Some issues regarding the central Mediterranean neotectonics

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(Received June 15, 2005; accepted October 7, 2005)

ABSTRACT The complex morphology of the Mediterranean region has originated from the long-lasting plate convergence between Africa and Eurasia. This plate convergence has been active since the late Cretaceous, with the subsequent continental collision, from the Eocene, there was an early subduction of the oceanic lithosphere. The uncertainties in palaeo-reconstructions make the long-term evolution of the Mediterranen region highly debated; however, even when GPS horizontal velocity measurements are available, the understanding of Mediterranean neotectonics is also affected by uncertainties. In a highly complex tectonic setting, such as the central Mediterranean, even accurate measurements are often not sufficient to resolve this ambiguity. The tectonics of the plate boundary between Africa and Europe in the Sicilian-Calabrian region; the nature of the deformation observed within the Adriatic region and the possible occurrence of one, or more platelets are examples of neotectonic settings still open for debate. Without attempting a comprehensive critical review of the neotectonics of the Mediterranean, this contribution aims at discussing some aspects mainly relevant to Italy and the surrounding regions.

1. Introduction

The Mediterranean region presents a complex morphology, characterized by deep basins and looping mountain belts, that has originated from the long-lasting plate convergence between Africa/Arabia and Eurasia (Fig. 1; Dewey *et al*., 1973, 1989; Horvath and Berckhemer, 1982; Dewey, 1988; Le Pichon *et al*., 1988; Royden and Burchfiel, 1989; Mantovani *et al*., 2002). The Africa-Eurasia plate convergence has been active since the late Cretaceous, with rates of convergence typically increasing eastwards, as the poles of relative rotation were located in the Atlantic region. Continental collision has been going on since the Eocene, following the early subduction of the oceanic lithosphere (Coward and Dietrich, 1989; Schmid *et al*., 1996).

The distribution of the current seismicity outlines the ongoing crustal deformation of the Mediterranean region (Fig. 2) fairly well. Grossly simplifying, the Mediterranean region records, from west to east, a passage from a simple deformation at the oceanic plate boundaries of the Atlantic, characterized by narrow seismic belts, to a broad belt of seismicity and deformation that characterizes the continental collision setting (McKenzie, 1972; England and Jackson, 1989). The weaker rheology of the continental lithosphere and the role of pre-existing faults or weakness zones seem to be the chief causes for such seismological and tectonic behaviour, (McKenzie, 1977). Accordinlgly, neotectonic studies have shown a high degree of complexity and variety of deformation in the various regions of the Mediterranean (e.g. Philip, 1987; Horvath, 1988). The continuous accummulation of good quality seismological data, in particular those recorded by

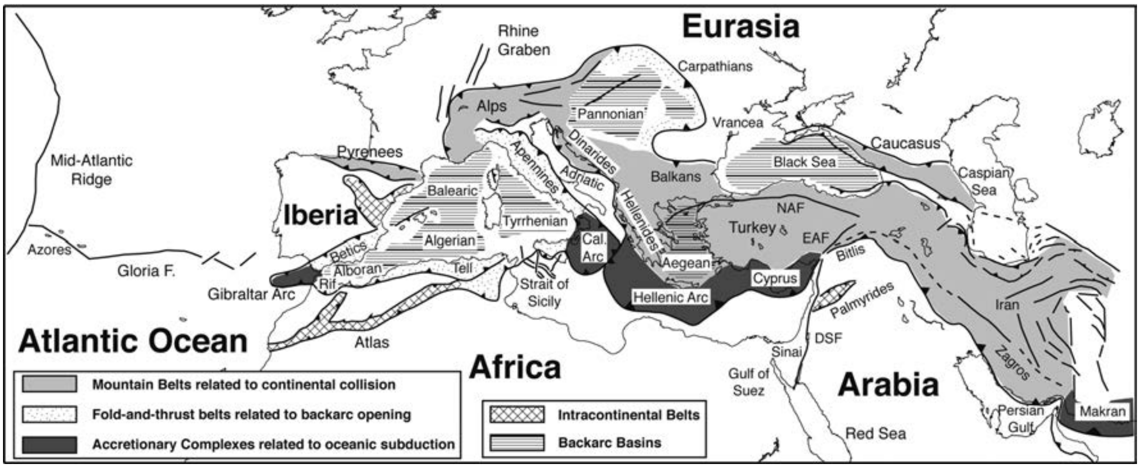


Fig. 1 - Main tectonic domains of the Mediterranean region (after Vannucci *et al*., 2004). Cal. Arc, Calabrian Arc; NAF, North Anatolian Fault; EAF, Eastern Anatolian Fault; DSF, Dead Sea Fault.

world-wide and regional networks where moment-tensor solutions are obtained, and the growing number of GPS stations now offering reliable measurements, keep the attention on Mediterranean neotectonics lively. The GPS results obtained by networks with a large number of stations purposely installed, in particular, have been a kind of breakthrough in neotectonic interpretations (eg. McClusky *et al*., 2000, 2003), often calling for a second view at formerly assessed geological interpretations.

Several contributions dealing with the Italian region and mostly based on GPS results have been recently published (e.g. Oldow *et al*., 2002; Serpelloni *et al*., 2002, 2005; Battaglia *et al*.,

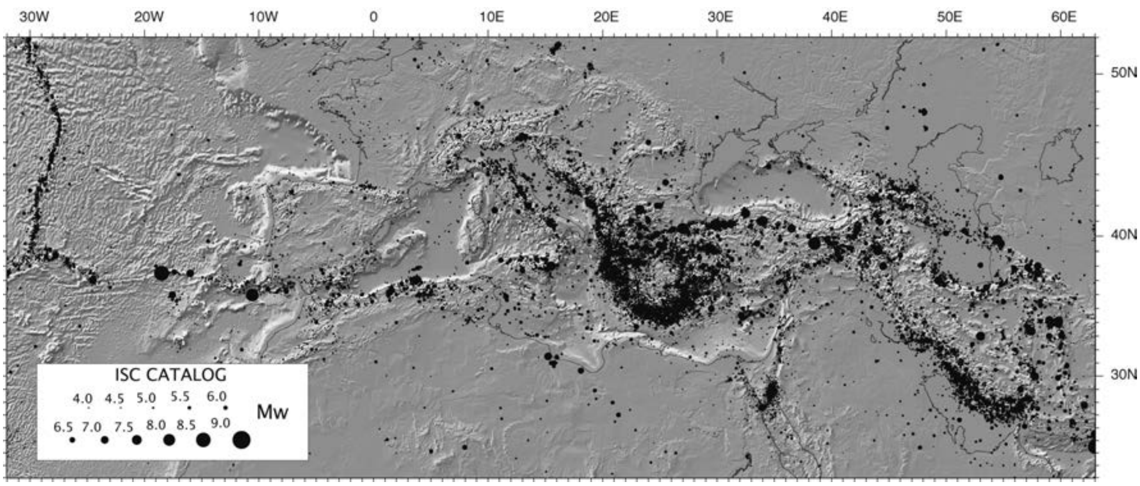


Fig. 2 - Distribution of instrumental seismicity in the Mediterranean region. Earthquakes shallower than 50 km taken from ISC catalogue (after Vannucci *et al*., 2004).

2004; D'Agostino and Selvaggi, 2004; Goes *et al*., 2004). In particular, the tectonics of the plate boundary between Africa and Europe in the Sicilian-Calabrian region, and the nature of the deformation observed within the Adriatic region are examples of neotectonic settings open to debate. In these instances, significant tectonic elements are inferred to be located at sea.

Without attempting to propose a new kinematic model for the central Mediterranean region, this contribution rather aims at commenting on the recent GPS results from the Adriatic region and Calabrian Arc, and at discussing the proposed kinematic models, taking into account the geological constraints derived from recent marine seismic surveys. Moreover, some comments will be addressed to the recent proposal of the occurrence of a newly initiated southward-dipping subduction zone in the southern Tyrrhenian Sea (Goes *et al*., 2004; Faccenna *et al*., 2005).

Throughout this paper neotectonics are defined, according to Yeats *et al*. (1997), as the tectonic processes now active, considering the geological time span during which they have been acting as presently observed, and the resulting structures (a defintion that is pretty close to that of active tectonics).

2. Central Mediterranean tectonics

Several tectonic processes, besides plate convergence-driven oceanic subduction and continental collision, have contributed to shaping the present Mediterranean Alpine orogen, mostly because of along-strike variability of lithospheric nature and convergence rates. Chief among them are passive sinking and rollback of the subducted lithosphere, leading to a backarc basin opening (e.g. Dewey, 1980), and tectonic escape of continental blocks away from boundaries of collisional indentation (e.g. Burke and Sengör, 1986). The large extensional basins of the Mediterranean region (Alboran, Algero-Balearic, Tyrrhenian, Pannonian, Aegean) formed as backarc basins on the wake of the retreating subductive boundary (Horvath and Berkhemer, 1982; Rehault *et al*., 1984; Malinverno and Ryan, 1986; Argnani and Savelli, 1999; Faccenna *et al*., 2001). In all, but one case (Pannonian basin), the subducting and retreating lithosphere belongs to the African plate.

It has also been suggested that, in some cases, the subducted lithosphere can be torn apart, both along the strike of the trench, following for instance the continental/oceanic boundary, or along a direction perpendicular to the trench (Wortel and Spakman, 2000; Wortel and Gover, 2004). The latter case seems applicable to the Calabrian region, where a vertical tear between the dense Ionian lithosphere, which is oceanic, and the buoyant continental lithosphere of Sicily has been supposed (Gvirtzman and Nur, 1999; Argnani, 2000; Argnani and Bonazzi, 2005).

The central Mediterranean is composed of several tectonic elements, the main one of which are i) the Tyrrhenian backarc basin, ii) a piece of continental lithosphere, the Adriatic region, partly surrounded by mountain belts (Apennines, Southern Alps and Dinarides), and iii) the deep Ionian basin. In the following, a brief description of the geological features that compose the central Mediterranean region is presented. For the sake of presentation the region is subdivided into a southern sector, including Sicily, the Calabrian Arc, the Southern Apennines and the Tyrrhenian basin, and a northern part, that includes the Northern Apennines, Alps, Dinarides and the Adriatic region.

3. Southern sector

The Tyrrhenian basin is located on the wake of the Apennines and Sicilian Meghrebides, with the current sea floor that is rather shallow in its northern part (less than 1000 m) and becomes deeper (over 3000 m) to the south (Fig. 1). The basin originated by backarc extension from the late Miocene to the Pleistocene, with tectonic activity getting progressively younger towards SE. The amount of extension is greater in the southern basin which, in fact, is characterized by a thin crust (less than 10 km) and high heat flow (Malinverno and Ryan, 1986; Patacca *et al*., 1990; Argnani and Savelli, 1999).

The Maghrebian fold-and-thrust-belt (FTB) of Sicily is composed by a stack of Meso-Cenozoic sediments deposited along the African passive margin and its adjacent basin (Fig. 1). This tectonic stack formed mostly during the coeval opening of the Balearic and Tyrrhenian backarc basins in a subductive environment and has been subsequently emplaced onto the continental foreland of Sicily since the Pliocene (Roure *et al*., 1990). The front of the Maghrebian FTB of Sicily, located in the southern offshore, appears sealed by late Pleistocene sediments (Argnani, 1987; Patacca and Scandone 2004), although some younger out-of-sequence thrusting has been reported on land (Lickorish *et al*., 1999). Extensional faulting, mainly trending ENE-WSW, affected the northern part of Sicily since the late Messinian, as part of the Tyrrhenian basin opening (Roure *et al*., 1990).

The Southern Apennines appear well correlatable to the Maghrebides of Sicily, and consist of a pile of thrust sheets composed mainly by basinal sediments encasing a thick carbonate platform unit, the Apennine Platform (Mostardini and Merlini, 1986; Casero *et al*., 1988, Menardi and Noguera, 2000). Units containing ophiolite slices from the Alpine Tethys are located in the most internal position. This tectonic stack, corresponding to an accretionary prism, was thrusted onto the Apulian carbonate platform, that represents the Adriatic continental foreland, in the early Pliocene. The subsequent deformation affected also the Apulian Platform and possibly its continental basement, although the degree of basement involvement is controversial (Scrocca *et al*., 2005). Thrusting within the Southern Apennines possibly stopped in the early Pleistocene (Patacca *et al*., 1997; Patacca and Scandone, 2001). NW-SE-trending extensional faulting affected the inner part of the Southern Apennines during the Tyrrhenian opening (late Miocene-early Pleistocene), whereas surficial ruptures due to recent and historical earthquakes are mainly concentrated about the mountain watershed (Valensise and Pantosti, 2001).

