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Structural and hydrogeological features of Pleistocene shear zones in the area of Rome (Central Italy)

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Abstract
The last tectonic episode observed in the Latium Tyrrhenian margin (Central Italy), few km east of Rome, is represented by a set of middle-upper Pleistocene N-S shear zones, characterised by complex geometric and kinematic setting. The easternmost of these shear zones displays a strike-slip component of motion and is located at the boundary between the Apennine carbonate chain and the volcanic areas. The distribution of travertine deposits and hydrothermal springs suggests that this fault zone acts as an impermeable barrier for lateral flow derived from superficial karstic circuit, and as a preferential upwelling surface for deep hydrothermal fluids. We propose that high fluid pressure could develop inside these fault zones favouring the reactivation of buried pre-existing crustal discontinuities and the local re-orientation of the stress field, as testified by the geometry and the kinematics of the surface fault pattern.

Key words *Tyrrhenian margin – middle-upper Pleistocene – shear zones – hydrogeology*

1. Introduction

It is widely demonstrated that the increase of fluid pressure could trigger failure of intact rocks or induce reactivation of pre-existing fault planes, even if they are unfavourably oriented (Sibson, 1990). Particularly, when the pressure of the fluid exceeds the minimum extensional stress, fracture and mineralized joint develop with an abrupt discharge of fluid (Ramsay, 1980; Waldner and Nur, 1984). The presence of high fluid pressure along fault zones could also induce a drop in the shear strength: if the pore pressure increases from an hydrostatic value in the boundary rocks to a much higher value inside the fault zone a rotation of the stress axes could occur (Byerlee, 1992).

In this note we present some structural and hydrogeological features of middle-upper Pleistocene shear zones located along the Latium Tyrrhenian margin, near Rome. These shear zones could represent a test site to analyse the possible relationships between fluid circulation and surface faulting. We particularly emphasize that reactivation processes of buried pre-existing crustal discontinuities and local re-orientation of the stress field, deduced by the geometry and the kinematics of the fault zone, could be favoured by high fluid pressure developed inside the fault zone.

2. Geological framework

The Tyrrhenian margin of Central Italy underwent an intensive extensional episode during the formation of the Tyrrhenian basin (Funiciello *et al.*, 1976). This area is

