3d Structure Of The Northern Marche Region, And Implications For The Active Tectonics Of The Outer Northern Apennines (Italy)

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Keywords: Structural geology, Fault reactivation, Geomorphology, Seismotectonics, 3D structural model

Abstract: The quaternary tectonics of the northern Marche sector of the outer Northern Apennines has been analysed. Late Miocene – Pliocene orogenic structures include mainly NE verging thrusts and associated folds whose geometry is locally controlled by slip on oblique and lateral ramp segments. Post-orogenic features consist mainly of roughly N-S trending normal faults and NE-SW striking, oblique-slip transfer faults with a left-lateral component of motion, resulting from WSW-ENE oriented extension. These faults, also affecting late-Quaternary continental deposits, hint at a recent tectonic behaviour congruent with the geomorphologic evolution of the study area. On the other hand, available focal mechanisms indicate a dominant NNW-SSE oriented compression, not compatible with NE directed thrusting. The inactivity of the thrust front off-shore is also well documented by the interpretation of seismic lines calibrated with borehole data, which points out that middle-upper Pleistocene siliciclastic deposits seal the orogenic features. On land, fluvial terraces maintain their overall parallelism even across the anticline ridges, hinting at a generalised vertical uplift, and disclaiming significant deformation by the growth of NW-SE trending folds ever since the latest mid-Pleistocene. Within this framework, active NNW-SSE oriented compression could be responsible for the reactivation of suitably oriented segments of pre-existing blind thrust faults (i.e. E-W to NE-SW striking oblique/lateral ramps), that in turn could control the evolutions of ENE-WSW trending sectors characterised by differential uplift.

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Introduction

The northern Marche area of central Italy is the locus of a moderate - yet significant - tectonic activity, as also witnessed by historical and instrumental seismicity [maximum intensity = IX MCS; maximum magnitude = 6; Gruppo di Lavoro CPTI 1999; Frepoli and Amato 2000]. Not only are the seismogenic sources of these earthquakes still unknown [Galadini et al. 2000], but also the tectonic regime and the possible existence and size of further, presently silent, sources is a matter of debate [Valensise and Pantosti 2001, and references therein]. As an example, Basili et al. [2002] and Vannoli et al. [2004] recently re-proposed the idea that blind thrust faults, accompanied by anticlinal growth, would characterise the active tectonics of the study area. These Authors also suggested that the earthquake potential of this area may be substantially different (i.e. higher) from that currently estimated, thus posing new concerns on the seismic hazard of this highly populated region. According to this view, thrust ramps would host the sources of the largest earthquakes in the northern Marche region [Vannoli et al. 2002]. More in general, according to Meletti et al. [2000] the outer Northern Apennines would be characterised by low/medium energy compressional earthquakes related to active frontal and lateral thrust ramps. However, different interpretations from that of active thrusting have also been put forward to explain present-day tectonics of the outer Northern Apennines [e.g. Bertotti et al. 1997; Carminati et al. 1999; Di Bucci and Mazzoli 2002; Argnani et al. 2003].

The variability of geological interpretations and seismotectonic models for the outer Northern Apennines most probably arise by the fact that this part of the chain is characterised by the coexistence of strongly contrasting data. For instance:

i. focal plane solutions are not only compressional, but also strike-slip and extensional, with variably oriented P and T axes [e.g. Gasparini et al. 1985; Zollo et al. 1995; Frepoli and Amato 1997; Mariucci et al. 1999; Frepoli and Amato 2000; Selvaggi et al. 2001];
ii. mesostructural data outline a middle-late Pleistocene stress field not compatible with thrust belt-related compression [e.g. Bertotti et al. 1997; Ghiselli and Martelli 1997; Morelli and Costa 1997; Piccardi et al. 1997; Borraccini et al. 2002];
iii. thrusts buried beneath the Po Plain and the Adriatic Sea appear to be sealed by middle-upper Pleistocene deposits [e.g. Bally et al. 1986; Argnani et al. 1997; Bertotti et al. 1997; Picotti et al. 1997; Coward et al. 1999; Di Bucci and Mazzoli 2002; Di Bucci et al. 2003]; and
iv. well breakout data mostly suggest active N-S compression [Montone and Mariucci 1999].