The Calabrian Arc represents the connection between the Maghrebides of Sicily and the Southern Apennines, and is characterised by a stack of basement units coming from a different level of an Hercynian continental crust (e.g. Bonardi *et al*., 2001). A thick forearc sedimentary succession crops out on the Ionian side of Calabria, supporting the accretion of the Calabrian arc terraines within a subduction system. Subduction has been going on till recently, or is still active, and a well defined seismic slab in the Mediterranean is located underneath Calabria (Selvaggi and Chiarabba, 1995). This seismic slab, which is almost vertical and reaches the depth of about 550 km, is physically connected to the oceanic lithosphere of the Ionian Sea. The External Calabrian Arc is a wide accretionary complex that extends into the Ionian Sea to touch the Mediterranean Ridge, SW of Kefallinia, and that is confined to the NE and SW by the Apulian and Malta Escarpments, respectively (Fig. 1). The onshore Calabrian Arc has been affected by a major uplift in the last 0.8 Ma, with rates close to 2.0 mm/yr (Westaway, 1993; Bordoni and

Valensise, 1998), and presents extensional grabens trending NE-SW and NW-SE filled by late Pliocene-Quaternary sediments (Tortorici *et al*., 1995).

The Ionian basin is one of the deeper stretches of sea in the Mediterranean and not much is known about its crustal structures and sedimentary fill. The evolution of this basin is, therefore, open to debate both in terms of age of events and nature of its crust. The larger part of the Ionian basin is currently covered by the External Calabrian Arc accretionary prism (Rossi and Sartori, 1981). Thick successions of platform carbonates however bound the basin on its north-eastern and south-western side, the Apulian Platform and Malta-Hyblean Platform, respectively, and are characterized by a very narrow steep slope (Scandone *et al*., 1981; Biju-Duval *et al*., 1982; Catalano *et al*., 2000). Studies of the crustal velocity structure of the Ionian based on expanded spread profiles suggest that the crust of the Ionian basin has a velocity structure similar to the oceanic crust (de Voogd *et al*., 1992). Paleogeographic reconstructions assign ages that range from early Createaceous to Permian to the Ionian oceanic lithosphere (e.g. Stampfli *et al*., 1991, 2001; Dercourt *et al*., 1993; Argnani, 2005).

It is worth noting that although it has been speculated that the recent uplift of Calabria could be due to the breakoff of the subducted Ionian slab (Westaway, 1993; Monaco and Tortorici, 2000), a connection between the Ionian basin and the slab currently subducted underneath the Tyrrhenian Sea is indicated both by the distribution of seismicity (Selvaggi and Chiarabba, 1995) and by S-wave propagation paths (Mele, 1998).

4. Northern sector

The Northern Apennines are composed of a tectonic stack of mainly east-vergent thrust units that originated during the late Cretaceous to the Present (Kligfield, 1979; Hill and Hayward, 1988). The initial stage of oceanic subduction lead to the formation of the Ligurian accretionary wedge, the uppermost nappe system of the Apennine stack, which was emplaced tectonically over the basinal sediments of the Adriatic continental margin. Subsequently, the local convergence between Adria and the continental Corsica-Sardinia block, rotating counterclockwise ahead of the Balearic backarc basin opening, led to a progressive deformation of the units of the Adriatic continental margin. The basement of the Tuscan succession has been affected by the deformation and outcrops of a few tectonic windows in the internal part of the Apennines (e.g. Apuane Alps and Monti Pisani). Following the convergence of Corsica-Sardinia, the eastward migration of a system of foredeep basins occurred, with the last foredeep basin presently located in the Po Plain and the Adriatic Sea (Ricci Lucchi, 1986; Argnani and Ricci Lucchi, 2001). A system of arcuate thrust faults located in the subsurface of the Po Plain (Pieri and Groppi, 1981), represents the most external front of the Apennines and appears sealed by Pleistocene sediments.

The Alps originated by the convergence, and subsequent collision, of the European and African plates, with the proper collision that occurred between Europe and Adria, the continental promontory of Africa (e.g. Coward and Dietrich, 1989). In the early stages of convergence, from late Cretaceous to early Eocene, a Mesozoic oceanic domain (Alpine Tethys) was subducted underneath Africa. Continental collision progressed from Middle Eocene onwards to originate the present mountain range (Roure *et al*., 1996; Dal Piaz *et al*., 2003). To mechanically balance the increased shortening and uplift of the Alpine belt, a crustal-scale retro-wedge thrust developed in the upper plate (Adria), originating the Southern Alps (Roeder, 1989).

The Eastern Alps represent the complex kinematic link between the Alps and the Alpine belt of eastern Europe, namely the Carpathians and the Dinarides, with the Pannonian basin that adds further complexity. Besides north-south shortening, strike slip and extensional faults characterised the Eastern Alps in late Oligocene - Miocene, causing an eastward lateral extrusion (tectonic escape) towards the Pannonian region (Ratschbacher *et al*., 1991).

Despite the long collisional boundary of the Alps, the Friuli region has recorded the largest earthquakes in the Eastern Alps, and in the Alpine region in general.

The Dinarides and Albanides are part of a continuous west-vergent FTB that runs from the Eastern Alps to the Hellenic Arc and that originated from the subduction of the Adriatic (Africa) domain underneath Europe. Basinal sediments, including Jurassic ophiolite slivers, occur in the inner part of the belt (e.g. Aubouin *et al*., 1970; Moretti and Royden, 1988). Ophiolites were emplaced on the Adriatic domain, once the oceanic basin closed, and thrusting subsequently affected the Adriatic-Dinaric carbonate platform (Celet, 1977). Thrusting terminated mainly in the early Oligocene over most of the Dinarides (Moretti and Royden, 1988), although continued until the Present in the southern Dinarides, Albanides and Hellenides (Auroux *et al*., 1984; Argnani *et al*., 1996). Strike slip tectonics seem to dominate from late Oligocene to the Present in the internal part of the belt, where the NW-SE-trending Drava-Sava system (dextral strike slip) marks the boundary with the Pannonian basin. The Albanides and Hellenides continue towards the south from the Dinarides. Moreover, the Albanides and Hellenides present a conspicuous Miocene-Pliocene clockwise rotation in their external units. Although the Hellenides represent a continuous belt from Albania to the Peloponnesos (Fig. 1), it is worth noting that the frontal part is characterised by a continental collision north of Kefallinia, whereas to the south of the island, oceanic subduction occurs (Underhill, 1989). The Adriatic Sea represents the foreland of the Apennines and Dinarides-Hellenides.

Palaeomagnetic data seem to indicate that Adria was a promontory of the African plate over most of the evolution of the central Mediterranean (Channell, 1996; Muttoni *et al*., 2001). Seismic surveys in the Adriatic Sea have shown the occurrence of tectonic structures, mainly open folds and reverse faults, particularly in the central Adriatic (Argnani *et al*., 1993, 2002; De Alteriis, 1995; Argnani and Frugoni, 1997; Bertotti *et al*., 2001). This deformation is limited and does not appear related to the outer Apennine fronts; moreover, the observed variety in structural directions, supports the reactivation of pre-existing faults in a regime of tectonic inversion. In fact, early Mesozoic extensional faults have been documented by oil industry research in the central Adriatic (Gambini *et al*., 1997). It has been suggested that stresses from the adjacent Dinarides and Apennines caused intraplate deformation; however, it is also possible that the stresses due to the Adria push, that is indenting Europe, are felt as far south as the central Adriatic.

5. Seismotectonics of the central Mediterranean: the view from focal mechanisms

A large number of reliable focal mechanisms covering the Mediterranean region have been made available by world-wide and regional seismic networks [e.g. Harvard Centroid Moment Tensor catalogue (Dziewonski *et al*., 1981; Dziewonski and Maternovskaya, 2000), INGV European-Mediterranean Regional Centroid Moment Tensor catalogue (Pondrelli *et al*., 2002, 2004a), ETH Swiss Seismological Survey catalogue (Braunmiller *et al*., 2002)] and by a revised compilation of published focal mechanisms [EMMA catalogue (Vannucci and Gasperini, 2004)]. The tectonic pattern outlined by focal mechanisms for the central Mediterranean is rather complex, reflecting the variety of tectonic settings (Fig. 3).

A belt of compressional earthquakes, with P axes that roughly fit the Africa-Europe convergence, is located in the southern Tyrrhenian Sea, whereas in the Maghrebian FTB of Sicily seismicity is reduced and lacks consistent focal solutions. This pattern of compressional focal

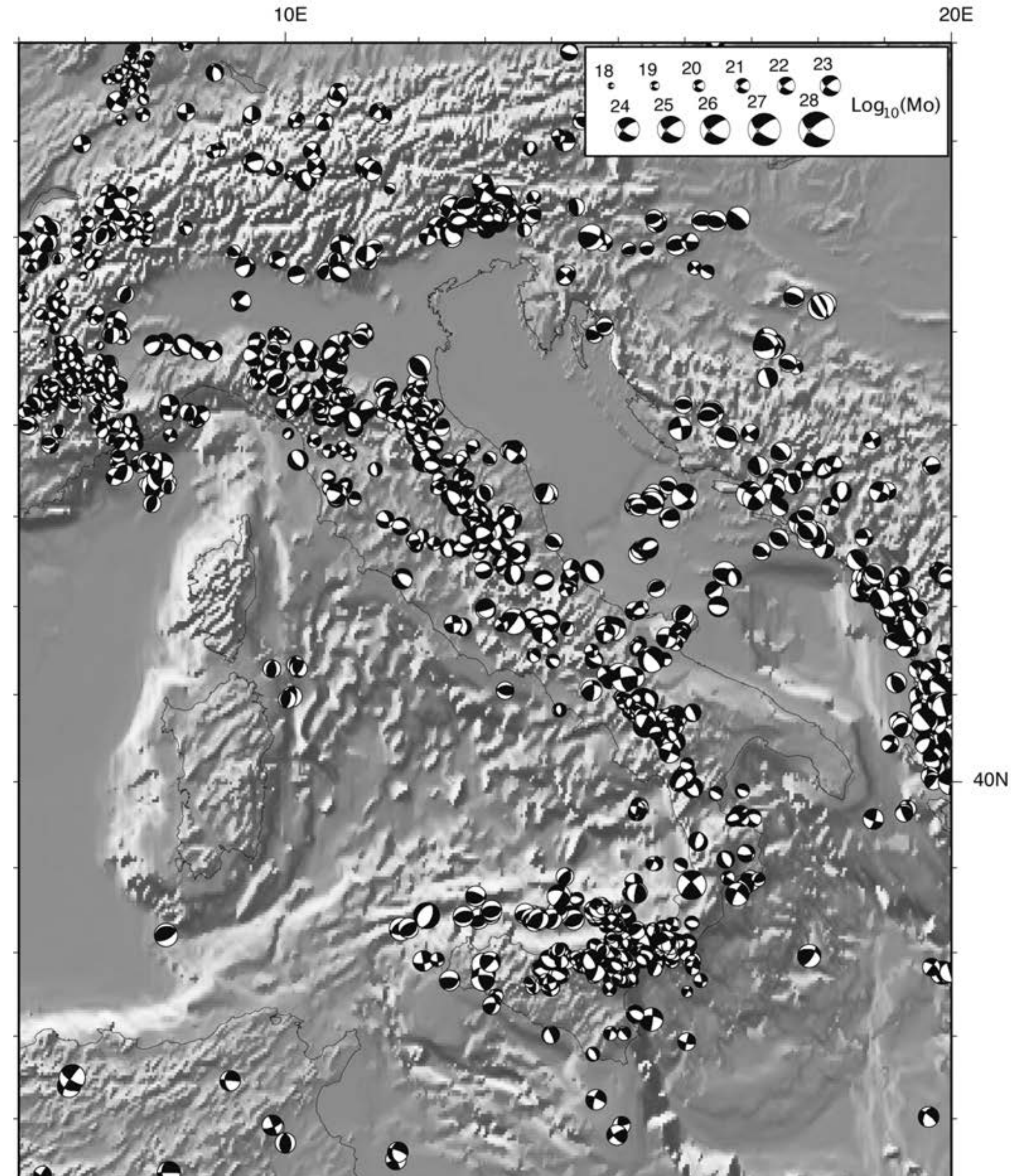


Fig. 3 - Focal mechanisms of earthquakes from moment tensors catalogues and EMMA database (Vannucci and Gasperini, 2004) with depth less than 50 km in the central Mediterranean (after Vannucci *et al*., 2004).

mechanisms, however, breaks down moving to the east, towards the Aeolian Islands, where strike-slip and extensional solutions dominate, marking the passage to the Calabrian Arc.

The structural complexity of the Calabrian Arc is reflected in the variety of focal solutions that display major changes in fault plane directions throughout this sector. The dominance of compression driven by the Africa-Europe convergence, previously seen along north Africa, is not present any more. This sort of disconnection with major plate motion can be observed all along the Apennines. It is only in the Eastern Alps that earthquakes show compressional focal solutions that possibly reflect major plate convergence.

