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Thrust vs normal fault decollements in the Central Apennines

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ABSTRACT

In the Central Apennines the Neogene-Quaternary normal faults and thrusts strike with different trends. Notoriously the normal faults followed and cut thrust planes progressively shifting their activity to the east. From the different trends of thrusts and normal faults, and on the base of their geometric relationship, we infer different depths of the decollement planes. Due to the slab retreat, compression and extension appear controlled by shear zones between the downgoing lithosphere and the mantle. Following these kinematics, the basal decollement of the accretionary prism is located at shallow level (upper crust), whereas the decollement of the extensional belt to the west appears located at the base of the crust in the hangingwall of the subduction. Therefore the thrust belt is thin-skinned and it appears to be more sensitive to the shallower Mesozoic inherited structure, generating undulations and transfer zones located at facies margins. The extensional belt is instead thick-skinned and the orientation of the normal faults is more independent of upper crust mechanical properties; they strike more linearly and they are probably controlled by deep crustal-scale decollements.

KEY WORDS: *Central Apennines, decollements (detachment) depth, slab retreat, thin-skinned compression, thick-skinned extension.*

RIASSUNTO

Sulla profondità dei piani di scollamento dei sovrascorrimenti e delle faglie normali in Appennino Centrale.

Nell'Appennino centrale le faglie distensive e i sovrascorrimenti Neogenico-Quaternari presentano direzioni diverse. I sovrascorrimenti hanno mediamente direzioni variabili da N-S a NO-SE, mentre le faglie distensive mostrano valori di direzione più costanti e orientate parallelamente alla catena, cioè NO-SE. Con una migrazione generale del sistema da ovest ad est, è ben noto che le faglie distensive hanno seguito e tagliato i sovrascorrimenti. In questa breve nota viene proposta una diversa profondità dei piani di scollamento dei sovrascorrimenti e delle faglie distensive sulla base del diverso andamento delle direzioni rispettive e delle relazioni geometriche tra i due diversi sistemi. Compressione e distensione appaiono controllate da piani di scollamento deducibili dalla cinematica imposta dall'arretramento della subduzione e dal suo approfondimento nel mantello. Secondo questa ricostruzione, lo scollamento basale del prisma di accrezione è localizzato nella crosta superiore, mentre lo scollamento della distensione è posto alla base della crosta, a tetto della subduzione. Per la sua maggiore superficialità, il prisma di accrezione è maggiormente sensibile alle anisotropie del margine continentale passivo Mesozoico, con le sue variazioni laterali di facies e di struttura, generando ondulazioni di oltre 30-40° nella direzione dei piani di sovrascorrimento. La fascia distensiva, avendo invece piani di scollamento più profondi alla base della crosta o litosfera, presenta faglie distensive con direzione più costante, probabilmente meno sensibile alle geometrie delle strutture pellicolari.

TERMINI CHIAVE: *Appennino centrale, profondità scollamenti, arretramento subduzione, compressione pellicolare, estensione crostale.*

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INTRODUCTION

The Apennines are a mainly Neogene-Quaternary accretionary prism generated by the westward subduction of the Adriatic plate (SCANDONE, 1979; TREVES, 1984; MALINVERNO & RYAN, 1986). Compression in the eastern side, and extension in the central-western part of the belt characterized the entire structural evolution of the Apennines. The paired compression and extension migrated eastward (MAZZANTI & TREVISAN, 1978; BARCHI *et alii*, 1998) while the hinge of the subduction and the slab rolled-back in the same direction (PATACCA & SCANDONE, 1989; GUEGUEN *et alii*, 1998). Thrusts shortened the sedimentary cover of the Mesozoic Adriatic passive continental margin (PAROTTO & PRATURLON, 1975; CASTELLARIN *et alii*, 1978; BERNOULLI *et alii*, 1979; BALLY *et alii*, 1986; CIPOLLARI *et alii*, 1995; PATACCA & SCANDONE, 1989). Relics of accreted oceanic crust may be found in Calabria, Tuscany and Liguria (e.g. BOCCALETTI *et alii*, 1990a,b). The normal faults cross-cut the whole thrust belt (e.g. KELLER *et alii*, 1994; BARCHI *et alii*, 1998). In the Central Apennines (fig. 1), thrusts strike with different trends with respect to the normal faults and we aim to investigate the nature of this angle: is it related to the rotation of the thrust sheets prior the extensional tectonics or is it related to different mechanical constraints of the two tectonic regimes? Decollement horizons are primary features in any type of tectonic settings, their depth being controlled by a number of factors, i.e. density of rocks, fluids distribution, shear strength and geodynamic constraints. In this paper we briefly discuss how the angle between thrusts and normal faults could be an indication of the different depths of the relative decollement planes. This theme has been one of the several lines of interest of Giampaolo Pialli during his prolific scientific career.

