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QUATERNARY TECTONICS OF THE NORTHERN MARCHE REGION, AND IMPLICATIONS FOR ACTIVE DEFORMATION IN THE OUTER NORTHERN APENNINES

CONTENTS

ABSTRACT

The Quaternary tectonics of the northern Marche sector of the outer Northern Apennines has been analysed. Orogenic structures within the study area include late Miocene – Pliocene, mainly NE verging thrusts and associated folds whose geometry is locally controlled by gliding on oblique and lateral ramp segments. Post-orogenic features consist mainly of normal and oblique-slip faults resulting from WSW-ENE oriented extension. These faults also affect late-Quaternary continental deposits and played an active role in controlling the geomorphologic evolution of the study area. On the other hand, fluvial terraces are substantially parallel, even across the anticline ridges, thus disclaiming any significant deformation by the growth of NW-SE trending folds since the second half of the mid Pleistocene. Off-shore, the inactivity of the thrust front is 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. Furthermore, available focal mechanisms indicate a dominant NNW-SSE oriented compression, not compatible with NE directed thrusting. 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 might control present-day seismicity and the evolution of roughly ENE-WSW trending sectors characterised by differential uplift.

KEYWORDS: Structural geology, Fault reactivation, Geomorphology, Seismotectonics.

1. INTRODUCTION

The northern Marche area (Fig. 1) is the locus of a moderate – yet significant – tectonic activity, as also witnessed by historical and instrumental seismicity (Imax = IX MCS; Mmax = 6; e.g. GRUPPO DI LAVORO CPTI, 1999). Not only are the seismogenic sources of these earthquakes still unknown, but also the tectonic regime and the possible existence and size of further, presently silent, sources is a matter of debate (VALENSISE & PANTOSTI, 2001, and references therein). As an example, BASILI *et alii* (2002) and VANNOLI *et alii* (2002) recently suggested that active NE-directed thrusting accompanied by anticlinal growth would characterise the study area. However, different interpretations have also been put forward to (e.g. DI BUCCI *et alii*, 2003 and references therein). The aim of this paper is to examine the controversial late-Quaternary tectonic setting of the northern Marche region within the larger framework of the outer zones of the Northern Apennines.

2. THE NORTHERN MARCHE AREA AND ADJACENT ADRIATIC OFF-SHORE: STRUCTURE, GEOMORPHOLOGY AND SEISMICITY

The structure of the study area 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 , as well as by field surveys (e.g. COWARD *et alii*, 1999 and references therein). Major faulted anticlines are generally sub-cylindrical, with NW-SE oriented, sub-horizontal, mean (p) 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; Fig. 2). These areas are characterised by large (> 60°) 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 alii*, 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 alii*, 1999; MAZZOLI *et alii*, 2001). A 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 (Fig. 2), whilst NE-SW lateral ramps occur in adjacent on-shore and off-shore sectors of the study area (COWARD *et alii*, 1999). Concerning the timing of thrust activityAlong the Adriatic coast, 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, while Pleistocene deposits off-shore appear to be, at least in part, not involved in thrusting (e.g. COWARD *et alii*, 1999 and references therein). The geometry of syn-orogenic strata cropping out in the coastal zone between the Metauro and

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Cesano Rivers (Fig. 1) indicates a mid-late Pliocene age for major fold growth in this area. The northern Adriatic off-shore presents a well known Quaternary marine sedimentary succession. As a whole, in the study area this Quaternary succession is about 1000 m thick. On seismic reflection lines, this succession is detectable with a detail that allows precise considerations on the Quaternary tectonics (Di Bucci and Mazzoli, 2002, 2003). 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 & Mazzoli, 2002; Di Bucci *et alii*, 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) tectonic structures have been recognised both in pre-Quaternary substratum rocks and in late-Quaternary continental deposits (Upper Pleistocene terrace alluvium, Upper Pleistocene-Holocene slope deposits). The surveyed faults 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. Such fault system has played an active role in controlling the geomorphologic evolution of the study area, at least in the middle Pleistocene and in the lower part of the late Pleistocene. Furthermore, the occurrence of Upper Pleistocene-Holocene faulted deposits suggests that WSW-ENE oriented extension might be active at present in the study area (Savelli *et alii*, 2002). Very low displacements have been documented for such recent faults, which are seldom associated with peculiar landforms. Indeed, even where some geomorphologic evidence is noticeable, only the effects of selective erosion are clearly recognisable, being the active role of the structure not discernible.