The Southern Apennines are dominated by earthquakes with extensional focal mechanisms with fault planes trending subparallel to the mountain range. Major earthquakes are located along the highest relief and fault planes, where they dip to the NE (e.g. Westaway and Jackson, 1987) as shown by detailed seismological studies. This kind of tectonics is therefore at variance with respect to the older backarc extensional tectonics that is characterised by a system of west dipping fault planes located near the Tyrrheanian coast. A somewhat more complex picture characterises the Central Apennines where some earthquakes with strike-slip focal mechanisms also occur. According to focal mechanisms, however, perpendicular mountain extensional faulting continues all the way to the Northern Apennines (Frepoli and Amato, 1997, 2000b). Some sparse earthquakes, with compressional focal mechanisms, occur from the pede-Apennines to the outer front of the Apennines, which one buried under the Po Plain. Additional seismicity is located in the central Adriatic, north of the Gargano Promontory (Console *et al.*, 1993), which often presents an epicentral depth below 10-15 km. Focal mechanisms for earthquakes located in this region are mainly compressional, supporting the hypothesized reactivation of Mesozoic structures.

Compressional seismicity characterizes the Eastern Alps, and the Friulian Alps in particular, with focal mechanisms indicating horizontal P-axes trending about NNW. This kind of seismic pattern, though with lower magnitude events, continues slightly to the east along the junction between the Alps and Dinarides.

Earthquakes with compressional focal mechanisms are abundant in the southern part of the Dinarides, particularly at the front of the FTB, with directions of thrust planes that are parallel to the structural trends (Renner and Slejko 1994; Peruzza *et al.*, 2002). Earthquakes with strike-slip and thrust focal solutions equally occur at the interior of the Dinarides, where seismicity, however, is less abundant. It is worth noting, that only a little seismicity occurs in the northern part of the Dinaride front (Fig. 2); rather, the compressional events of the southern Dinarides seem to find their continuation in the diffuse seismicity of the central Adriatic and the outer part of the Northern Apennines (Figs. 2 and 3).

6. Neotectonic issues

The proposed palaeo-reconstructions for the evolution of the Mediterranean region suffer several uncertainties, mostly due to the long time span used. However, despite the shorter time span and the abundant direct observations coming from seismology and geodesy, it appears that the studies of Mediterranean neotectonics are also affected by large uncertainties. This is mostly because even accurate measurements are not often sufficient to resolve the ambiguity of interpretation in a highly complex tectonic setting, and this is particularly true for the western-central Mediterranean region (Fig. 4), where the velocities measured by GPS stations are much reduced when compared to those observed in the Aegean region (McClusky *et al*., 2000). Moreover, the extensive presence of sea in the central Mediterranean makes it difficult to operate GPS networks that allow an exhaustive kinematic description. One of the most difficult tasks is to relate the measurements of current velocity obtained from GPS stations, to the geological structures, whose activity is often integrated over much longer time spans.

New kinematic models have been proposed on the basis of the recent GPS results from the Adriatic region (Oldow *et al*., 2002; Battaglia *et al*., 2004) and the Calabrian Arc (Goes *et al*., 2004; D'Agostino and Selvaggi, 2004) implying, in some instances, the occurrence of important geological structures located at sea. In the following, the geological constraints derived from recent marine seismic surveys are presented and discussed with respect to the GPS-based

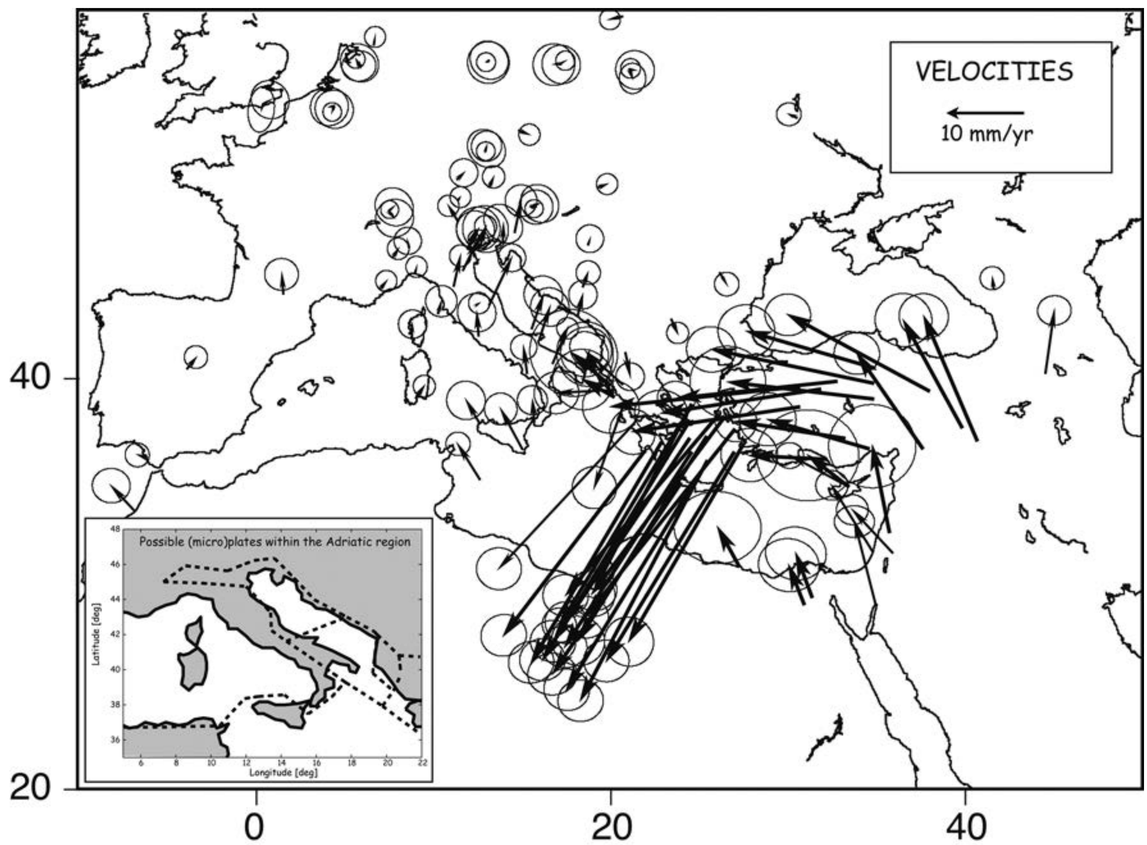


Fig. 4 - GPS motion with respect to Eurasia from stations covering the whole Mediterranean region [after Battaglia *et al*. (2004), velocities compiled from McClusky *et al*. (2000), Serpelloni *et al*. (2001, 2002), Battaglia *et al*. (2004)]. Note the marked drop in velocities when moving from the eastern to the central-western Mediterranean. Inset shows the possible microplates identified within the Adriatic region on the basis of GPS results (after Battaglia *et al*., 2004). Rigid blocks with slip along their boundaries (dotted lines) are assumed.

kinematic models. The occurrence of a newly-initiated southward-dipping subduction zone in the southern Tyrrhenian Sea, which has been recently proposed (Goes *et al*., 2004; Faccenna *et al*., 2005), is also discussed.

6.1. Adriatic region

Plate kinematic models presenting various segmentations of Adria, either as an individual microplate or fragmented into two pieces, have been recently presented on the basis of GPS measurements (e.g., Oldow *et al*., 2002; Calais *et al*., 2002; Battaglia *et al*., 2004). These models are invariably based on the assumption of rigid block deformation, with blocks which are necessarily delimited by plate boundaries. Although these recent contributions refer extensively to each other, either for comparison or contrast, they seem to pay little attention to the regional geological literature. This aspect is particularly disappointing as several papers have dealt with the geology of the Adriatic regions in the last 20 years (Finetti, 1984; De Dominiciis and Mazzoldi, 1987; Argnani *et al*., 1993; De Alteriis, 1995; Argnani and Frugoni, 1997; Argnani *et al*., 2001, 2002). As a result of this kind of approach, idealized tectonic features, that hardly find any support in the literature, have often been taken as the boundaries (plate boundaries!) of the blocks into which Adria has been subdivided.

Because of the above-mentioned shortcomings, the contribution of these kinematic proposals to the comprehension of geological processes at work in the Adriatic region is only limited, when not misleading. This, in spite of the interesting results obtained from the various GPS permanent networks, now showing rather stable solutions (Caporali, 2003).

Several hypothetical black boundaries have been proposed as occuring within the Adriatic region [for a review see Babbucci *et al*. (2004)]. The main ones, although differing according to the authors, are roughly located around the Gargano promontory and south of Salento, the tip of Puglia.

Following an early proposal of Westaway (1990), the mild seismicity of the central Adriatic (Fig. 2), already noted by Robert Mallet in 1858 (Reports to the British Association for the Advancement of Science), is taken as the expression of a roughly E-W boundary connecting the Apennines and Dinarides passing north of the Gargano promontory (Fig. 4, inset). An alternative boundary that can decouple the Adriatic into two parts is assumed to run south of the Gargano promontory, partly following the E-W-trending Mattinata fault system (e.g. Favali *et al*., 1993).

Moreover, most of the authors working on GPS data conside Adria decoupled from Africa [see Babbucci *et al*. (2004) for a critical view]. Such a boundary is supposed to run south of Salento, with an E-W trend (Anderson and Jackson, 1987), or, alternatively, is located along the NNW-SSE-trending Apulia Escarpment.

Good quality seismic reflection profiles have been recently acquired in the Adriatic region in order to characterize its deformation, and their interpretation (Argnani *et al*., 1993, 1996, 2002, 2004a, 2004b) has led to a rather detailed tectonic mapping (Fig. 5).

The occurrence of a significant and rather diffuse deformation affecting the central Adriatic foreland appear evident on seismic profiles (Fig. 6a). The structures are mainly folds and reverse faults indicating an active compressional regime, as also supported by focal mechanisms. Altogether, the fold axes of major structures outline (Argnani and Frugoni, 1997) a deformed belt that trends roughly NW-SE across the central Adriatic (Fig. 5), and that merges to the south with

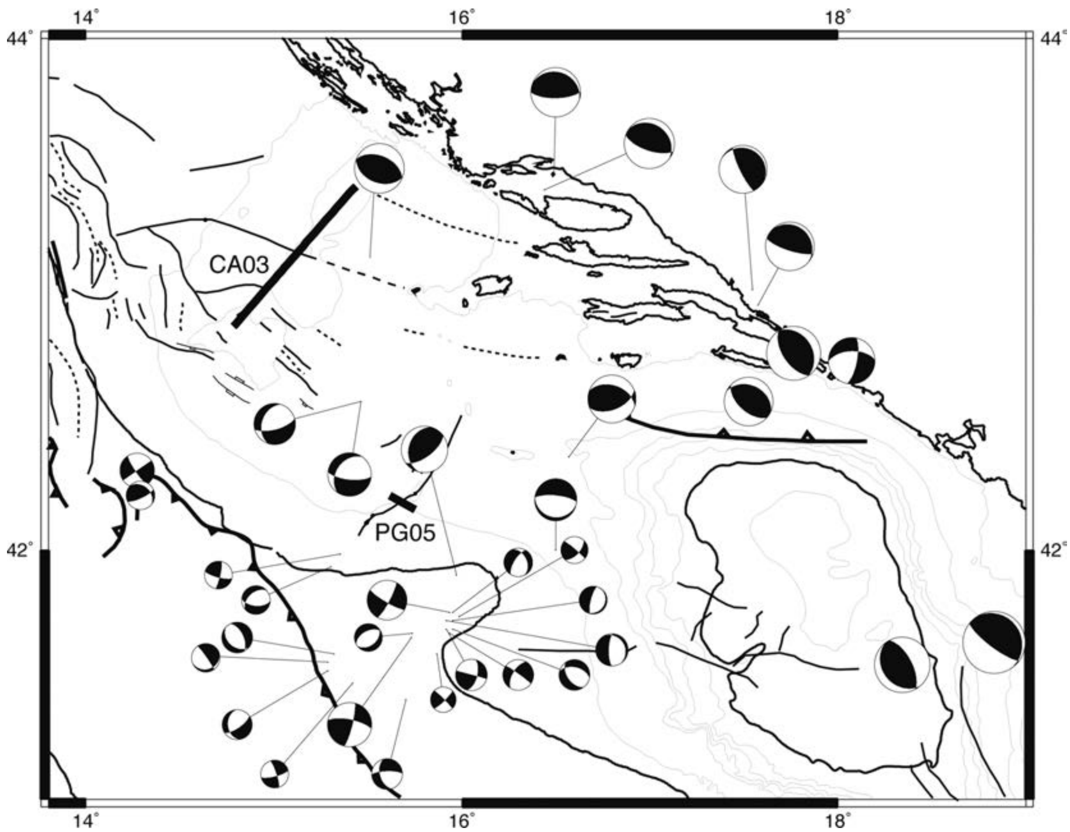
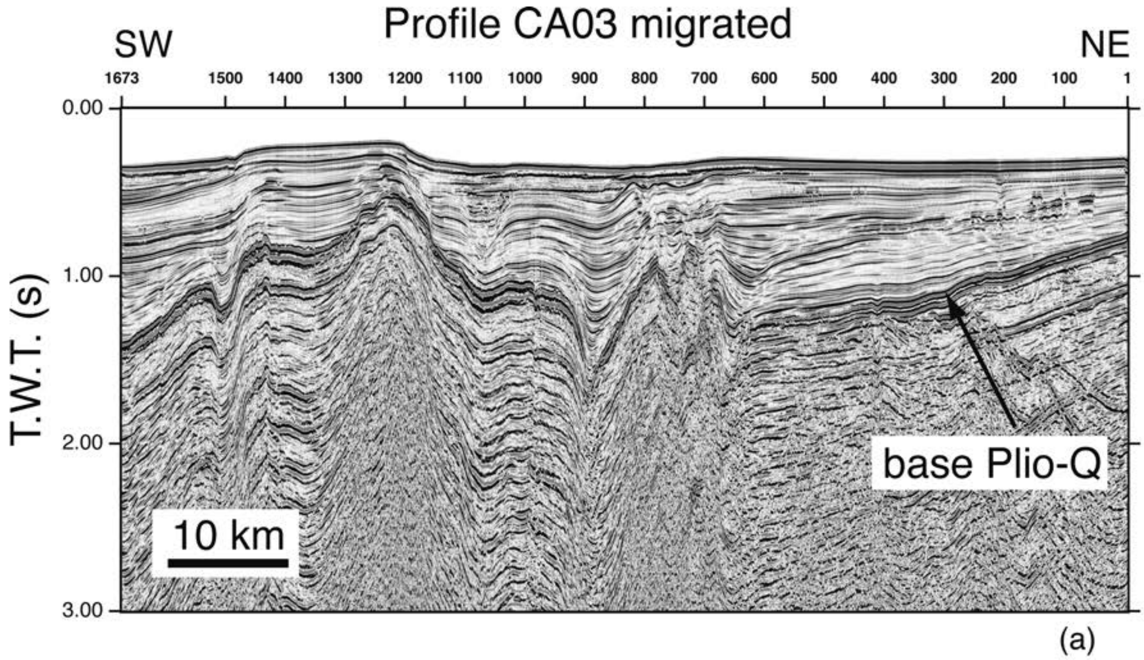


