usually occur as asymmetric bodies, bounded on their southwest/south sides by major Quaternary normal faults, and thrust in a northeasterly direction over Tertiary formations. Thrust sheets of more plastic material (flysch and Mesozoic-to-Cenozoic claystone) underlie areas of moderate relief, as do Miocene and Pliocene claystone, sandstone and conglomerate. The last group is both syntectonic and tangentially displaced, and is found in particular south and east of Benevento. Southwest of Montefusco, Pliocene marine deposits are now found at an altitude of almost 800 m.

Quaternary deposits can be divided into four groups:

1) Slope breccia from limestone massifs: the

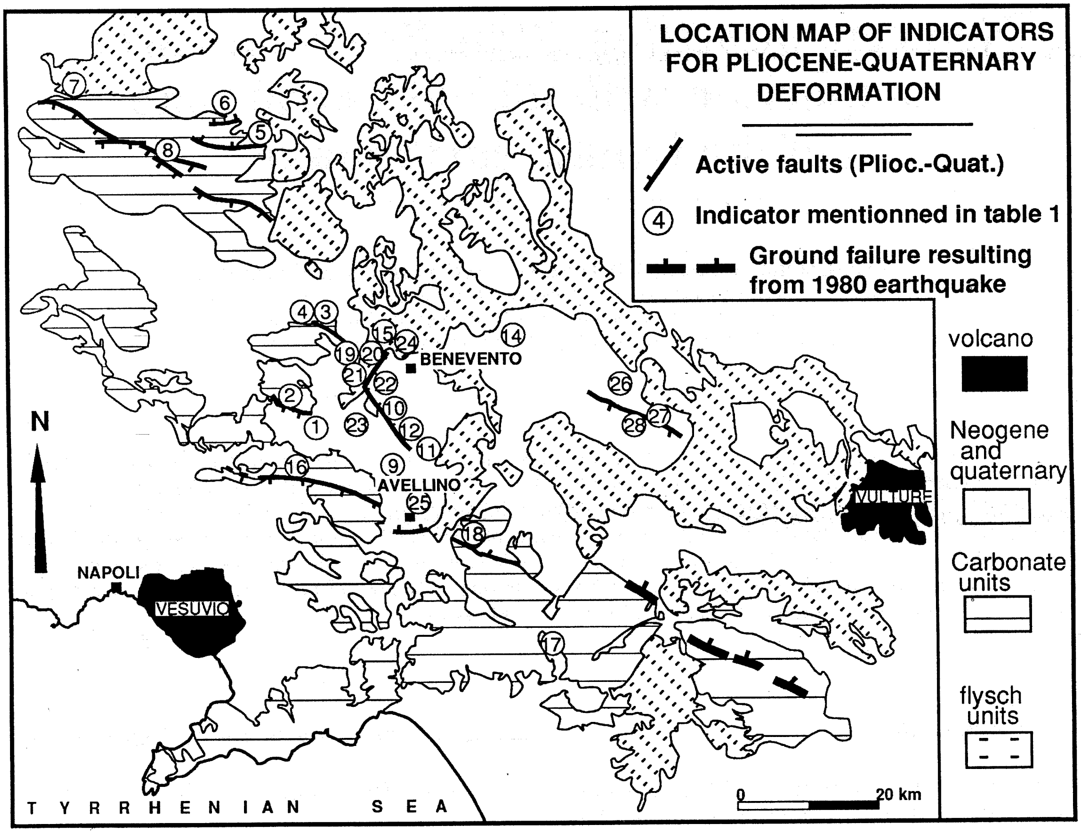

Fig. 1. Location map of indicators of Pliocene-Quaternary deformation in the area around Benevento, Italy (geology simplified after Bonardi *et al.*, 1988).

oldest (Early Quaternary) well-cemented ones derive from periglacial erosion of fault scarps.

2) Alluvial formations: mainly river terraces, stepped at different levels and well developed near Benevento, itself built on a terrace at the confluence of the Calore and Sabato rivers. The highest and oldest is said by Bergomi *et al.* (1975) to be of Riss age (200 000 to 400 000 B.P.).

