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Foreland deformation in the Central Adriatic and its bearing on the evolution of the Northern Apennines

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Abstract
Seismic profiles in the Central Adriatic show the presence of a WNW-ESE trending belt (Central Adriatic Deformation Belt, CADB) where broad folds of Quaternary age occur. Seismicity in the Adriatic foreland seems to be localised along the CADB which is interpreted as the result of foreland deformation linked to the Apennine fold-and-thrust belt and possibly due to the presence of an inherited structural discontinuity. Geological arguments indicate that the CADB lineament can continue underneath the Northern Apennines and might have affected its recent evolution, characterised by the rise of a linear orographic front.

Key words *foreland deformation – seismicity – Central Adriatic Sea*

1. Introduction

1.1. *Geological setting*

The Northern-Central Adriatic is a shallow sea enclosed by the coastlines of Italy and former Yugoslavia (fig. 1). Seismic refraction data (Geiss, 1987) indicate a 30 km thick crust, typical of continental regions, and low heat flow, < 60 mW/m^2 (Mongelli *et al.*, 1991) suggests a fairly old lithosphere. Three thrust-and-fold belts, the E-verging Apennines, S-verging Southern Alps and W-verging Dinarides surround on three sides the Northern-Central Adriatic that, therefore, represents their foreland. The stratigraphy encountered in exploration wells (Ori *et al.*, 1986; Argnani *et al.*, 1991) indicates, typically, an evolution from Triassic-early Jurassic carbonate platforms to middle Jurassic-late Cretaceous carbonate pelagic sediments. This stratigraphy records the rifting and ensuing continental break up that led to the opening of the Tethyan ocean. From the Paleocene to late Miocene the hemipelagic clastic input increased progressively until it became dominant, recording the progression of the Africa-Europe convergence. On the western side of the Northern-Central Adriatic a Plio-Quaternary foredeep basin is related to the Apennine fold-and-thrust belt and represents the latest in a series of eastward migrating Cenozoic foredeep basins (Ricci Lucchi, 1986).

1.2. *Objectives*

In general, foreland areas are considered relatively undeformed but in several instances it has been shown that this is not the case, and

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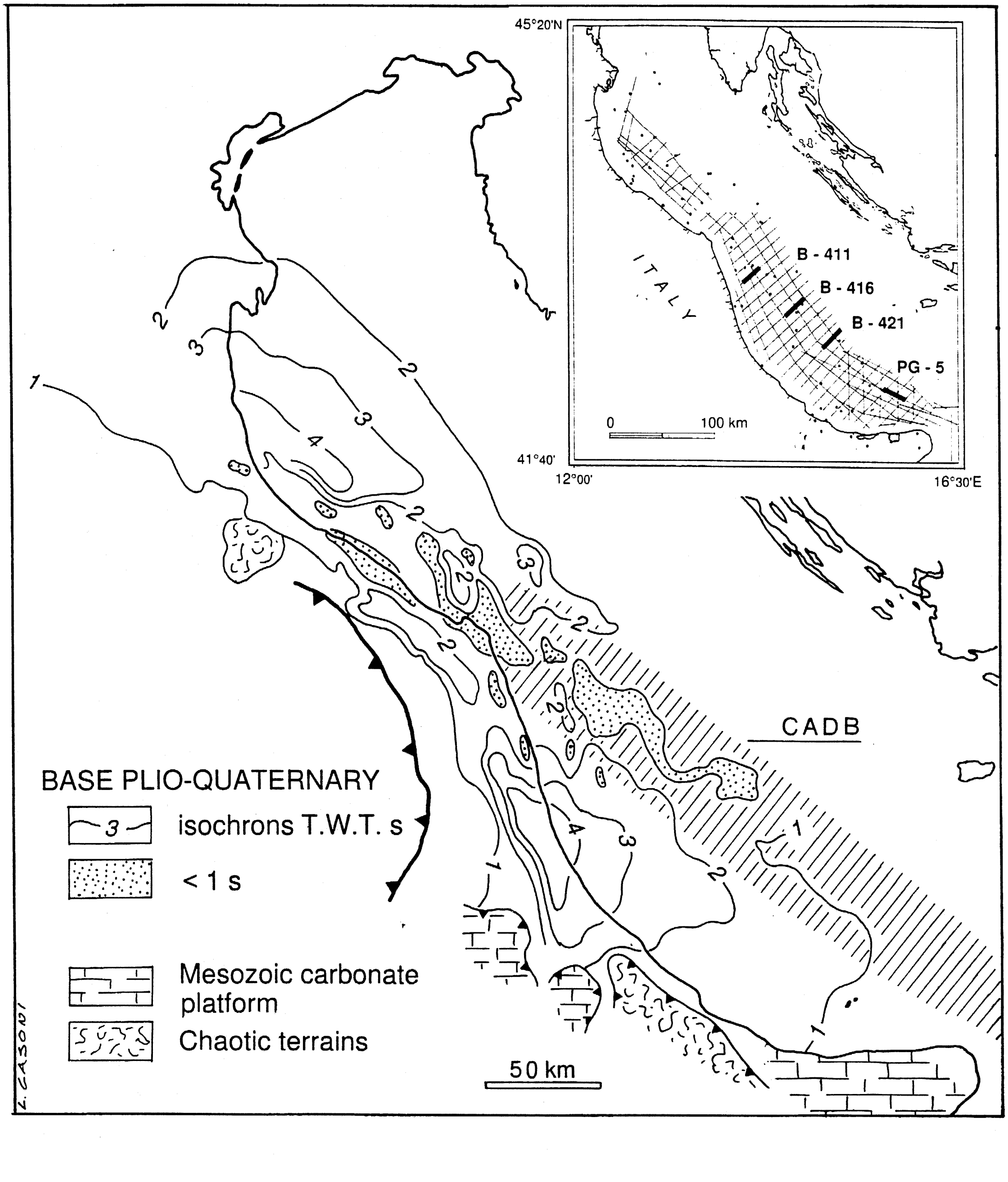

