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LATE PLEISTOCENE N-S SHEAR ZONES ALONG THE LATIUM TYRRHENIAN MARGIN: STRUCTURAL CHARACTERS AND VOLCANOLOGICAL IMPLICATIONS

Abstract. By the means of structural analyses, five important N-S striking shear zones, active during the Late Pleistocene, have been discerned on the Latium Tyrrhenian margin. From the kinematic point of view, these shear zones are characterised by a transition from strike-slip to extensional tectonics through transtensional, moving from the border of the Apennine chain to the coast. The main right-lateral strike-slip shear zone is discontinuously elongated with a N-S trend from the western Sabina chain to the Colli Albani volcanic district. The correspondence of this outcropping strike-slip shear zone to crustal discontinuities is suggested by magmatological, geochemical and geophysical data. The possible connection between this main discontinuity and the offshore lineaments should be one of the topics investigated by the CROP11 profile.

INTRODUCTION

The Northern Tyrrhenian sea is a triangular shaped, thinned and stretched continental basin (Selli and Fabbri, 1971; Finetti and Del Ben, 1986; Rehault et al., 1987; Sartori et al., 1989; Kastens and Mascle, 1990). The western border of the basin is characterised by a N-S elongated margin, while the eastern is NW-SE striking. The Tuscan-Latium continental platform represents the major part of this margin, which is characterised by a less than 25 km thick crust (Wigger, 1984), anomalous heat flow (Mongelli and Zito, 1991) and by a huge volcanic province. The Northern Tyrrhenian magmatism developed in four main phases, from 14 Ma to the Pleistocene-Olocene boundary, with a time-space migration from west to east (e.g. Serri et al., 1991). Along the Latium margin, two main volcanic provinces occurred: the "Tuscan province" (Marinelli, 1961) (Cimini, Tolfa, Ceriti group), which developed from Upper Pliocene to Pleistocene, and the "Roman comagmatic province" (Washington, 1906). In Latium, the latter is characterised by five potassic, mainly explosive, volcanic districts (Vulsini, Vico, Sabatini, Colli Albani and Ernici) elongated on the NW-SE trending Tyrrhenian margin (Funiciello et al., 1976; Locardi et al., 1977) (Fig. 1).

In recent decades, structural and geophysical studies have shown that complex "polyphase" tectonics defines the relationships between the Tyrrhenian margin and the Apenninic chain. In particular, a strike-slip tectonic style, superimposed over the thrust tectonics, has an important role in the Neogene Central Apennines architecture. In Central Italy, strike-slip tectonics has been recognised by many Authors inside the chain (De Wijkerslooth, 1934; Dallan Nardi et al., 1971; Parotto and Praturlon, 1975; Castellarin et al., 1978; Parotto, 1980; Funiciello et al., 1981; Salvini and Vittori, 1982; Ghisetti and Vezzani, 1988; Cavinato and Sirna, 1988; Locardi, 1988; Montone and Salvini, 1989; Corrado et al., 1990; Alfonsi et al., 1991; Mattei and Miccadei, 1991; Montone, 1991). These studies demonstrate that the strike-slip tectonics

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developed mainly with N-S trending right-lateral, and NW-SE trending left-lateral faults. Recent paleomagnetic data suggest that in Neogene times this region was affected by a complex history of block-rotations. The Sabina area underwent clockwise rotation after the Middle Miocene, superimposed on the post-Messinian counter-clockwise rotation of the Latium-Abruzzi platform (Mattei et al., 1991). These data demonstrate that block-rotation mechanisms and strike-slip tectonics play an important role in the dynamic evolution of the Central Apennines.

By means of detailed geological and structural analyses, performed mainly on Pleistocene deposits, we point out the presence of N-S trending strike-slip features even along the Latium Tyrrhenian margin. In this note, we discuss the geometry, the kinematics and the age of activity of the N-S striking shear zones distributed from the Apennine chain to the coast. We then focus on the relationships with the NW-SE striking extensional system. Moreover, a connection with the potassic Pleistocene volcanism will be proposed.

LATIUM MARGIN GEOLOGICAL OUTLINE

Geophysical, stratigraphical, and structural studies show that the Latium margin is characterised by three different tectonic systems (Funiciello et al., 1981) mainly buried below the Upper Pleistocene volcanic cover. The trends of these features are NW-SE to NNW-SSE, NE-SW and N-S (Fig. 1). In this paper, we focus on the N-S striking system, taking into account the relationships with the other two systems.

On the Tuscan-Latium margin (Bartolini et al., 1982), the main extensional features are NW-SE to NNW-SSE striking basins, filled by thick sequences of clay-sand and conglomerates. If we consider the oldest post-orogenic (''neo-autochthonous'') sedimentary deposits as syn-rift deposits, we can assume that the growth of these basins is confined within a period of time from Messinian (clastic and gypsum facies) to Lower Pleistocene. Moreover structural propagation of these basins shows a north-eastward migration towards the Apenninic chain. During Middle and Late Pleistocene these pre-existing tectonic features experienced vertical isostatic motion. The volcanic districts of the Roman Comagmatic Province began their activity at the border of these basins, with quite regular behaviour.

The NW-SE striking extensional basins are bordered by a system of NE-SW extensional faults. The age of these structures, like that of the NW-SE ones, ranges from Messinian to Lower Pleistocene. The NE-SW system has been interpreted as transfer faults (sensu Gibbs, 1984) of the NE-SW striking extensional axis (Bartole et al., 1991; Liotta, 1991).

The main trend of the Northern Thyrrenian margin is given by N-S striking basins, well evident from Corsica (Jolivet et al., 1991) to Elba (Keller and Pialli, 1990), with listric normal faults bordering half-graben basins (e.g. Bartole et al., 1991). Even the N-S oriented alignment of the Neogene magmatic episodes and the magnetic anomalies are consistent with this trend (AGIP, 1982).

STRUCTURAL ANALYSIS

Several Authors have suggested the presence of N-S striking structures, which cross-cut the whole Latium margin. In order to define the geometry and the kinematics of these tectonic features, we performed a geological and structural analysis on the Meso-Cenozoic deposits, syn/post-rift Pliocene and Pleistocene sedimentary deposits, and volcanic sequences in the area.