GEOLOGICAL SETTING

The area belonging to the Central Apennines considered here is shown in fig. 1. The northern part is mainly composed by Mesozoic pelagic sequences of the Sabina-Umbria-Marche domain, whereas the southern part is rather composed of Mesozoic carbonate platform sequences of the Lazio-Abruzzi domain. In the Sabina-Umbria-Marche Mesozoic basinal domain, the Pliocene and Pleistocene grabens trend N50-60°W, about 45° counterclockwise with respect to the folds and thrusts of the Neogene accretionary prism in this sector (fig. 1). In the southern part of the area, in the Lazio-Abruzzi Mesozoic carbonate platform domain, normal faults are instead more frequently parallel to the strike of the pre-existing

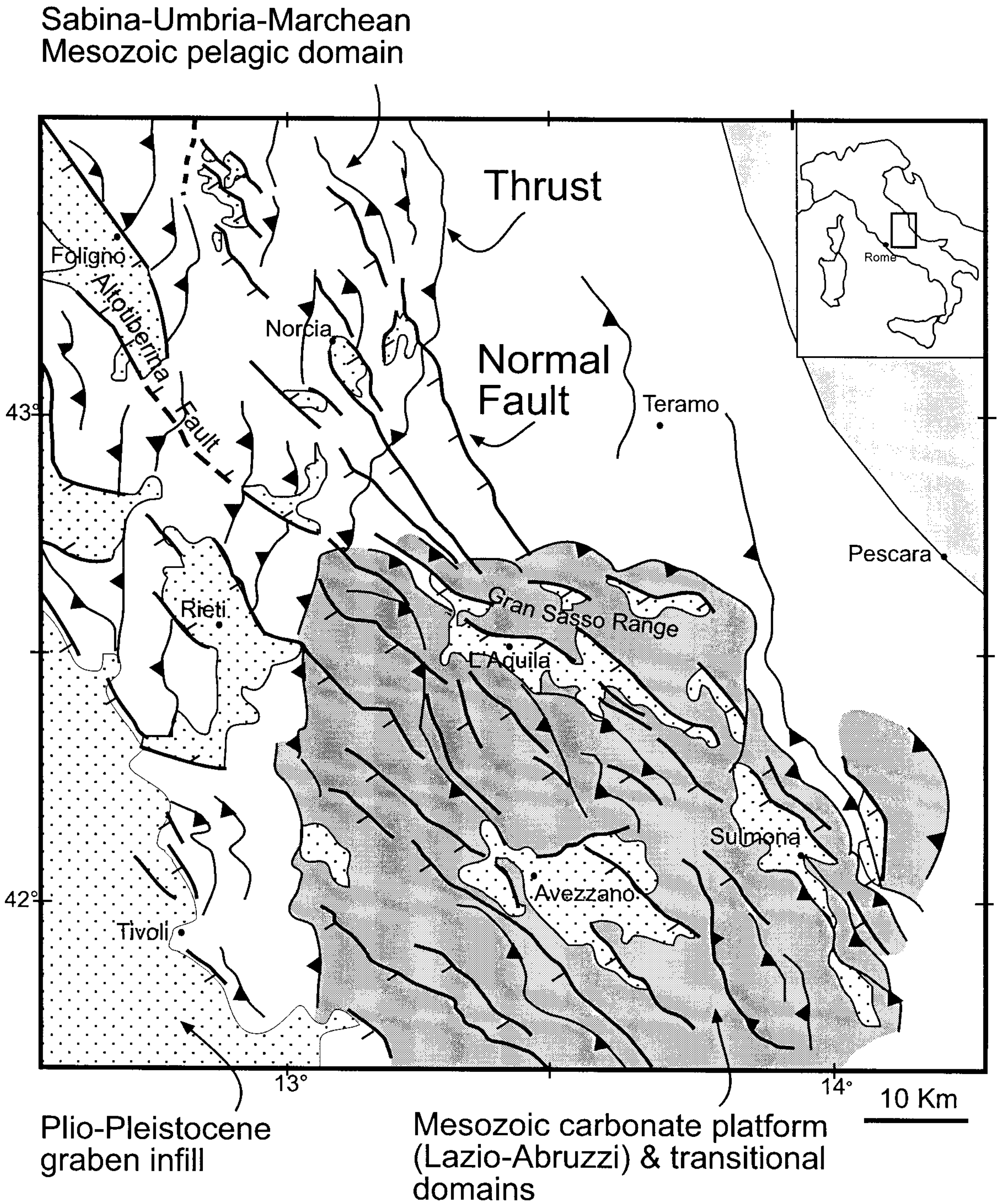

Fig. 1 - Thrust planes and extensional faults present independent trends in the Central Apennines. Thrusts strike mainly N-S in the Mesozoic basinal successions in the northern part of the map, whereas they change direction to NW-SE in the carbonate platform domain to the south. Normal faults rather strike more constantly NW-SE, across the whole area. Miocene-Quaternary thrusts direction is more severely controlled by Mesozoic architecture than the Pliocene-Quaternary extensional faults. The normal fault indicated as the Alto Tiberina is the interpreted prolongation of the fault described more to the northwest by BARCHI *et alii* (1998).
– *I sovrascorrimenti e le faglie normali mostrano andamenti diversi nell'Appennino centrale. I sovrascorrimenti hanno una direzione circa N-S attraverso le successioni mesozoiche di bacino a nord e assumono direzione NW-SE nel dominio della piattaforma carbonatica a sud. I sovrascorrimenti di età neogenica sono più strettamente controllati dalla geometria delle strutture mesozoiche rispetto alle faglie normali pliocenico-quaternarie. La faglia normale indicata come Alto Tiberina rappresenta la prosecuzione ideale della linea descritta più a nordovest da* BARCHI *et alii (1998).*

compressive features. In the eastern part of the belt, the angle between structures still occurs.