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 alii*, 1996; Di Bucci *et alii*, 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 alii*, 1995). Specifically, close to the modern coastline 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

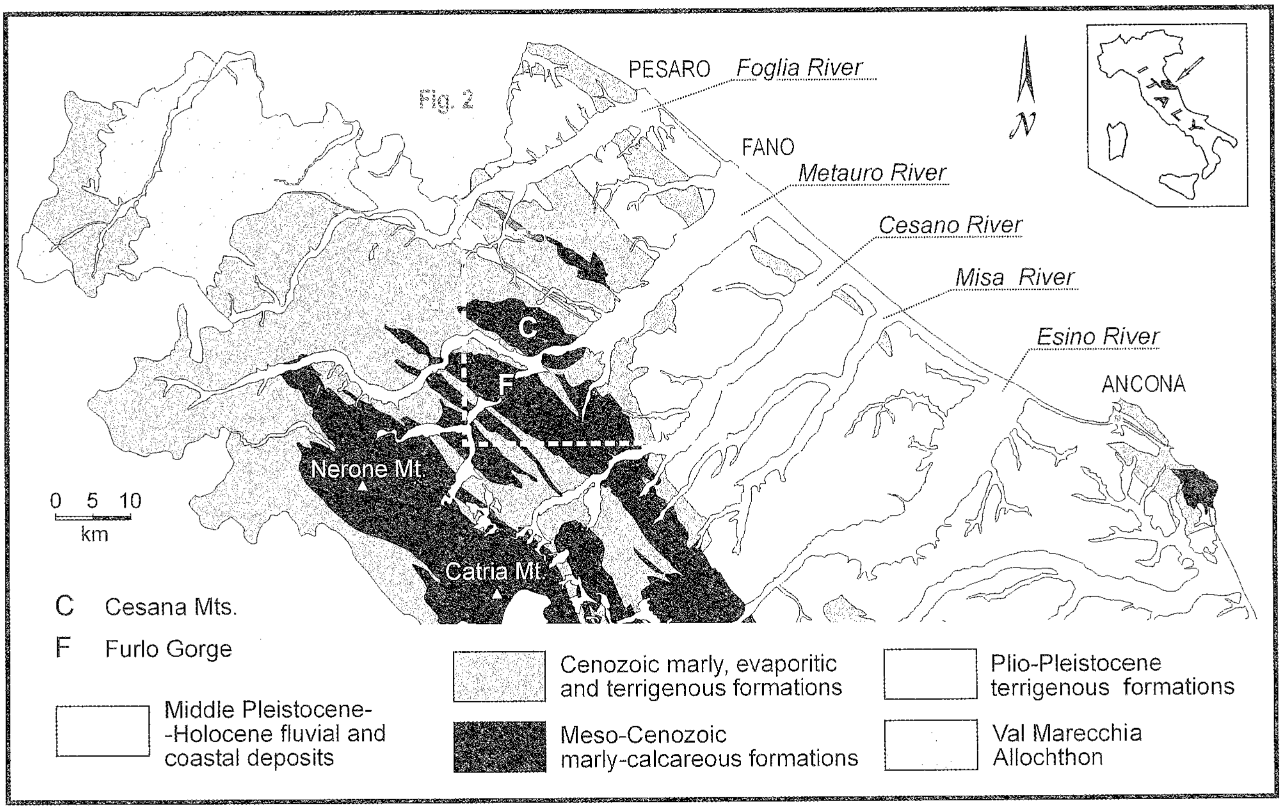

Fig. 1 - Geological sketch map of the northern Marche area. Box shows location of the 3D model shown in Fig. 2.