Five narrow N-S striking shear zones have been recognized: all of them dissect the Late Pleistocene deposits. They are regularly arranged with an average separation of roughly 20-40 km (Fig. 1). A short description of the shear zones from west to east will be presented. More detailed data are available in Alfonsi et al. (1991), Maiorani et al. (1992), Faccenna and Funiciello (1993) and Faccenna et al. (1993).

Bracciano shear zone (Bsz). The N-S trending extensional Bsz stretches for 30-40 km, from Castel Giuliano to Oriolo Romano village; the continuation of the shear zone across the Vico

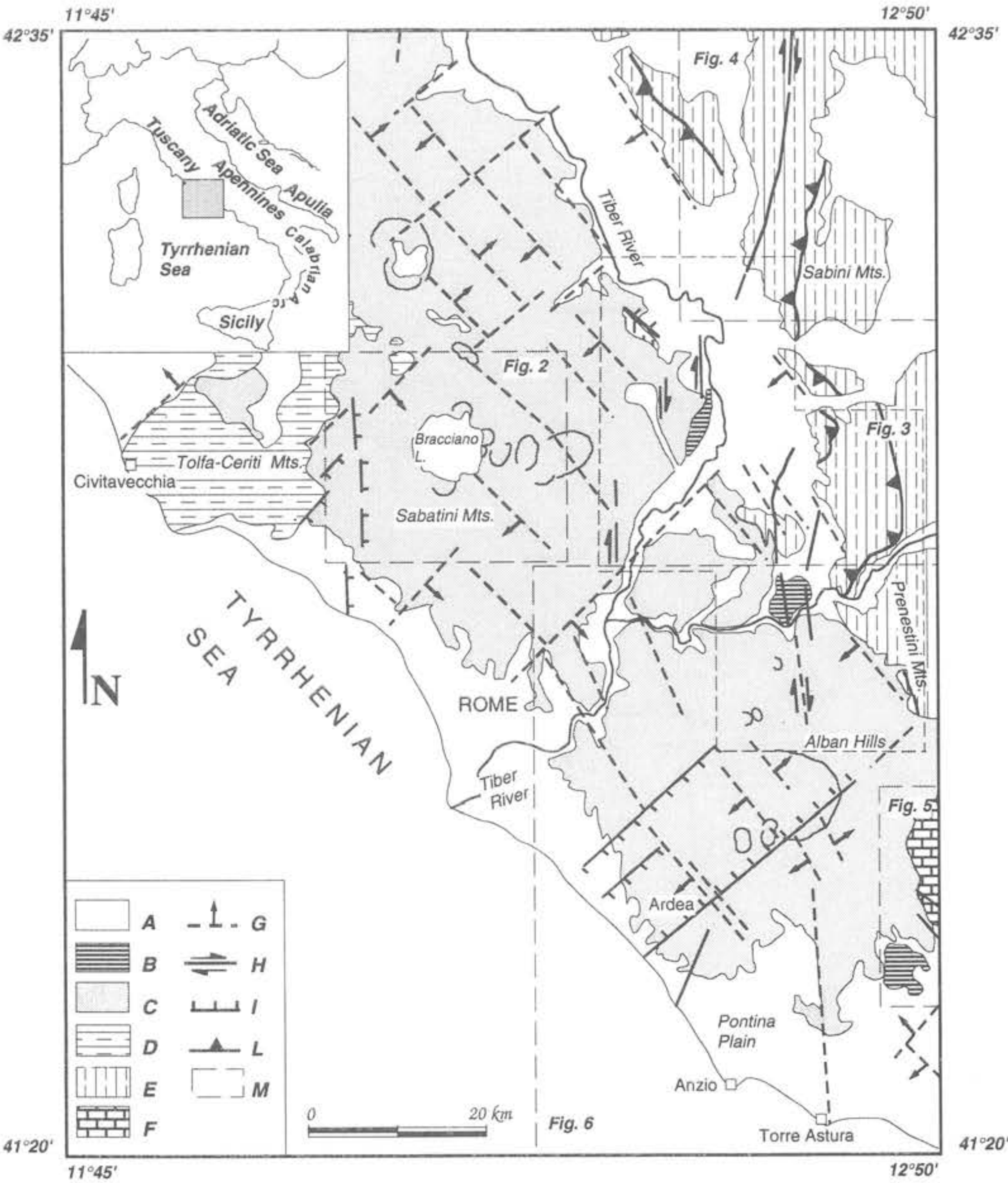

Fig. 1 - Schematic map of the Latium Tyrrhenian margin. A) Sedimentary sequences of the "neo-autochthonous cycle" (Messinian-Pleistocene); B) travertine deposits (Quaternary); C) volcanic sequences (Pliocene-Pleistocene); D) Tolfa units (Upper Cretaceous-Eocene); E) Sabina units (Upper Triassic - Upper Miocene); F) Lepini Mts. units (Cretaceous); G) main buried faults, where the arrow indicates the downthrow limb; H) strike-slip faults; I) normal faults; L) thrust faults; M) areas illustrated in the figures.

volcanic district is not detectable, but it is evident between Viterbo and Bomarzo. In this area, in fact, N-S striking tectonic and morpho-tectonic features have been observed by Sollevanti (1983). The southern part of this shear zone is expressed by a system of 2-3 km long N-S striking discrete segments, and the whole shear zone is 3-5 km wide (Fig. 2). This shear zone is composed of normal faults and extensional joint systems, all showing a consistent N-S orientation. This extensional behaviour is observed even on the other minor N-S striking normal faults pervading the Tolfa and Bolsena area. This shear zone cuts across all the Sabatini volcanic sequences, and was active during the Upper Pleistocene.