The highest structural level, in the western side of the central-northern Apennines, comprises the oceanic-derived deposits, including ophiolitic bodies, referred to the Ligurian Nappe (BOCCALETTI *et alii*, 1990a,b), the crystalline basement, and the Tuscan Nappe (metamorphic and non-metamorphic), developed on the ancient passive continental margin. These sequences, organized in several thrust sheets, are recently named the «Etruscan belt» by BARCHI *et alii* (1998), whereas the more external part involves meso-cenozoic sequences deposited on the Jurassic-Cretaceous southern passive margin of Neothetys (BERNOULLI *et alii*, 1979; KLIGFIELD, 1979). This passive paleo-margin was characterized by the development, from Middle Liassic on, of two main depositional environments controlled by passive margin extensional tectonics: in the north, the Sabina-Umbria-Marche basin domain (COLACICCHI *et alii*, 1970; CENTAMORE *et alii*, 1971; COOPER & BURBI, 1986) and, in the south, the Lazio-Abruzzi carbonate platform domain (ACCORDI, 1964; ACCORDI *et alii*, 1988). The Sabina-Umbria-Marche basin sequence comprises lithologies, with markedly contrasting competence, including carbonate platform sediments (Late Triassic-Early Liassic) and a multilayer pelagic sequences (Liassic to Eocene), made up mostly of limestones with cherty nodules and bands. At the base of the sedimentary cover, the evaporites rocks of the Upper Triassic Anidridi di Burano Formation represents one of the main detachment levels of the Northern Apennines. The Lazio-Abruzzi sedimentary sequences (Triassic to Upper Cretaceous) are made of a thick pile (about 3000m of thickness) of subsiding platform sediments (mostly limestone and dolomite rocks) from Upper Triassic to Paleocene, with transgressive Middle Miocene skeletal limestone of open shelf, and sedimentary sequences of shelf edge and slope to basin, from Dogger to Miocene (ACCORDI *et alii*, 1988). The base of all these sequences is made of the Triassic dolomite, which is the main detachment level in this sector of the chain (BALLY *et alii*, 1986).