Fig. 1. Structural map of the base of the Plio-Quaternary succession (TWT in seconds) in the Central-Northern Adriatic. Location of seismic profiles is also included. The position of the Central Adriatic Deformation Belt (CADB) is indicated in oblique ruling.

a variety of tectonic patterns have been reported from such a setting (Molnar and Tapponnier, 1975; Sengor, 1976; Allmendinger *et al.*, 1983; Ziegler, 1987; Argnani, 1990). Based on a set of multichannel seismic reflection profiles (fig. 1) and on exploration wells, and with relation to the Adriatic foreland, this contribution aims at addressing the following aspects: 1) to show that a recent deformation is present in the Central Adriatic foreland; and 2) to illustrate that seismicity in the Central Adriatic can be linked to foreland deformation. Finally, it will be argued that the same tectonic lineament present in the foreland interferes with the recent evolution of the Northern Apennines. Previous studies carried out in the area based on seismic profiles have mainly focussed on the foredeep sedimentary filling (Ori *et al.*, 1986; Schwander, 1989) or on the structural styles at the thrust front (Argnani *et al.*, 1991; Argnani and Gamberi, 1996), although in some cases the presence of foreland deformation has been mentioned (Argnani *et al.*, 1991; De Alteriis, 1996).

2. Foreland deformation in the Central Adriatic

2.1. *Geological evidence*

Besides the front of the Apennine fold-and-thrust belt and the location of the main depocentres of the present foredeep basin, the structural map of the base of the Plio-Quaternary (figs. 1 and 7; Argnani and Gamberi, 1996; Bigi *et al.*, 1990) also shows a WNW-ESE trending belt of structural highs that run from the city of Ancona to the island of Pelagosa (hereafter named CADB, Central Adriatic Deformation Belt). Folds affecting the base of the Plio-Quaternary succession occur along the CADB with axes aligned along the belt. Seismic profiles across the CADB (fig. 2) indicate that deformation was active during the Quaternary. The structures can be described as broad gentle folds, with subvertical axial planes, due to shortening that involves at least the whole Mesozoic succession.

In its southern portion the CADB merges with the NE-SW-trending Tremiti Deformation Belt (TDB) where seismic activity and Plio-Quaternary folding have been reported (Argnani *et al.*, 1993). A profile across the TDB (fig. 3) shows a broad SE-verging fold due to blind thrust. The Tremiti Islands are located on the frontal limb of this fold and in fact, the island appears as an SE-dipping monocline (Selli, 1971); a larger tilt of the Miocene unit with respect to the Pliocene one is also reported. Wedging of reflections within the Plio-Quaternary succession indicate that the deformation was active during this interval of time.