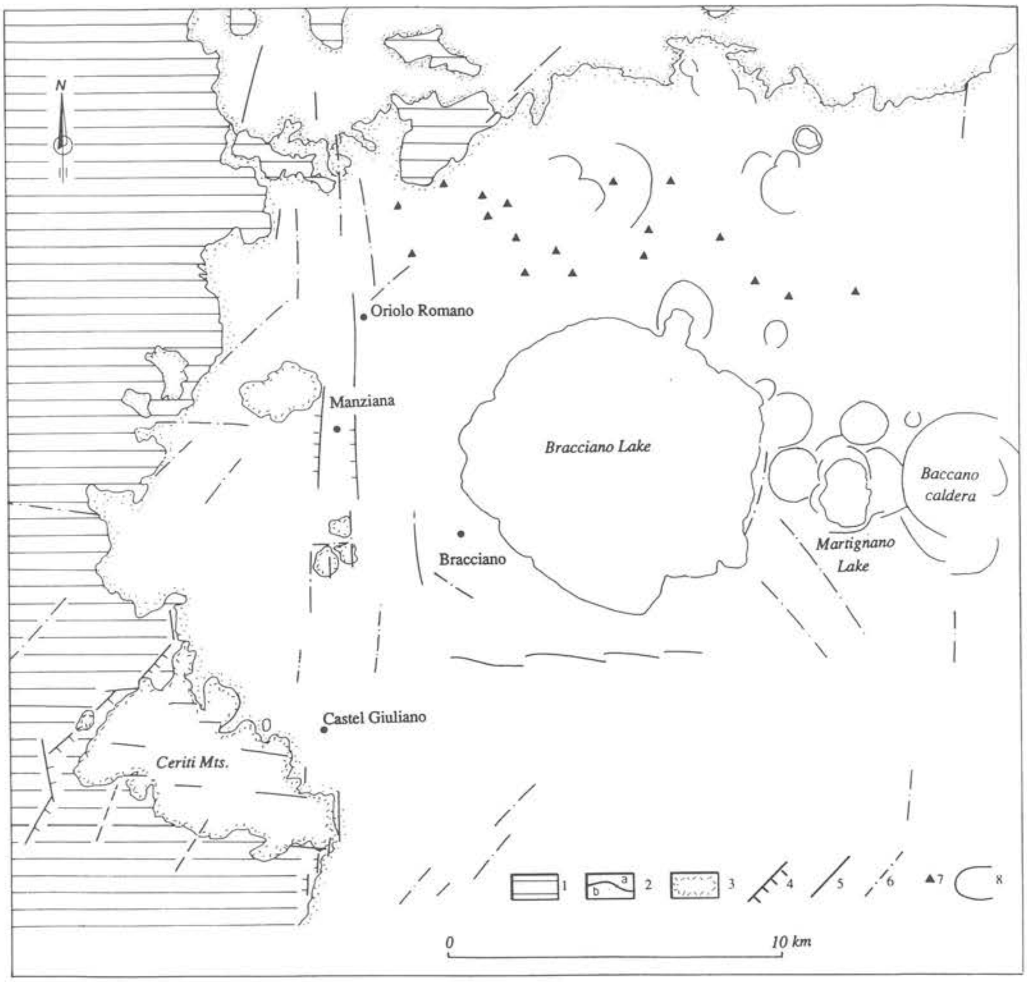

Fig. 2 - Structural synthetic map of Bracciano area. 1) Tolfa units (Upper Cretaceous-Eocene); 2) Vico (a)-Sabatini (b) pyroclastic deposit boundaries; 3) lava domes; 4) normal faults; 5) faults, 6) morphotectonic features; 7) volcanic centers; 8) crater and caldera rims.

Soratte Mt. shear zone (SMsz). On the south of Mt. Soratte, a system of N-S striking segments, with a dextral en echelon array, is present. This shear zone is 15 km long 10, wide and is composed of 4 segments, each 3-4 km long. The separation between the single segments is 4 km and is much larger than their overlap, which is less than 1 km. (Fig. 3) The surface geometry of the single segments is characterised by steep fault planes arranged in an en echelon array, or by a "negative-flower-like" structure. The slickensides on fault planes show a superimposition of oblique or right-lateral strike-slip events on dip-slip extensional ones, suggesting a transtensional mechanism for the SMsz. The activity of this shear zone is delimited by the age of the Sabatini sequences (430/360 ka) which are clearly cut by the strike-slip tectonics. The horizontal displacement observed on single fault planes is everywhere less than 10 m.

Sabina shear zone (Ssz). A N10°E oriented right-lateral strike-slip fault system has been recognised along the western margin of the Sabina Mts.. The major shear zone outcrops from the Terni basin to Casperia village, in an area located 50 km north of Rome (Fig. 4). This shear zone is accompanied by a set of splays whose dips range from 90° to 30° degrees and which developed across hundreds of meters from the main fault zone. A set of isocline to chevron shaped folds, whose axial planes generally dip toward the east, together with compressio-

