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Block tectonics in thin-skin style-deformed regions: examples from structural data in central Apennines

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Abstract
Peliminary results from a block-tectonic modelling of central Apennines are presented. These were produced through the preparation of a theoretical tectonic-block generation model in thin-skin deformed structural levels. Although the field campaign is not yet completed, found evidences together with obtained results are considered of interest for scientist working on the geodynamics of this sector and summarized in the present paper. After the main chain building developed, a new, less intense, regional tectonic event took place (Lower Pliocene?) This produced the dissection of the Latian-Abruzzi Platform thrust domain into a two-order rigid-block system. First-order structures present NW-SE elongations and are separated by sub-parallel fault zones that show a prevailing left-lateral strike-slip displacement of some kilometers. Such limited offsets were sufficient to produce the complex ridges and basins framework observed in this region. Five first-order structures were described. Almost each of these can be subsequently subdivided into a series of second-order rigid blocks and basins. Interactions among these are responsable for a series of deformational structures observed along their margins, such as restraining and releasing bends, push-ups, ridges, positive flowers and even small-scale pull-apart. Structural data were utilized to prove small amount of relative block rotations between the two south-westernmost blocks. The model produced can not only explain the ridges and basins coeval evolution in the area, but it also accounts for the complex relation between the N-S Olevano-Antrodoco Thrust (part of the Ancona-Anzio Line story) and the E-W Gran Sasso Front.

1. Introduction

In the last decade a number of block tectonic models has been proposed. These were computed along main strike-slip shear zones and concern the dissection of the crust into a series of homogeneous blocks, that often suffered rotations around vertical axes. Such models partly satisfied the evidences derived by paleomagnetic studies (among others, McKenzie and Jackson, 1986, Nur *et al.*, 1986).

Although the proposed models allow considerable rotations, the questions of the thickness and of the de-coupling mechanism at the base of the rotated blocks are still on debate. In the mentioned works the Authors apply their models in areas interested by shear zones developed by tectonics that apparently involve the entire lithosphere and argue that the base of the main blocks should be placed in the lithosphere-astenosphere transition zone.

The presence of block rotations in sectors of the Apennines deeply involved by thin-skin–style tectonics, as evidentiated by the results of paleomagnetic investigation (Mattei *et al.*, 1991), increases the opportunity of the development of a version of these models limited to the upper crustal levels.

The main characteristic of thin-skin tectonics is the limitation of the deformation (including the possible break into homogeneous blocks) above a detachment layer buried at a depth of up to 15 km, as derived from bibliographic information (Bally *et al.*, 1988; Woodward *et al.*, 1989). This layer acts as a total de-coupling surface between the upper deformed portion and the crust.

2. Theoretical block formation model

The dynamics of block formation in thin-skin tectonics have been analyzed by a simplifield three-dimensional model (see fig. 1) as the result of the break of a series of privileged planes. These are:

- the basal detachment layer *d*,
- the front fault plane (ramp) *f*,
- the two lateral planes (tear faults) *t*.

The block separation will take place when the component of the weight force parallel to the detachment layer F_g will equal the strength R_d, R_f and R_t on the faces *d*, *f* and *t* of the block. That is when

$$F_g = R_d + R_f + 2R_t \qquad (1)$$

Quantifying expression (1), we obtain

$$F_g = w \cdot h \cdot l \cdot \rho \cdot g \cdot \sin\gamma \cdot (l + h/(2 \cdot \mathrm{tg}\alpha)) \qquad (2)$$

$$R_d = l \cdot w \cdot (\sigma_0' + \mathrm{tg}\phi' \cdot h \cdot \rho \cdot g \cdot \cos^2\gamma) \qquad (3)$$

$$R_f = h \cdot w \cdot (\sigma_0 + 0.5 \cdot \mathrm{tg}\phi \cdot h \cdot \rho \cdot g \cdot \cos^2\alpha) / \sin\alpha \qquad (4)$$

$$R_t = \sigma_0 \cdot (l \cdot h + h^2 (2 \cdot \mathrm{tg}\alpha)) \qquad (5)$$

where

ϕ rock internal friction angle,
σ_0 rock cohesion,
ϕ' detachment layer internal friction angle,
σ_0' detachment layer cohesion,
α dip of fault plane,
γ dip of the detachment layer,
ρ rock density,
g gravity acceleration,
l length of block,
w width of block,
h depth to detachment layer.

From the substitution of expressions (2)-(5) in (1) we obtain a relationship that, for given rheological conditions and dipping of the detachment layer, relates the dimensions of the block:

$$l = \phi\,(h,w) \qquad (6)$$

Figure 2 shows graphical examples for both extensional and compressional tectonics and for rheologies and geometries of the detachment layer similar to Latian-Abruzzi Platform (LAP) domain during the main shortening phases.

Some useful considerations emerge from the analysis of the found relation. First of all, these give the theoretical verification that block formation should be a common phenomenon in thin-skin environments, both for extensional and compressional tectonics. Secondly, the relationship shows that, for sufficiently wide (as width: dimension normal to transport direction) blocks,