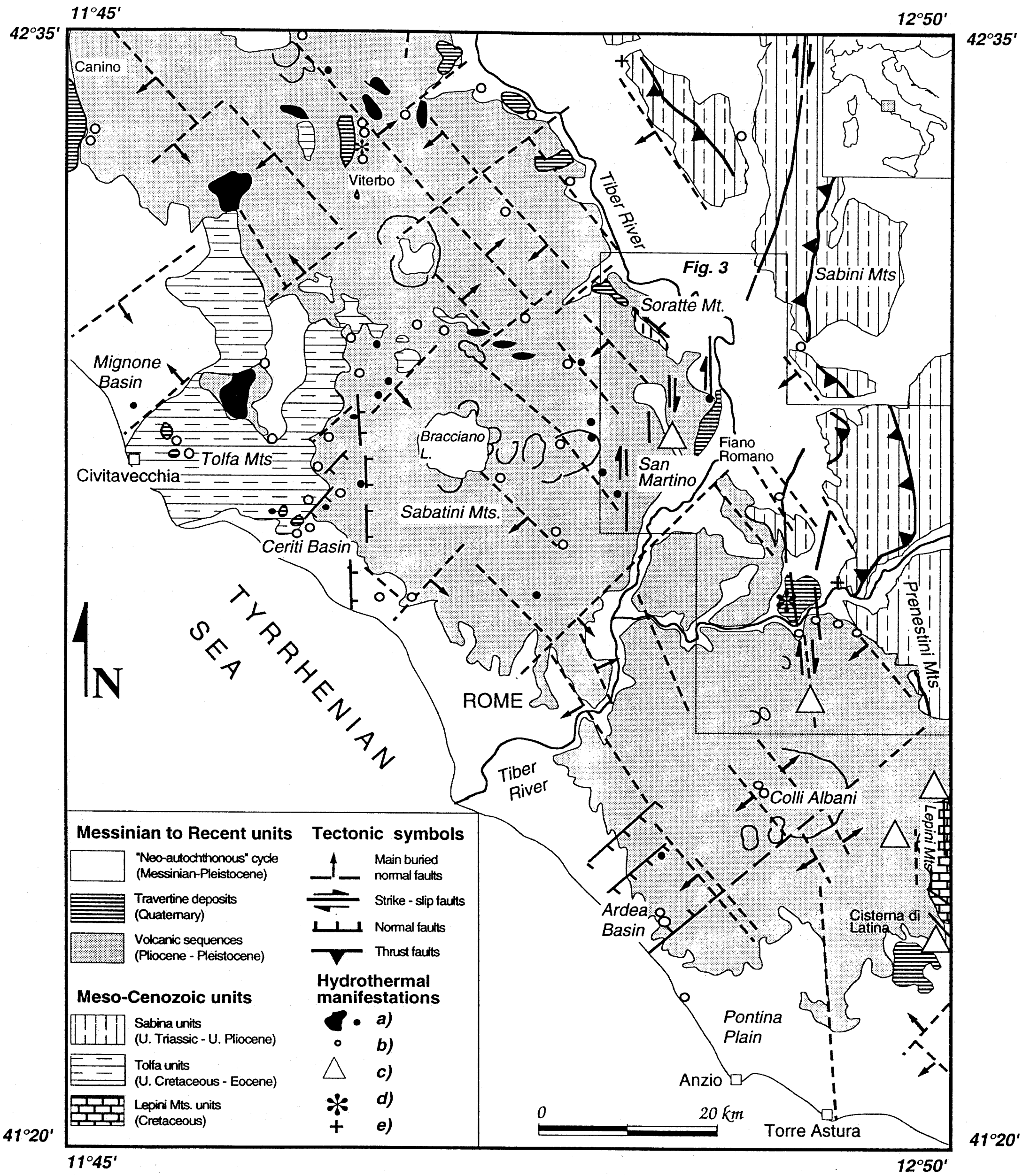

Fig. 1. Schematic map of the Latium Tyrrhenian margin, with main hydrothermal manifestations. Legend of hydrothermal manifestations: a) alunite and kaolin mineralization (from Lombardi and Mattias, 1979); b) main selected gas leaks associated with small springs (with a temperature often > 20°C) (from Boni *et al.*, 1988); c) main sinkhole groups; d) main springs affected by hydrothermal activity (T > 20°C) (from Boni *et al.*, 1988); e) main mineralized springs (TDS > 0.75 g/l; T < 20°C) (from Boni *et al.*, 1988).

presently characterised by a thin crust, less than 25 km (Wigger, 1984), anomalous high heat flow (100/200 mW/m^2, Mongelli and Zito, 1991) and by the presence of large upper Pliocene-Quaternary volcanic provinces. This extensional regime led to the formation of deep NW-SE and NNW-SSE normal faults which border basins filled by thick sequences of clastic marine and continental deposits dating back from Messinian up to lower Pleistocene (fig. 1). These faults are intersected by a system of transfer structures, oriented NE-SW, parallel to the main extensional axis. In the Latium region, intensive volcanic activity accompanied and followed crustal extension and reached a climax during the middle-upper Pleistocene, with the high potassium volcanism of the Roman comagmatic province (Locardi *et al.*, 1977). Volcanic edifices and lava domes developed at the border of the extensional basin and at the intersection of the NE-SW, NW-SE and N-S fracture zone. At the same time, during the middle-upper Pleistocene, a system of N-S trending shear zones cross cut all the pre-existing features. These shear zones are spaced along the Latium margin, with an average distance of 20-40 km, and represent the last tectonic episode observed in the area.

We first will define the general structural characteristics of these middle-upper Pleistocene shear zones and we will then emphasize their interaction with deep hydrothermal circuit.

3. Structural setting

In the Latium region, nearby Rome, a set of narrow N-S striking shear zones affects middle-upper Pleistocene volcanic and sedimentary deposits (fig. 1). More than 1500 structural data, at the outcropping scale, have been collected to constrain the kinematics of these shear zones. In this note we present a brief description of these shear zones, from west to east. More detailed data are in Alfonsi *et al.* (1991), Maiorani *et al.* (1992), Faccenna and Funiciello (1993), Faccenna *et al.* (1994), Sagnotti *et al.* (1994).