Fig. 5 - Structural map showing the main tectonic lineaments of the central Adriatic with focal mechanisms taken from Harvard and MedNet catalogues and from Frepoli and Amato (2000a). Location of seismic profiles CA03 and PG05, shown in Fig. 6, is also indicated by thick black lines. Most of the structures identified, represented as axes of anticlines and thrust fronts (thick lines with triangles), shows activity during the Quaternary. Note the broad area of deformation that extends over the central Adriatic foreland and that is also connected to the southern part of the Dinaride thrust front.

a major deformation belt Argnani *et al*., 1993, 2004b) that trends NE-SW and crosses the Tremiti Islands (Fig. 6b). Although folds and reverse faults are abundant in the central Adriatic, there is no evidence of a single major discontinuity that can act as a boundary at the lithospheric scale, as required by most GPS-based kinematic modelling (e.g. Battaglia *et al*., 2004). A very similar kind of deformation has been observed south of the Gargano promontory (Argnani *et al*., 1993, 2004a), with a deformation belt that continues to the east from the E-W-trending Mattinata Fault, located onshore (Fig. 5). Even in this case, however, the occurrence of a single, major discontinuity cutting the Adriatic plate does not find support.

A limited seismicity has been recorded south of Salento, the tip of Puglia, and a few focal mechanisms obtained by first arrivals suggest the occurrence of strike-slip faulting (Fig. 3). Although this region might have also been the site of a rather large historical earthquake which affected both southern Puglia and the Ionian Islands [February 20, 1743, Mw 6.9: Gruppo di



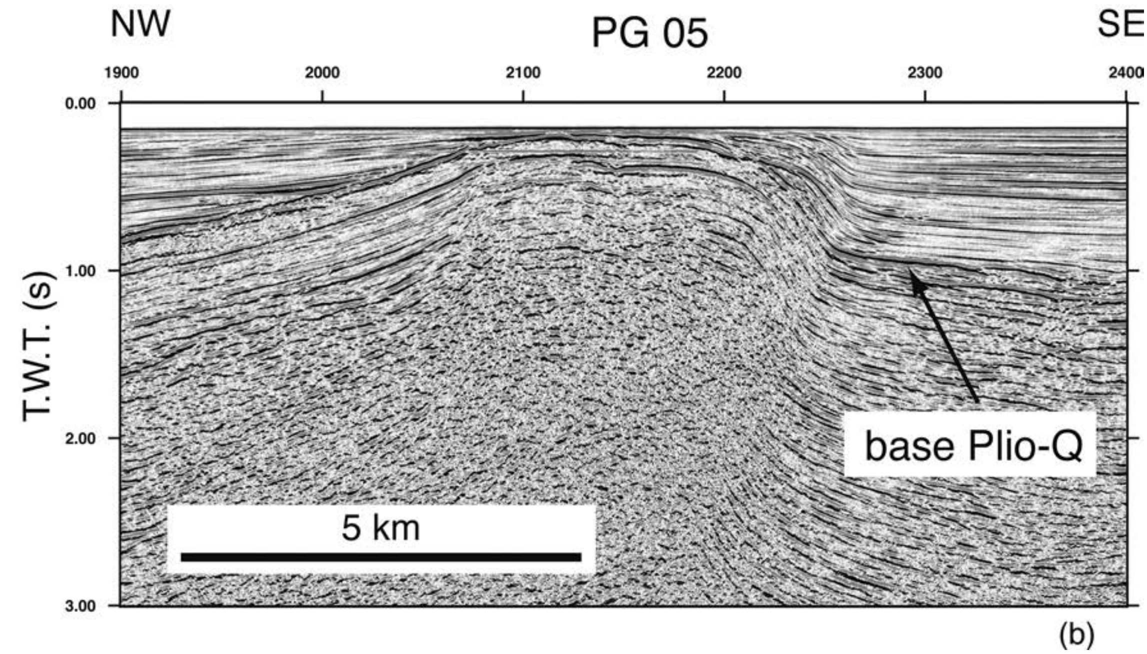


Fig. 6 - a) Seismic profile CA03 crossing the central Adriatic foreland and showing the extensive folding affecting the Plio-Quaternary sediments. Note the large vertical exaggeration b) Seismic profile PG05 crossing the Tremiti deformation belt and showing a broad fold described by the reflector marking the base of the Plio-Quaternary succession. Note the growth strata in the Plio-Quaternary sediments on the southern limb of the fold. Profile locations are on Fig. 5.

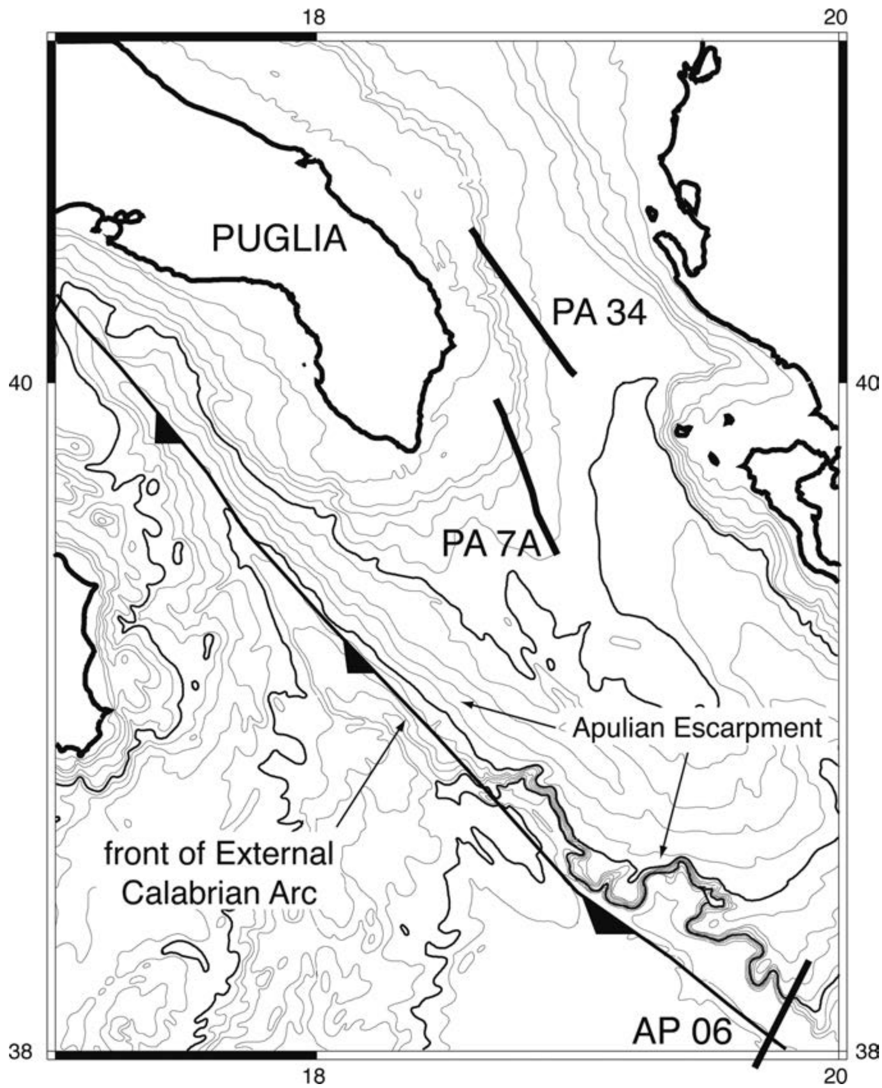


Fig. 7 - Bathymetry of the north-eastern part of the Ionian Sea showing the Apulian Escarpment and the front of the External Calabrian Arc. Location of seismic profiles shown in Figs. 8 and 9 is also indicated.

Lavoro CPTI, 2004) not much seismic activity is currently going on. In the early attempts to account for the active tectonics of the Adriatic region, the limited seismicity of the Otranto Channel was taken as the expression of a boundary decoupling Adria from Africa (Anderson, 1987; Anderson and Jackson, 1987), a suggestion that is still followed (e.g. Goes *et al*., 2004). Seismic profiles over this region show the occurrence of extensional faults of limited extent that trend roughly NW-SE (Mascle *et al*., 1984; Argnani *et al*., 2001). These faults are located on the crest of the Adriatic plate that has been arched under the double load of the Calabrian Arc, to the west, and Hellenides, to the east. Major tectonic structures trending E-W are remakably absent south of Salento, as shown by the seismic profiles where the Plio-Quaternary sediments are almost undeformed (Figs. 7 and 8).