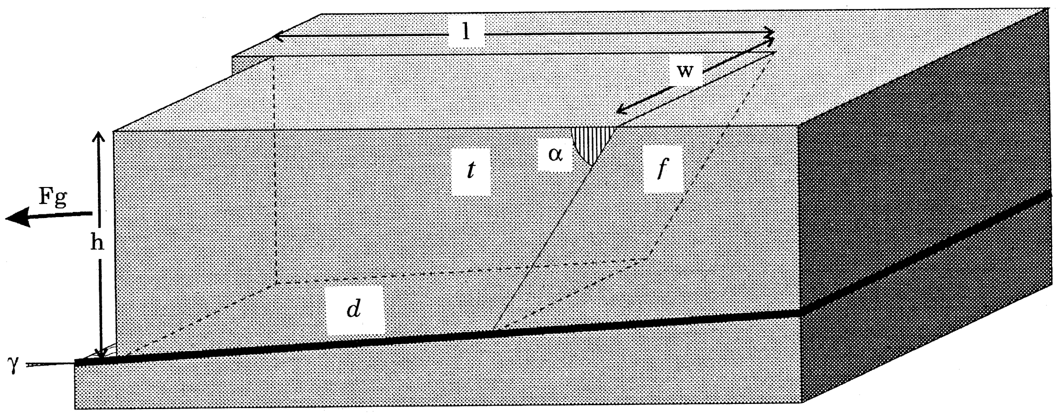

Fig. 1. Sketch of the proposed model for block generation in thin-skin tectonics. Legend: d = detachment layer; f = *ramp* rupture plane; t = *lateral ramp* rupture plane; l = length of the block; w = width of the block; h = thickness of the block; a = dip of plane f; g = dip of plane d; F_g = weigth force component parallel to detachment plane.

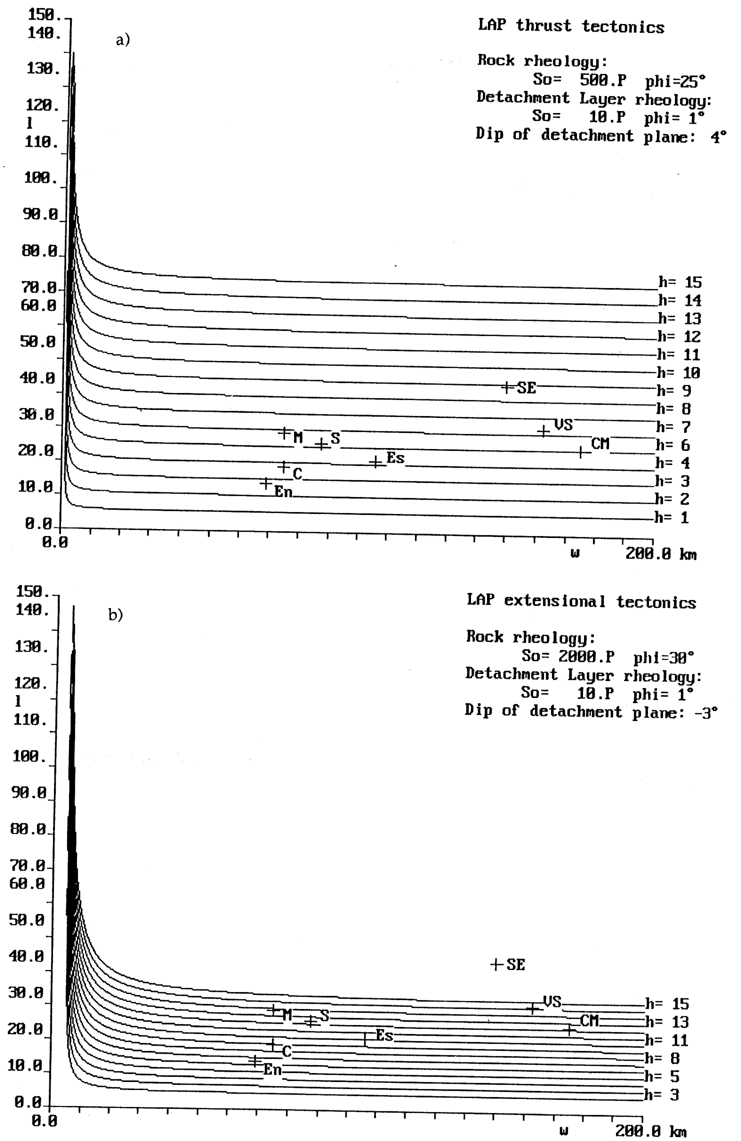

Fig. 2. Graphics showing some solutions for block dimensions and shapes according to the proposed model. *X*- axes represent widths *w* in km of blocks, *Y*-axes represent block lengths *l* in km. Curves represent the solutions for thickness between 1 to 15 km. the utilized values are presented in the upper right corners and represent the possible rheological and geometrical characteristics of LAP domain during the main shortening tectonic event. Diagram a) shows solutions for compressional events, while diagram b) is relative to the extensional ones. From the surface dimensions of block we can tentatively compute the thicknesses of the main blocks as identified in the present work and by assuming their generation as the effect of the shortening phase. This choise was due to the obtained more reliable values than those computed in extensional tectonics. Legend (refer to fig. 4): Es) SW Ernici Mts. block; En) NE Ernici Mts. block; S) Simbruini Mts. block; SE) Ernici Mts.-Simbruini Mts.-Mt.Cairo sector; C) Carseolani Mts. block; M) Marsica block; CM) Carseolani Mts.-Fucino-Marsica sector; VS) Mt.Nuria-Mt.Velino-Sirente-Montagna Grande sector.

the length/width ratio tends to become proportional to their thicknesses. In other words we can compute the depth to the main detachment layer of single blocks (such as thrust sheets) by knowing their length and width and giving an appoximation of the rheologies and geometries of the system.

Another useful consideration is the different geometry of extensional tectonics with respect to compressional ones. In the first situation and for the same block length we observe a minor value of the length/width ratio and less critical thickness and horizontal dimensions can be considered proportional (fig. 2). The different geometries of ramp planes in the two tectonic situations take into account for it. The result is in a relatively shorter and more homogeneous block formation during extensional tectonic episodes.

Furthermore, the strong relation of the geometries with the rheologies on the fault planes will induce reactivation phenomena on pre-existing fault planes, even if not completely compatible with acting stresses and kinematics. Anyhow the ratio between acting forces and rheologies of superficial rock is high enough to exclude an entirely brittle mechanics among blocks as proposed by McKenzie and Jackson (1986) and the possibility of block rotations around vertical axes should be limited to the existence of bending fault planes or of concurrent faults that are coherent with the block rotation, as discussed in Nur *et al.* (1986).