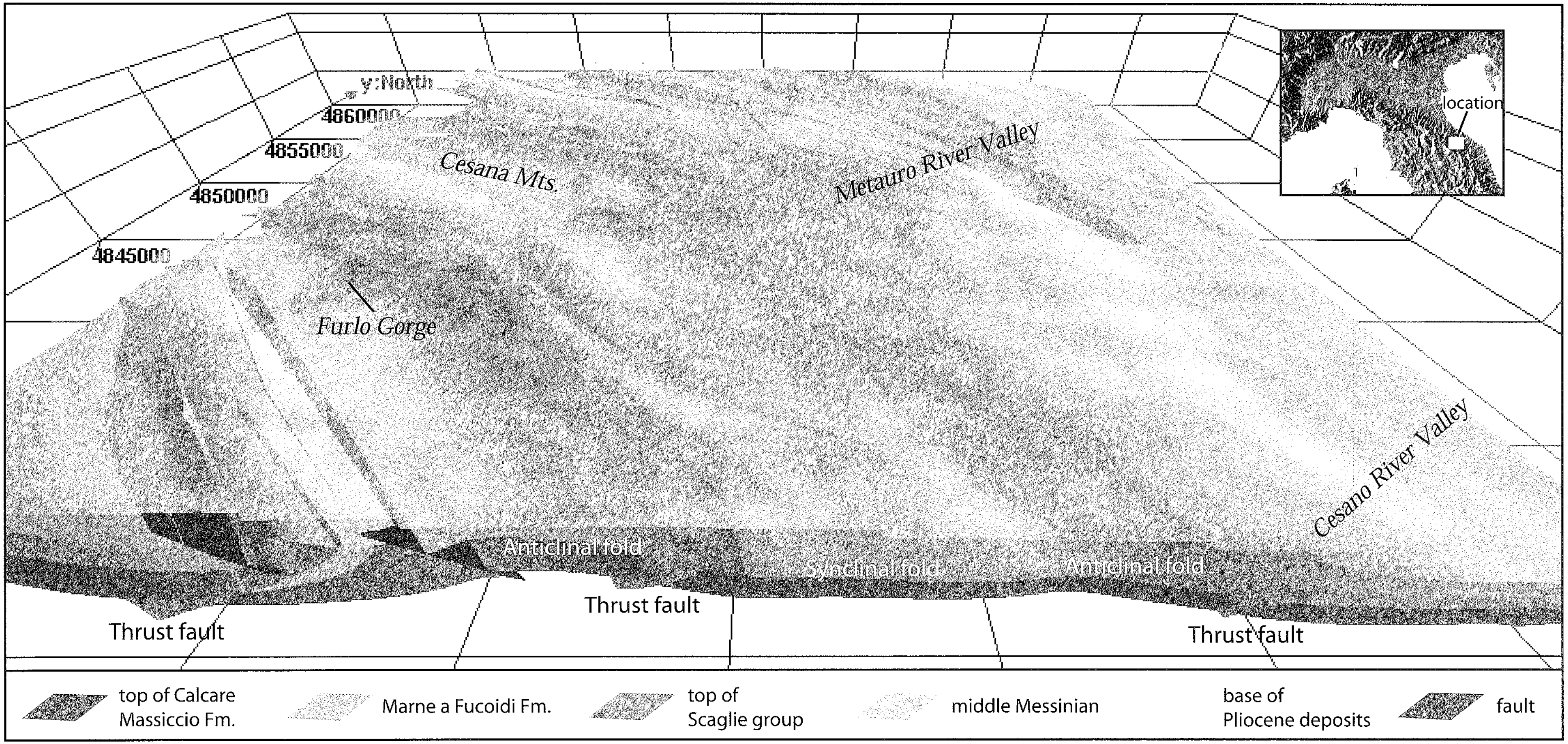

Fig. 2 - 3D Model of the lower Metauro River basin and adjoining area.

activity ever since the second half of middle Pleistocene (cf. NESCI *et alii.*, 1992; DI BUCCI *et alii*, 2003; MAYER *et alii*, 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 alii*, 2003 and references therein). Although some local terrace-levels convexities seemingly underline minor differential movements, their occurrence – apparently unrelated to the pattern of folds and associated thrust-faults of the area – can be associated with vertical uplift itself and/or to middle-late Pleistocene normal faulting (DI BUCCI *et alii*, 2003). A marked down-valley terrace-level convergence also occur (cf. ELMI *et alii*, 1987; NESCI *et alii*, 1990) in response to both strong sea-level falling during the cold aggradation stages (i.e. floodplain construction stages) and higher uplift/down-cutting 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 direction (i.e. perpendicular to the strike of the thrust belt) can be assessed for the northern Marche river basins (cf. ELMI *et alii*, 1987; FANUCCI *et alii*, 1996). In addition, from a morphotectonic perspective, the marked south-eastwards (i.e. towards the right valley-sides) deflection of the northern Marche trunk rivers can be an important topic. In actual fact – although such long-debated behaviour is object of several different interpretations (cf. DI BUCCI *et alii*, 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 alii*, 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 alii*, 2002; BORRACCINI *et alii*, 2002).

Concerning the present-day seismic activity of the study area, the centralised seismic network of the Istituto Nazionale di Geofisica e Vulcanologia recorded 83 seismic events from 1987 to 2000. Epicenter distribution is very scattered. Earthquake depths are generally comprised within the first 20 km of the crust, with maximum hypocenters clustering between 0 and 15 km. Most of the events have magnitude <3.0 while only a few of them (12) have magnitude between 3.0 and 4.1 (SANTINI, 2003). Focal mechanisms, obtained for the events of highest magnitude, are mostly characterised by a sub-horizontal maximum compressional (P) axis oriented about NNW-SSE (Fig. 3).