In the Central Apennines, the main thrusts are characterized by a general northeastward vergence (BIGI *et alii*, 1997; VEZZANI & GHISETTI, 1998) and they may be locally inverted by normal faults (BIGI *et alii*, 1995; D'AGOSTINO *et alii*, 1998). The outcropping thrusts involving the Mesozoic Sabina-Umbria-Marche basin successions trend mainly N-S, whereas they strike mainly NW-SE in the Lazio-Abruzzi Mesozoic platform domain to the south (fig. 1). A salient exist in the accretionary prism in the Sabina-Umbria-Marche basinal successions, relative to a recess to the southeast in the Lazio-Abruzzi platform area. Another salient or arc occurs in the transitional zone between the basin and the platform in the Gran Sasso range (fig. 1). Evidence of transpressional kinematics occurs on the E-W and N-S trending thrust fault planes, and out-of-sequence reactivation of more internal thrusts has been locally recorded.

During the accretionary process, mainly acting in the Neogene age, a series of foredeep turbidite sequences were deposited, deformed and accreted according to the polarity of the evolving thrust-foredeep system (RICCI LUCCHI, 1986; PATACCA & SCANDONE, 1989; BOCCALETTI *et alii*, 1990a,b; BIGI *et alii*, 1999). From the Miocene on, the accretionary prism was contemporaneously involved in extensional tectonics along its central-western side, developed under conditions of general uplift of the Apennines, and generating the main grabens (Tuscan grabens, Tevere graben, Rieti Plain, L'Aquila Plain, Fucino Plain ecc.), documented by many Authors (BERTINI & BOSI, 1970; BAGNAIA *et alii*, 1989; BERTINI *et alii*, 1989; MENICHETTI & MINELLI, 1991; BROZZETTI & LAVECCHIA, 1994; D'AGOSTINO *et alii*, 1994; LAVECCHIA *et alii*, 1994; BIGI *et alii*, 1995; CAVINATO & MICCADEI, 1995; BONCIO *et alii*, 1996; CALAMITA *et alii*, 1996; BARCHI *et alii*, 1998).

MODEL

The extension in the Apennines may be generated by the eastward retreat of the subduction hinge, generating an area to be compensated by the hangingwall crust (DOGLIONI *et alii*, 1999) «falling» to the East. This extension is dominantly accomodated on master normal faults dipping to the east-northeast and conjugate southwest-dipping normal faults; examples may be the northeastward-dipping Alto Tiberina fault and its conjugate system activated by the seismic sequence in the Umbria-Marche regions during 1997-1998 (BARCHI *et alii*, 1998; BONCIO *et alii*, 1998). Extension in the Apennines and the Tyrrhenian sea is also generated by the relative divergence between the mountain range and Sardinia-Corsica; this relative movement is still ongoing according to geodetic data (BIANCO *et alii*, 1998). This extension should have generated lithospheric-scale rifting with west-southwest-dipping master faults along the western Apennines.