Another important factor that controls eq. (2) is the extremely low velocity of relative motion of the block over the detachment layer, that can efficiently be considered a viscous material, thus simplifying the solutions of this equation by minimizing cohesion and friction values for this layer.

3. The contribution of structural analysis

The common practice to estimate the displacement along fault planes by plane off-sets (such as bedding planes) is one of the reasons for the difficulties that geologists face in evaluating strike-slip tectonics and consequently block rotations around vertical axes.

Some of the results that can be achieved through structural studies, typically mapping of structural axes and stress/strain orientations, allow block identification techniques that follow the results from paleomagnetics.

Two are the main contributions of structural studies in the tectonic environments. The first consists in block boundary identification and in the dynamic/kinematic modeling of their interactions. The second lies in the contribution to the evaluation of type and entity of relative motions and rotations.

In the first case evidences can be derived by the three-dimensional geometrical and structural re-interpretation of existing geological mapping, together with specific fieldwork. These investigations tend to identify lithologies that are high deformed, fragmented and/or elongated, or that result with lower values of friction angle and cohesion due to their composition or rheological history. Such units potentially can constitute fault zones or be the effect of the kinematics of major faults. Investigations in the field allow an estimation on the mechanics and entity of the movements.

Often the level of deformation along block margins results very complex and fracture patterns cannot be solved as a dynamic effect alone (as proposed in Salvini and Vittori, 1982). An efficient interpretation can be achieved by relating them directly to kinematic modeling of relative motions among adjacent blocks.

Local distorsions of regional paleo-stress fields induced by contemporary block interactions give evidences in case of limited relative motions. A careful examination allows the separation of the local component (block actions) with respect to the regional one.

Eventually reconstructed paleo-stress trajectories relative to tectonic events prior to the block formation constitute markers that provide indications relative to the successive relative motions, in strong analogy with paleomagnetic evidences. In the following pages, a specific example in the LAP domain is presented.

4. Tectonic modeling of Latium-Abruzzi platform (LAP) domain

The described arguments were utilized in the preparation of a kinematic modeling of the portion of central Apennines where the tectonic domain of Latium-Abruzzi carbonatic platform (LAP) outcrops (fig. 3). A Meso-Cenozoic carbonatic platform sequence characterizes its lithology. This succession is stratigraphically topped with terrigenous sequences of Tortonian to Messinian age. The borders of this geodynamic unit are marked to the N,W and E by sediments that testify its passage to bacinal areas. For an exhaustive description of the stratigraphy of the area, we suggest Parotto and Praturlon (1975) and Accordi and Carbone (1988) and the complete bibliography of these papers.

The reason for the interest in this area lies in its structural setting that is well evidenced also by regional morphology. A marked NW-SE tectonic trend characterizes this sector, in striking contrast with the N-S orientations of the bordering structures to the East and to the West, or even the E-W structural directions that characterize its Northern margin.

Such abrupt changes in the orientations brought to the identification of two main tectonic lines corresponding to the transition narrow zones: the Ancona-Anzio Auct./Olevano-Antrodoco (OA) Line (Migliorini, 1950; Parotto and Praturlon, 1975) to the West and an analogous one, the Ortona-Roccamonfina Line to the East (Parotto and Praturlon, 1975).

Many authors (among others, Castellarin *et al.*, 1978; Funiciello *et al.*, 1980; Locardi, 1988; Salvini and Tozzi, 1988; Bigi *et al.*, 1990; Patacca *et al.*, 1990) interpreted these lines as the result of a shortening tectonic event developed in two phases, differing either in vergences or by hypothesizing a relative rotation of the structures in meanwhile the two phases. The proposed models cannot justify some evidences as the relatively older age of the thrusts along the OA Line than those that characterize the Northern margin (Bigi *et al.*, 1990). In the first location N-S–oriented structures overthrust NW-SE–oriented ones; in the latter sector (Montagna dei Fiori-Gran Sasso) the structural setting suggests the opposite.

Similarly, the proposed models were not satisfactory in modeling the strike-slip component evidenced along some of the NW-SE–trending tectonic lines (Montone and Salvini, 1990; 1991). The uneven distribution of ridges and basins present in the area could not equally fit in the previous proposed models.

According to our model, these evidences constitute the effects of a series of block interactions and of their internal deformations.

Evidences utilized for the preparation of the model can be grouped into three main cathegories: 1) examination of existing geologic maps, 2) structural investigations and 3) detailed geologic-structural fieldwork in key areas (such as the margins of the blocks).

For the first cathegory we carefully analyzed stratigraphical displacements as deduced from published maps (Servizio Geologico d'Italia, various years). Tha main component of the offsets was determined through the comparison of the various stratigraphic displacements along each fault zone, including the effects of secondary faulting. In most cases, such as for the NW-SE faults in the Northern sector of the investigated area, this investigation revealed their later strike-slip reactivation.

Studies in the second cathegories include data collected in the last decade by various authors and preliminarly synthesized by Salvini and Tozzi (1988), where the complete bibliography is present. These studies pertain mainly to the Western sector of the investigated area. Results from a series of specific fieldworks were added to these data and showed the presence of a major strike-slip component along the faulting associated to NW-SE tectonic lines.

The third cathegory includes a detailed geological-structural fieldwork and mapping of a key zone along one of the main NW-SE fault zones, the Val Roveto Line (Montone and Salvini, 1990; 1991), a series of reconnaissance along the entire line and the borders of the Piana del Fucino Basin, where the disruptive 1915 earthquake was located.

Since the collected evidences strongly agree with the proposed theoretical modeling, we tentatively extended it to the entire LAP domain, even if the data collection is still incomplete.