3. DISCUSSION AND CONCLUDING REMARKS

Available data clearly indicate the inactivity of the external compressional front of the northern Marche Apennines in the last 800 ka. 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, ENE-WSW trending sectors characterised by differential uplift have been identified based on geomorphologic analysis (e.g. DRAMIS, 1992). It could be speculated that active faults in the study

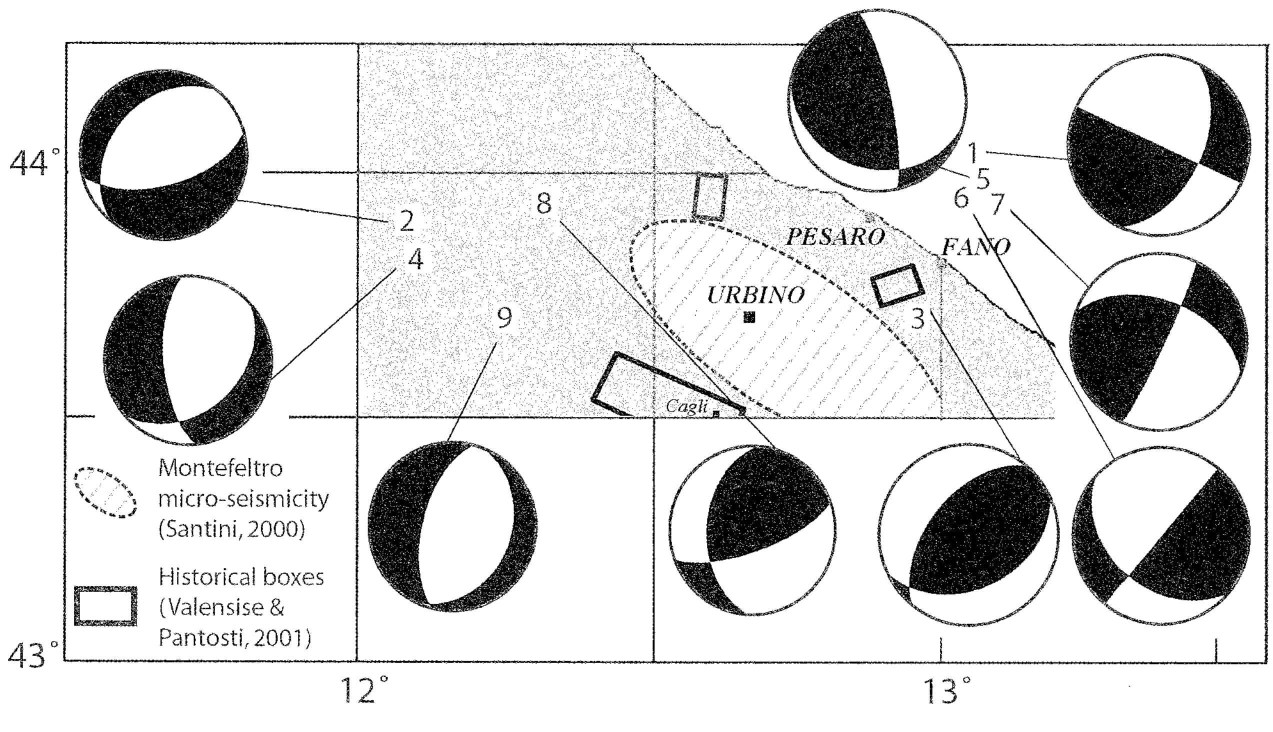

Fig. 3 - Epicenter location and focal mechanisms of the main seismic events recorded in 1987-2000 (after SANTINI, 2003).

area are 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 the seismological data described above. A similar process of fault reactivation within the framework of the described stress field is 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 external outer Apennines and the related Apulia-Adria foreland during the whole middle Pleistocene-Holocene time span (outer Northern Apennines: e.g. BERTOTTI *et alii*, 1997; ARGNANI *et alii*, 2003; outer Central-Southern Apennines and Apulia-Adria foreland: e.g. FAVALI *et alii*, 1993; MANCINI *et alii*, 2003; DI BUCCI & MAZZOLI, 2002, 2003 and references therein). A NNW-SSE oriented compression is also in good agreement with the stress field related to the Friuli seismicity (PERUZZA *et alii*, 2002, and references therein). All these data suggest a coherent behaviour of the Adria plate within the framework of Africa-Europe geodynamics (DI BUCCI & MAZZOLI, 2002, 2003 and references therein; HOLLENSTEIN *et alii*, 2003).

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