A note on Northern Marche seismicity: new focal mechanisms and seismological evidence

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Abstract
A geodynamic interpretation of the Northern Marche region is difficult, the zone being characterized by complex structures which cannot be defined in the form of a simple, standard model. It is unquestionable that the geodynamic setting, whatever it is, bears a strong influence on the seismic hazard assessment of a region, and this is the background reason for the present note. In order to obtain a more detailed picture of seismological evidence in this zone, 11 new fault plane solutions of crustal events with $2.9 < M < 4.3$ were calculated, using data recorded by the national seismic network of the Istituto Nazionale di Geofisica e Vulcanologia in the period 1990-2000. The aim is to add local information to the previous studies by Frepoli and Amato (1997, 2000). A possible result of this new study is the division of the Northern Marche region into three areas with different focal mechanism categories: the inner area of the Apenninic belt, the Adriatic on-shore and the Adriatic off-shore. This note is intended to be a contribution to update seismological evidence in the Northern Marche region.

Key words focal mechanisms – Northern Apennines – Adriatic off-shore – seismological evidence

1. Introduction
For the Northern Apennines, available data consistently indicate active extension in the axial zone of the chain, where the main active structures consist of border faults to a series of NW-SE oriented intramontane basins (Lunigiana, Garfagnana, Mugello, Casentino, high Tiber Valley; e.g., Galadini et al., 2001). A general agreement exists on the fact that a roughly NE-SW oriented minimum stress axis ($\sigma_3$) is dominant in this part of the orogen (Borghini et al., 2000).

In the studied rectangular area (outer Northern Apennines and related Adriatic off-shore; fig. 1), thrust tectonics has been widely documented by field surveys and by the interpretation of seismic reflection lines and deep wells (e.g., Bally et al., 1986; Barchi et al., 1998).
On-shore, available field data show that the most important evidence of active tectonics in the studied area is a well documented and generalised Pleistocene uplift (e.g., Dramis, 1992; Borraccini et al., 2002).

The studied area is the locus of a moderate – yet significant – tectonic activity, as also witnessed by historical and instrumental seismicity ($I_{\text{max}} = \text{IX MCS}; M_{\text{max}} = 6$; Gruppo di Lavoro CPTI, 1999; Frepoli and Amato, 2000). The sources of these earthquakes are not well known (Galadini et al., 2000) and the possible existence and size of currently silent sources is a matter of study (Valensise and Pantosti, 2001).

2. Seismic data

Many focal mechanisms of moderate events with magnitudes ranging between 4.0 and 5.8 have been determined for the Northern Apennines. The available fault-plane solutions of the period 1939-1980, calculated from arrival times and polarities read from seismic bulletins, were reported by Gasparini et al. (1985): the best focal mechanisms are shown in fig. 1 as selected by Zoback (1992), which used $P$ and $T$ axes to divide the data into five main stress regime categories and an unknown category when the data provide no information on relative stress magnitudes (see table I).

![Fig. 1. Fault-plane solutions from Gasparini et al. (1985) (in black), CMT solutions (in light grey), solutions of the four largest events of the Porto San Giorgio sequence of July 1987 from Riguzzi et al. (1989) and of the six largest events of the Colfiorito sequence of September-October 1997 from Santini et al. (2003) (dark grey), and the studied area (in the box) of the Northern Marche region.](image-url)

<table>
<thead>
<tr>
<th>Plunges of axes (pl)</th>
<th>FPS categories by Zoback (1992)</th>
<th>Figure 4 notation (label color)</th>
<th>Legenda</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$T$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{pl} \geq 52^\circ$</td>
<td>$\text{pl} \leq 35^\circ$</td>
<td>NF</td>
<td>blue labels</td>
</tr>
<tr>
<td>$40^\circ \leq \text{pl} \leq 52^\circ$</td>
<td>$\text{pl} \leq 20^\circ$</td>
<td>NS</td>
<td>blue labels</td>
</tr>
<tr>
<td>$\text{pl} &lt; 40^\circ$</td>
<td>$\text{pl} \leq 20^\circ$</td>
<td>SS</td>
<td>red labels</td>
</tr>
<tr>
<td>$\text{pl} \leq 20^\circ$</td>
<td>$\text{pl} &lt; 40^\circ$</td>
<td>SS</td>
<td>red labels</td>
</tr>
<tr>
<td>$\text{pl} \leq 35^\circ$</td>
<td>$\text{pl} \geq 52^\circ$</td>
<td>TF</td>
<td>green labels</td>
</tr>
<tr>
<td>$\text{pl} \leq 20^\circ$</td>
<td>$40^\circ \leq \text{pl} \leq 52^\circ$</td>
<td>TS</td>
<td>green labels</td>
</tr>
<tr>
<td>others</td>
<td>others</td>
<td>UC</td>
<td>black labels</td>
</tr>
</tbody>
</table>
The figure displays also two Centroid Mo-
ment Tensor (CMT) solutions of the Norcia
(1979) and Perugia (1984) earthquakes, the focal
mechanisms of four events of the Porto San Giorgio
seismic sequence of July 1987 (Riguzzi et al.,
1989) and the focal mechanisms of six events
of the Colfiorito seismic sequence of September-
October 1997 (Santini et al., 2003). The two CMT
solutions show an evident normal-fault regime
along the portion of the Apenninic belt, while the
strike-slip solution of the Ancona (1972) event,
shows a compressional axis \( P \) with ENE-WSW
orientation (Frepoli and Amato, 1997).