Although the nature of the connection between CADB and TDB is not completely understood because of the lack of data, the structural style of the two deformation belts are very similar and the age of activity coincides. A close link between the two structures can therefore be inferred. The almost perpendicular trends of the two belts, both oriented at an angle with respect to the Apennine thrust front, suggest that they might represent inherited features reactivated during the Apennine deformation.

Although folding is discontinuously distributed along the CADB, the Free Air Gravity map (fig. 4; Sandwell *et al.*, 1994) supports the presence of a lineament to which the folds can be related. Altogether, this foreland deformation can be interpreted as the superficial expression of a relatively deep seated discontinuity.

2.2. *Seismological evidence*

So far, the seismo-tectonic models of Italy (Scandone *et al.*, 1990) or of the Central Apennines (Lavecchia *et al.*, 1994) have paid little attention to the Adriatic tectonic setting, despite the fact that a certain amount of seismicity, with a few significant earthquakes, has been reported (Console *et al.*, 1993; Renner and Slejko, 1994).

In the Central Adriatic earthquakes occur both along the Apennine thrust front but also away from it (fig. 5; ING, 1993). The distribution of the epicentres that do not follow the

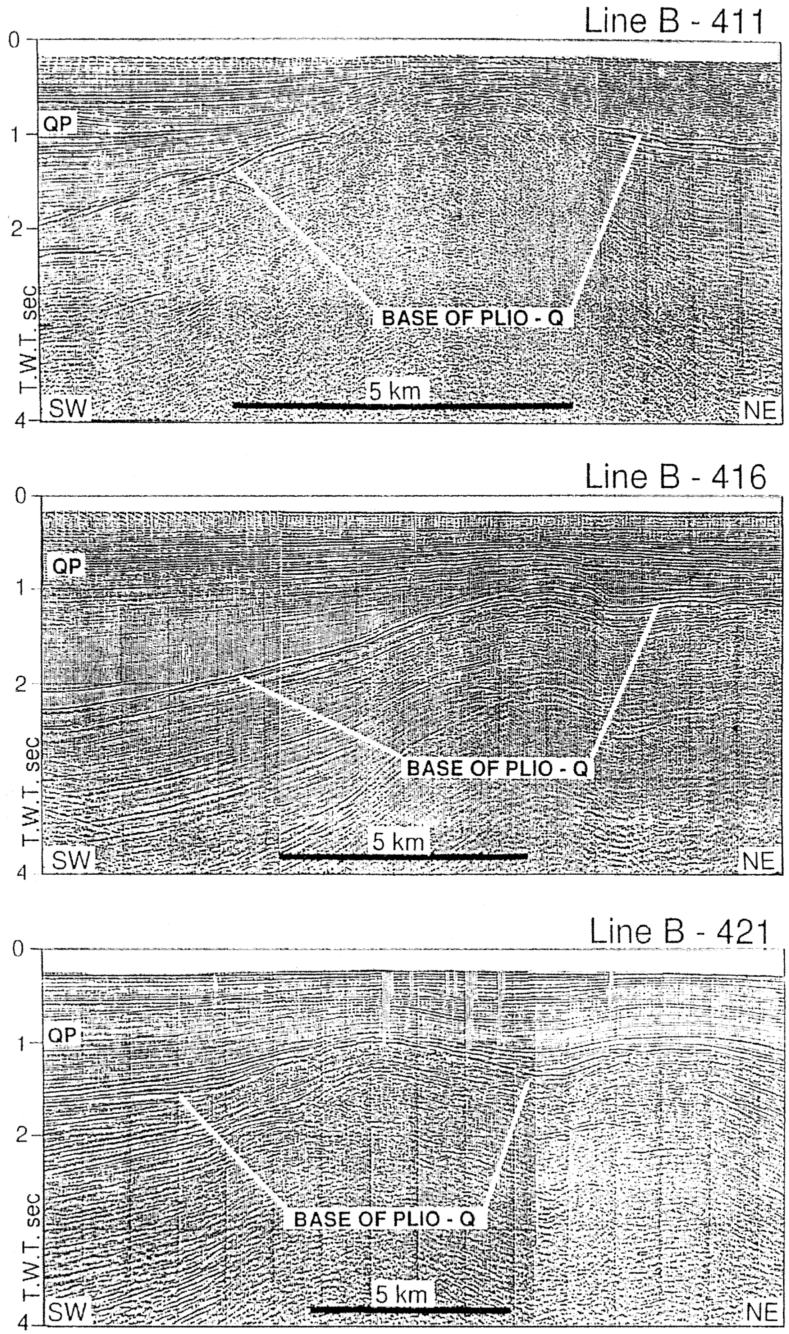

Fig. 2. Seismic profiles across the Central Adriatic Deformation Belt. Note that folding affects the Quaternary Prograding (QP) on top of the structures. Location in fig. 1.

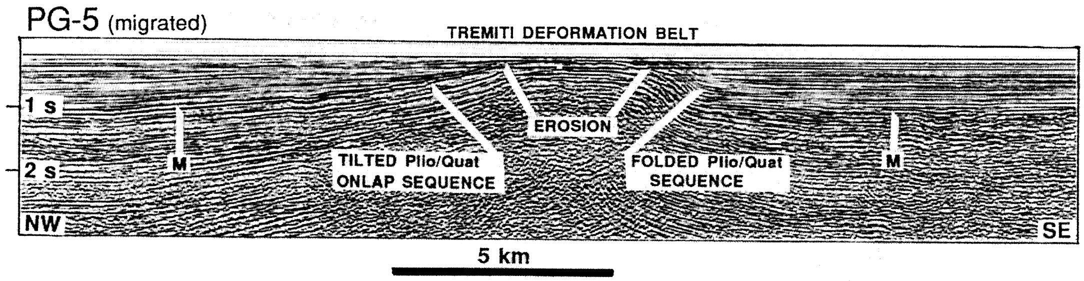

Fig. 3. Seismic profile across the Tremiti Deformation Belt. M = base of Plio-Quaternary. See location in fig. 1 (after Argnani *et al.*, 1993). Note the wedging of reflections within the Plio-Quaternary succession indicating the continuous growth of the structure.