The aim of this paper is to examine the controversial active tectonic setting of the northern Marche region within the larger framework of the outer zones of the Northern Apennines by the integration of structural, geomorphological and seismological data.

3D structural model of the northern Marche area

The visualisation and validation in three dimensions of the structure of the study area was carried out by the integration of surface geological and sub-surface data. Original field mapping of the onshore sector combined with the interpretation of seismic reflection profiles calibrated with well logs from hydrocarbon exploration allowed us to construct a three dimensional model showing the main geological features. This process involved the integration of shallow cross-sections based on geological map data and those derived from interpretation, calibration and conversion from time to depth of seismic profiles. Once the line drawing from seismic profiles were converted in geological cross-sections, they were imported in a geo-referenced virtual space and correlations among stratigraphic horizons were carried out in order to obtain surfaces corresponding to the main stratigraphic boundaries. Important assumptions and interpretations of faults and related folds were taken in account to define their features. For example, to define fault tip lines, additional cross-section were built between the main ones in order to close fault surfaces, taking into account common length/displacement relationships.

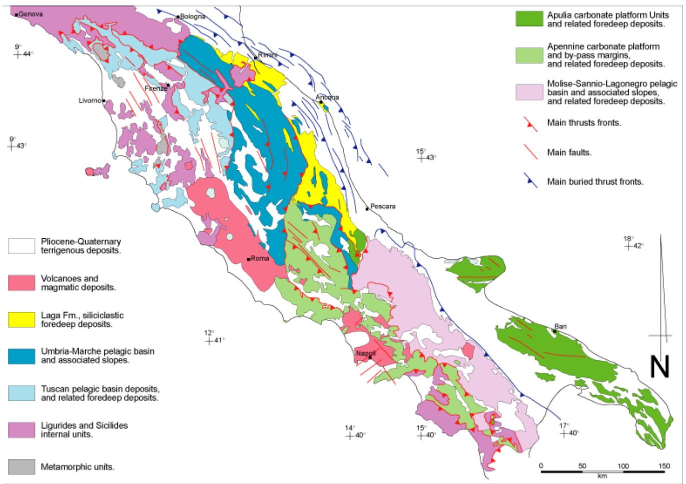
The 3D model allows a better visualisation and understanding of the main features of the study area.

Geological setting

The Apennines (Figure 1) are an east to northeast vergent fold and thrust belt which developed as a result of convergence between the continental margins of Corsica-Sardinia (of European origin) to the west, and of the Adriatic block (of African affinity) to the east, within the general framework of late Cretaceous to Present Africa-Europe plate convergence [e.g. Dewey et al. 1989]. Miocene to Early Pleistocene [Di Bucci and Mazzoli 2002] thrust accretion across the Adriatic (or Apulian) continental margin was accompanied by Tyrrhenian back-arc extension [Mazzoli and Helman 1994, and references therein].

Much of the Apennine chain has been dissected by normal and strike-slip faults that locally post-date thrust structures. In the interior of the chain (e.g. Tuscany), these faults control Mio-Pliocene basins [e.g. Decandia et al. 1998] and therefore are coeval with thrust structures that were active further to the east [Elter et al. 1975]. The thrust front migrated eastward over time, with extension following, so that folds and thrusts along the east margin of the Italian peninsula, which are the products of the final stages of contractional deformation in the Apennines, developed toward the end of the early Pleistocene. At 700-800 ka a major geodynamic change occurred and a new tectonic regime established itself in the Apennine chain and adjacent foothill areas [e.g. Di Bucci and Mazzoli 2002, and references therein]. The structures related to this new regime are characterized by a NE-SW oriented maximum extension direction and consist of normal, oblique- and strike-slip faults that post-date and dissect the thrust belt, and remain seismically active [e.g. Di Bucci and Mazzoli 2002, and references therein].