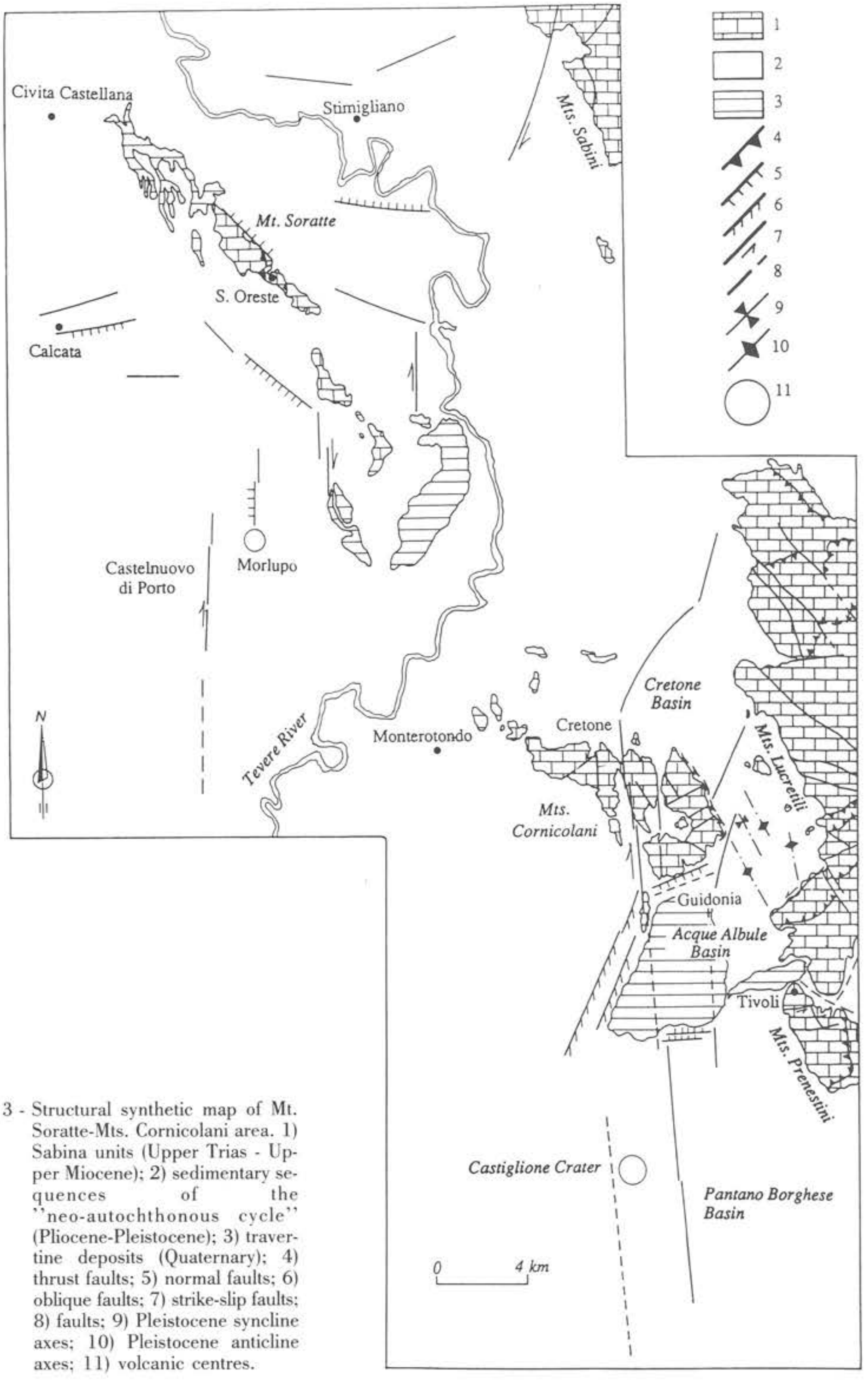

Fig. 3 - Structural synthetic map of Mt. Soratte-Mts. Cornicolani area. 1) Sabina units (Upper Trias - Upper Miocene); 2) sedimentary sequences of the ''neo-autochthonous cycle'' (Pliocene-Pleistocene); 3) travertine deposits (Quaternary); 4) thrust faults; 5) normal faults; 6) oblique faults; 7) strike-slip faults; 8) faults; 9) Pleistocene syncline axes; 10) Pleistocene anticline axes; 11) volcanic centres.

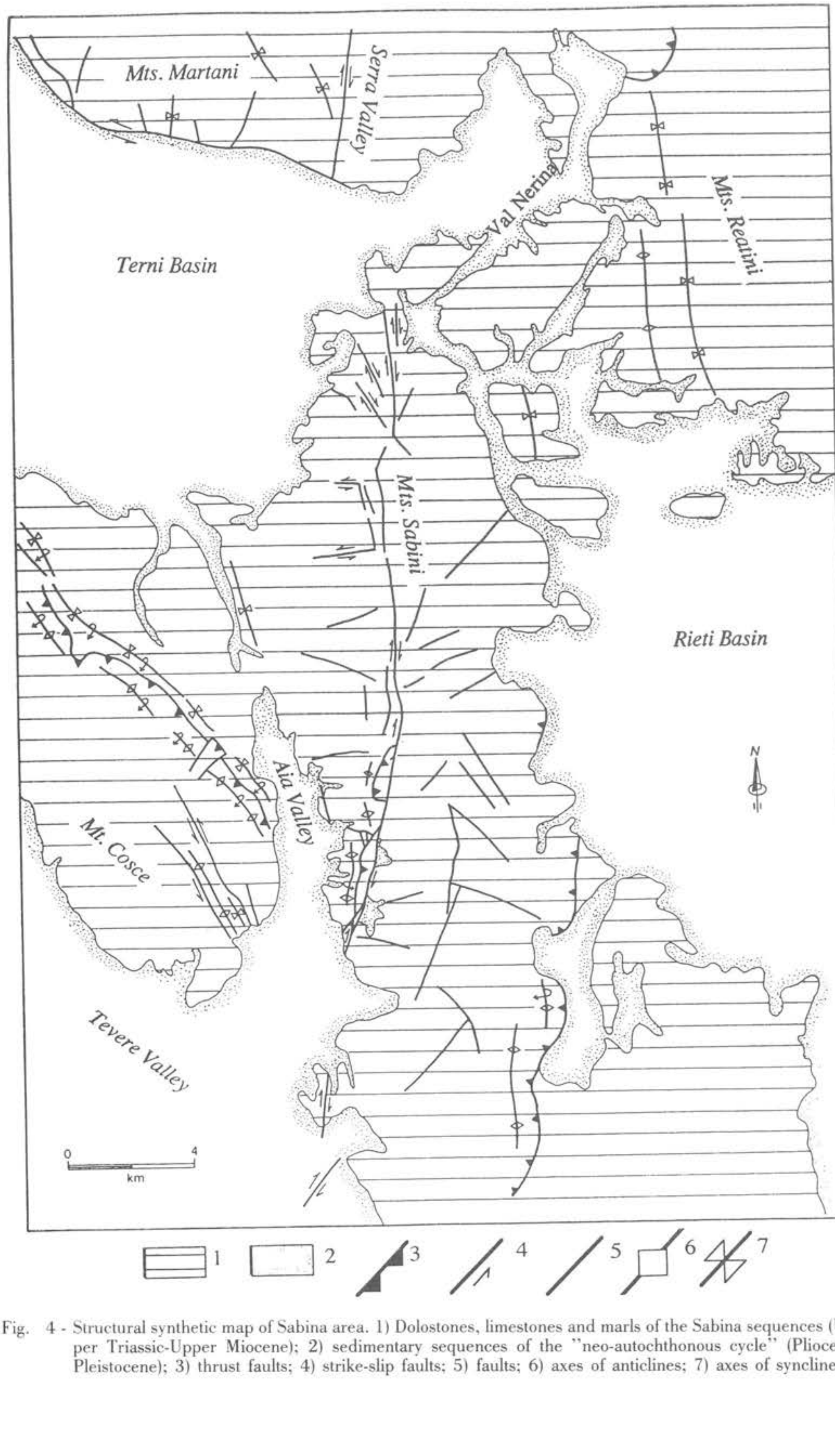

Fig. 4 - Structural synthetic map of Sabina area. 1) Dolostones, limestones and marls of the Sabina sequences (Upper Triassic-Upper Miocene); 2) sedimentary sequences of the "neo-autochthonous cycle" (Pliocene-Pleistocene); 3) thrust faults; 4) strike-slip faults; 5) faults; 6) axes of anticlines; 7) axes of synclines.