The westernmost shear zone is located immediately to the west of the Bracciano volcanic depression and in the Tolfa-Ceriti Mts. (fig. 1). This shear zone is less than 30 km long and 3-5 km wide and it is composed by a N-S system of 2-3 km long segments. These segments display a normal motion and are frequently associated with N-S oriented tensional joints (fig. 2). Moving to the east, south of the Soratte Mt., a 15 km long-10 km wide shear zone outcrops with four N-S striking segments, disposed in an en-echelon dextral array. The separation between the single segments is about 4 km and is much larger than the overlapping, which is less than 1 km (fig. 3). The surface geometry of the faults is characterised by en-echelon outcropping scale faults or negative «flower» structures affecting middle Pleistocene volcanic and sedimentary deposits. Slickensides on fault planes display a superimposition of dextral strike-slip/oblique-slip motion on dip-slip motion suggesting a transtensional regime of deformation (fig. 4). North of this shear zone a main N-S strike-slip fault zone occurs in the Sabina chain (fig. 1). This dextral strike-slip shear zone cuts the Meso-Cenozoic carbonate sequence and develops with a narrow system of fault segments and folds arranged in a complex «flower» structure (Alfonsi *et al.*, 1991).

South-west of Soratte Mt., in the Acque Albule area (figs. 1 and 3), a 30 km long-6 km wide shear zone affects the middle-upper Pleistocene sedimentary and volcanic sequences. It is formed by a system of N-S striking right lateral strike-slip faults (fig. 5), with an about 2.8 separation/overlapping ratio (in agreement with the Aydin and Nur (1982) statistical evaluation) (fig. 3). In the overstepping areas subsiding morphological depressions, with «pull-apart» like geometry, occur. N30°E splay junctions, with an oblique motion, and