The normal fault systems show a NW-SE trend (N140° ± 10°) forming an angle of about 50° with the N-S segment of thrusts. Generally, the NW-SE trending fault system gave rise to faulted blocks stepping down to the SW. These normal faults, characterized by high dip angle plane, dislocate the compressive structures; their faults plane are long (tens to hundreds km) and rectilinear and seem not to be dependent on the structural setting of previous compressive structures which show in general shallow decollement layers: these faults probably reach to deep crustal levels. Evidence for the deep nature of the normal faults also come from fluids and mantle gas emissions along graben margins (e.g., ITALIANO *et alii*, 2000). The seismicity associated with the 1980 Irpinian earthquake shows that the E-NE-dipping normal faults cross cut almost the entire crust (about 25 Km thick, SCARASCIA *et alii*, 1994), since hypocentres were located at about 15 Km depth (AMATO & SELVAGGI, 1993), at the base of the brittle upper crust. In the central-northern Apennines it has also been documented the presence of E-NE-dipping normal faults such as the Alto Tiberina fault along the CROP 03 seismic profile (BARCHI *et alii*, 1998). Most of the W-SW-dipping normal faults may be interpreted as antithetic, conjugate and more superficial faults (e.g. BONCIO *et alii*, 1996; 1998; BARCHI *et alii*, 1998). Other faults, generally with a low angle fault plane, break at the contact with main thrusts and show evidence of a later inversion of a thrust surface (BIGI *et alii*, 1995; D'AGOSTINO *et alii*, 1998).

The relationship between thusts and normal faults suggests that the decollement planes of the frontal compression and the internal extension associated with the Apennines subduction may have different depths: «thin-skinned» for the thrust planes, mainly located at the top or the upper parts of the basement, enabling large thrust-sheets rotations (MATTEI *et alii*, 1998); «thick-skinned» for the internal normal faults, affecting the entire crust, and inhibiting significant rotations.

The eastward retreat of the Adriatic subduction zone implies that the slab sinks and generates a shear couple at the boundary with the host mantle; mantle compensation is expected into the area previously occupied by the slab (DOGLIONI *et alii*, 1999). Therefore slab retreat may kinematically explain the contemporaneous occurrence of