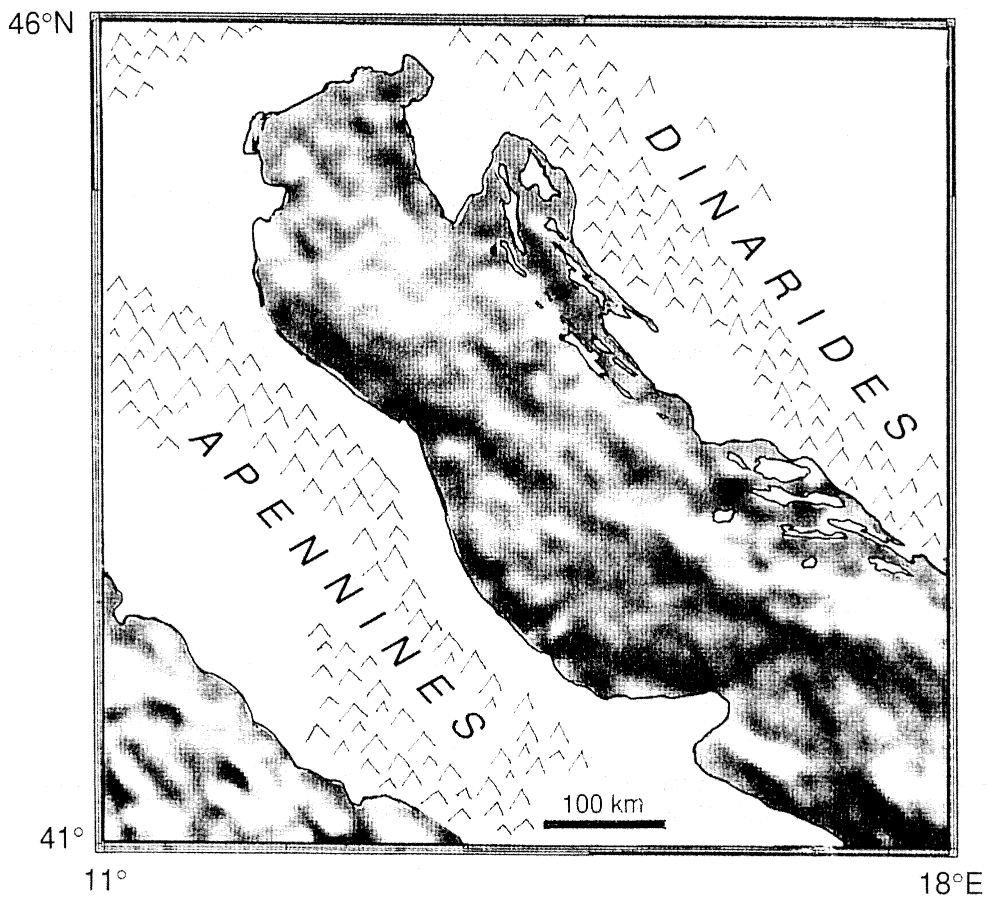

Fig. 4. Free Air Gravity anomaly map of the Central Mediterranean (data after Sandwell *et al.*, 1994).The NW-SE-trending lineament in the Central Adriatic has the same orientation as the CADB, which is located on top of it.