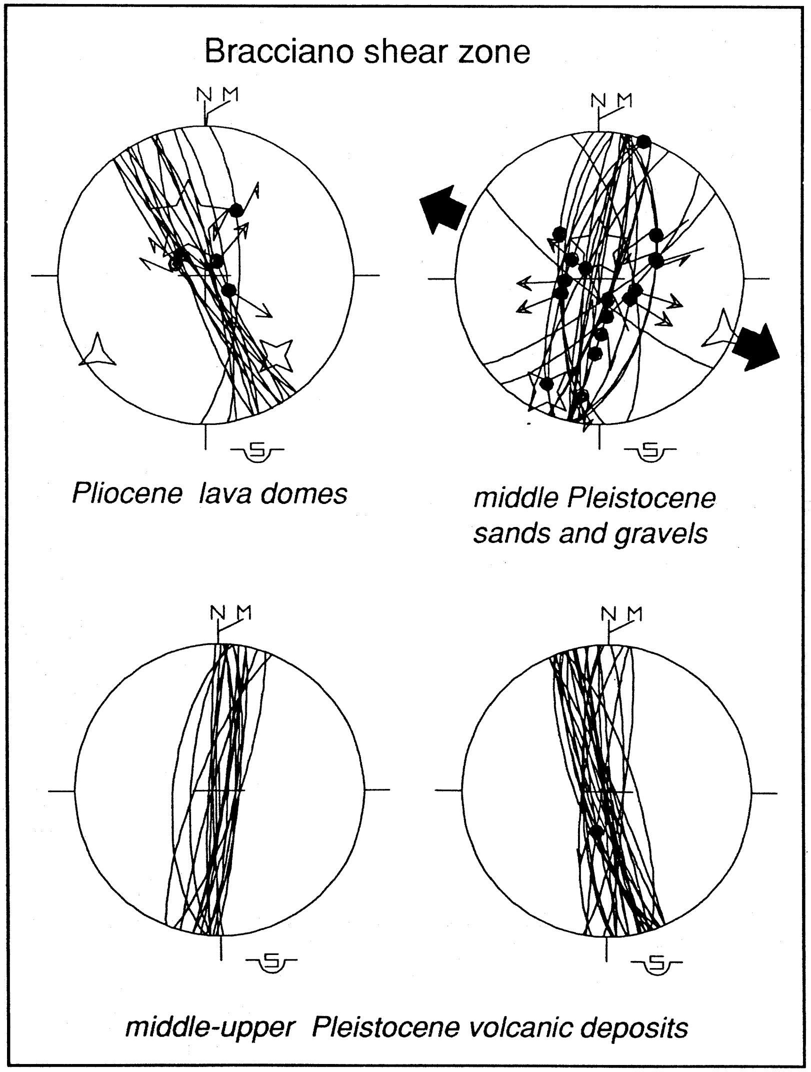

Fig. 2. Representative Schmidt nets (lower hemisphere) of the Bracciano area shear zones (fig. 1). Upper nets: lines indicate fault planes with circles that indicate strike and dip of striae, arrows the movement. Big arrows outside the net indicate the $\sigma 3$ direction (reconstructed by means of Angelier and Goguel (1979) method). Lower nets: lines indicate fault planes (right) and joint planes (left).

N40°E-60°E extensional structures are linked to the 30 km long strike-slip master fault.

This fault zone intersects the Colli Albani volcanic district (fig. 1). Its probable continuation towards south, both on-shore and off-shore, has been pointed out by geophysical analysis (Di Filippo and Toro, 1980; Mariani and Zitellini, 1986; Chiocci, 1989). Finally, south-east of the Acque Albule shear zone, another minor shear zone affects the western border of the Lepini