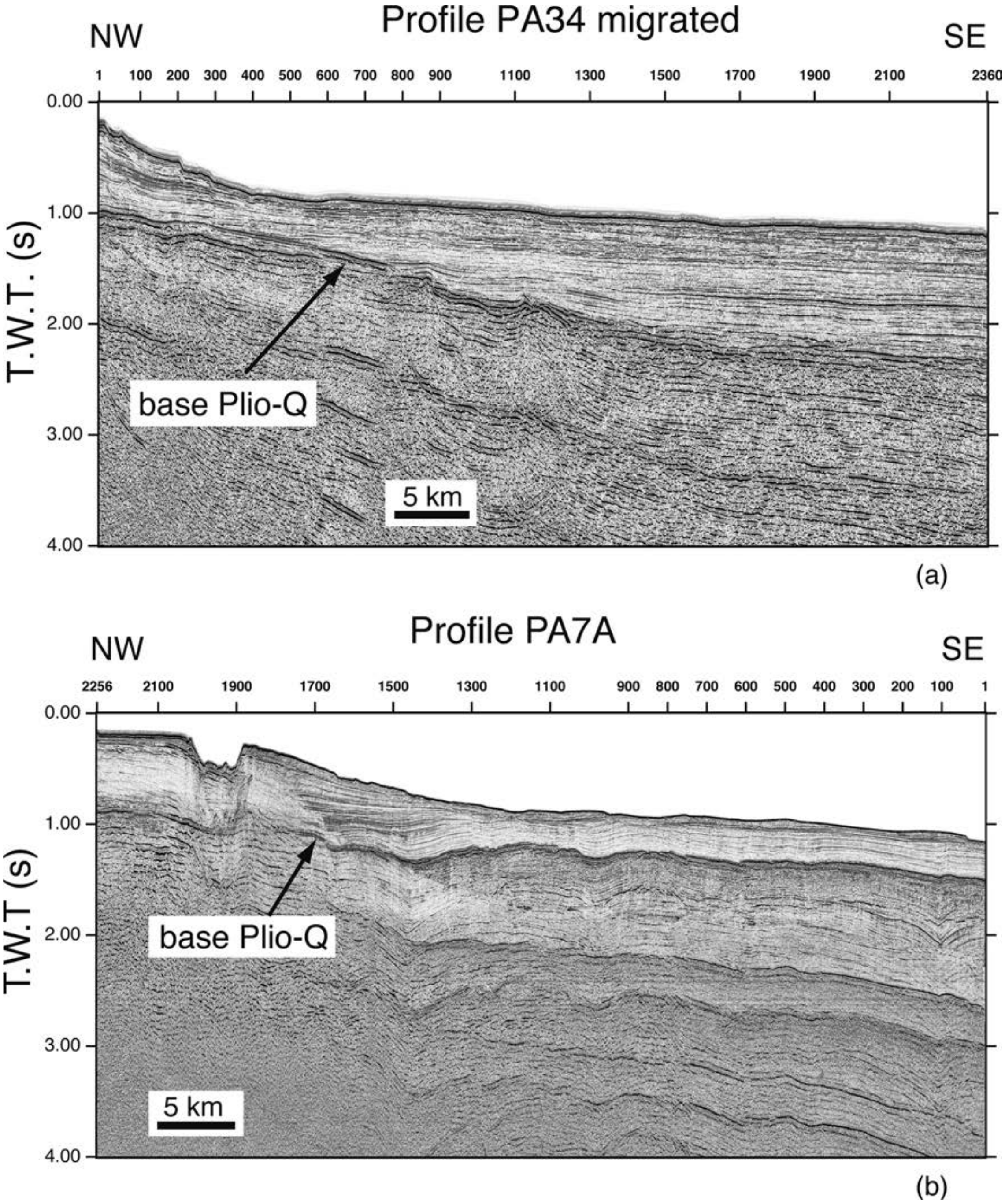


Fig. 8 - Seismic profiles PA34 and PA7A. The two profiles trend NW-SE and cover the area located south of the tip of Puglia (see Fig. 7 for location). Note that no major discontinuity affecting the Plio-Quaternary sedimentary succession is observed.

The Apulian Escarpment is the steep, erosional margin of the Mesozoic Apulian carbonate platform, and represents the north-eastern boundary of the deep Ionian basin (Fig. 7). Because of its sharp morphological expression, it has also been considered as a possible boundary of an independent Adria plate (Battaglia *et al.*, 2004; Serpelloni *et al*., 2005). The External Calabrian Arc accretionary wedge is resting onto the Apulian Escarpment over most of its length, making it difficult to assess an eventual tectonic activity along the escarpment. However, some embayments occur along the erosional carbonate margin and have been filled by Plio-Quaternary sediments (Fig. 7). A seismic profile, crossing the Apulian Escarpment, shows that the flat-lying Plio-Quaternary sediments are resting on the carbonate platform margin without any deformation (Fig. 9). On the other hand, the same strata have been deformed close to the External Calabrian Arc accretionary wedge, which currently appears active.

In summary, the occurrence of the suggested plate boundaries is not supported by geological evidence, nor by the distribution of seismicity; rather, a complex pattern of deformation seems to characterize the Adriatic region (see e.g. Caporali *et al.*, 2003). Any kinematic model that aims at fitting the GPS velocities should in some way account for the non-rigid behaviour of the Adriatic region.

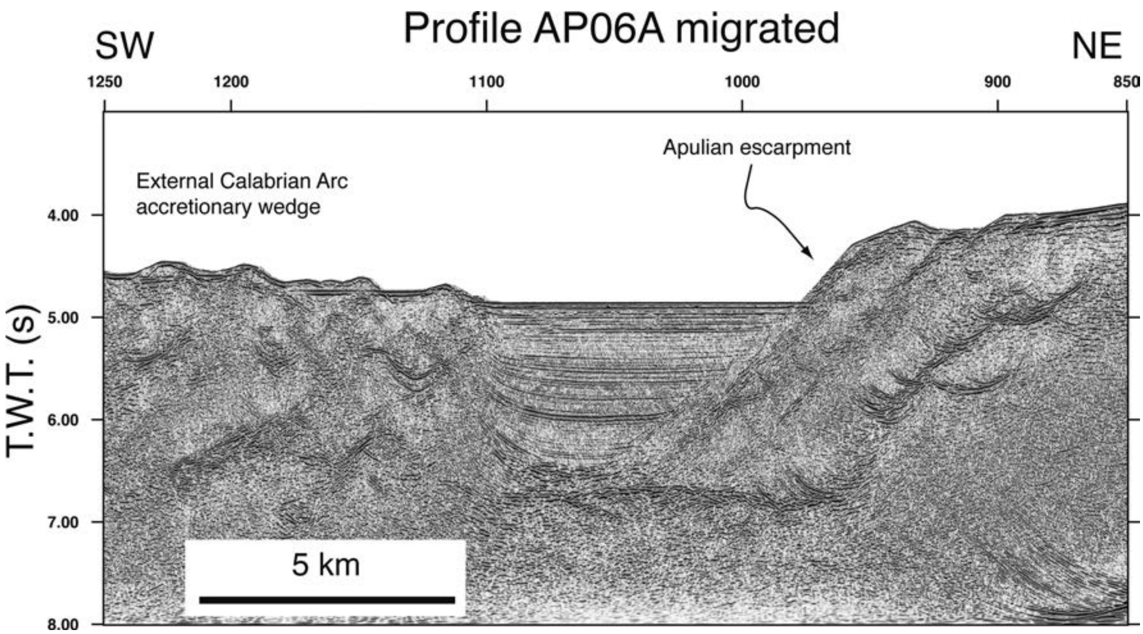


Fig. 9 - Seismic profile AP06A crossing the Apulia escarpment and entering the External Calabrian Arc accretionary wedge (see Fig. 7 for location). Note the subhorizontal and subparallel reflections onlapping undisturbed the Apulian escarpment. The same reflections are slightly folded close to the accretionary wedge which, therefore, appears to be active.

6.2. Calabrian Arc

The kinematics description of the Calabrian Arc region has greatly benefitted from the recently acquired GPS measurements (Hollestein *et al.*, 2003; D'Agostino and Selvaggi, 2004; Goes *et al.*, 2004; Jenny *et al.*, 2004; Pondrelli *et al.*, 2004b). It appears that no, or very limited, backarc spreading is currently active in the Tyrrhenian Sea, which is moving more or less like the Eurasian plate; and, therefore, slab rollback has ceased. Calabria, on the other hand, is moving independently from both Eurasia and Nubia. The lack of information about the relative motion of the Ionian region, however, does not allow us to distinguish between the hypothesis of an Ionian lithosphere connected to Nubia, as opposed to an independent Ionian lithosphere. In the former case, subduction is taken to be still active beneath the Calabrian Arc (Fig. 10a), at the rather limited rate of ca. 5 mm/yr, and plate convergence is supposed to be partitioned by the occurrence of a forearc sliver that includes Calabria (D'Agostino and Selvaggi, 2004). Other authors, instead, assume that the Ionian lithosphere is moving separately from Nubia, and that subduction is locked underneath the Calabrian Arc (Goes *et al.*, 2004; Jenny *et al.*, 2004). In this case, Calabria is supposed to be carried NNE-ward with respect to Eurasia, along with the Ionian lithosphere (Fig. 10b), as a result of a major tectonic reorganization that has affected the central Mediterranean around 0.8-0.5 Myr (Jenny *et al.*, 2004; Goes *et al.*, 2004).

The two above-mentioned kinematic solutions, that have been proposed to account for GPS observations, imply the occurrence of some kind of tectonic boundaries in order to accomplish the independent motion of Calabria.

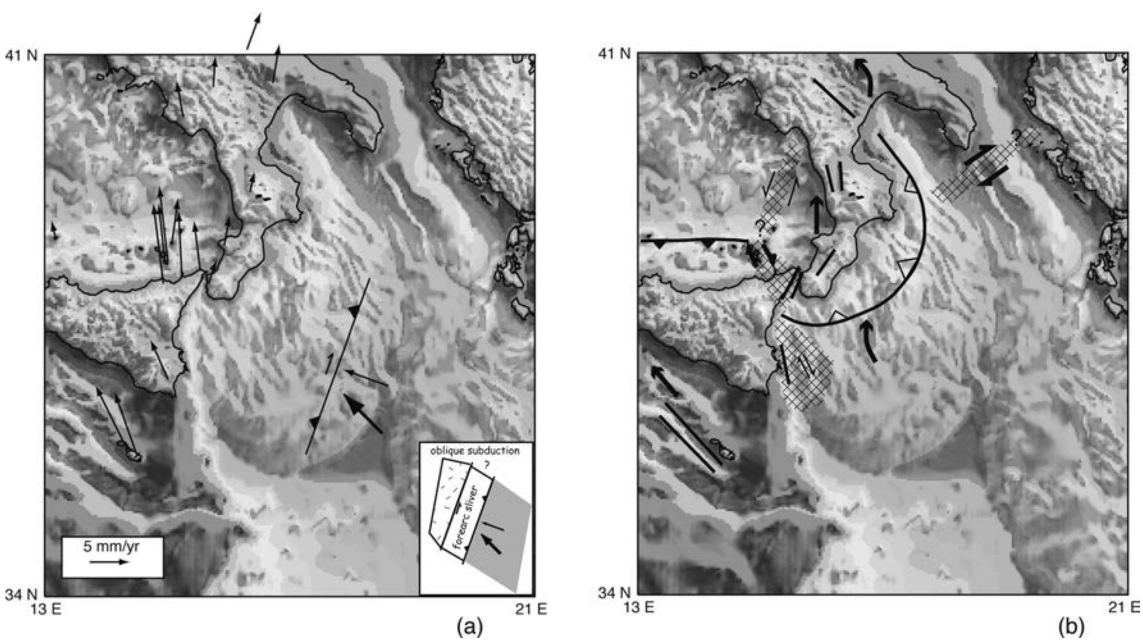


Fig. 10 - a) GPS motions with respect to Eurasia for stations located in the Sicily-Calabria region (after D'Agostino and Selvaggi, 2004). Inset summarizes the forearc sliver model proposed by the authors. b) Tectonic sketch for the Calabrian-Ionian region based on combined interpretation of GPS and seismological data (after Goes *et al.*, 2004; Jenny *et al.*, 2004). Large-scale rotation of blocks is indicated by arrows, whereas the grid pattern indicates belts of active deformation. The Calabrian Arc subduction is assumed to be locked.

Within the assumption of Calabria moving independently as a forearc sliver, a sinistral strike-slip fault with direction sub-parallel to GPS motion is required on the Tyrrhenian side of Calabria (Fig. 10a). Although recent geophysical studies concerning the neotectonics of the SW Tyrrhenian basin are lacking, the coverage of seismic profiles collected in the 70's is good enough to rule out the occurrence of a major active fault that could help to accommodate the NNE-ward motion of Calabria (e.g. Barone *et al*., 1982; Fabbri *et al*., 1982). The lack of major faults bounding the Tyrrhenian side of Calabria also seems supported by the recently released morpho-bathymetric map of the Tyrrhenian Sea (Marani *et al*., 2004), which coverages, however, a limited water depth of over 500 m.

Furthermore, the component of motion parallel to the trench should only occur within the arc-accretionary wedge system, whereas a northward motion with direction comparable (and larger magnitude) to that observed in Calabria has been measured also in stations located in Puglia, sitting on the foreland of the Apennines. It seems, therefore, that if some partitioning is occurring within the Calabrian Arc accretionary wedge, it cannot be simply described by the motion of a forearc sliver.

If, on the other hand, it is assumed that the whole Ionian lithosphere and the Calabrian Arc are moving together, and independently with respect to Eurasia and Nubia, a system of neotectonic faults is expected to bound the newly developed Ionian plate (Fig. 10b). The internal deformation in the Ionian region is supposed to be due to a major tectonic reorganization that caused the locking of the Calabrian subduction, with the pull from the Aegean slab becoming the dominant force in play (Goes *et al*., 2004; Jenny *et al*., 2004).

A kind of loose boundary that runs across the southern Tyrrhenian basin, through the N-S branch of the Aeolian Islands and along the Malta Escarpment has been proposed (Jenny *et al*., 2004), together with a boundary that cuts across the Adria plate south of Salento with a NE-SW trend (Fig. 10b). The difficulty of placing an active boundary in the southern Tyrrhenian basin has been discussed above. Moreover, no obvious boundary can be located south of Apulia (Fig. 8), where seismic profiles seem to rule out the occurrence of a major tectonic discontinuity (Argnani *et al*., 2001).