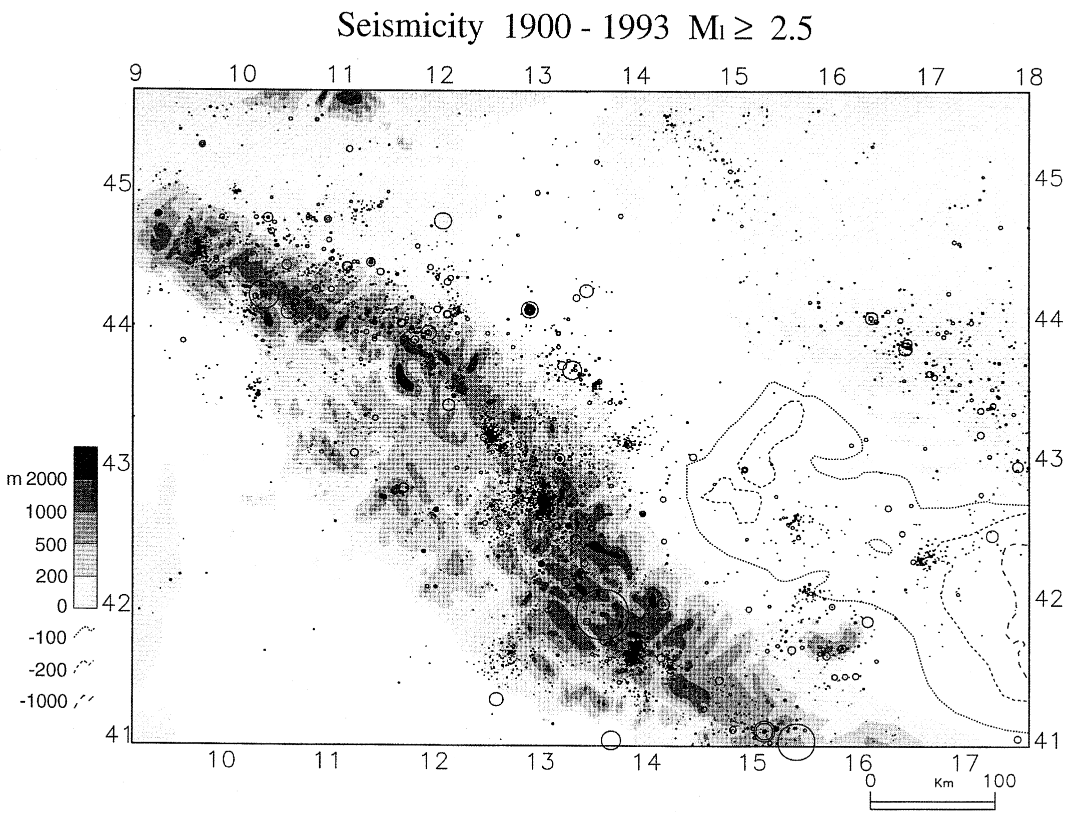

Fig. 5. Instrumental seismicity in the study area (ING, 1993). Bathymetry of the Adriatic sea and topography of the Italian peninsula are also displayed.

thrust front is not random: they tend to be located over the CADB.