The present-day structural framework of the LAP domain relates to a complex tectonic evolution. This developed through the succession of two distinct tectonic phases. First a strong shortening of the superficial units took place in Late

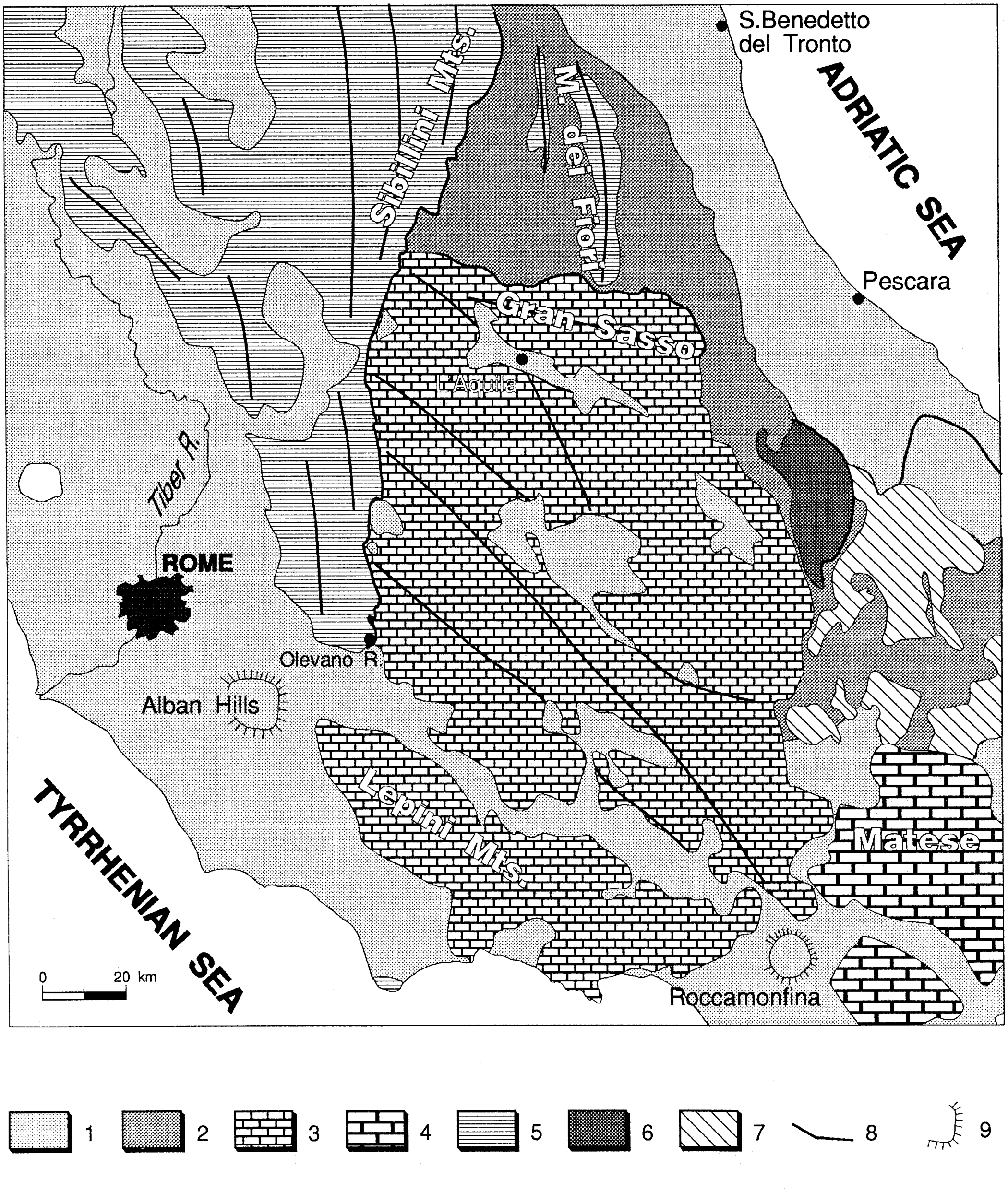

Fig. 3. Regional tectonic framework of the area. Legend: 1) Plio-Pleistocene sedimentary of volcanic units; 2) chain units affected by orogenic transport during Early Pliocene times; 3) units of the Latian-Abruzzi Platform (LAP) domain; 4) units of the Matese Platform domain; 5) units of the Umbrian-Marche-Sabini domain; 6) Maiella unit; 7) sub-Ligurian units; 8) main structural and tectonic lines; 9) main Quaternary central volcanoes (modified from Funiciello *et al.*, 1980).

Miocene- Pliocene times (Bigi *et al.*, 1990). Such shortening produced the Apenninic thrust chain; afterward the area was interested by limited shortening with Eastern vergence together with the activation of left-lateral strike-slip regional faults.

The first phase is the effect of a wide crustal shortening. Related deformations show a NE vergence and, together with the age of sedimentary terrigenous deposits, give a Lower Tortonian (in the SW sector) to Messinian (NE sector) age of first deformation (Patacca *et al.*, 1990). A possible rotation of the entire LAP domain might be subtracted to the present-day orientation of the structures (NW-SE), orientation that was utilized to determine the NE vergence.

Deformation style consists mostly of reverse and thrust fault systems, often conjugate (Andersonian). Associate is a frequent slip on bedding discontinuities and locally strike-slip conjugate fault systems. At a more regional scale the shortening is related to the development of a series of flats and ramps (Dahlstrom, 1969). A series of preferential detachment layers are present. The sole thrust developed in Triassic evaporite sediments (Parotto and Praturlon, 1975). Other important detachment layers are the Orbitolina Layer of Aptian-Albian age, the top of Lower Cretaceous layers and the Orbuline Marls (Serravallian to Tortonian age) (Accordi and Carbone, 1988).

The existence of several detachment layers contributed to the dissection of the LAP domain into numerous horse structures, often characterized by incomplete stratigraphic succession.