3) Lacustrine/fluviolacustrine formations: common south of Benevento, where they are embedded in Pliocene deposits, they seem to dominate the highest terrace on the left bank of Fiume Calore.

4) Volcanic deposits are either ejecta (some intercalated in recent Quaternary deposits) or ignimbrites, 35 000 and 12 000 years old.

2.2. *Criteria for recognizing faults active during the Quaternary*

The neotectonic study uses structural, microtectonic and geomorphologic methods. The first two were used in all cases, particularly for studying faults and slickensides in Pliocene/Quaternary deposits, to see if the stress field had changed with time. A geomorphological study of landforms associated with faulting (Birot, 1965; Guéremy, 1984) was particularly useful for studying carbonate massifs and for comparison with the 1980 epicentral area. The southern Apennines have been subjected to very strong uplift since the last major compression phase during the Middle Pliocene. Resulting landforms, associated with faults, are highly varied (Bousquet and Guéremy, 1969; Brancaccio *et al.*, 1979, 1981). Morphological analysis is thus needed to define the relative roles played by tectonics and erosion.

Lithological contrasts can be considerable, where faults juxtapose Mesozoic carbonates against flysch and other unconsolidated deposits, and the strong Quaternary uplift has caused considerable erosion of the latter. For these reasons, the most pronounced scarps are composite, created by faulting but mostly shaped by erosion, the role of tectonics being difficult to quantify through the lack of precise Quaternary marker beds (fig. 2, A2 and A3).

For true fault scarps, not counting several spectacular scarps that are in fact thrust fronts, direct geological observation can give a figure for Quaternary throw along the fault, but geomorphological study provides more data. The analysis of such scarps is mainly based on their type of erosion (Guéremy, 1984). Carbonate rocks in particular were subjected to strong frost action during cold Quaternary periods with a periglacial climate. Along the faults this led to the accumulation of scree in the down-thrown section caused by the erosion of the higher side, giving an angle to the slope of 30° to 35° on carbonate rocks (equilibrium slope or Richter's slope: VR, fig. 2, B1). The scree, which is variably cemented and consolidated, can itself be affected and deformed by faulting: *e.g.*, Santuario del Taburno and Madonna della Grotta (indicator 3 on table I), where scree bedding was tilted 35° or more. On the south flank of Taburno, fan-shaped structures and small faults in scree show that fault movement was synchronous with deposition.

Reactivation of faults creates an offset in the slope, between the top of the scree and the equilibrium slope that initially was one continuous slope (fig.2, B2). Renewed erosion then can cause scree to mask the fault (fig. 2, B3). This figure also shows inherited fault scarps, shown by the presence of benches that are evidence of sufficiently strong tectonic activity during the Quaternary for straightening of the slope to have been impossible. The presence of such rejuvenated fault scarps is a good indicator for recent movement along the fault, in particular when it can be followed over a long distance.

2.3. *Results*

Major indicators (Ind.) for the Pliocene-Quaternary deformation, deriving from our work in the Benevento area, are shown in fig. 1 and in table I.

1) Geological/geomorphological indicators of Quaternary tectonic activity are mainly found along N 120°-140° «Apennine trend» and N 090°-100° faults. Breccias along carbonate fronts and affected by such faults are difficult to date (Early?- Middle? Quaternary). Traces of recent movement were seen on only two faults: deformed Würm scree on the south slope of Mt. Avella (Ind. 16) and a rejuvenated fault scarp in the Matese Massif (Ind. 8).

2) A systematic search for neotectonic indicators in the most recent fluviatile terraces and volcanic rocks around Benevento remained fruitless, but pebbles in the oldest terrace of Fiume Calore show dissolution and compression striae.

3) Microtectonic measurements, though too few to be processed by station, indicate that, contrary to the accepted thought, deformation seems polyphase after the Late Pliocene. In fact, as in the Eboli area (Gars and Lippmann, 1983), several compression microstructures (and some mesostructures) were found in Pliocene and Quaternary deposits, in an area where normal Quaternary faults dominate.