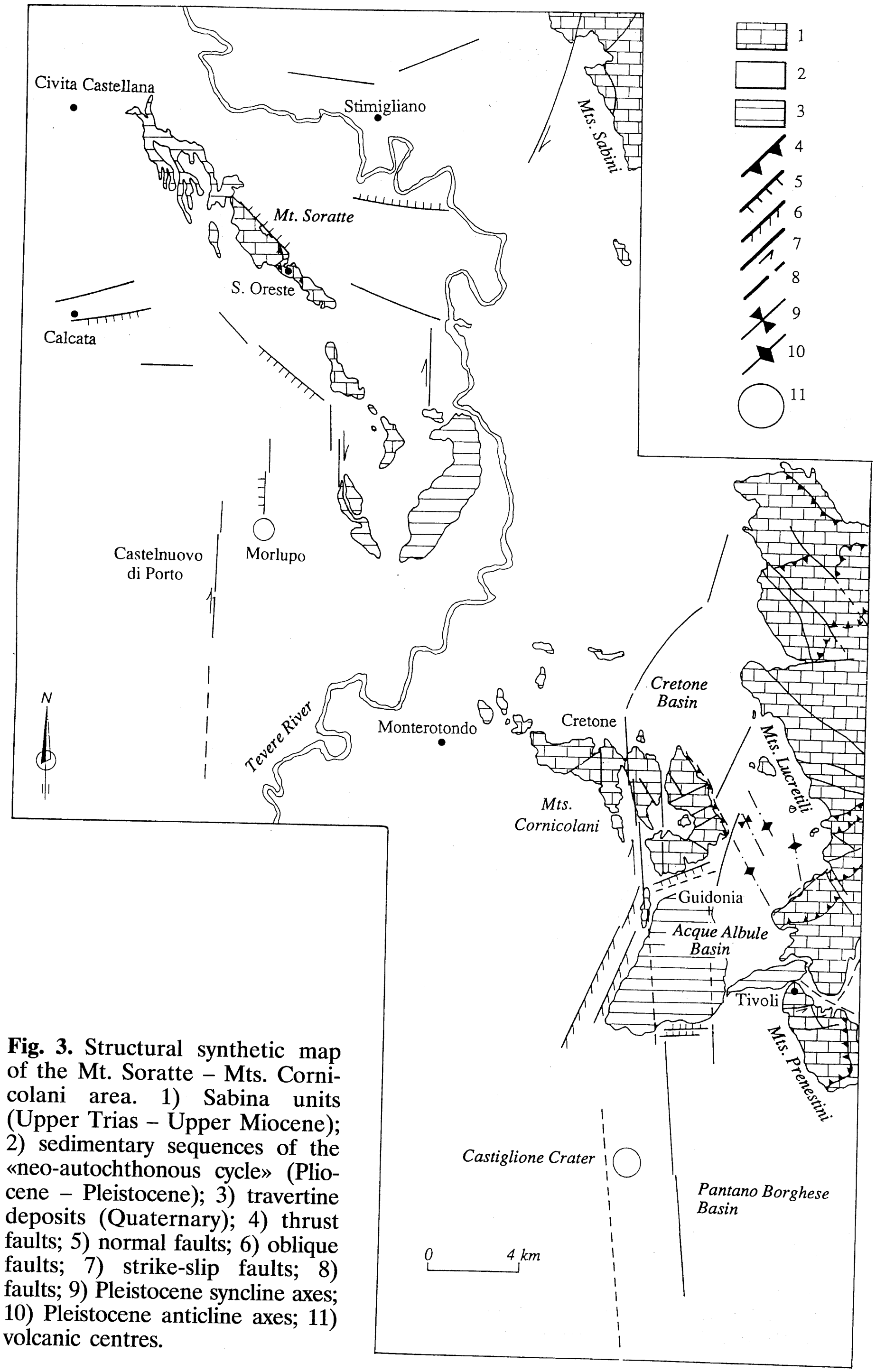

Fig. 3. Structural synthetic map of the Mt. Soratte – Mts. Cornicolani area. 1) Sabina units (Upper Trias – Upper Miocene); 2) sedimentary sequences of the «neo-autochthonous cycle» (Pliocene – Pleistocene); 3) travertine deposits (Quaternary); 4) thrust faults; 5) normal faults; 6) oblique faults; 7)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