Extensional tectonics took place at the end of this event (or possibly also during its later episodes) and was probably related to gravitative re-equilibrium. This extension deeply involved the pre-existing ramp-flat geometry. It is important to notice the brittler deformational characters than the previous event. This feature provoked, along the main ramp zones, a series of NW-SE–elongated weaker bands due to intense cleavage.

The successive tectonic phase rises more interest for our modeling and its age is difficult to determine, even if considerations on relative age of deformations allowed Bigi *et al.* (1990) to give a Lower Pliocene starting age to the associated deformations.

This phase shows a more complex structural framework than the previous ones. Structural deformations consist of thrust and reverse, often conjugated, fault systems, featuring an ENE shortening vergence. Often conjugate strike-slip faulting is associated, together with N-S, NW-SE and E-W strike-slip faults, and E-W normal faulting (Parotto and Praturlon, 1975; Funiciello *et al.*, 1980; Salvini and Vittori, 1982; Montone and Salvini, 1990; 1991).

From the kinematic point of view this new phase produced, in the western margin of the LAP domain, a series of thrusts that show a regional N-S alignment (OA Line) together with N-S–trending right-lateral strike-slip regional faults immediately to the West (Castellarin *et al.*, 1978; Alfonsi *et al.*, 1991). Inside the LAP domain the effect is a swarm of NW-SE left-lateral strike-slip faults zones, often related to the reactivation of the aforementioned alignments characterized by a lower strength. The result is a tectonic setting that is heavily modified, despite the small changes in stratigraphical and structural vertical displacements. As an example, the best analyzed of these faults, the Val Roveto Line, despite of its regional dimension (of the order of 100 km), shows strike-slip displacement of few kilometers, as deduced by the analysis of deformational structures that are associated and located in its NW segment (Montone and Salvini, 1990; 1991).

The displacement *versus* length computed ratio is typical of block tectonics rather than Andersonian (dynamic) ones. The average distance among NW-SE main faults is of the order of 20 km, and this indicates that this block tectonics developed in upper crustal levels.

According to the model, in the area between the Lepini Mts. and the Gran Sasso Mt. the LAP domain is dissected into five main blocks with a characteristic NW-SE–elongated shape. Their Western and Eastern margins coincide respectively with the Ancona-Anzio and the Ortona-Roccamonfina Lines (fig. 4).

NW-SE narrow shear zones characterize the NE and SW margins of each block. As previously depicted, these zones played different roles during the tectonic evolution of the region. Field investigations showed strong evidences of left-lateral strike- slip kinematics as the latest activity.

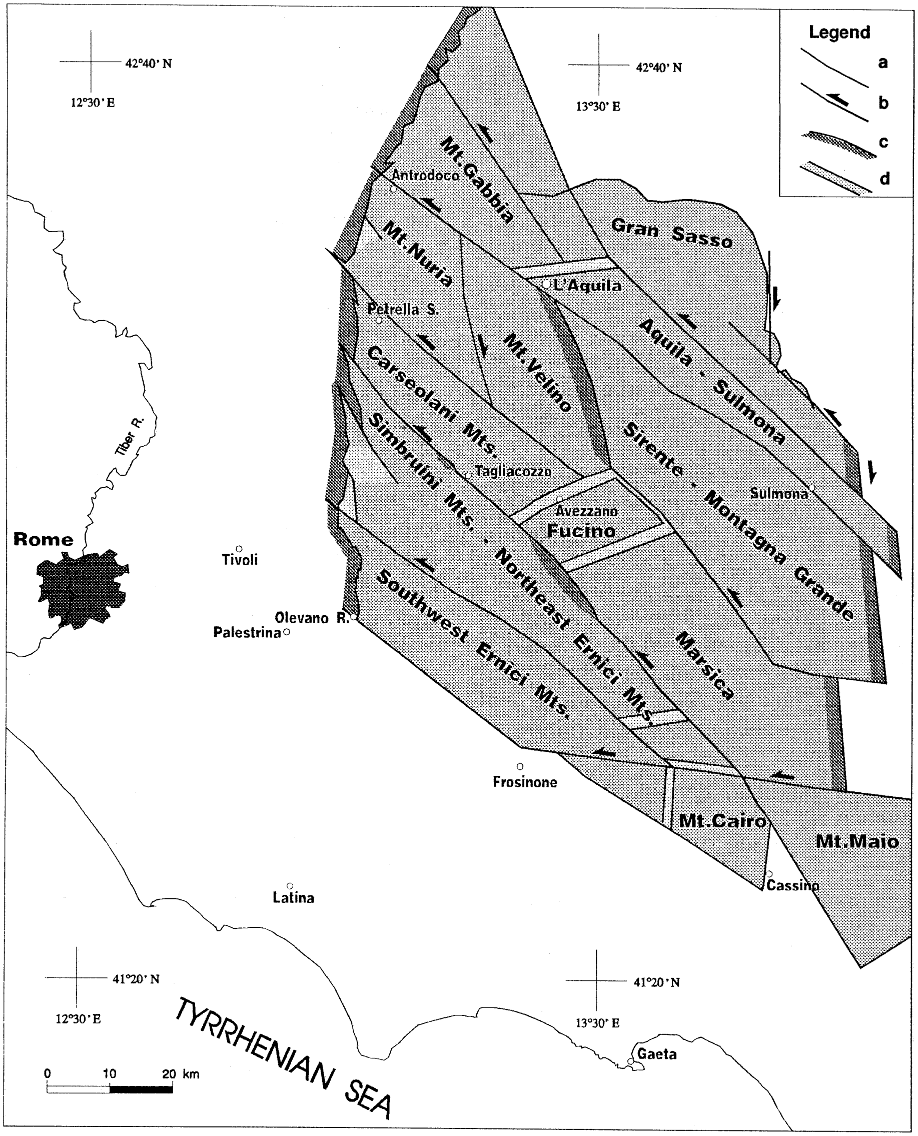

Fig. 4. Model of the tectonic framework of the LAP domain as related to the block tectonic event. Legend: a) block margins with uncertain motion; b) block margins with prevalent strike-slip motion; c) block margins with prevalent compression; d) block margins with prevalent extension.