Figure 1. Geological sketch map of the Apennines



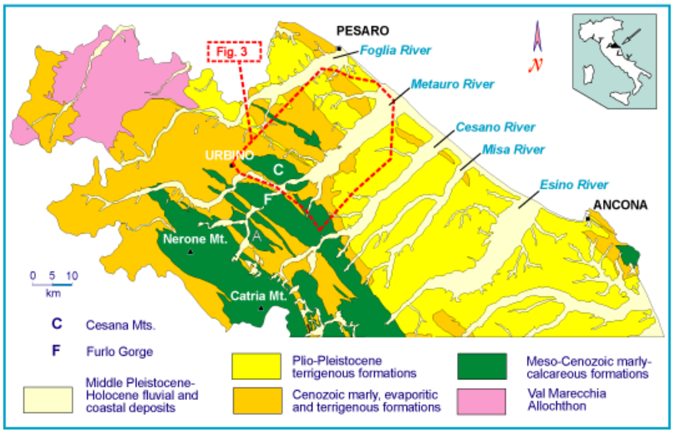
Geological sketch map of the Apennines.

Main features of the northern Marche area

Structure

The structure of the study area (Figure 2) is dominated by mainly NW-SE trending regional folds and associated NE verging thrusts. Thrust tectonics along the Northern Apennine foothills, and in the northern Marche area in particular, is well documented by field surveys integrated with the interpretation of seismic reflection lines and deep wells carried out for hydrocarbon exploration [e.g. Mazzoli 1994; Casabianca et al. 1995; Arcaleni et al. 1996; De Donatis et al. 1996, 1998; Coward et al. 1999; De Donatis 2001; Mazzoli et al. 2001; Butler et al. 2003].

Figure 2. Geological sketch map of the northern Marche area

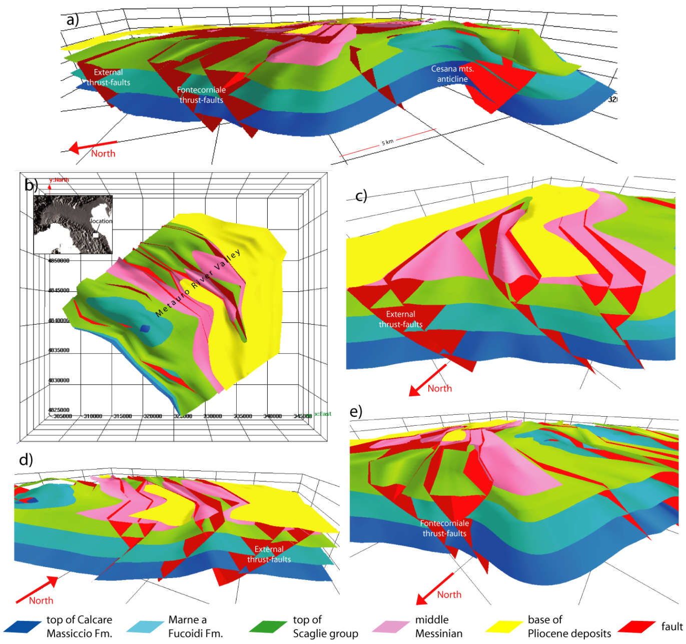


Box shows location of the 3D model of Figure 3 .

Major faulted anticlines are generally sub-cylindrical [as defined by Ramsay and Huber 1987], with NW-SE oriented, sub-horizontal, mean (fold axes. However, fold sectors showing substantial distortion from the regional trend also occur (e.g. northwestern periclinal termination of the Monti della Cesana anticline; Figure 3). These areas are characterised by large (> 45°) rotations around a vertical axis, as indicated by paleomagnetic data. Significant rotational deformation has been related to the occurrence of lateral thrust tips and/or gliding and moulding on blind oblique thrust ramps [Mazzoli et al. 2001]. Thrust faults within the study area consist in fact of mostly blind, relatively short and discontinuous segments characterised by anastomosing geometries and important development of oblique and lateral ramps [Coward et al. 1999; Mazzoli et al.

2001]. The 3D structural model of the Metauro River Valley area, for instance, shows that roughly E-W trending, blind oblique ramps characterise the northern sectors of major thrust faults (Figure 3), whilst NE-SW lateral ramps occur in the off-shore sector of the study area [Coward et al. 1999].

Figure 3. 3D Model of the lower Metauro River basin and adjoining area



3D Model of the lower Metauro River basin and adjoining area.