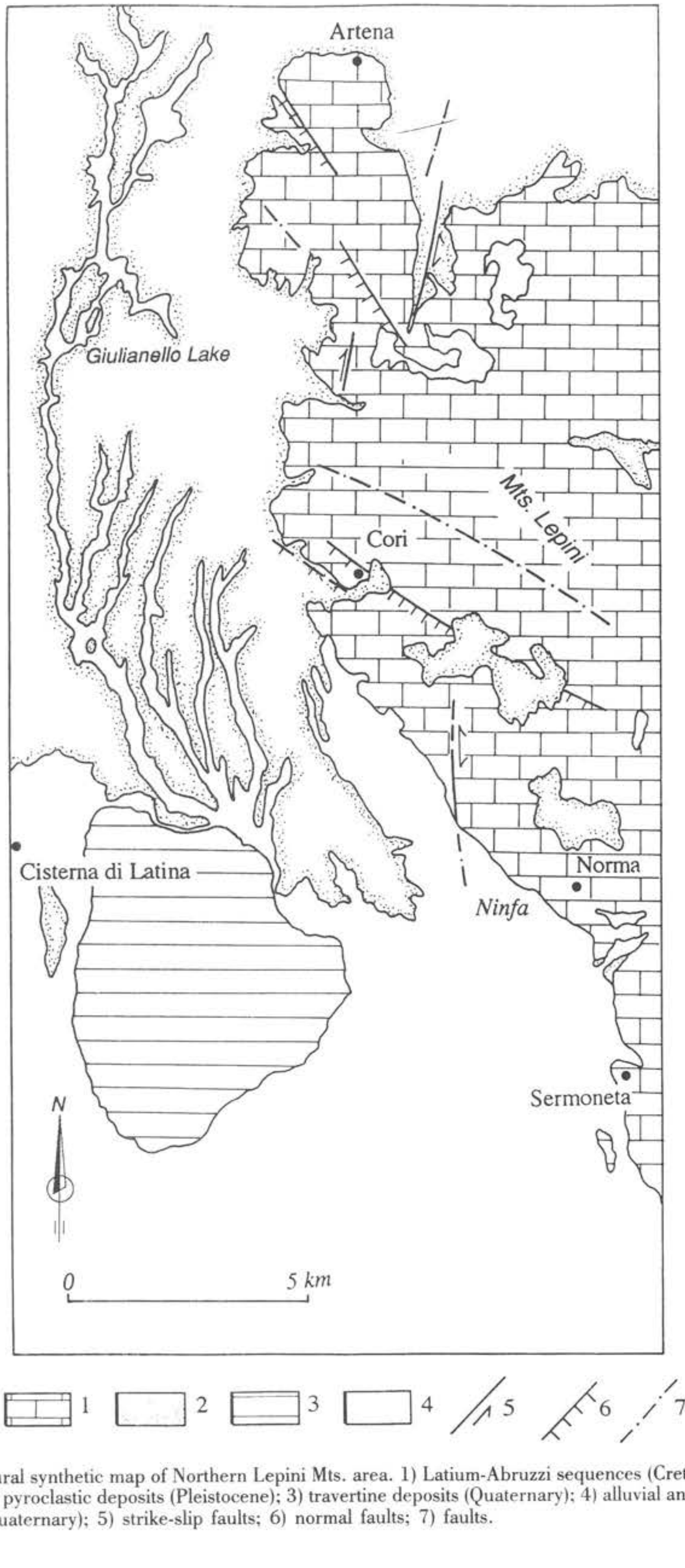

Fig. 5 - Structural synthetic map of Northern Lepini Mts. area. 1) Latium-Abruzzi sequences (Cretaceous); 2) Colli Albani pyroclastic deposits (Pleistocene); 3) travertine deposits (Quaternary); 4) alluvial and colluvial deposits (Quaternary); 5) strike-slip faults; 6) normal faults; 7) faults.

nal and pull-apart structures, are the typical features outcropping toward the west side of the main fault. The Ssz shows a main right-lateral strike-slip motion which has been active from post-Upper Miocene to Upper Pleistocene in a number of different pulses. In fact an episode of extensional tectonics followed the main strike-slip deformation. Normal faults are predominantly sub-vertical and oriented N50°W. This tectonic phase also led to the dip-slip reactivation of pre-existing, N20°E and N40°E oriented, strike-slip faults. We attribute the 100 m differential vertical displacement of the Lower Pleistocene shoreline, outcropping on both sides of the main strike-slip element, to this tectonic event. Anyway, the latter tectonic activity of the fault seems still to be a strike-slip motion, as is visible near Cantalupo village, where Late Pleistocene Sabatini volcanic deposits are cut by N40E strike-slip faults.

Acque Albule shear zone (AAsz). In the Acque Albule area, near Tivoli, a 30 km long - 6 km wide shear zone has been recognised. It is formed by a system of N-S striking right-lateral strike-slip faults, with a separation/overlap ratio around 1/3 (Fig. 3). In the overstepping area, the interaction of these strike-slip segments causes the formation of a pull-apart basin (Acque Albule). The master feature is a strike-slip fault that can be discontinuously followed, for at least 27 km, from Cretone village (north) to the border of the Colli Albani volcanic district (south). This feature is accompanied by a N20°E striking oblique-slip divergent splay, and by a pervasive system of N40°E-60°E striking extensional joints and normal faults.

Geological and radiometric analyses (230Th/234U disequilibrium), on the fracture calcite fillings, constrain the age of the tectonic events. The master fault main activity is confined between the emplacement of the pyroclastic flows (530 ka-360 ka) up to Holocene times, with climaxes around 178 (+66, -44) ka and 49 (+8, -8) ka.

The southern continuation of this shear zone intersects the Colli Albani volcano: its prosecution on the Piana Pontina has beeen pointed out by Di Filippo and Toro (1980) and by Malatesta and Zarlenga (1986) by the means of gravimetric and stratigraphic data. Moreover, off-shore seismic reflection data reveal the presence of a set of post-orogenic en echelon folds probably related to strike-slip tectonics (Marani and Zitellini, 1986; Chiocci, 1989).

Northern Lepini Mts. shear zone (NLMsz). Between the villages of Norma and Artena, another N-S shear zone has been observed. This feature is rather discontinuous and is composed of three segments (Fig. 5). Negative flower structures and steep strike-slip faults are present. Both dip-slip and strike-slip movements along N-S striking fault planes have been observed. The deformations affect the Colli Albani volcanic deposits and thus strike-slip faults were active after 430 ka.

