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

Andrea Argnani(1) and Francesco Frugoni(2)
(1) Istituto di Geologia Marina, C.N.R., Bologna, Italy
(2) Istituto Nazionale di Geofisica, Roma, Italy

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/m² (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 elastic 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
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 rela-
tion 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 pre-
sent 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; Schwan-
der, 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 men-
tioned (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 de-
pocentres of the present foredeep basin, the
structural map of the base of the Plio-Quater-
nary (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 (Ar-
gnani 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 re-
ported. Wedging of reflections within the Plio-
Quaternary succession indicate that the deforma-
tion was active during this interval of time.

Although the nature of the connection be-
tween CADB and TDB is not completely un-
derstood because of the lack of data, the struc-
tural 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 an-
gle with respect to the Apennine thrust front,
suggest that they might represent inherited fea-
tures reactivated during the Apennine deforma-
tion.

Although folding is discontinuously dis-
tributed 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 deforma-
tion can be interpreted as the superficial ex-
pression of a relatively deep seated discontinu-
ity.

2.2. Seismological evidence

So far, the seismo-tectonic models of Italy
(Scandone et al., 1990) or of the Central Apen-
nines (Lavecchia et al., 1994) have paid little
attention to the Adriatic tectonic setting, de-
spite the fact that a certain amount of seismic-
ity, 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 distri-
bution 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,
Focal Mechanisms

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.

Magnetic 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
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 interfere with it.

Acknowledgements

Discussions with Fabio Speranza, Massimo Mattei, Alberto Frepoli, and, in particular, with Fabiano Gamberi, have substantially contributed to refining our view on the geology of the Northern Apennines. Paola Montone and Giusy Lavecchia greatly improved the manuscript with their careful reviews. Luciano Casoni is gratefully thanked for drafting assistance. This is IGM contribution No. 1057.

REFERENCES