Earthquake hypocentral depths in the order of a few kilometres (Console *et al.*, 1993), located in the upper crustal layers, point towards a deep seated feature, further supporting the interpretation of a deep lineament controlling the foreland deformation derived from seismic profiles.

Focal mechanisms (fig. 6) are available only for a few earthquakes (Renner and Slejko, 1994; Console *et al.*, 1989, 1993; Frepoli and Amato, 1997). Some of them, located along the CADB (north of Ancona and north of the Tremiti Islands), display sinistral strike-slip along NW-trending fault planes.

3. Possible extension of the CADB underneath the Northern Apennines

Since the beginning of oil exploration in the Po Plain, it was recognised that the buried front of the Northern Apennines presents three major arcs (Agip Mineraria, 1959; Pieri and Groppi, 1981) and some papers have been devoted to explaining such a geometry (*e.g.*, Castellarin *et al.*, 1986). However, little attention has been paid to the fact that the orographic front of the Northern Apennines is markedly linear from Piacenza to Ancona. This orographic front is on the continuation of the CADB (fig. 7). It will be argued, on the basis of geological and seismological arguments,

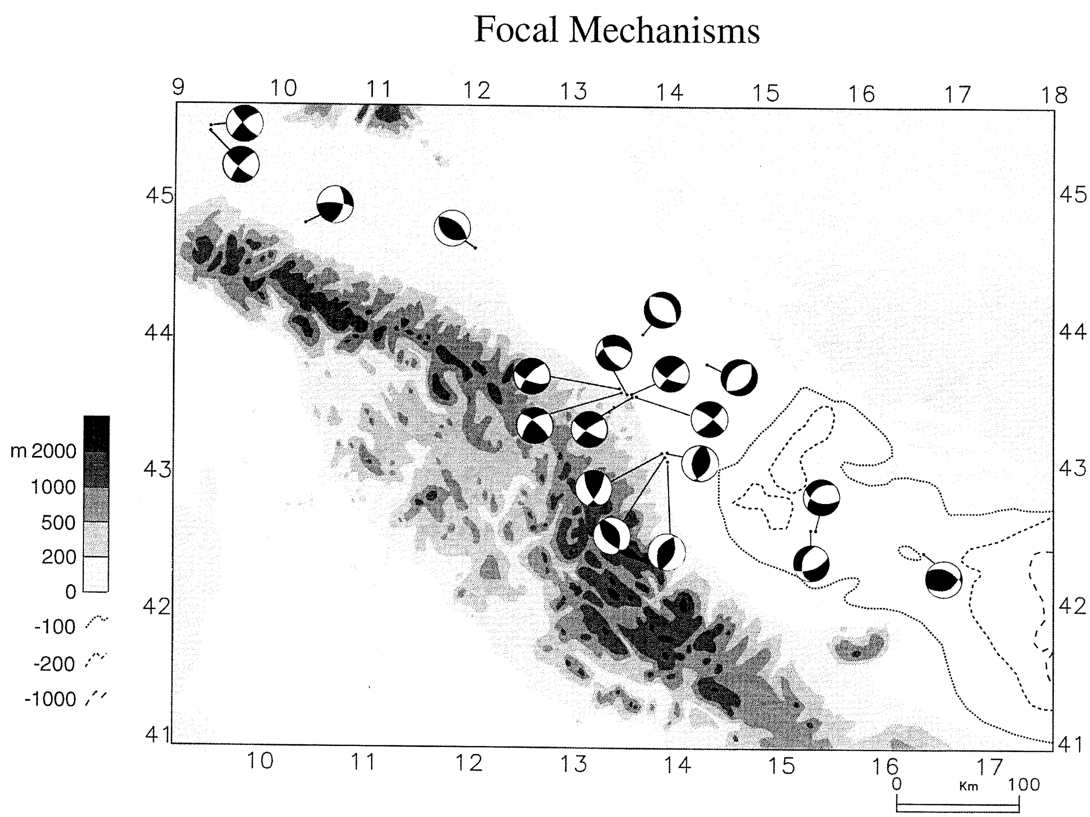

Fig. 6. Focal mechanisms for the Adriatic and Northern Apennines (after Gasparini *et al.*, 1985; Renner and Slejko, 1994; Pondrelli *et al.*, 1995). In the Northern Apennines only thrust and strike-slip solutions are shown.

that the lineament present in the Central Adriatic can continue underneath the Northern Apennines, affecting its recent evolution.