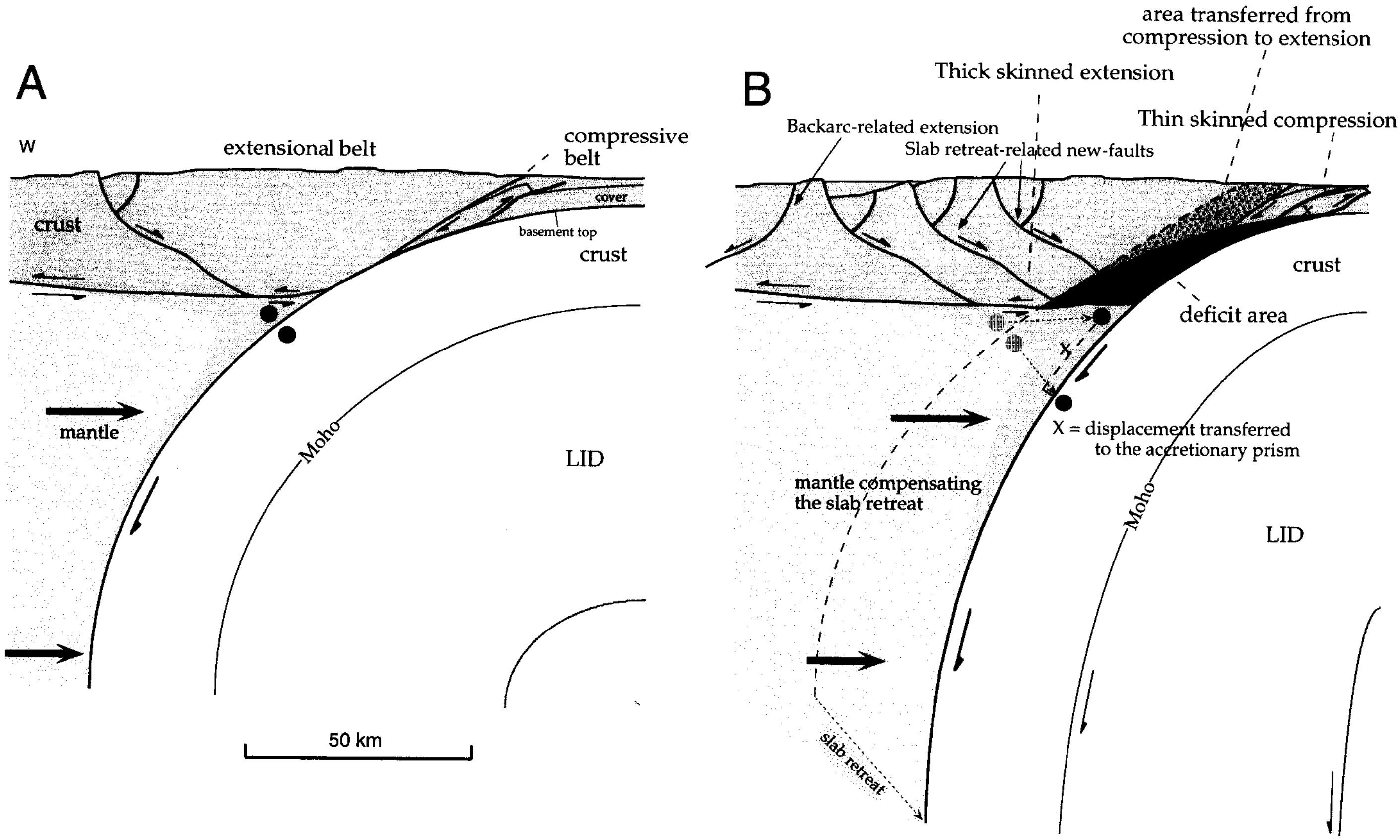

Fig. 2 - Two-fold stages of an ideal section across the Apennines subduction. A, reference stage, where two black dots are located one in the hangingwall mantle and one in the downgoing lithosphere. B, incremental stage of subduction; the black area represents the crustal deficit generated by the retreat of the subduction, outside the area of active compression. New normal faults are induced by gravitative compensation of the crust in the hangingwall of the subduction hinge. Normal faults are hypothesized to crosscut the crust, assuming ductile shear in the lower crust. The slab retreat should determine a shear between the downgoing lithosphere and the asthenospheric mantle in the hangingwall which is moving eastward to compensate the retreat, as indicated by the new position of the two black dots; the shear is transferred to the the basal decollement of the accretionary prism in the upper crust. This thin-skinned interpretation of the shallow decollement is supported by the mainly sedimentary cover and the limited volumes accreted in the Apennines prism. Therefore the accretionary prism with a shallower decollement appears to be controlled more by the mechanical properties of the upper crust (i.e., sedimentary cover and possibly upper basement), whereas extension should be controlled by the rheology of the entire crust. The different depth of the related decollements could explain the different strike of thrusts and normal faults of the central Apennines as shown in Fig. 1. The lithospheric mantle (LID) is probably missing or very thin below the hangingwall crust as suggested by kinematics and shear wave attenuation studies (DOGLIONI, 1991; MELE *et alii*, 1996). Modified after DOGLIONI *et alii* (1999).
– Due stadi di una sezione ideale attraverso la subduzione Appenninica. A, stadio di riferimento, con due punti neri posizionati rispettivamente nel mantello a tetto e nella litosfera in subduzione. B, stadio successivo della subduzione, dove l'area nera rappresenta il deficit crostale generato dall'arretramento della subduzione, fuori dell'area in compressione. Nuove faglie distensive sono indotte dalla compensazione gravitativa della crosta a tetto della cerniera della subduzione. Le faglie normali sono ipotizzate tagliare l'intera crosta, assumento taglio duttile nella crosta inferiore. L'arretramento dello slab dovrebbe determinare anche un disaccoppiamento tra la litosfera in subduzione e il mantello astenosferico a tetto che si muove verso est a compensare l'arretramento della subduzione, come indicato dalla nuova posizione dei due punti neri di riferimento. La zona di taglio è trasferita al prisma di accrezione il cui piano di scollamento appare posizionato nella crosta superiore. Questa interpretazione di tettonica pellicolare del prisma di accrezione è supportata dalla presenza principalmente di rocce di copertura sedimentaria e dai limitati volumi coinvolti nel prisma appenninico. In questa interpretazione cinematica, il prisma di accrezione con un piano di scollamento pellicolare sarebbe controllato principalmente dalle proprietà meccaniche della crosta superiore (copertura sedimentaria e forse la parte alta del basamento cristallino), mentre l'estensione sarebbe invece vincolata dalle proprietà reologiche dell'intera crosta. La differente profondità dei piani di scollamento potrebbe spiegare la diversa orientazione dei sovrascorrimenti e delle faglie normali dell'Appennino centrale come indicato in fig. 1. La crosta a tetto della subduzione manca probabilmente del sottostante mantello litosferico (LID), come indicato dalla cinematica e dal fattore Q delle onde sismiche (DOGLIONI, 1991; MELE et alii*, 1996). Modificato da DOGLIONI* et alii *(1999).*