The abrupt decrease of their displacement in the Western and Eastern margins introduces further evidences for block tectonics and can be explained by the limited N-S right-lateral strike-slip displacements present in those areas (Alfonsi *et al.*, 1991) and by assuming a clockwise relative rotation among blocks of the order of few degrees.

Since the structural levels among adjacent blocks show little displacements relatively to this last tectonic event, we tend to exclude significant regional dip-slip components in the last activity of such faults. On the other hand, the interaction among blocks produced, within each block, a series of strike-slip faults together with local compressional and extensional deformations, resulting in a secondary further dissection of LAP domain. Most of these deformations relates to the kinematics of the NW-SE left-lateral strike-slip movement among blocks.

The result is the generation of a series of ridges and push-up structures (such as possibly the Velino Mt.) and extensional basins (possibly like the Piana del Fucino, near Avezzano) that show a typical E-W and NW-SE parallelogram shape. The size of these structures typically ranges from 10 to 20 km by side.

In few cases and at a smaller case, we identified elongated basins that are related to *pull-apart* mechanics, as Tagliacozzo Plain, along the Val Roveto Line (Montone and Salvini, 1991).

For the three south-easternmost blocks, an estimate of the relative rotation was computed through the analysis of the geometries of the deformations related to the older tectonic phase (NE shortening). The used method follows what discussed in the previous section.

The results from structural data (main compression orientation – sigma 1) were processed through a computer program that prepared a series of azimuthal distribution analyses along a NE-SW section (fig. 5). The study followed the methodologies presented in Wise *et al.* and in Salvini (1992). These analyses were repetead each kilometer and involved data included in a circular area of 20 km of radius and centered along the section (fig. 6). Each analysis includes the preparation of an azimuthal frequency histogram. These histograms are then compared through a best-fit program with a series of Gaussian curves to get mean azimuth and standard deviation of the preferential orientations. Main resulting peaks were eventually represented in an azimuth *versus* distance diagram in the position corresponding to the center of the analysis as squares with a dark tone proportional to their relative importance, by implementing the method proposed by Wise and McCrory (1982).

The examination of such diagrams allows the individuation of homogeneous strike domains and their variations as 1) abrupt change in orientation, 2) disappearing or 3) progressive rotation.

With the adopted methodology it was possible to detect the rotations of the paleo-stress trajectories and to model them as the result of successive block movements. For a complete description of the procedure, refer to Salvini (1992).

The resulting diagrams in fig. 7 show a relative clockwise rotation of 12° of the Simbruini Mts. block with respect to the NE Ernici Mts. one. In between these blocks a 10 km wide band is present, featuring a scattered distribution of trajectories. This scattering is most probably the effect of more intense rotations in the strike-slip zone between the two blocks.

The presence of such relative rotation represents a major factor to take into account when preparing balanced cross-section of the area, that is one of the goals of our research team for the CROP-11 project.

The application of the model to the entire LAP domain allowed a tentative reconstruction of the kinematic evolution for the last tectonic event. The result is the stretching in a NNW-SSE direction of the whole domain that originally should have had a more regular quadrangolar shape.

5. Conclusions

The proposed tectonic model should represent part of the basin-chain-trough-foreland evolution of the Tyrrhenian Sea-Apennines-Adriatic Sea system and is cronologically placed at the end of the last main shortening and thrusting event.

The developed kinematics can be related to the present-day complex geodynamical framework of Central Mediterranean Sea Region (Bigi *et al.*, 1990; Patacca *et al.*, 1990).

To the west Tyrrhenian Sea basin is active and shows a strong extension with oceanic crust formation and trending E-W at the East side of the LAP domain. To the NE the Apenninic units present underthrusted by Adriatic Plate units with a regional NE- SW trend.

The engine for the kinematics of the LAP domain can reside on the contemporary presence of two different tectonic trends: NE-SW to the East and E-W to the West. The presence of two main structural breaks in the Tyrrhenian Sea, roughly along the 41°N Parallel, and in the Adriatic Sea, at the 42°N (Favali *et al.*, 1990), plays a