3.1. *Geological arguments*

Field data indicate that the orographic front of the Northern Apennines originated during the Quaternary (Castellarin *et al.*, 1986) and, in fact, seismic profiles across this front show an uplifted Plio-Quaternary succession at the foot of the orographic front (Pieri, 1983). This uplift appears of particular importance as it is followed by a major phase of sedimentary prograding that fills in the basin.

The easiest way to explain the linearity of the orographic front and its structural expression is to invoke a more or less linear, relatively deep seated ramp that affected the basal decollement trajectory. As the thrust units move onto the deep steep ramp, they are uplifted to originate the present Northern Apennine relief; this uplift promotes erosion and gives rise to the major sedimentary prograding.

A further support to the presence of a deep seated ramp comes from recent paleomagnetic work in the area between the Marecchia river and Gran Sasso, where the Apennine thrust front touches the continuation of the CADB at an angle (Speranza *et al.*, 1997). Paleomag-

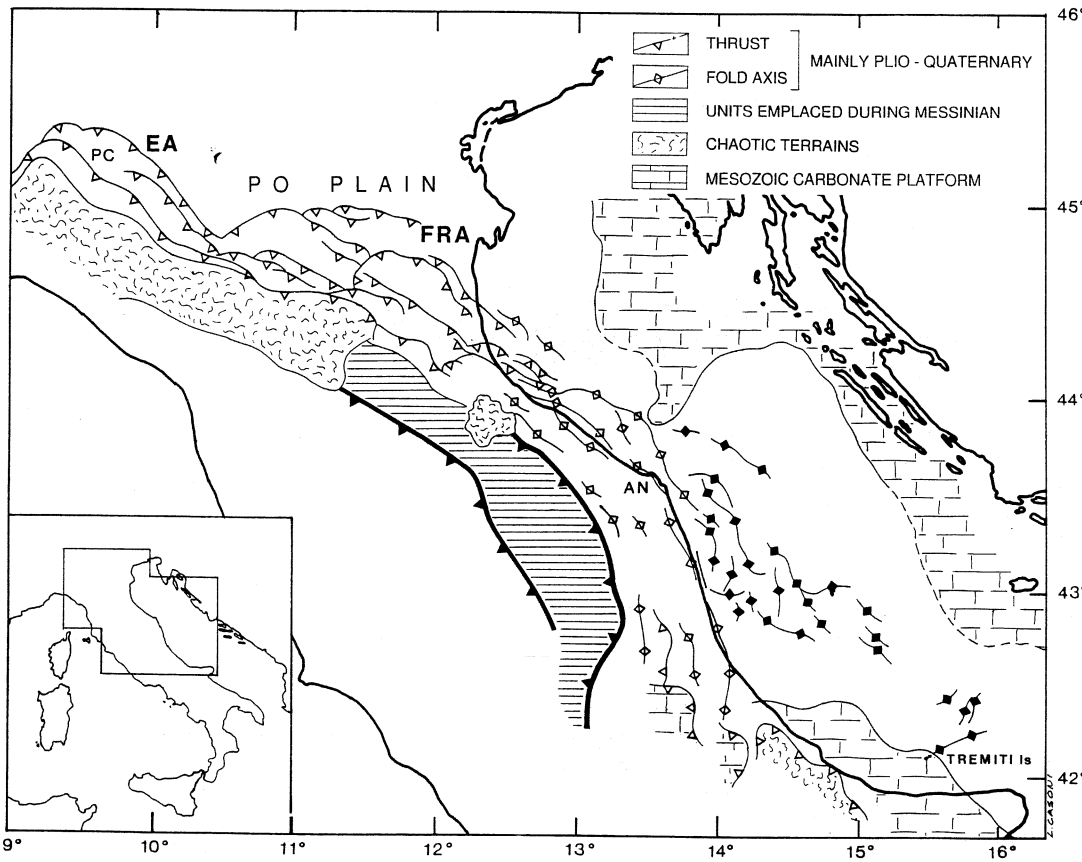

Fig. 7. Simplified structural map of the Northern Apennine and Central Adriatic. The present orographic front, running from Piacenza (PC) to Ancona (AN), coincides, more or less, with the front of the chaotic terrains.The Emilia Arc (EA) and the Ferrara-Romagna Arc (FRA) are buried underneath the Po Plain. Fold axes located along the CADB, and indicated with filled in rhombs, represent foreland deformation.