coupled E-vergent compression to the east and extension to the west (fig. 2). In this model:

1) The basal decollement at the front of the Apennine accretionary wedge is directly connected to the shear couple between the top of the downgoing lithosphere and the mantle replacing the retreating the slab;

2) The retreat of the slab also generates a new «open» crustal space in the hangingwall of the subduction hinge; this area is constantly compensated by the crustal material being dragged and stretched by the underlying mantle flow, and collapsing from the «west» to «east» in the hangingwall of the subduction.

The eastward roll-back of the subduction hinge generates a volume deficit in the hangingwall lithosphere which is following and trying to compensate the hole. This is what can be considered as the trench suction force (FORSYTH & UYEDA, 1975) and it may be responsible for the main «eastward» dipping normal faults in the Apennines which should probably be differentiated from the normal faults associated to the Tyrrhenian backarc rifting. In fact the first ones are associated to a geodynamic context of general uplift, whereas the second ones are mainly located in a subsiding area.

On the other hand, the shortening in the accretionary wedge can be explained as related to the shear couple between the downgoing and retreating lithosphere and the eastward compensating mantle, the displacement being transferred upward and peeling off the sedimentary cover and possibly the upper part of the basement from the foreland lithosphere (fig. 2). This kinematic model describes the eastward migrating compression-extension pair, triggered by the subduction rollback and by the simultaneous asthenospheric mantle replacement.

In this model, frontal compression and internal extension have respectively shallow and deep decollements. Compression appears to be mainly thin-skinned, involving the sedimentary cover and the upper part of the basement of the foreland. Extension is rather thick skinned, cross-cutting the entire crustal section of the subduction hangingwall. Therefore the basal decollement of the accretionary prism could be at about 6 to 12 km depth, whereas the decollement of the extensional belt might be deeper at about 20-30 km depth, at the base of the hangingwall crust (fig. 2). Note that the crust in the hangingwall of the subduction probably comprises the entire lithosphere, being the lithospheric mantle (LID) mainly lost by subduction and replaced by a new section of mantle (DOGLIONI, 1991).

The lithostatic load is larger for normal faults than for the external thrusts, allowing larger rotations of the thrust sheets with respect to the extensional features.

The lower lithostatic load acting on the external thrust sheets could also be responsible for the larger effect of the inherited mechanical properties of the sedimentary cover on the thrust planes geometry. Thrusts in fact undulate around the Lazio-Abruzzi platform, whereas normal faults mainly cross-cut the platform-margins and strike more linearly.

Deep decollements in the lower crust, close to the mantle boundary, are supposed to be high grade metamorphism shear zones (e.g., KELLER *et alii*, 1994).

CONCLUSIONS

The different orientation of Neogene-Quaternary normal faults and thrusts in the Central Apennines (fig. 1) could be determined by their respective deep and shallow decollement depths (fig. 2). Undulations in the thrust planes are coherent with oblique ramp transport with a transpressive component. In the N-S trend of the thrusts, right-lateral transpression is inferred. In the central Apennines, cross-sections cannot be easily balanced because compressive features and extensional ones are oblique each other. The model proposed, differently from the ones published so far, combine the slab retreat process with the aforementioned observations to explain the contemporaneous occurrence of single vergent compression to the east, generated by the shear between the downgoing lithosphere and the asthenosphere during sinking and retreat of the slab (fig. 2); the model also suggests that in the Apennines-Tyrrhenian system there may be extension generated by the mass deficit generated by the slab rollback, which may be a different process with respect to the well known backarc extension in the Tyrrhenian side to the west.

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