The main problem faced by the hypothesis of an Ionian plate that is independent from Africa, however, bears on the location of the southern boundary of the Ionian plate. It has been suggested that this boundary could continue along the Malta Escarpment to the south, towards the coast of Africa and then eastwards, to isolate an Ionian-Eastern Mediterranean plate (Benedetti *et al*., 2005). However, there is little, if any, geological evidence, nor indication from seismicity (Fig. 2) in support of the occurrence of such a long boundary. Moreover, whereas little is known on the neotectonics along the African margin of the eastern Mediterranean basin, the active tectonics along the Malta Escarpment appear to be limited to its northern portion, offshore Sicily (Argnani and Bonazzi, 2003, 2005).

In summary, although the new GPS results offer additional constraints to the geological interpretation of the Calabrian region, some major discrepancies still occur, and the boundaries of the blocks, or platelets, with apparently coherent GPS motion, need to be identified and characterized. As these boundaries are often located at sea, additional geophysical studies need to be carried out in the Ionian region in order to solve (or try to solve) the current ambiguity of interpretations.

6.3. Compressional belt offshore northern Sicily

Focal mechanisms (Fig. 3) have recently shown the occurrence of a compressional belt located in the southern Tyrrrhenian Sea, north of Sicily (Pondrelli *et al*., 2004b; Vannucci *et al*., 2004). P-axes trend NNE-SSW, a direction in good agreement with the Nuvel-1 global motion of Africa relative to Europe (DeMets *et al*., 1990) and with the similar VLBI and permanent GPS determined velocities (Ward, 1994; Caporali *et al*., 2003; D'Agostino and Selvaggi, 2004; Serpelloni *et al*., 2005). This belt trends roughly E-W and extends for some 200 km, with an eastern termination near the Island of Salina, in the Aeolian Islands. Moreover, GPS data indicate that the convergence between Nubia and Eurasia is absorbed completely, or by a large extent, in the seismic belt located in the southern Tyrrhenian Sea (Hollenstein *et al*., 2003; D'Agostino and Selvaggi, 2004; Goes *et al*., 2004; Serpelloni *et al*., 2005).

These pieces of evidence have led to infer the onset of a new tectonic regime, with the young Tyrrhenian lithosphere that has started being subducted to the south, underneath Sicily (D'Agostino and Selvaggi, 2004; Goes *et al*., 2004; Faccenna *et al*., 2005).

Geological data in that region, however, give little support to the occurrence of a subduction zone. In fact, both seismic profiles (Fabbri *et al*., 1982; Spagnoli, 1988; Pepe *et al*., 2000, 2004) and multibeam swath bathymetry (Marani *et al*., 2004) show no obvious trace of a single, large-scale geological feature chracterized by compression. Moreover, extensional tectonics have been documented up to late Pliocene - early Pleistocene in the sedimentary basins located along the northern Sicilian slope (Fabbri *et al*., 1982; Spagnoli, 1988; Pepe *et al*., 2000). Finally, the southern Tyrrhenian basin is characterized by high heat flow [e.g. Argnani and Savelli (2001) and references therein] and a thin lithosphere (less than 50 km) which is expectedly rather buoyant and difficult to be subducted.

It should be also mentioned that a different interpretation, based on an E-W-trending dextral simple shear acting along the southern Tyrrrhenian margin, has been proposed to account for the observed seismicity (Giunta *et al*., 2004). However, the great complexity of the inferred fault network, where strike slip faults dominate, is not supported on seismic profiles or on multibeam swath bathymetry.

The docking of an accretionary wedge onto the continental margin has previously occurred along northern Africa, to originate the Tell FTB belt in the middle-late Miocene (Frizon de Lamotte *et al*., 2000). If reversal of subduction is the following evolutionary step, we should see it in an advanced stage along the northen African margin, where about 10 Myr have elapsed since the supposed slab breakoff (Carminati *et al*., 1998); but even there, indication is very scanty (Deverchere *et al*., 2004) and open to debate. Moreover, it seems that the Africa Eurasia convergence along north Africa has been absorbed by foreland deformation in the Atlas during Quaternary (Frizon de Lamotte *et al*., 2000; Piquet *et al*., 2002), rather than by the initiation of a new subduction with opposite polarity.

It might be interesting to note that even in places like the Banda Arc, where docking of an accretionary prism and a volcanic arc onto the Australian continent occurred during Pliocene, and where more extensive indications of reversal of subduction are present, the real onset of a new subduction cannot be surely assessed (Snyder *et al*., 1996).

As a possible alternative, it should be considered that extension has affected the southern Tyrrhenian margin, until the Pleistocene, and, therefore, it seems possible that a recent change in the tectonic regime towards compression across the whole orogenic belt would affect, in the first place, the part of the orogenic belt that was more undercritical in terms of orogenic taper, i.e. the part that had previously been undergoing extension. In fact, the portions of the Maghrebian orogenic belt that have been subsequently extending seem to be particularly sensitive to the fluctuations of compressional stress, as shown by the widespread inversion occurring in the Egadi basins (Gamberi and Argnani, 1995). If this is the case, there is no need to have e reversal in the subduction polarity, an event for which there is no apparent evidence. Although a reversal in subduction can be the ultimate fate of the western Mediterranean orogeny, the current tectonic activity seems to record something different.

It is worth noting that the onset of a new subductive boundary in the southern Tyrrhenian would affect the kinematics of the region more, creating a dextral transform boundary between the NW-dipping Ionian subduction and the S-dipping Tyrrhenian subduction, with the Messina Straits being located within this transform belt [the diffuse transfer zone of Goes *et al*. (2004)]. Within this interpretation, for instance, extensional faulting in the Messina Straits is due to plate kinematics rather than to regional causes, such as uplift (Monaco and Tortorici, 2000). Therefore, to better constraint the kinematics of the south-eastern Tyrrhenian corner has relevance on the assessement of seismic hazard in a region that has suffered the largest and most damaging Italian earthquakes.

Conclusions

The growing amount of GPS velocity measurements in the central Mediterranean region is challenging previously consolidated neotectonic interpretations. However, the many papers offering kinematic models for the central Mediterranean, or for part of it, often ignore the geological constraints available, particularly when marine areas are concerned. This contribution has attempted to present and discuss some of the inconsistencies of GPS-based models which appear when geological data from marine areas are taken into account. In particular, the assumption of rigid plate kinematics that has often been applied to the Adriatic region seems difficult to reconcile with geological evidence. Perhaps, further efforts should be directed on modelling procedures that can take into account intraplate deformation, when fitting GPS horizontal velocities to obtain crustal scale kinematics.

An additional aspect, which is currently puzzling, concerns the lack of sound geodynamic processes that can account for some of the GPS-derived kinematics. Carefully devised geodynamical modelling would possibly help in better understanding the current kinematics of the Mediterranean, and, therefore, in better assessing the potential seismic hazard of this region. It should be noted, however, that a reliable kinematic description should be based on GPS data from permanenent stations with time series longer than 3 years (Caporali, 2003), whereas the kinematics obtained from local networks is not always easily fitted within the regional frame.

It may also be useful to consider the three-dimensionality of the deformation in the central Mediterranean. For instance, major deformation of the Adria lithosphere occurs in the region located south of Salento, where the double loading of the subducted slab by the External Calabrian Arc, to the west, and the Hellenides, to the east and south-east, causes bending of the lithosphere with a small radius of curvature (Moretti and Royden, 1988; Argnani *et al*., 2001).

The ensuing rheological weakening may perhaps focus the deformation in this region, though without developing a well-defined plate boundary, allowing counter clockwise rotation of Adria under the push of Africa-Eurasia convergence.

Acknowledgments. E. Serpelloni and A. Caporali are thanked for having invited this contribution to the GNGTS 2004 and for their useful review of the manuscript. C. Bonazzi and M. Rovere helped me with displays of seismic profiles. Several discussions with E. Serpelloni, G. Vannucci, S. Pondrellli, A. Morelli and P. Gasperini have greatly helped in shaping my understanding of the Mediterranean neotectonics. Any misunderstanding, however, is my own responsibility.

REFERENCES

Anderson H.; 1987: *Is the Adriatic an African promontory?* Geology, **15**, 212-215.

Anderson H. and Jackson J.; 1987: *Active tectonics of the Adriatic region*. Geophys. J. R. Astr. Soc., **91**, 937-983.

Argnani A.; 1987: *The Gela Nappe: evidence of accretionary melange in the Maghrebian foredeep of Sicily*. Mem. Soc. Geol. It., **38**, 419-428.

Argnani A.; 2000: *The southern Tyrrhenian subduction system: recent evolution and neotectonic implications.* Annali di Geofisica,. **43**, 585-607.

Argnani A.; 2005: *Possible record of a Triassic ocean in the southern Apennines*. Boll. Soc. Geol. It., **124**, 109-121.

Argnani A. and Bonazzi C.; 2003: *Neotectonics of the Eastern Sicily Offshore: recent reactivation of an old structure*. In: Workshop on Seismogenic faulting and seismic activity in the Calabrian Arc region, Taormina, 16-18 October 2003, pp. 12-13.

Argnani A. and Bonazzi C.; 2005: *The Malta Escarpment fault zone offshore eastern Sicily: Pliocene-Quaternary tectonic evolution based on new multichannel seismic data.* Tectonics, 24, TC4009, doi:10.1029/2004TC001656, 2005.

Argnani A. and Frugoni F.; 1997: *Foreland deformation in the Central Adriatic and its bearing on the evolution of the Northern Apennines.* Annali di Geofisica, **40**, 771-780.

Argnani A. and Ricci Lucchi F.; 2001: *Tertiary siliciclastic turbidite systems.* In: Vai G.B. and Martini I.P. (eds). Anatomy of a Mountain: the Apennines and adjacent Mediterraneanbasins, Kluver Academic Pub., Dordrecht, The Netherlands, pp. 327-350.

Argnani A. and Savelli C.; 1999: *Cenozoic volcano-tectonics in the southern Tyrrhenian Sea: space-time distribution and geodynamic significance.* J. Geodynamics, **27**, 409-432.

Argnani A. and Savelli C.; 2001: *Magmatic signature of episodic backarc rifting in the southern Tyrrhenian sea.* In Ziegler P., Cavazza W., Robertson A.H.F.R. and Crasquin-Soleau S. (eds), PeriTethys Memoir 6: Rift/Wrench Basins and Passive Margins. Mem. Mus. d'Histoire Nat., **186**, pp. 735-754.

Argnani A., Favali P., Frugoni F., Gasperini M., Ligi M., Marani M., Mattietti G. and Mele G.; 1993: *Foreland deformational pattern in the southern Adriatic sea*. Annali di Geofisica, **36**, 229-247.

Argnani A., Bonazzi C., Evangelisti D., Favali P., Frugoni F., Gasperini M., Ligi M., Marani M. and Mele G.; 1996: *Tettonica dell'Adriatico meridionale*. Mem. Soc. Geol. It., **51**, 227-237.

Argnani A., Frugoni F., Cosi R., Ligi M. and Favali P.; 2001: *Tectonics and seismicity of the Apulian Ridge south of Salento Peninsula (Southern Italy)*. Ann. Geofisica., **44**, 527-540.

Argnani A., Bonazzi C. and Costa Pisani P.; 2002: *Neogene deformation in the central Adriatic Sea.* Milano, Boll. Geof. Teor. Appl., **42**, 135-138.

Argnani A., Bonazzi C. and Rovere M.; 2004a: *Seismic expression of the Mattinata Fault offshore south Gargano*. Abstract, GIGS, Prato, 28-30 Gennaio 2004.

Argnani A., Rovere M., Del Castello M. and Bonazzi C.; 2004b: *Seismic images of the Tremiti Deformation Belt*. Abstract, GIGS, Prato, 28-30 Gennaio 2004.

Aubouin J., Blanchet R., Cadet J-P., Celet P., Charvet J., Chorowicz J., Cousin M. and Rampnoux J-P.; 1970: *Essai sur la geologie des Dinarides*. Bull. Soc. geol. de France, **6**, 1060-1095.

Auroux C., Mascle J. and Rossi S.; 1984: *Geologia del margine ionico delle isole Strofadi a Corfù (estremità settentrionale dell'Arco ellenico)*. Mem. Soc. Geol. It., **27**, 267-286.

Babbucci D., Tamburelli C., Viti M., Mantovani E., Albarello D., D'Onza Francesca, Cenni N. and Mugnaioli E.; 2004: *Relative motion of tthe Adriaic with respect to the confining plates: seismological and geodetic constraints.* Geoph. J. Int., **159**, 765-779.

Barone A., Fabbri A., Rossi S., Sartori R.; 1982: *Geological structure and evolution of the marine areas adjacent to the Calabrian arc*. Earth Evolution Sciences, **3**, 207-221.

Battaglia M., Murray M.H., Serpelloni E. and Buergmann R.; 2004: *The Adriatic region: an independent microplate within the Africa-Eurasia collison zone*. Geoph. Res. Lett., **31**, L09605, doi: 10.1029/2004GL019723, 2004.

Benedetti L., Nocquet J.M., and Tapponnier P.; 2005: *Active kinematics of Italy and adjacent regions: fragmentation of the Africa-Adria plate*. Geophysical Research Abstract, **7**, EGU General Assembly, Wien, **7**, 09781.