netic data collected in the Messinian Laga Formation show counter-clockwise rotation of the thrust units that tend to align along the Northern Apennine orographic trend in the north; in the south, where the thrust units approach the thick Latio-Abruzzi carbonate platform, minor clockwise rotations occur (Speranza *et al.*, 1997). In the same time interval, on the Tuscan Tyrrhenian margin no rotation was observed (Mattei *et al.*, 1996) and this suggests that rotation at the thrust front may be due to the presence of «obstacles» (fairly steep ramps, thick carbonate platforms) that affect thrust propagation and induce rotations (fig. 8).

3.2. *Seismological arguments*

Despite the fact that the Northern Apennine front stretches to quite an extent underneath the Po Plain, very little seismicity is associated with the buried portion (fig. 5). Compressional earthquakes are mainly located along the orographic front. Within fold-and-thrust belts, ramps are more susceptible to seismicity than

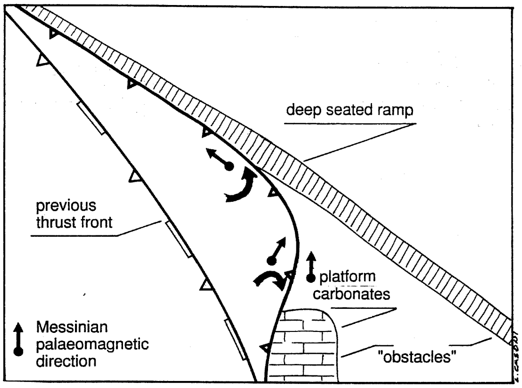

Fig. 8. Conceptual sketch illustrating how «obstacles» present in the foreland can affect thrust rotation. An advancing and almost rectilinear thrust front is deflected by obstacles present in the foreland, The thrust front rotates in order to assume the attitude of the obstacles it impinges on. The sketch is inspired by the arcuate shape of the Sibillini thrust front in the Central Apennines, where paleomagnetic rotations of Messinian sediments have been found (Speranza *et al.*, 1997).

flats as friction is greater, and this is particularly true when the ramp is due to a preexisting discontinuity which has an angle steeper than the typical ramp angles (Wiltschko and Eastman, 1983).

Some of the focal mechanisms available at the front of the Northern Apennines indicate compression but, in some cases, a strike-slip component is also displayed (Gasparini *et al.*, 1985). Assuming that the WNW-ESE plane, parallel to the orographic front, represents the fault plane, a sinistral strike-slip is expected. This last observation could well fit with the sinistral strike-slip found in the CADB along NW-SE-trending fault planes (Renner and Slejko, 1994), indicating that the same stress might propagate from the fold-and-thrust belt to the foreland. Most of these old focal mechanisms have very poor quality (Zoback, 1992) but the presence of some NW-SE sinistral strike-slip is confirmed by more recent and reliable analyses which show a general NE-SW-oriented *P* axis for both thrust and strike-slip solutions (Frepoli and Amato, 1997).

4. Conclusions

Both geological and seismological evidence suggests that a recent deformation occurred along a WNW-ESE-trending belt in the Central Adriatic (CADB). This portion of the Adriatic represents the foreland of the Apennine fold-and-thrust belt and the deformation observed can be related to foreland tectonics. The CADB can be linked to the Tremiti Deformation Belt, already known as a recently deformed area, to define a foreland deformation system with associated seismic activity.

The CADB is interpreted as due to a relatively deep seated lineament that can extend underneath the Northern Apennines where it has been responsible for the linearity of the present orographic front and for the recent uplift and present seismicity of the Northern Apennines.

It is suggested that the lineament acts as an obstacle which causes the thrust units to rotate counter-clockwise when they interfer with it.

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