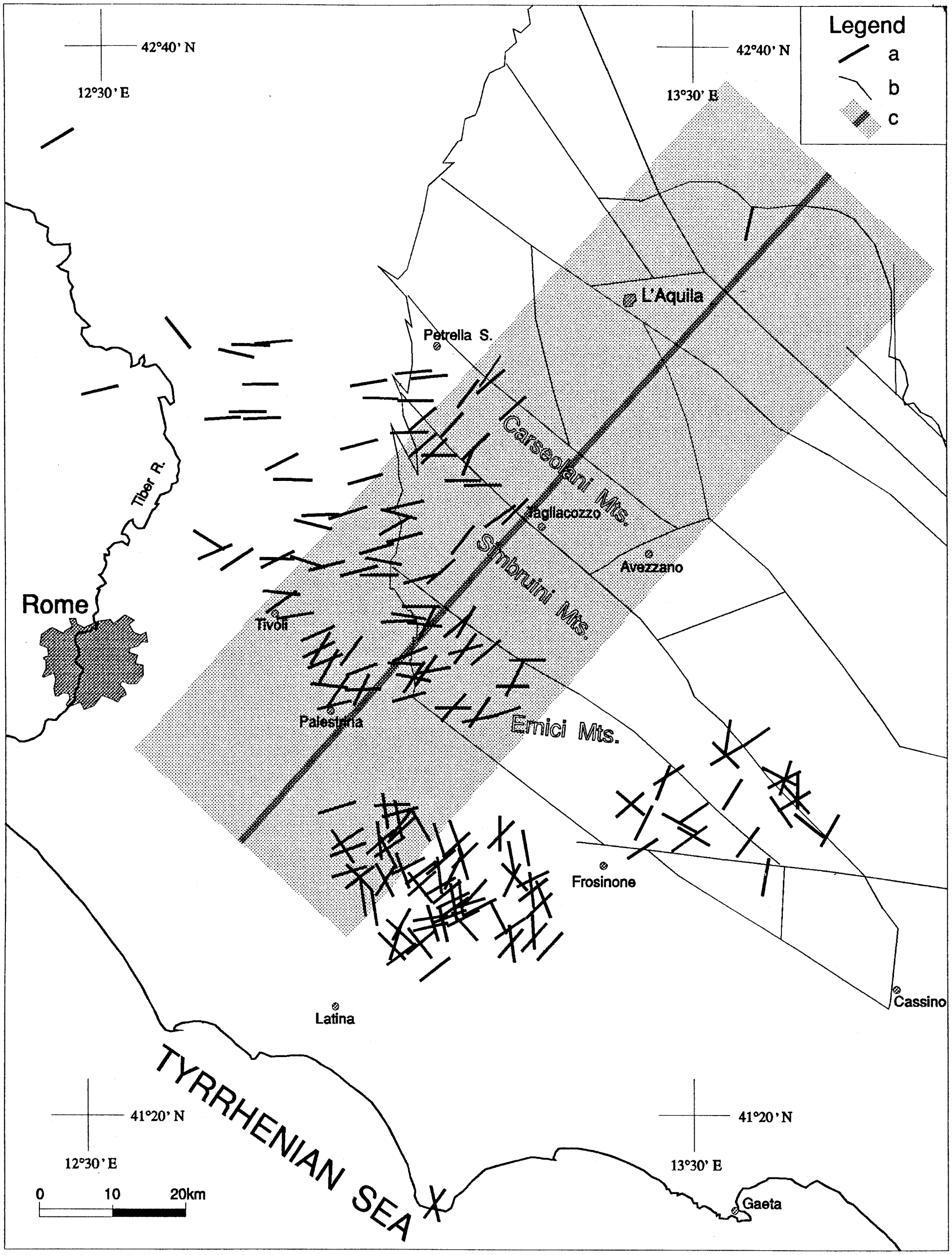

Fig. 5. Synthesis of the maximum compression directions during the main shortening tectonic event as derived with the rotational axes method (Salvini and Vittori, 1982) from our data base (Salvini and Tozzi, 1988 and reported bibliography). Legend: a) maximum compression direction (sigma 1) with tectonic vergence; b) block margins; c) trace of the axis of the sigma-1 cross-section of fig. 7 together with the utilized selection area (see text).

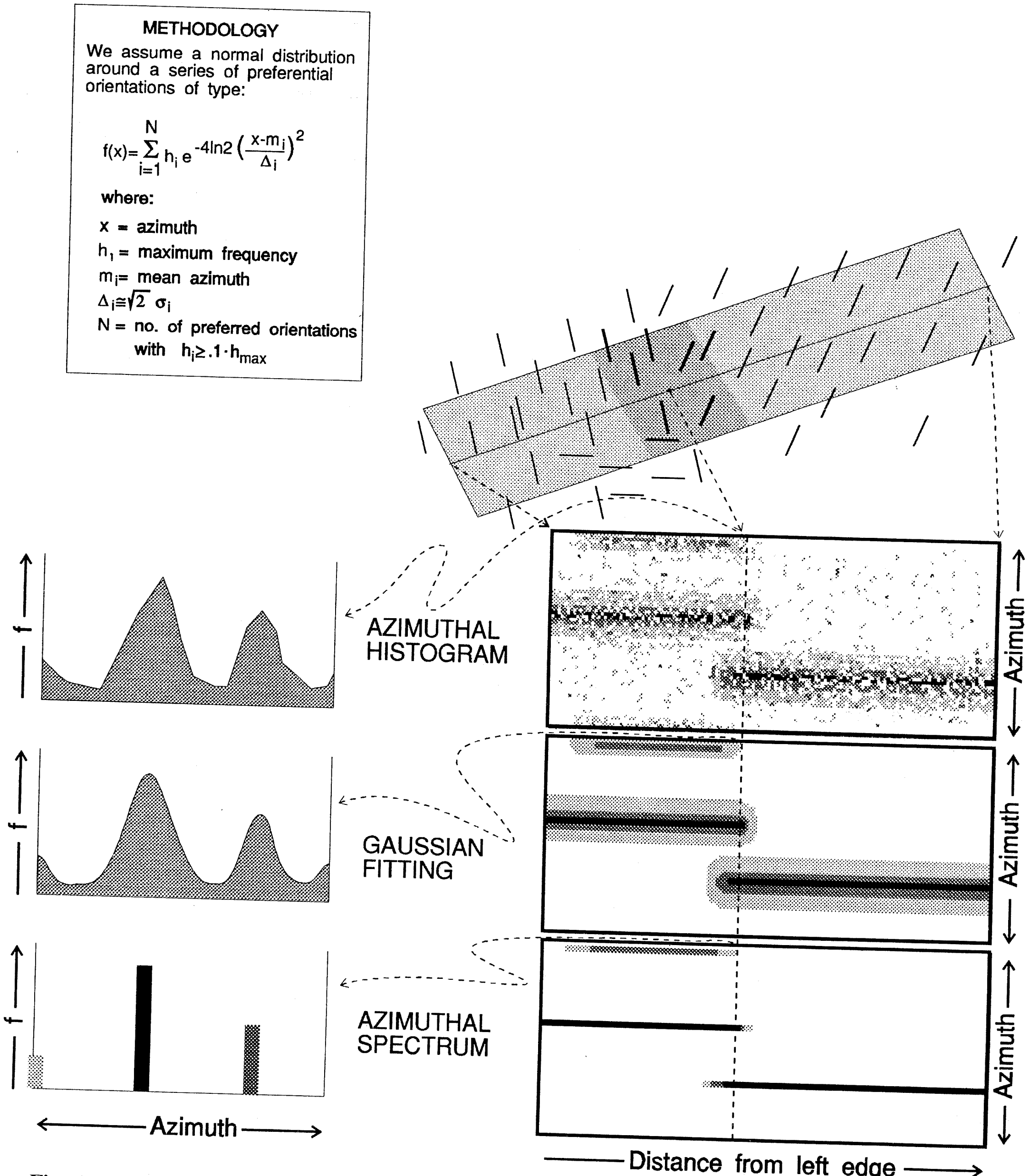

Fig. 6. Sketch illustrating the adopted azimuthal methodology (see text).

first role in the development of the LAP domain geodynamics and contribute to further complicate the kinematic framework in the Apenninic Chain between the two parallels.