Bertotti G., Picotti V., Chilovi C., Fantoni R., Merlini S. and Mosconi A.; 2001: *Neogene to Quaternary sedimentary basins in the south Adriatic (Central Mediterranean): foredeeps and lithospheric buckling*. Tectonics, **20**, 771-787.

Biju-Duval B., Morel Y., Baudrimont A., Bizon G., Bizon J.J, Borsetti A.M. and 11 Others; 1982: *Donnees nouvelles sur le marges du bassin Ionien profond (Mediterranee Orientale) resultats des campagnes Escarmed*. Rev. Inst. Francais Petrole, **37**, 713-731.

Bonardi G., Cavazza W., Perrone V. and Rossi S.; 2001: *Calabria-Peloritani terrane and northern Ionian Sea*. In: Vai G.B. and Martini I.P. (eds), Anatomy of a Mountain: the Apennines and adjacent Mediterranean Basins, Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 287-306.

Bordoni P. and Valensise G.; 1998: *Deformation of the 125 ka marine terrace in Italy: tectonic implecations*. In Stewart I. S. and Vita Finzi C. (eds), Coastal Tectonics, Geol. Soc. London, Spec. Publ., **146**, pp. 71-110.

Braunmiller J., Kradolfer U. and Giardini D.; 2002: *Regional moment tensor determination in the European-Mediterranean area – initial results.* Tectonophysics, **356**, 5-22

Burke K. and Sengör C.; 1986: *Tectonic escape in the evolution of the continental crust*. In: Barazangi M. and Brown L. (eds). Reflection Seismology: the continental crust, AGU Geodyn. Ser., **14**, pp. 41-53.

Calais E., Nocquet J.-M., Jouanne F. and Tardy M.; 2002: *Current strain regime in the Western Alps from continuous Global Positioning System measurements, 1996-2001*. Geology, **30**, 651-654.

Caporali A.; 2003: *Average strain rate in the Italian crust inferred from a permanent GPS network-I. Statistical analysis of time-series of permanent GPS stations*. Geoph. J. Int., **155**, 241-253.

Caporali A., Martin S. and Massironi M.; 2003: *Average strain rate in the Italian crust inferred from a permanent GPS network – II. Strain rate versus seismicity and structural geology.* Geoph. J. Int., **155**, 254-268.

Carminati, E., Wortel, M.J.R., Spakman, W. and Sabadini, R.; 1998: *The role of slab detachment processes in the opening of the western-central Mediterranean basins; some geological and geophysical evidence.* Earth and Planetary Science Letters, **160**, 651-665.

Casero P., Roure F., Endignoux L., Moretti I., Mueller C., Sage L. and Vially R.; 1988: *Neogene Geodynamic evolution of the Southern Apennines*. Mem. Soc. Geol. It., **41**, 109-120.

Catalano R., Doglioni C. and Merlini S.; 2000: *On the Mesozoic Ionian Basin*. Geoph. J. Intern., **144**, 49-64.

Celet P., 1977: *The Dinaric and Aegean Arcs: the geology of the Adriatic*. In: Nairn A.E.M., Kanes W.H. and Stehli F.G. (eds), The Ocean Basins and Margins, Plenum Press, **4**, pp. 215, 261.

Channell J.E.T.; 1986: *Palaeomoagnetism and continental collision in the Alpine Belt and the formation of late-tectonic extensional basins.* In Coward M.P. and Ries A.C. (eds), Continental Collision, Geol. Soc. London, Spec. Publ., **19**, pp. 261-284.

Console R., Di Giovambattista R., Favali P., Presgrave B.W. and Smriglio G.; 1993: *Seismicity of the Adriatic microplate.* Tectonoph., **218**, 343-354.

Coward M. and Dietrich D.; 1989: *Alpine tectonics an overview.* In: Coward M., Dietrich D. and Park R. (eds), Alpine Tectonics, Geological Society of London Special Publication, **45**, pp. 1-29.

D'Agostino N. and Selvaggi G.; 2004: *Crustal motion along the Eurasia-Nuubia plate boundary in the Calabrian Arc and Sicily and active extension in the Messina Straits from GPS measurements.* J. Geoph. Res., **109**, B11402, doi:10.1029/2004JB002998, 2004.

Dal Piaz G.V., Bistacchi A. and Massironi M.; 2003: *Geological outline of the Alps*. Episodes, **26**, 175-180.

De Alteriis G.; 1995: *Different foreland basins in Italy: examples from the central and southern Adriatic Sea*. Tectonophysics, **252**, 349-373.

De' Dominiciis A. and Mazzoldi G.; 1987: *Interpretazione geologico-strutturale del margine orientale della piattaforma Apula.* Mem. Soc. Geol. It., **38**, 163-176.

DeMets C., Gordon R.G., Argus D.F., and Stein S.; 1990: *Current plate motions.* Geoph. J. Int., **101**, 425-478.

de Voogd B., Truffert C., Chamot-Rooke N., Huchon P., Lallemant S. and Le Pichon X., 1992: *Two-ship deep seismic sounding in the basins of the Eastern Mediterranean Sea*. Geoph. J. Inter., **109**, 536-552.

Dercourt J., Ricou L.E. and Vrielynck B. (eds); 1993: *Atlas Tethys Palaeoenvironmetal Maps.* Gauthgier-Villars, Paris, 307 pp.

Deverchere J., Yelles K., Domzig A., Mercier de Lepinay B., Bouillin J.-P. Gaullier V., Bracene R., Calais E., Savoye B., Kherroubi A., Le Roy P. and Pauc H. and Dan G.; 2004: *Active thrust faulting offshore Boumerdes, Algeria, and its relations to the 2003 Mw 6.9 earthquake*. Geoph. Res. Lett., **32**, L04311, doi:10.1029/2004GL021646, 2005

Dewey J.F.; 1980: *Episodicity, sequence, and style at convergent plate boundaries.* Geol. Assoc. Can. Spec. Pap., **20**, 553-537.

Dewey J.F.; 1988: *Extensional collapse of orogens.* Tectonics, **7**, 1123-1139.

Dewey J.F., Pitman W.C. III, Ryan W.B.F. and Bonnin J.; 1973: *Plate tectonics and the evolution of the Alpine system*. Geol. Soc. Am. Bull., **84**, 3137-3180.

Dewey J.F., Helman M.L., Turco E., Hutton D.H.W. and Knott S.D.; 1989: *Kinematics of the western Mediterranean.* In: Coward M.P., Dietrich D. and Park R.G. (eds), Alpine Tectonics, Geol. Soc. London, Spec. Publ., **45**, pp. 265-283.

Dziewonski A.M., Chou T.A. and Woodhouse J.H.; 1981: *Determination of earthquake source parameters from waveform data for studies of global and regional seismicity*. J. Geophys. Res., **86**, 2825-2852

Dziewonski A.M. and Maternovskaya N.N.; 2000: *Centroid-moment tensor solutions for October-December 1999*. Phys. Earth Planet. Int., **121**, 205-221.

England P. and Jackson J.; 1989: *Active deformation of the continents*. Ann. Rev. Earth Plan. Sci., **17**, 197-226.

Fabbri A., Rossi S., Sartori R. and Barone A.; 1982: *Evoluzione neogenica dei margini marini dell'Arco Calabro-Peloritano: implicazioni geodinamiche*. Mem. Soc. Geol. It., **24**, 357-366.

Faccenna C.B., Thorsten W., Lucente F.P., Jolivet L. and Rossetti F.; 2001: *History of subduction and back-arc extension in the Central Mediterranean*. Geophysical Journal International, **145**, 809-820. doi:10.1046/j.0956-540x.2001.01435.x

Faccenna C., Civetta L., D'Antonio M., Funiciello F., Marghriti L. and Piromallo C.; 2005: *Constraints on mantle circulation around the deforming Clabrian slab.* Geoph. Res. Lett., **32**, L06311, doi:10.1029/2004gl021874, 2005.

Favali P., Funiciello R., Mattietti G., Mele G., and Salvini F.; 1993: *An active margin across the Adriatic Sea (central Mediterranean Sea).* Tectonophysics, **219**, 109-117.

Finetti I.; 1984: *Structure and evolution of the Adriatic microplate.* Boll. Oceanol. Teor. Appl., **2**, 115-123.

Frepoli A. and Amato A.; 1997: *Contemporaneous extension and compression in the northern Apennines from earthquake fault-plane solutions*. Geophys. J. Int., **129**, 368-388.

Frepoli A. and Amato A.; 2000a: *Fault plane solutions of crustal earthquakes in Southern Italy (1988-1995): seismotectonic implications*. Annali di Geofisica, **43**, 437-467.

Frepoli A. and Amato A.; 2000b: *Spatial variation in stresses in peninsular Italy and Sicily from background seismicity*. Tectonoph., **317**, 109-124.

Frizon de Lamotte D., Saint Bezar B. and Bracene R.; 2000: *The two main steps of the Atals building and geodynamics of the western Mediterranean.* Tectonics, **19**, 740-761.

Gamberi F. and Argnani A.; 1995: *Basin formation and inversion tectonics on top of the Egadi foreland thrust belt (NW Strait fo Sicily)*. Tectonophysics, **252**, 285-294.

Gambini R., Thomas R. and Morandi S.; 1997: *Inversion tectonics on the central Adriatic Sea.* In: FIST, Geoitalia 1997, 5-9 Ottobre 1997, Riassunti, **2**, pp. 170-171.

Giunta G., Luzio D., Tondi E., De Luca L., Giorgianni A., D'Anna G., Renda P., Cello G., Nigro F. and Vitale M.; 2004: *The Palermo (Sicily) seismic cluster of September 2002, in the seismotectonic framework of the Tyrrhenian Sea-Sicily border area*. Annali di Geofisica, **47**, 1755-1770.

Goes S., Giardini D., Jenny S., Hollenstein C., Kahle H.-G. and Geiger A.; 2004: *A recent reorganization in the south-central Mediterranean*. EPSL, **226**, 335-345

Gruppo di lavoro CPTI; 2004: *Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04)*. INGV, Bologna. http://emidius.mi.ingv.it/CPTI/

Gvirtzman Z. and Nur A.; 1999: *The formation of Mount Etna as the consequence of slab rollback.* Nature, **401**, 782-785.

Hill K.C. and Hayward A.B.; 1988: *Structural constraints on the Tertiary plate tectonic evolution of Italy*. Mar. Petr. Geol., **5**, 2-16.

Hollenstein Ch., Kahle H.-G., Geiger A., Jenny S., Goes S. and Giardini D.; 2003: *New GPS constraints on the Africa-Eurasia plate boundary zone in southern Italy*. Geoph. Res. Lett., **30**, doi:10.1029/2003GL017554, 2003

Horvath F.; 1988: *Neotectonic behaviour of the Alpine-Mediterranean region.* In: Royden L.H. and Horvath F. (eds), The Pannonian Basin, AAPG Mem., **45**, pp. 49-55.

Horvath F. and Berckhemer H.; 1982: *Mediterranean backarc basins*. In: Berckhemer H. and Hsu K. (eds), Alpine-Mediterranean Geodynamics, AGU Geodynamic Series, **7**, pp. 141-173.

Jenny S., Goes S., Giardini D., Hollenstein Ch. and Kahle H.-G.; 2004: *Earthquake recurrence from seismic and geodetic strain rates in the South-Central Mediterranean.* In: Abstract, **6**, EGU General Assembly, Nice.

Kligfield R.; 1979: *The Northern Apennines as a collisional orogen.* Am. J. Sci., **279**, 676-691.

Le Pichon X., Bergerat F. and Roulet M.J.; 1988: *Plate kinematics and tectonics leading to the Alpine belt formation; A new analysis.* Geol. Soc. Am., Spec. Paper, **218**, 111-131.

Lickorish W.H., Grasso M., Butler R.W.H., Argnani A. and Maniscalco R.; 1999: *Structural styles and regional tectonic setting of the "Gela Nappe" and frontal part of the Maghrebian thrust belt in Sicily*. Tectonics, **18**, 655-668.

Malinverno A. and Ryan W.B.F.; 1986: *Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking in the lithosphere.* Tectonics, **5**, 227-245.

Mantovani E., Albarello D., Babbucci D., Tamburelli C. and Viti M.; 2002: *Trench-arc-backarc systems in the Mediterranean area: examples of extrusion tectonics*. J. Virtual Explorer, **8**, 125-141.

Marani M.P., Gamberi F., Bortoluzzi G., Carrara G., Ligi M. and Penitenti D.; 2004: *Seafloor bathymetry of the Ionian Sea.* In:. Marani M.P, Gamberi F. and Bonatti E. (eds), From seafloor to deep mantle: architecture of the Tyrrhenian backarc basin, Memorie Descrittive della Carta Geologica D'Italia, **44**.