The only events in previous studies suggesting
an evident active compression along the outer
part of the Apenninic belt in the Northern Marche
occurred on January 26, 1990, and December
15, 1991, as recolored in dark grey in fig. 2 by
Frepoli and Amato (1997).

The earthquakes analyzed in this study are
located in the Northern Marche from 43° to
44°N and from 12° to 13.5°E (table II). Arrival
times and polarities were accurately re-picked
from digital seismic waveforms recorded by
the seismic network of the INGV in the period

The duration magnitudes \( M_d \) of these events
range between 3.0 and 4.2. The smaller events
are not considered because their mechanism
cannot be calculated with good accuracy due
to the lack of off-shore seismograph stations:
therefore it is advisable to consider magnitudes
greater than 3-3.5. The locations of considered

Table II. Parameters of the seismic events whose epicentres and focal mechanisms are shown in fig. 4.

<table>
<thead>
<tr>
<th>Label</th>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>Depth (km)</th>
<th>( M_d )</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>rms (s)</th>
<th>( F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1990</td>
<td>August</td>
<td>27</td>
<td>44.02</td>
<td>13.177</td>
<td>5.0</td>
<td>3.9</td>
<td>115°</td>
<td>50°</td>
<td>0°</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>1991</td>
<td>November</td>
<td>22</td>
<td>43.842</td>
<td>12.062</td>
<td>5.9</td>
<td>3.0</td>
<td>165°</td>
<td>60°</td>
<td>(-70°)</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>1996</td>
<td>June</td>
<td>28</td>
<td>43.769</td>
<td>12.995</td>
<td>27.5</td>
<td>3.4</td>
<td>155°</td>
<td>40°</td>
<td>110°</td>
<td>0.16</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>2000</td>
<td>February</td>
<td>22</td>
<td>43.79</td>
<td>12.083</td>
<td>8.0</td>
<td>3.0</td>
<td>265°</td>
<td>65°</td>
<td>(-120°)</td>
<td>0.01</td>
<td>0.13</td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
<td>May</td>
<td>5</td>
<td>44.014</td>
<td>13.192</td>
<td>5.0</td>
<td>4.1</td>
<td>195°</td>
<td>25°</td>
<td>30°</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>June</td>
<td>25</td>
<td>43.886</td>
<td>13.147</td>
<td>5.0</td>
<td>3.5</td>
<td>130°</td>
<td>90°</td>
<td>(-50°)</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>7</td>
<td>2000</td>
<td>June</td>
<td>27</td>
<td>43.883</td>
<td>13.200</td>
<td>5.0</td>
<td>3.4</td>
<td>115°</td>
<td>85°</td>
<td>40°</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>8</td>
<td>2000</td>
<td>August</td>
<td>1</td>
<td>43.929</td>
<td>12.318</td>
<td>5.0</td>
<td>4.2</td>
<td>160°</td>
<td>70°</td>
<td>130°</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>9</td>
<td>2000</td>
<td>December</td>
<td>27</td>
<td>43.678</td>
<td>12.245</td>
<td>5.0</td>
<td>3.2</td>
<td>115°</td>
<td>30°</td>
<td>(-80°)</td>
<td>0.13</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Fig. 3. Lower hemisphere, equal-area projection of the 11 selected fault plane solution presented in this study. Compression and dilatation polarities are indicated with crosses and circles, respectively. The 9 focal mechanisms of fig. 4 are the first solutions; in the case of double solutions (5 and 7), the second solutions with a worse stability are shown.
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events were verified with the computer program HYPOINVERSE (Klein, 1989) using the velocity structure reported in table III.