3. Comparison with the epicentral area of the 1980 earthquake

The Benevento area having the same structural setting as the epicentral area of the 1980 Irpinia earthquake was useful to study the geological and geomorphological aspects of this major seismic event in the southern Apennines. Surface failure resulting from an earthquake was identified for the first time in Italy (Bollettinari and Panizza, 1981; Cinque *et al.*, 1981), in several traces over a distance of about 38 km (Pantosti and Valensise, 1990a) in the north flanks of mounts Picentini and Marzano. This failure followed the «Apennine» trend of N 120°-140°, along a normal fault dipping NE with a slight sinistral offset; maximum vertical throw was

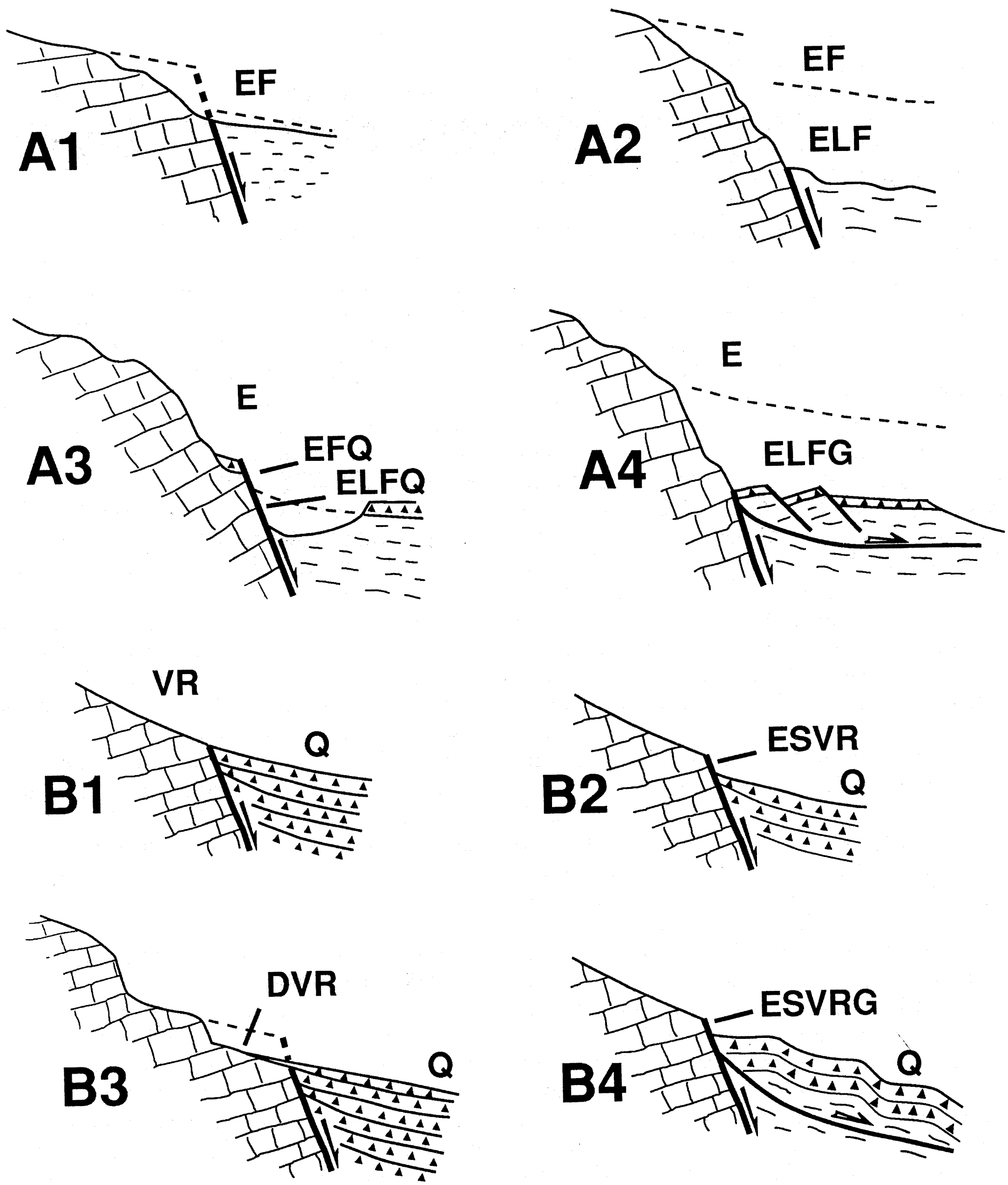

Fig. 2. Morphology associated with faults in the Benevento and Irpinia areas. A1: Fault scarp (EF) of uncertain age. A2: Composite fault scarp of uncertain age: fault scarp (EF) and fault-trace scarp (EFL). A3: Composite scarp: old fault scarp and/or fault-trace scarp (E); fault scarp younger than Quaternary breccia (EFQ); fault-trace scarp younger than Quaternary breccia (ELFQ). A4: Composite scarp: (E) as A3; fault-trace scarp made visible through erosion and ground movements affecting Quaternary breccia (ELFG) as at Senerchia (cf. Bousquet *et al.*, 1983; Lipmann, 1984). B1: Eroded fault scarp: bare eroded slope (VR); periglacial faulted scree (Q). B2: Tectonic scarp below VR slope (ESVR). B3: Rejuvenated fault scarp with 'benches' due to incomplete erosion (DVR). B4: Fault scarp below VR slope, bared by gravity sliding (ESVRG), as at Serra de San Giacomo (cf. Lipmann,1984).

Indicator number	Geographical location	Type of observation	Age
1	Bonea (south Taburno)	Normal faults in breccia	Early Quaternary
2	Santuario del Taburno	Normal faults in breccia	Early Quaternary
3	Madonna della Grotta (Camposauro)	Vertical position of breccia along fault (throw ??)	Post Early Quaternary
4	Solopaca road (Camposauro)	Vertical position of breccia along fault (throw ??)	Post Early Quaternary Pre Holocene