Concerning the timing of thrust activity, the analysis of syn-depositional compressional structures related to fold growth reveals that their youngest age post-dates the early Pliocene along the Adriatic coast [e.g. De Donatis et al. 1996, 1998; Coward et al. 1999]. The geometry of syn-orogenic strata cropping out in the coastal zone between the Metauro and Cesano Rivers (Figure 2) indicates a mid-late Pliocene age for major fold growth in this area. Lower Pleistocene deposits off-shore appear to be slightly involved in the deformation associated with the frontal thrust of the Apennine chain. In contrast, the upper part of the Quaternary succession shows undeformed reflectors (including unconformities) that extend for kilometres and overlie and seal the most external thrusts of the belt [Di Bucci and Mazzoli 2002; Di Bucci et al. 2003]. These data suggest that NE directed thrusting at the front of the Northern Apennines ended in early Pleistocene times.

Within the on-shore sector of the study area, recent (i.e. post-thrusting) faults have been recognised in both pre-Quaternary substratum rocks and late-Quaternary continental deposits (upper Pleistocene terrace alluvium, upper Pleistocene-Holocene slope deposits). The surveyed faults, characterised by very low documented displacements, are all compatible with WSW-ENE oriented extension. They appear to form part of a hard-linked fault system mostly including roughly N-S trending normal faults and NE-SW striking, oblique-slip transfer faults with a left-lateral component of motion. Although most of the observed recent ruptures are clearly sealed by mid-late Pleistocene and Holocene slope-waste and alluvium, the occurrence in several sites of late Pleistocene-Holocene faulted deposits suggests that WSW-ENE oriented extension might be active at present in the study area [Savelli et al. 2002].

Geomorphology

Within the on-shore sector, both the along-valley and vertical distribution of stream terraces provide some constraints on the age of thrusting and folding as well as on the neotectonic behaviour of such area. The major valley terraces have been categorised as strath-terraces and fill-terraces. The former (mid Pleistocene, 170-300 m above the floodplain) hint at an overall tectonic origin, the latter (mid-late Pleistocene-Holocene p.p., 30-160 m above the floodplain) result from the effects of climatic variations combined with a generalised tectonic uplift [e.g. Fanucci et al. 1996; Di Bucci et al. 2003, and references therein]. Many minor late Pleistocene - Holocene terraces resulting from a complex series of genetic factors are also recognisable [e.g. Nesci et al. 1995]. Specifically, close to the modern coast-line the latest Pleistocene - Holocene (unpublished radiocarbon dating bear out such chronological attribution) terrace-alluvium top-surfaces merge into a quite continuous strip of coast-terraces (heights from 2-3 m up to ca. 15 m).

Fluvial terraces are substantially parallel, even across the anticline ridges, thus hinting at a generalised vertical uplift and disclaiming any significant deformation by fold activity ever since the second half of middle Pleistocene [Nesci et al. 1992; Di Bucci et al. 2003; Mayer et al. 2003, and references therein]. Evidence (e.g. convex valley flanks profiles, ongoing confinement of alluvial fans) for an increasing middle-late Pleistocene valley deepening - most likely related to an enhancing vertical uplift rate - can be also pointed out [e.g. Nesci et al. 2002; Di Bucci et al. 2003 and references therein].

Although some local terrace-levels convexities underline minor (i.e. fairly less than valley down-cutting amount) differential movements [e.g. Nesci et al. 1990], their occurrence - apparently unrelated to the pattern of folds and associated thrust-faults of the area - can be associated with differential rates of vertical uplift and/or to middle-late Pleistocene normal faulting [Di Bucci et al. 2003]. A marked down-valley terrace-level convergence also occur [cf. Elmi et al. 1987; Nesci et al. 1990] in response to both strong sea-level falls shortly before each of the main middle-late Pleistocene "cold-aggradation" fluvial events and higher uplift/downcutting rates in the internal areas. As the off-shore "points of convergence" of each valley terrace-flights are placed at different distances from the modern coastline, differential neotectonic behaviours of sectors stretching in an overall NE-SW / NNW-SSE direction (c.ca perpendicular to the strike of the thrust belt) can be assessed for the northern Marche river basins [cf. Elmi et al. 1987; Dramis 1992; Fanucci et al. 1996].