The proposed model takes into account the apparent inconsistency of the chronological relations among the main tectonic lines in the area and the sequences of ridges and basins that char-

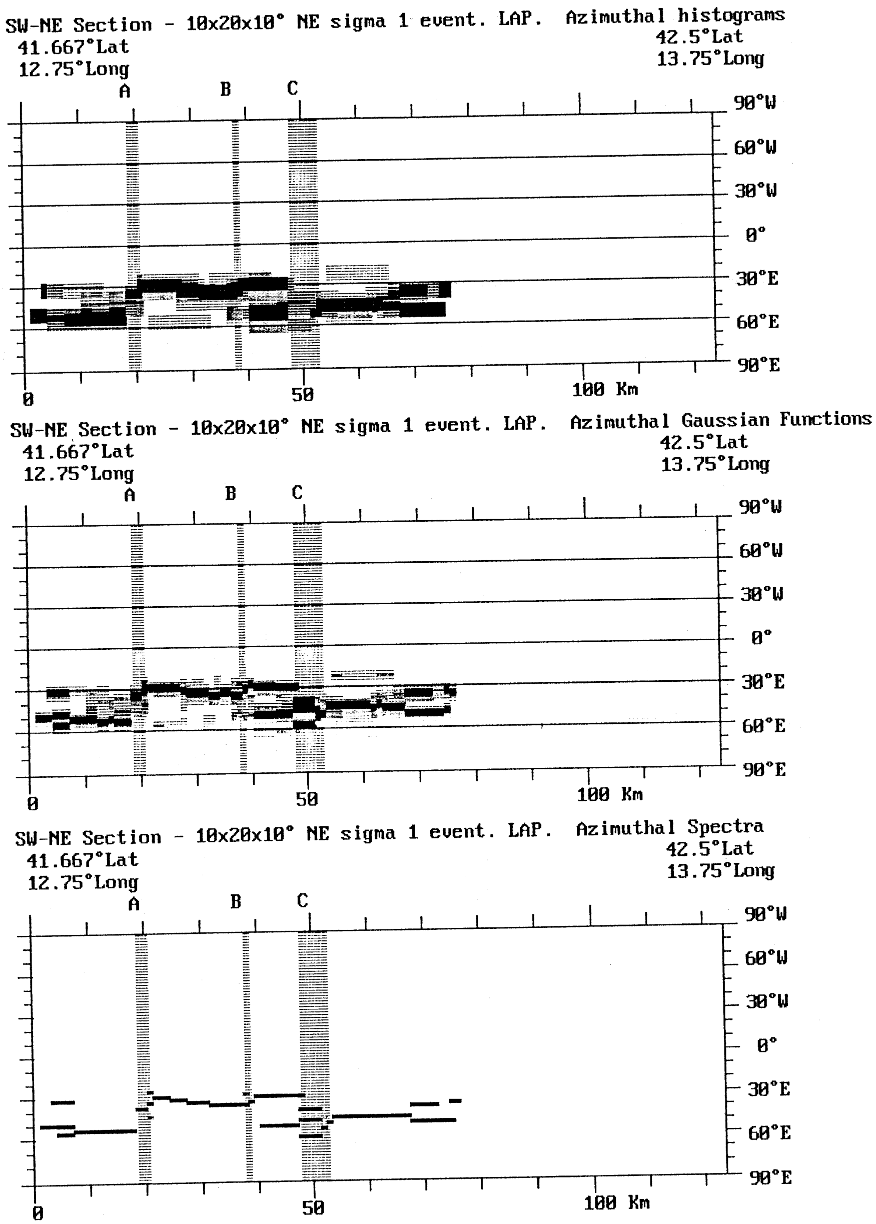

Fig. 7. Azimuthal sigma-1 cross-section (see fig. 5 for location). The applied method follows Salvini (1992) and is summarized in the text and in fig. 6. The linear coordinate along the profile corresponds to the *X*-axis, from SW to NE. *Y*- axis represents the azimuth. Darker zones represent dominant azimuths along the profile. A rotation of 12° between the SW Ernici Mts. block (A-B zone, mean azimuth: N32°E) and the NE Ernici Mts.-Simbruini Mts. (zone NE of transition C, mean azimuth N44°E) is clearly visible and is accompanied by a more scattered deformed zone (B-C) between the two sectors.

acterize the LAP domain. According to the model, the Olevano- Antrodoco Line would represent the outermost envelope of a series of thrusts and basins with *én échelon* shape and limited displacement. These are in their turn related to the small relative rotation of blocks in the Lap domain. The contemporary activity along the Gran Sasso thrust front could be associated to it. The existence of recent widely elongated tectonic depressions with limited vertical displacements is easily related to the partial detachment among adjacent blocks, as the evidences along the main regional fault zones proved. We like to stress anyhow that the activities of some of these regional tectonic lines, often with their strike-slip components, have been already described by previous Authors (among others, Parotto and Praturlon, 1975; Funiciello *et al.*, 1980).

Eventually, we remind that this model is still at the proposing stage and that specific field work is in progress to improve it.

Acknowledgments

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