The geometric characteristics of these shear zones provide further information about the tectonic evolution of the area.

The discrete segments that form the AAsz are arranged with a ratio separation/overlap of around 0.3, typical of a pure strike-slip fault zone (Aydin and Nur, 1982; Aydin and Schultz, 1990). According to a modelling by Naylor et al. (1986), the development of a divergent splay oblique junction in the AAsz could indicate a further evolution phase in a strike-slip regime after the formation of the N-S striking shears (Fig. 4).

The SMsz displays slightly overlapped and much more separated segments then the AAsz. This geometric array, together with the kinematics indicators, suggests a different evolution for the two shear zones. If we consider that these shear zones developed in the Pleistocene units, during the same interval of time, the geometrical and kinematic differences between them could be a function of two parameters:

- amount of horizontal displacement (Tchalenko, 1968; Wilcox et al., 1973; Naylor et al., 1986);

- differential rheological conditions (mainly lithology, heat flow, pore pressure, state of stress) (Mandl, 1988).

Considering that heat flow values (Calamai et al., 1977; ENEL, 1987; Mongelli and Zito, 1991) and sedimentary and volcanic sequence thicknesses (Baldi et al., 1975; 1976; Toro, 1977; Funiciello et al., 1979; Amato et al., 1986) are roughly similar for the AAsz and SMsz, we suggest that the AAsz differs from the SMsz by the greater amount of horizontal displace-

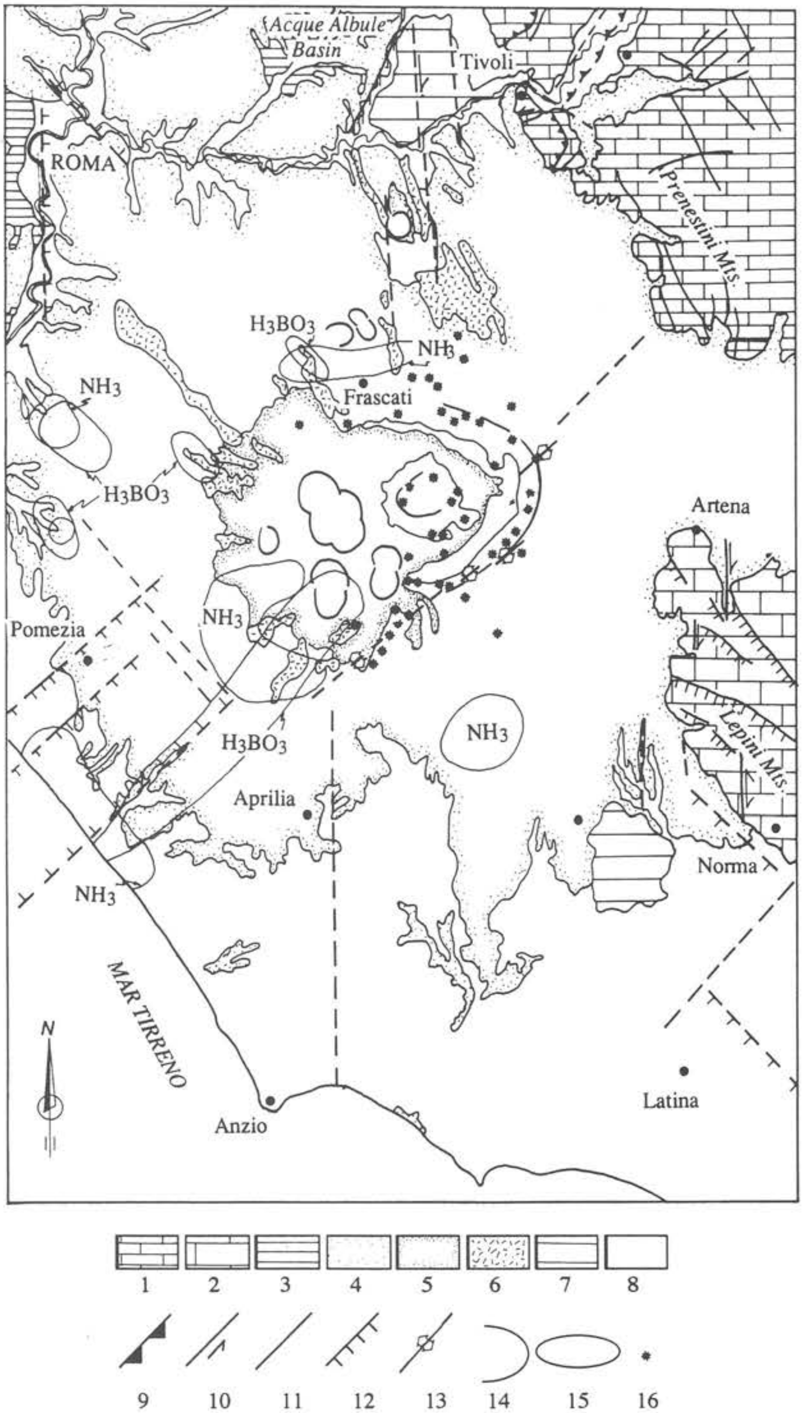

Fig. 6 - Structural synthetic map of the Colli Albani district area. 1) Dolostones, limestones and marls of the Sabina sequences (Upper Triassic-Upper Miocene); 2) Latium-Abruzzi carbonate sequences (Cretaceous); 3) sedimentary sequences of the "neo-autochthonous cycle" (Pliocene-Pleistocene); 4) Colli Albani pyroclastic flow rocks and air-fall deposits (Pleistocene); 5) Colli Albani pyroclastic rocks of hydromagmatic origin (Late Pleistocene); 6) Colli Albani undersaturated lavas (Pleistocene); 7) travertine deposits (Quaternary); 8) alluvial and colluvial deposits (Quaternary); 9) thrust faults; 10) strike-slip faults; 11) faults; 12) normal faults; 13) tensional fractures and dikes; 14) crater and caldera rims; 15) gas anomalies; 16) volcanic centers.

Fig. 7 - N40°E striking feeder dike outcropping in the Castellaccio Mt. scoria cone, on the eastern border of the Tuscolano-Artemisio caldera rim.

ment along the buried master fault. On the contrary, the Bracciano area is located inside the Cesano geothermal region (Calamai et al., 1977), with a 150-200 mW/m^2 heat flow (Mongelli and Zito, 1991), and a deeper carbonate bedrock zone.