If the recent faults mentioned in the previous section are taken into account, it can observed that they are seldom associated with peculiar landforms. Moreover, any specific active control of individual ruptures in the geomorphology of the study-area is not discernible even when a fault bears some geomorphologic evidence, being the only effects of differentiate erosion clearly recognisable (e.g. deep gullies actively entrenching along NE-SW oblique-slip transfer faults sealed by undeformed later-middle Pleistocene alluvium). Hence, although the geomorphologic effect of individual ruptures can be regarded as negligible or indefinable, the surface expression of the deformation produced by the recent fault system can be envisaged to have played an active role in controlling the landscape evolution of the study area [e.g. Di Bucci et al. 2003], at least in the middle Pleistocene and in the lower part of the late Pleistocene. In this respect, the marked south-eastwards (i.e. towards the right valley-sides) deflection of the northern Marche trunk rivers can be an important morphotectonic topic. In actual fact - although such long-debated behaviour is object of several different interpretations [cf. Di Bucci et al. 2003, and references therein] - the occurrence of a strong valley axis deflection towards the core of an anticline (i.e. Monti della Cesana; Borraccini et al. 2002) highlights, in the Metauro River valley, an overall control by WSW-ENE oriented structures rather than by anticline growth mechanisms [e.g. Savelli et al. 2002; Borraccini et al. 2002].

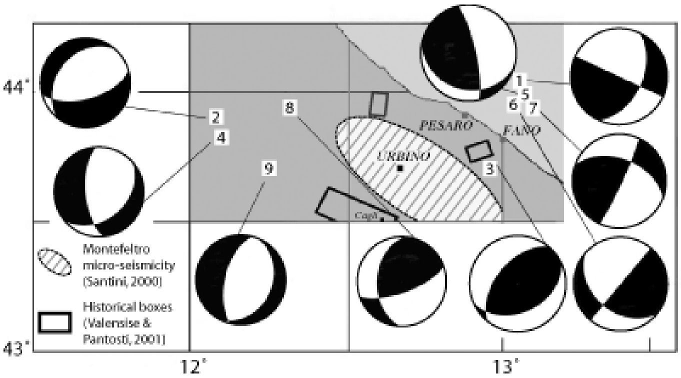
Seismicity

Analysis and correlation of historical and instrumental events for the Northern Apennine foothills and adjacent Adriatic indicate that this area is characterised by a moderate seismicity (epicentral maximum intensity hardly reaching a value of IX MCS), with maximum magnitudes of about 6 (Gruppo di Lavoro CPTI, 1999) and hypocentral depths generally in the first 20 km [Frepoli and Amato 1997]. Only a few instrumental events display a magnitude larger than 4.5. The related focal mechanisms show a lack of homogeneity, as they include: (i) normal fault solutions with NW-SE oriented nodal planes [Gasparini et al. 1985; Mariucci et al. 1999]; (ii) reverse fault solutions with WSW-ENE striking nodal planes [Selvaggi et al. 2001]; and (iii) strike-slip fault solutions with WNW-ESE and NNE-SSW nodal planes [Gasparini et al. 1985; Mariucci et al. 1999].

The same inhomogeneity also characterises minor seismicity which, according to Frepoli and Amato [1997], shows a predominance of thrust and strike-slip fault solutions with respect to normal fault solutions. The latter Authors also identify, for the study area, a horizontal, SW-NE oriented 1 and a steeply dipping (60°) 2, suggesting a stress regime "closer to a strike-slip than a reverse-faulting regime" [Frepoli and Amato 2000].

The area specifically analysed in the present study is characterised by a low concentration of seismic events [Santini 2000]. Recently Di Bucci et al. [2003] and Santini [2003] analysed the instrumental seismicity of the area comprised between 12.7°E and 13.2°E of longitude, and between 43.5°N and 44.0°N of latitude (therefore including the area of the present study). The latter Authors considered the events that occurred in years 1987-2000, recorded by the centralised Italian Telemetered Seismic Network (ITSN) of the Istituto Nazionale di Geofisica e Vulcanologia. Most of the 83 recorded events have magnitude < 3.0, while only a few of them show magnitude values between 3.0 and 4.1. Epicentre distribution is very scattered, and hypocentral depths are generally comprised within the first 20 km of the crust, clustering between 0 and 15 km. Focal mechanisms were obtained by Santini [2003] for the events of highest magnitude (Table I). They are mostly characterised by a sub-horizontal maximum compressional (P) axis oriented about NNW-SSE, although variations also occur (Figure 4).