Good values of rms residuals were obtained for most analyzed earthquakes; in particular the rms values of locations have residuals below 0.25 s; furthermore, a misfit of polarity quality factor ($F$) was below 0.20. The fault plane solutions were calculated with the program FPFIT (Reasenberg and Oppenheimer, 1985) and the 11 fault plane solutions were obtained with more than eight polarities.

3. New focal mechanisms

This classification is founded on the assumption that the earthquake focal mechanisms reflect the state of stress of the Northern Marche region, implying that the $P$- and $T$-axes, to a first approximation, correspond to the principal stress axes $\sigma_1$ and $\sigma_3$, respectively.

Figure 3 shows fault plane solutions for 9 events which occurred in the Northern Marche from 1990 to 2000. The multiple solutions are due both to the low weight of some polarities and to the low azimuthal coverage of data on the focal sphere. In fig. 4 the solutions with the smaller uncertainties were chosen, represented by the first solutions of the 9 focal mechanisms of fig. 3; if one considers the alternative solutions, the tectonic setting does not change much.

The 9 first solutions of fig. 3 are divided as follows:

- three solutions (labels 2, 4 and 9) belong to the pure normal-fault category (NF);
- two solutions (labels 3 and 5) belong to the pure thrust-fault category (TF);
- one solution (label 8) belongs to the thrust-fault with small strike-slip category (TS);
- three solutions (labels 1, 6 and 7) are included in the unknown-stress-field category (UC).

If plunges of the axes of solutions are inside or outside the ranges defined in table I with differences of only one degree these solutions were assigned to the appropriate category: in this case, one solution (label 5) belongs to the thrust-fault with small strike-slip category with a difference of 0.2 degrees, as it is possible to see in table II.

The eastern part of the examined area was also affected by a few historical events of magnitude larger than 5.5. The estimated sources of these events are shown in fig. 4. The northernmost box (west of Pesaro) represents the source of the Coriano earthquake (December 25, 1786;
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43.98°N; 12.58°E), an event of intensity $I_0 = \text{VIII}$ and equivalent magnitude $M_e = 5.5$ (Gruppo di Lavoro CPTI, 1999). This source is derived by the analysis of the isoseismal map produced by Guidoboni and Ferrari (1986); it strikes $20^\circ \pm 15^\circ$ and is 5.6 km long and 5.2 km wide.

The two other sources, instead, are exclusively derived from intensity data by applying the method proposed by Gasperini et al. (1999), as the quality of the obtained solution allowed the representation of the source by an oriented rectangular box (Valensise and Pantosti, 2001). The box south-west of Fano (43.71°N; 12.97°E) corresponds to the September 21, 1897 earthquake ($I_0 = \text{VII}$ and $M_e = 5.4$; Gruppo di Lavoro CPTI, 1999) and strikes $73^\circ \pm 48^\circ$. The southernmost box represents the seismic source for the Cagli event (43.59°N; 12.51°E) which occurred on June 3, 1781 ($I_0 = \text{IX-X}$ and $M_e = 6.2$; Gruppo di Lavoro CPTI, 1999). This source strikes $118^\circ \pm 17^\circ$.

4. Conclusions

The Northern Apennine chain was described as a tectonic belt characterized by extension (e.g., Lavecchia, 1988; Decandia et al., 1998). General agreement exists on the fact that a NE-SW oriented minimum stress axis ($\sigma_3$) is dominant in the axial zone of the chain (Mariucci et al., 1999; Boncio et al., 2000). A possible result of this study is the division of the Northern Marche region into three areas with different seismological evidences:

- the inner area of the Apenninic belt, which is characterized by extension;
- the Adriatic on-shore, which shows evidence of active compression;
- the Adriatic off-shore, which shows not very clear evidence of active compression.

In the extensional area, the $T$-axes of normal solutions (2, 4 and 9 in fig. 4) do not have a homogeneous orientation, while in the compressional area the $P$-axes of thrust solutions (3 and 8 in fig. 4) have a dominant NW-SE direction (in agreement with compressive stress regime mapped by Montone et al. (1999) in northern surrounding zones of the Northern Marche).

Finally, the Adriatic off-shore zone shows not clear seismological evidence of nevertheless possible active compression; on the other hand no earthquake with magnitude $\geq 5$ occurred during historical times in the off-shore zone of the Northern Marche region (fig. 5a,b).
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REFERENCES


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