Finally, moving from west to east, a progressive kinematic transition along Pleistocene N-S trending shear zones has been observed: from pure N-S extensional (Bsz), to pure right-lateral strike-slip (AAsz-Ssz), through transtensional (SMsz). The geometric array suggests that these shear zones could be the result of a Pleistocene reutilization in simple shear, of buried pre-existing structures, like the one recognised in the Meso-Cenozoic carbonate chain (Ssz or NLMsz).

VOLCANOLOGICAL CONSIDERATIONS

Five Pleistocene potassic explosive volcanic districts (Vulsini-Vico-Sabatini-Colli Albani and Ernici) lie on the Latium margin. Colli Albani is the only one intersected by the N-S oriented strike-slip shear zone.

The Colli Albani volcanic district is located on the southern prosecution of the Olevano-Antrodoco line where the Sabina pelagic units overthrust the south-western corner of the Latium-Abruzzi carbonate platform (Funiciello and Parotto, 1978). These structures rotated differently after Middle Miocene times. On the basis of a recent paleomagnetic study, clockwise rotations have been recognised in the N-S oriented Sabina chain, while counter-clockwise rotations have been recorded in the NW-SE oriented Latium-Abruzzi platform (Mattei et al., 1991). The tectonic features of the Colli Albani area fully reflect this peculiar structural position; in fact three main fracture systems are present in the area: NNW-SSE to NW-SE, NE-SW and N-S (Gasparini et al., 1989). The NNW-SSE to NW-SE feature represents the orientation of the Ciampino structural high (Toro, 1976; Funiciello and Parotto, 1978) which is probably bordered by normal faults, as observed in the neighbouring Lepini Mts.. Focal mechanisms, coming from earthquakes corresponding to the central edifice of Colli Albani, show a N50°E striking T-axis, relative to a N40°W fault plane (Amato et al., 1991). Moreover, freatomagmatic craters, of the last volcanic activities (150-30ka; De Rita et al., 1988) seem to be located along this buried master fault (Funiciello and Parotto, 1978). The NE-SW striking feature is detectable from the coast (Pomezia area) to the chain. Along the coast, it is formed by a system of normal faults and is marked by the rising up of deep fluids (Governa et al., 1989; ENEL, 1990).

Its continuation inside the volcanic area is defined by the N40°E trending alignment of dikes and scoria cones (Fig. 6) (De Rita et al., 1988). Two N-S striking segments overstep in the Colli Albani district. Comparing with the features observed in the releasing area (e.g., Acque Albule pull-apart basin), a system of tensional features, N40°E striking, develops in the Southern part of the Tuscolano-Artemisio caldera, as is revealed by alignments of scoria cones, dikes (Fig. 7), explosive centers and geochemical anomalies. We suggest that, as in other volcanic areas (Robinson et al., 1976; Weaver and Hill, 1978/79; Bacon et al., 1980; Duffield et al., 1980; Weaver et al., 1987; Aydin et al., 1990) "local crustal spreading" and dilation mechanisms on strike-slip faults in the overstep area could help the magma to rise up. This singular tectonic pattern reflects the petrologic and geochemical character of the Colli Albani products. In fact, the Colli Albani volcano products show a peculiarly homogeneous HKS composition, with less than 50% of SiO_2 content (Trigila et al., 1991), and homogeneous stable isotopic ratios of $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ (Turi et al., 1991), in comparison to the other Latium volcanic districts. Following the Author's suggestions, the isotope content has proved very useful to elucidate the geodynamic significance of the Colli Albani district. The Sr and O contents, in fact, demonstrate that all the Colli Albani volcanites are constantly produced by the same geodynamical conditions. The Nd and Sr isotopic values show a high concentration in the volcanic districts north of Rome, with respect to the Colli Albani. This difference is related to the very high crustal thermal flow in the Tuscan region as far as Rome.

Moreover, in Italy, the isotopic analyses clearly distinguish between two different magmatic provinces: the first one, north of the Colli Albani, characterized by an end member enriched in crustal components; the second one south of the Colli Albani, probably related to an upper mantle source modified by a recent subduction (Fig. 8).

On the basis of these data it is possible to consider the Colli Albani district as the boundary between two regions with different geodynamic evolutions; the correspondence between the location of the Colli Albani and other minor volcanic edifices of the Central Apennines (e.g. Colle Fabbri, Cupaello, Polino) and the shear zone belt is also evident, which may finally be better focused in order to improve our knowledge of the main geodynamics in the evolution of peninsular Italy.

DISCUSSION

A 150 km long discontinuous strike-slip shear zone from the Sabina chain to the Colli Albani area has been recognised. This fault zone developed in the easternmost sector with three right-lateral strike-slip shear zones (NLMsz-AAsz-Ssz).

Moving to the west and northwest, we observe, along the N-S striking shear zones, a transition from strike-slip to extensional tectonics, through transtensional, with a decrease of the Late Pleistocene horizontal displacements.

The relationship between N-S trending tectonics and the NW-SE extensional basin is still a topic of discussion. However, several considerations suggest that the strike-slip tectonics do not act as transfer zones (sensu Gibbs, 1984) to accommodate areas with different rates of extension:

- the N-S striking narrow shear belt extends inside the Sabina Apenninic chain;

- the N-S oriented tectonics show an activity up to Late Pleistocene times, when the NW-SE striking tectonics operate only with vertical isostatic dip-slip motion;

- the transition from strike-slip to dip-slip motion cannot be interpreted as transfer tectonics sensu stricto; this excludes the N-S striking tectonics being caused by a stress tensor permutation. Moreover, the right-lateral motion is in disagreement with the N20°-40°E extensional axis. On the basis of these considerations, we suggest that two tectonic systems, N-S and NW-SE trending, were active contemporaneously along the Latium Tyrrhenian margin in Pliocene-Pleistocene times.