5	Guardiareggia (North Matese)	Opposite dip in breccia along major normal fault	Post Early Quaternary
6	Boiano (North Matese)	Fault line scarp eroded slope	Post Early (?) Quaternary
7	Gallo (Matese)	Normal dextral fault, scarp below fault line scarp	Early (?) Quaternary
8	East Gallo (Matese)	Fault scarp below Richter slope	Holocene ?
9	Arpaise (N. Avella massif)	Normal fault	Post Early Quaternary
10	Confini (N. Avella massif)	Reverse fault	Post Pliocene
11	Petruro Irpino (N. Avella massif)	Normal fault	Post Pliocene
12	Ceppaloni (N. Avella masif)	Normal fault	Post Pliocene
13	Torrioni (N. Avella massif)	Normal fault	Post Pliocene
14	Stazione di Paduli (Calore valley)	Microfault striated pebbles	Post Middle Quaternary
15	Motorway road-bed	Microfaults, reverse faults, folds	Post Early Quaternary
16	Monte Avella (south flank)	Normal fault in breccia of Würm (?) age	Recent Post Quaternary
17	Acerno Basin	Normal fault	Post Middle Quaternary
18	San Stefano del Sole	Breccias tilted to 60°	Post Middle Quaternary (?)
19	Masseria Cabola	Normal synsedimentary fault	Intra Pliocene
20	Masseria Cabola	Reverse fault	Post Pliocene
21	Masseria Scriabacca	Normal synsedimentary fault	Intra Pliocene
22	Masseria Feleppa	Normal synsedimentary fault	Intra Pliocene
23	Tuffara clay quarries	Normal fault	Post Pliocene
24	Masseria Tornaciello	Normal (?) faults	Post Middle Quaternary
25	Avellino	Tilted terraces	Post Middle Quaternary
26	Baronia (Fiumeri quarries)	Reverse faults	Intra Pliocene
27	Baronia (Carife)	Normal faults	Post Pliocence
28	Baronia (Ufita valley)	Trapezoidal facets (?)	Quaternary Recent

Table I. Indicators of Pliocene-Quaternary deformation mapped in the Benevento area.

about 1 m in the Piano delle Pecore. These observations agree with seismological data (mechanism, existence of multiple failure; Bernard and Zollo, 1989). Near Mt. Marzano, west of the Pecore plain, failure followed a pre-existing fault, juxtaposing Mesozoic carbonate rock against Quaternary breccia (fig. 2, B2).