Mascle J., Auroux C. and Rossi S.; 1984: *Structure geologique superficielle et evolution recente de la dorsale apulienne (Mer Ionienne)*. Rev. Inst. Francais Petrole, **39**, 127-142.

McClusky S., Balassanian S., Barka A., Demir C. Ergintav S., Gerogiev I., Gurkan O., Hamburger M., Hurst K., Kahle H., Kastens K., Kekelidze G., King R., Kotzev V., Lenk O., Mahmoud S., Mishin A., Nadariya M., Ouzounis A., Paradissis D., Peter Y., Prilepin M., Reilinger R., Sanli I., Seeger H., Tealeb A., Toksoz M.N. and Veis G.; 2000: *Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus*. J. Geoph. Res., **105**, 5695-5719.

McClusky S., Reilinger R., Mahmoud S, Ben Sari D. and Tealeb A.; 2003: *GPS constraints on Africa (Nubia) and Arabia plate motions*. Geophys. J. Int., **155**, 126-138.

McKenzie D.P.; 1972: *Active Tectonics of the Mediterranean Region.* Geoph. J. Royal. Astron. Soc., **30**, 109-185.

McKenzie D.P.; 1977: *Can Plate Tectonics describe continental deformation?* In: Biju Duval B. and Montadert L. (eds). Inter. Symp. Struct. History Mediterr., Technip, Paris, pp. 189-196.

Mele G.; 1998: *High-frequency wave propagation from mantle earthquakes in the Tyrrhenian Sea: new constraints for the geometry of the South Tyrrhenian subduction zone*. Geoph. Res. Lett., **25**, 2877-2880.

Menardi Noguera, A. and Rea, G.; 2000: *Deep structure of the Campanian-Lucanian arc (Southern Apennines, Italy).* Tectonophysics, **266**, 233-249.

Monaco C. and Tortorici L.; 2000: *Active faulting in the Calabrian arc and eastern Sicily.* J. Geodyn., 29, 407-424.

Moretti I. and Royden L.; 1988: *Delfection, gravity anomalies and tectonics of doubly subducted continental lithosphere: Adriatic and Ionian Seas.* Tectonics, **7**, 875-893.

Mostardini F. and Merlini S.; 1986: *Appennino centromeridionale. Sezioni geologiche e proposta di modello strutturale.* Mem. Soc. Geol. It., **35**, 177-202.

Muttoni G., Garzanti E., Alfonsi L., Cirilli S. and Germani D.; 2001: *Motion of Africa and Adria since the Permian: paleomagnetic and paleoclimatic constraints from northern Libya.* Earth Plan. Sci. Lett., **192**, 159-174.

Oldow J.S., Ferranti L., Lewis D.S., Campbell J.K., D'Argenio B., Catalano R., Pappone G., Carmignani L., Conti P. and Aiken C.L.V.; 2002: *Active fragmentation of Adria, the north Africa promontory, central Mediterranean orogen*. Geology, **30**, 779-782.

Patacca E. and Scandone P.; 2001: *late thrust propagation and sedimentary response in the thrust-belt-foredeep system of the Southern Apennines (Pliocene-Pleistocene)*. In: Vai G.B. and Martini I.P. (eds), Anatomy of a Mountain: the Apennines and adjacent Mediterranean Basins, Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 401-440.

Patacca E. and Scandone P.; 2004: *The Plio-Pleistocene thrust belt-foredeep system in the Southern Apennines and Sicily. Geology of Ital*y. In: Special Vol. Italian Geol. Soc. for the IGC 32 Florence 2004, pp. 93-129.

Patacca E., Sartori R. and Scandone P.; 1990: *Tyrrhenian basin and Apenninic arcs. Kinematic relations since late Tortonian times*. Mem. Soc. Geol. It., **45**, 425-451.

Patacca E., Scandone P. and Meletti C.; 1997: *Variazioni di regime tettonico nell'Appennino meridionale durante il Quaternario*. In: AIQUA annual meeting abstracts with program, Parma, pp. 21.

Pepe F., Bertotti G., Cella F. and Marsella E.; 2000: *Rifted margin formation in the south Tyrrhenian Sea: A high-resolution seismic profile acrross the north Sicily passive continental margin*. Tectonics, **19**, 241-257.

Pepe F., Bertotti G. and Cloetingh S.; 2004: *Tectono-stratigraphic modelling of the North Sicily continental margin (southern Tyrrhenian Sea)*. Tectonoph., **384**, 257-273.

Peruzza L., Renner G. and Slejko D.; 2002: *Stress field along the eastern Adriatic coast from earthquake fault plane solutions*. Memorie della Societa Geologica Italiana, **57**, 409-418.

Philip H.; 1987: *Plio-Quaternary evolution of the stress field in Mediterranean zones of subduction and collision.* Annales Geophys., **5B**, 301-320.

Pieri M. and Groppi G.; 1981: *Subsurface geological structure of the Po Plain, Italy.* Pubblicazione 414, Progetto Finalizzato Geodinamica, C.N.R., 13 pp.

Piquet A., Tricart P., Guraud R., Laville E., Bouaziz S., Amrhar M. and Ait Oulai R.; 2002: *The Mesozoic-Cenozoic Atlas belt (North Africa): an overview*. Geodin. Acta, **15**, 185-208.

Pondrelli S., Morelli A., Ekstroem S., Mazza S., Boschi E. and Dziewonski A.M.; 2002: *European-Mediterranean regional Centroid Moment Tensors Catalog: 1997-2000.* Phys. Earth Planet. Int., **130**, 71-101

Pondrelli S., Morelli A., and Ekstroem S.; 2004a: *European-Mediterranean regional Centroid Moment Tensor Catalog: solutions for the years 2001 and 2002.* Phys. Earth Planet. Int., **145**, 127-147.

Pondrelli S., Piromallo C. and Serpelloni E.; 2004b: *Convergence vs. retreat in Southern Tyrrhenian Sea: Insights from kinematics.* Geoph. Res. Lett., **31**, L06611, doi:10.1029/2003GL019223, 2004.

Ratschbacher L., Frisch W. and Linzer H-G.; 1991: *Lateral extrusion in the Eastern Alps, Part 2: structural analysis.* Tectonics, **10**, 257-271.

Réhault J.-P., Boillot G. and Mauffret A.; 1984: *The western Mediterranean Basin geological evolution*. Mar. Geol., **55**, 447-477.

Renner G. and Slejko D.; 1994: *Some comments on the seismicity of the Adriatic region*. Boll. Geof. Teor. Appl., **36**, 381-398.

Ricci Lucchi F.; 1986: *The Oligocene to Recent foreland basins of the Northern Apennines.* Spec. Publ. International Association Sedimentologists, **8**, 165-185.

Roeder D.; 1989: *South-Alpine thrusting and trans-Alpine convergence.* In: Coward M., Dietrich D. and Park R. (eds), Alpine Tectonics, Geological Society of London Special Publication, **45**, pp. 211-227.

Rossi S. and Sartori R.; 1981: *A seismic reflection study of the external Calabrian Arc in the N Ionian Sea (eastern Mediterranean)*. Marine Geophysical Researches, **4**, 403-426.

Roure R., Choukroune P. and Pollino R.; 1996: *Deep seismic reflection data and new insights on the bulk geometry of mountain ranges*. C.R. Acad. Sci. Paris, **322**, serie IIa, 345-359.

Roure F., Howell D.G., Mueller C. and Moretti I.; 1990: *Late Cenozoic subduction complex of Sicily.* J. Struct. Geol., **22**, 259-266.

Royden L. and Burchfiel B.C.; 1989: *Are systematic variations in thrust belt style related to plate boundary processes? (the western Alps versus the Carpathians)*. Tectonics, **8**, 51-61.

Scandone P., Patacca E., Radoicic R., Ryan W.B.F., Cita M.B., Rawson M., Chezar H., Miller E., McKenzie J. and Rossi S.; 1981: *Mesozoic and Cenozoic rocks from the Malta Escarpment (central Mediterranean)*. American Association of Petroleum Geologists Bulletin, **65**, 1299-1319.

Schmid S., Pfiffner A., Froitzheim N., Schoenborn G. and Kissling E.; 1996: *Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps*. Tectonics, **15**, 1036-1064.

Scrocca D., Carminati E. and Doglioni C.; 2005: *Deep structure of the southern Apennines, Italy: Thin-skinned or thick-skinned?* Tectonics, **24**, TC3005, doi:10.1029/2004TC001634, 2005

Selvaggi G. and Chiarabba C.; 1995: *Seismicity and P-wave image of the southern Tyrrhenian subduction zone.* Geoph. J. Int., **121**, 818-826.

Serpelloni E., Anzidei M., Baldi P., Casula G. and Galvani A.; 2005: *Crustal velocity and Stran-rate Fields in Italy and Surrounding regions: New Results from the analysis of Permanent and Non-Permanent GPS Networks*. Geoph. J. Int., **161**, 861-880.

Serpelloni E., Anzidei M., Baldi P., Casula G., Galvani A., Pesci A. and Riguzzi F.; 2001: *Geodetic deformations in the Central-Southern Apennines (Italy) from repeated GPS surveys,* Ann. Geofis., **44**, 627-648.

Serpelloni E., Anzidei M., Baldi P., Casula G., Galvani A., Pesci A. and Riguzzi F.; 2002: *Combination of permanent and non-permanent GPS networks for the evaluation of the strain-rate field in the central Mediterranean area*. Boll. Geof. Teor. Appl., **43**, 195-219.

Snyder D., Prasetyo H., Blundell D.J., Pigram C.J., Barber A.J., Richardson A. and Tjokosaproetro S.; 1996: *A dual doubly vergent orogen in the Banda Arc continet-arc collision zone as observed on deep seismic reflection profiles*. Tectonics, **15**, 34-53.

Spagnoli F.; 1988: *Morfostrutture, geometrie deposizionali e tettonica plio-quaternarie del bacino di Cefalù, Tirreno meridionale*. Unpublished Degree Thesis, Università degli Studi di Bologna.

Stampfli G., Marcoux J. and Baud A.; 1991: *Tethyan margins in space and time*. Palaeogeo., Palaeoclim., Palaeoec., **87**, 373-410.

Stampfli G., Mosar J., Favre P., Pillevuit A., and Vannay J.-C.; 2001: *Permo-Mesozoic evolution of the western Tethyan realm: the Neo-TethysEast Mediterranean basin connection*. In: Ziegler P., Cavazza W., Robertson A.H.F.R. and Crasquin-Soleau S. (eds), PeriTethyan Rift/Wrench Basins and Passive Margins, Mem. Mus. d'Histoire Nat., **186**, pp. 51-108.

Tortorici L., Monaco C., Tansi C. and Cocina O.; 1995: *Recent and active tectonics in the Calabrian arc (Southern Italy)*. Tectonoph., **243**, 37-55.

Underhill J. R., 1989: *Late Cenozoic deformation of the Hellenide foreland, western Greece*. Geol. Soc. Am. Bull, **101**, 613-634.

Valensise G. and Pantosti D.; 2001: *Seismogenic faulting, moment release patterns and seismic hazard along the central and southern Apennines and the Calabrian arc*. In: Vai G.B. and Martini I.P. (eds). Anatomy of a Mountain: the Apennines and adjacent Mediterranean Basins, Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 495-512.

Vannucci G. and Gasperini P.; 2004: *The new release of the database of Earthquake Mechanisms of the Mediterranean Area (EMMA Version 2)*. Annali di Geofisica, suppl. **47**, 307-334.

Vannucci G., Pondrelli S., Argnani A., Morelli A., Gasperini P. and Boschi E.; 2004: *An atlas of Mediterranean seismicity*. Annali di Geofisica, suppl. **47**, 247-306.

Ward S.N.; 1994: *Constraints on the seismo-tectonics of the central Mediterranean from very long baseline interferometry*. Geoph. J. In., **117**, 441-452.

Westaway R.; 1990: *Present-day kinematics of the plate boundary zone between Africa and Europe, from Azores to the Aegean*. Earth and Plan. Sc. Lett., **96**, 393-406.

Westaway R.; 1993: *Quaternary uplift of southern Italy*. J. Geoph. Res., **87**, 741-772.

Westaway R. and Jackson J.; 1987: *The earthquakes of 1980 November 23 in Campania-Basilicata (Southern Italy)*. Geoph. J. Royal Astr. Soc., **90**, 375-443.

Wortel R.J.R. and Govers R.; 2004: *Dynamic consequences of plate tearing at lateral terminations of subducting slabs: Slab-Transfer Edge-Propagator (STEP) fault*s. Abstracts, 224-6, 32 IGC, Florence, Italy, August 20-28.

Wortel M.J.R. and Spakman W.; 2000: *Subduction and slab detachment in the Mediterranean-Carpathian region*. Science, **290**, 1920-1917.

Yeats R.S., Sieh K. and Allen C.R.;1997: *The Geology of earthquakes.* Oxford Univ. Press, 568 pp.

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