We propose that the transition between a N-S trending strike-slip zone to an extensional

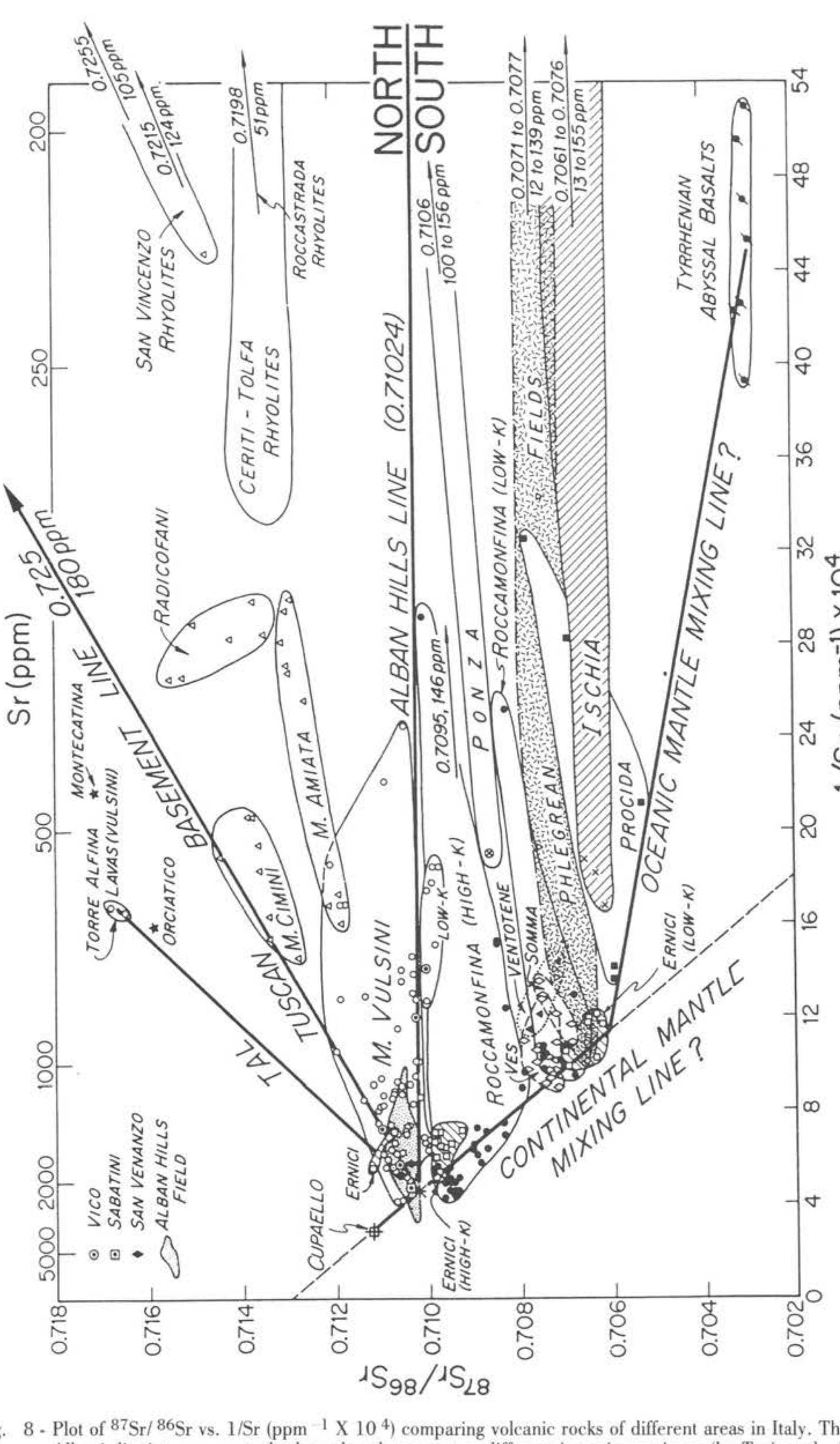

Fig. 8 - Plot of $^{87}Sr/^{86}Sr$ vs. 1/Sr (ppm $^{-1}$ X 10^{4}) comparing volcanic rocks of different areas in Italy. The Colli Albani district represents the boundary between two different isotopic provinces (by Turi et al., 1991).

one, showing the same orientation, could be better explained by a partitioning of the "near-field stress" along the major elements than a rotation of the principal stress axes. Recent works (Mount and Suppe, 1987; Zoback and Zoback, 1991; Ben-Avraham and Zoback, 1992) point out that this partitioning is due to particular relations between frictional parameters of the principal discontinuities and the surrounding crust.

The hypothesis that the N-S trending major fault zone represents the boundary between areas with different shear strenght parameters is also supported by geochemical and geophysical data.

Tuscan and Roman Comagmatic province isotopic compositions display a Low-K, with $^{87}Sr/^{86}Sr$ (0.706) and $\delta^{18}O$ (+6) on the south of Colli Albani area, and high-K, with $^{87}Sr/^{86}Sr$ (0.711) and $\delta^{18}O$ (+7) on the north (Ferrara et al., 1985; Rogers et al., 1985; Turi et al., 1991). Other meaningful indications are related to the $\delta^{13}C$ contents of the Latium travertine deposits (Manfra et al., 1976): a contribution by decarbonatation at depth in samples located west of the main N-S shear zone is absent in all the eastward located sites (Valle Latina). This difference may be related to the different geothermal regimes in the two different regions. A sharp decrease of heat flow, moving from the Tuscan-Latium province (about 120 mW/m^2), toward the chain (about 50mW/m^2) (Mongelli et al., 1991) has been observed: the border between the two areas is roughly N-S trending and corresponds to the major fault zone. Moreover, sulphur isotope contents in minerals and the deep fluid distribution also show a possible connection with the aforementioned shear belt; the deepest fluids and those less contaminated by meteoric fluids seem to differ from Civita Castellana, north of Mt. Soratte, to the Anzio area near the Tyrrhenian coastline (Cavarretta and Lombardi, 1992, Governa et al., 1989).

The isotopic values define two different regions, and this differentiation is evident even in the other geophysical parameters. In fact a probable change in crustal thickness is shown along a N-S trending zone (Wigger, 1984), in an area that is fairly consistent with surface faulting, and associated with strike-slip tectonics.

Differential rotations about vertical axes have been recognised in the chain in Upper Cretaceous to Middle-Upper Miocene sequences outcropping in the Sabina and Latium-Abruzzi structures. The main tectonic boundaries between areas which experienced different rotations are the N-S oriented Olevano-Antrodoco line and Sabina shear zone. The N-S crustal discontinuities could be also confirmed by the block rotation mechanism which may control both the thrust geometry and the strike-slip features.

The possible connection between the main discontinuity and the offshore lineament should be one of the topics investigated by the CROP11 profile.

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