Figure 4. Epicentre location and focal mechanisms



Epicentre location and focal mechanisms of seismic events listed in Table I (after Santini 2003).

Table 1. Parameters of the seismic events whose epicentres and focal mechanisms are shown in Fig. 3 (from SANTINI, 2003).

Label	Year	Month	Day	Lat. (°N)	Long. (°E)	Depth (km)	M_d	Strike	Dip	Rake
1	1990	August	27	44.02	13.177	5.0	3.9	115°	50°	0°
2	1991	November	22	43.842	12.062	5.9	3.0	165°	60°	-70°
3	1996	June	28	43.769	12.995	27.5	3.4	155°	40°	110°
4	2000	February	22	43.79	12.083	8.0	3.0	265°	65°	-120°
5	2000	May	5	44.014	13.192	5.0	4.1	195°	25°	30°
6	2000	June	25	43.886	13.147	5.0	3.5	130°	90°	-50°
7	2000	June	27	43.883	13.200	5.0	3.4	115°	85°	40°
8	2000	August	1	43.929	12.318	5.0	4.2	160°	70°	130°
9	2000	December	27	43.678	12.245	5.0	3.2	115°	30°	-80°

In synthesis, the analysed seismicity confirms the same complexity shown by minor and major seismicity at a regional scale [for a review, see Di Bucci and Mazzoli 2002, and references therein] and cannot be used to reliably constrain present-day activity or inactivity of the thrust front in the study area. Therefore, other geophysical and geological data sets need to be taken into account.

Discussion and summary

Available data clearly indicate the inactivity of the external compressional front of the northern Marche Apennines in the last 800 ka [e.g. Di Bucci and Mazzoli 2002; Di Bucci et al. 2003]. Surface geological data show that the study area is instead characterised by middle Pleistocene-Holocene normal faulting related with ENE-WSW extension. Comparable inferences can be drawn from geomorphologic data. On the other hand, available focal mechanisms indicate a dominant NNW-SSE oriented compression and the activity of roughly ENE-WSW striking reverse faults. No faults with this strike and kinematics have been detected in outcrop. However, within the framework of the generalised, significant uplift governing the late Quaternary evolution of the study area, NE-SW to ENE-WSW trending sectors characterised by differential uplift have been identified based on geomorphic analysis [e.g. Elmi et al. 1987; Dramis 1992; Fanucci et al. 1996]. It could be speculated that active faults in the study area are mainly represented by lateral/oblique thrust ramps generated in Mio-Pliocene times and presently buried beneath Plio-Pleistocene syn- and post-orogenic deposits.

These fault segments are in fact suitably oriented for reactivation in a stress field characterised by a sub-horizontal maximum compressional (P) axis oriented about NNW-SSE as suggested by seismological data described above. Moreover, a dominant NNW-SSE oriented compression is also envisaged to occur a few tens of kilometres to the south, in the Monte Conero area [E. Tondi, pers. comm. 2003].

These main features of the stress field, although with spatial permutations of the principal stress axes, appear to characterise not only the study area, but also most of the outer Apennines and the related Apulia-Adria foreland during the whole middle Pleistocene-Holocene time span (outer Northern Apennines: e.g. Bertotti et al. 1997; Ghiselli and Martelli, 1997; Morelli and Costa 1997; Piccardi et al. 1997; outer Central-Southern Apennines and Apulia-Adria foreland: e.g. Console et al. 1989; Favali et al. 1993; Alessio et al. 1995; Mancini et al. 2003; Di Bucci and Mazzoli 2003). A NNW-SSE oriented compression is also in good agreement with the stress field related to the Friuli seismicity [Peruzza et al. 2002, and references therein]. All these data suggest a coherent behaviour of the Apulia-Adria foreland within the framework of Africa-Europe geodynamics [Mazzoli and Helman 1994; Ward 1994; Di Bucci and Mazzoli 2002; Hollenstein et al. 2003].

Acknowledgments

We thank Stefano Santini and Antonella Megna for the seismological data and the useful discussions. Constructive review by Gideon Rosenbaum helped to improve the paper.

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A. 3D Model

Three dimensional model showing the main geological features of the study area. The 3D model can be opened using 4DVistaTM, a free software downloadable from www.mve.com web site.