A geomorphological study of failures is equally interesting. As near Benevento, the most obvious scarps in the epicentral area are more affected by erosion than tectonics (clearly seen on either side of the Sele valley between mounts Picentini and Marzano (fig. 2 A2, A3, A4). The morphological expression of the fault before the

1980 event was more discreet than its geological expression; nothing is visible at the SW end of the failure near Piano de San Gregorio Magno, a karst depression with Quaternary deposits, where failure effects of earlier earthquakes could easily have been erased by erosion or agriculture. Above the village, a recent fault scarp (fig. 2, B2) can be seen with the same direction, but facing the other way.

Farther east, on either side of the Piano delle Pecore, the fault is halfway up a small slope, and the surface failure created a rejuvenated fault scarp (fig. 2 B1 before and B2 after the earthquake). As vegetation and soil masked the contact between limestone and breccia, the presence of a Quaternary fault was difficult to suspect before the earthquake.

These observations reconfirm the validity of using this kind of scarps (scarp under Richter's slope) as criteria for active faults, although one must be certain that failure was really created by faulting, and not by differential compaction or mere sliding of the unconsolidated material (fig. 2, B4). However, even when certain, these observations pose a major problem as they seem to contradict palaeoseismic results. Trenches dug in the Pecore and San Gregorio plains (Pantosti and Valensise, 1990b) show that faulting affected Holocene deposits. Earthquakes with a magnitude of that of 1980 are estimated to recur with a frequency of about 1700 years. As far as is known (Wallace, 1977; Bousquet, 1984; Serva *et al.*, 1987), this time span suffices to erode all traces of a Holocene scarp of a few tens of centimetres in unconsolidated deposits. But it seems unlikely that this could happen outside the plains, on much more competent rock slopes. Lacustrine deposits cannot be used to calculate recurrence, as was done for the El Asnam earthquake of the same year (Philip and Meghraoui, 1983): no lake formed on the Pecore plain after the earthquake, but it might be possible that this karst depression was not only for climatic reasons repeatedly filled with water during the Holocene.

Based on geomorphological data, earthquake recurrence could well be much longer than 1700 years. The case is similar to that of the Spitak earthquake fault, located at the foot of an incompletely eroded Richter's slope. This fault, however, is subject to periglacial erosion conditions, and its recurrence times are much longer (Philip *et al.*, 1992).

4. Conclusions

Most faults around Benevento, studied for seismic microzonation and showing evidence of Quaternary activity, follow the «Apennine» trend, a few having an E-W trend. In view of the difficulty to identify faults outside carbonate rocks, particularly around Benevento, it is possible that the E-W trend is much more common than hitherto thought. Erosion along faults, helped by strong Quaternary uplift, can create grandiose scarps. However, the case of the Irpinia earthquake (also along an «Apennine» fault) demonstrates that major earthquakes can be related to morphologically minor faults.

We consider that a longer recurrence than that estimated until now would better correlate with this type of fault. To reconcile the data on historical seismicity (large number of destructive earthquakes) with the results of neotectonic work (few indicators of recent seismicity), all faults with an «Apennine» trend should be considered as potential «source zones». This contradicts Boschi *et al.* (1990): five major seismogenic faults are responsible for most historical seismicity in the 200 km from Isernia to south of Potenza along the axis of the mountains. The first seismological results of the microzonation programme (microseismic swarm in an E-W to ESE-WNW direction, just north of Benevento in 1990) confirm the existence of seismogenic E-W structures.

Concentration of seismic activity in only two major fault directions («Apennine» and E-W) would indicate that this part of the Apennines is subject to nonradial extension (σ 2 and σ 3 are horizontal and of similar value), enabling all faults to move, regardless of their direction.

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