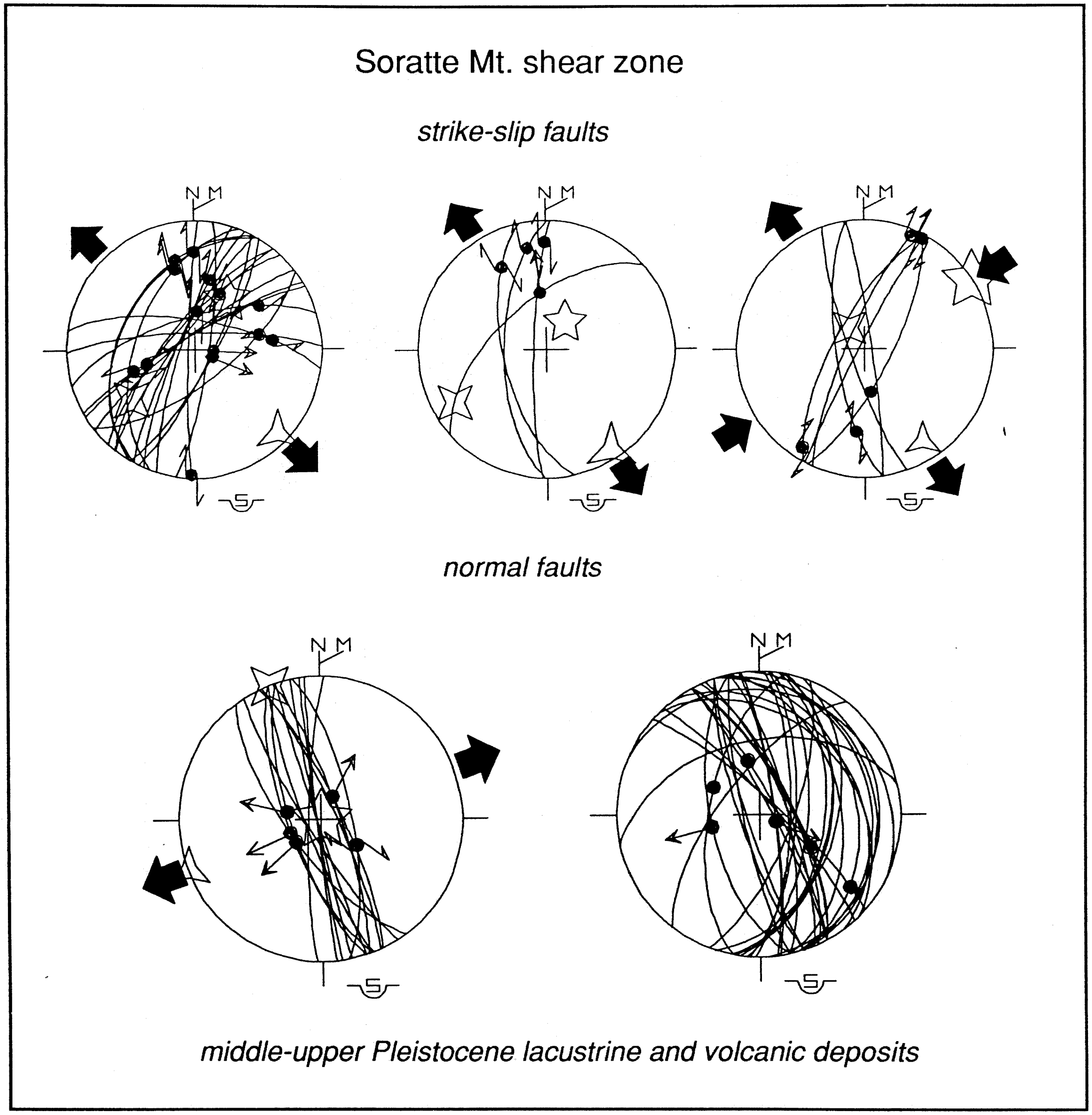

Fig. 4. Representative Schmidt nets (lower hemisphere) of the Soratte Mt. area shear zones (figs. 1 and 3). Lines indicate fault planes with circles that indicate strike and dip of striae, arrows the movement. Big arrows outside the net indicate the $\sigma 3$ and the $\sigma 1$ directions (reconstructed by means of Angelier and Goguel (1979) method).

Mts. It is constituted by three small N-S striking segments, which affect sedimentary and volcanic sequences, with a strike-slip component of motion.

The overall pattern of deformation defines a major discontinuous strike-slip fault zone, elongated from the Sabina chain to the Pontina Plain (fig. 1).

All the single shear zones display the following common characteristics:

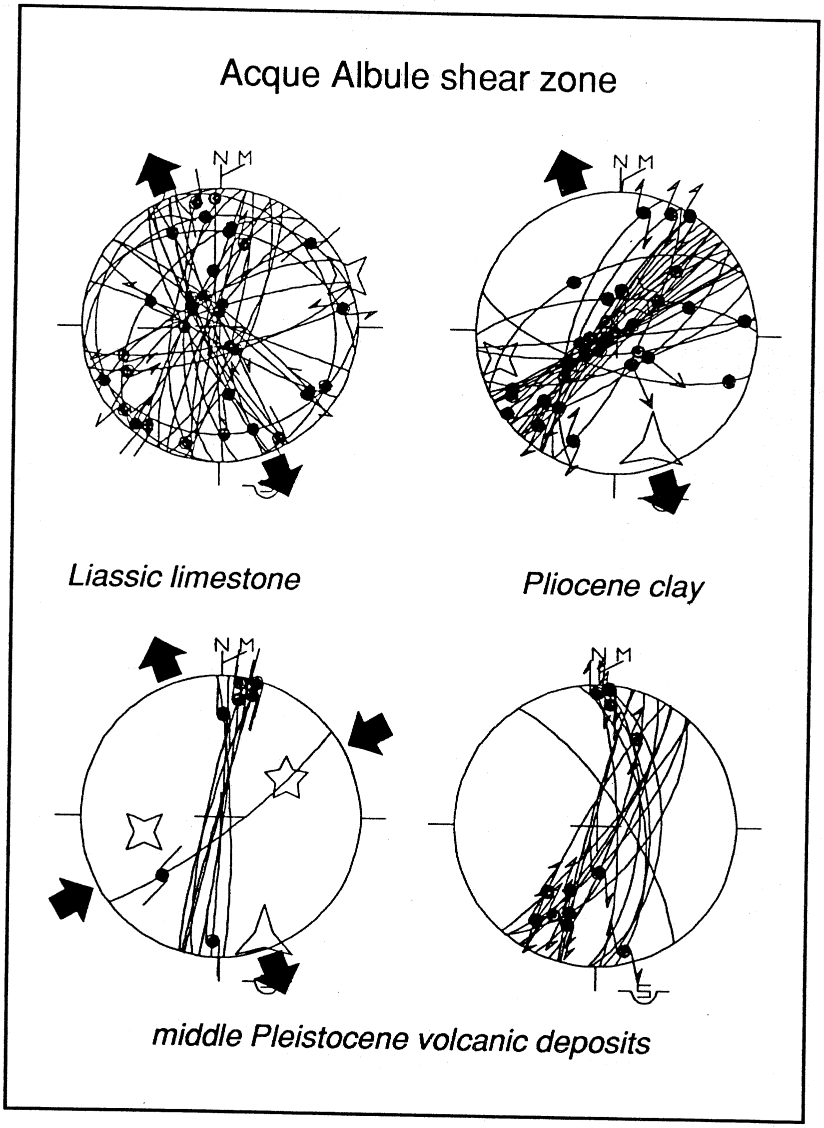

Fig. 5. Representative Schmidt nets (lower hemisphere) of the Acque Albule area shear zones (figs. 1 and 3). Lines indicate fault planes with circles that indicate strike and dip of striae, arrows the movement. Big arrows outside the net indicate the $\sigma 3$ and the $\sigma 1$ directions (reconstructed by means of Angelier and Goguel (1979) method).

1) a middle-upper Pleistocene age of activity, deduced by the age of the affected deposits;

2) a segmentation of the fault zone, constituted by 3-5 km long, en-echelon arranged, discrete segments;

3) a progressive kinematic transition from extension to right lateral strike-slip,

throughout transtension, moving eastward. This transition is underlined by the geometry and by the kinematics observed along the fault planes.

The surface array of faulting of each shear zone (composed by en-echelon segments), compared with the results of small-scale models (Wilcox *et al.*, 1973; Naylor *et al.* 1986), suggests that these shear zones develop for a simple shear reactivation of buried pre-existing structures, like the one recognized in the Sabina chain.

4. Hydrogeological features

The hydrogeological system of the Latium margin is characterised by two main circuits: the first and the largest one, mainly superficial, is composed by fresh groundwaters which go throughout fractured and karstic carbonate sequences; the second one, much deeper, is characterised by hydrothermal fluids linked to perivolcanic circuit (Boni *et al.*, 1980; Governa *et al.*, 1989). While the first one seems mainly to be controlled by local permeability barriers (*i.e.* fault and stratigraphic level) the second one seems to be influenced by crustal anisotropy and deep structures.

In order to define the control exerted by recent tectonic structures on the deep hydrothermal circuit, we examine the geometry and the location of active or fossil deposits linked with the deeper circuit. Particular care has been devoted to the Acque Albule area, which represents a test site for the relationships between hydrogeology and tectonics. We analysed the possible tectonic meaning of travertine deposits, of karstic hydrothermal-related manifestation as sinkholes and of high termality or mineralized springs.

4.1. *Travertine deposits*

Huge travertine deposits represent a good marker of CO_2 rich fluids, often connected with hydrothermal circulation. Several travertine *plateaux*, are widespread along the Latium margin and their deposition is related to the final stage of the explosive volcanic activity (Manfra *et al.*, 1976). Actually, they are mostly distributed at the border of the main volcanic districts, beside the Apenninic carbonate chain (fig. 1) where fresh waters of the superficial karstic circuit mix with the deeper one. The systematic isotope analysis performed on these deposits indicates that the largest outcropping travertine *plateaux*, as Canino, Acque Albule, Cisterna di Latina, Fiano Romano and partially Viterbo (fig. 1), are characterised by a high $^{13}C/^{12}C$ ratio (Manfra *et al.*, 1976). The high ratio indicates that the travertine deposition is related to a decarbonatation process of Mesozoic units at depth, linked to the circulation of deep chemical aggressive fluids. Three of these travertine *plateaux* (Acque Albule, Fiano Romano and Cisterna di Latina) seem to be directly connected with the N-S oblique or strike-slip shear zones.

The Acque Albule deposit, one of the largest and well known travertine *plateau*, quarried since Roman time (the name «travertine» itself derived from Latin «tiburtinus» Late Imperial denomination of the Tivoli area), is located in a subsiding upper Pleistocene basin inside the Acque Albule strike-slip shear zone. The travertine body is rhombochasm-like shaped, 2.5 km wide and 7 km long, as indicated by the travertine base contour lines (fig. 6). Travertine deposits are in average 60 m thick and in Acque Albule locality the base of the travertine is at least at 20 m b.s.l. The western and eastern margins of the deposit are steep and N-S striking corresponding to the main strike-slip faults, while the northern and southern margins are roughly NE-SW trending.

Chronological age, calculated by the $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ activity ratio of the carbonate fraction, indicates that the Acque Albule travertine has been deposited since 165 ka, with an average rate of 0.43 mm/y. The ages of the slickensided

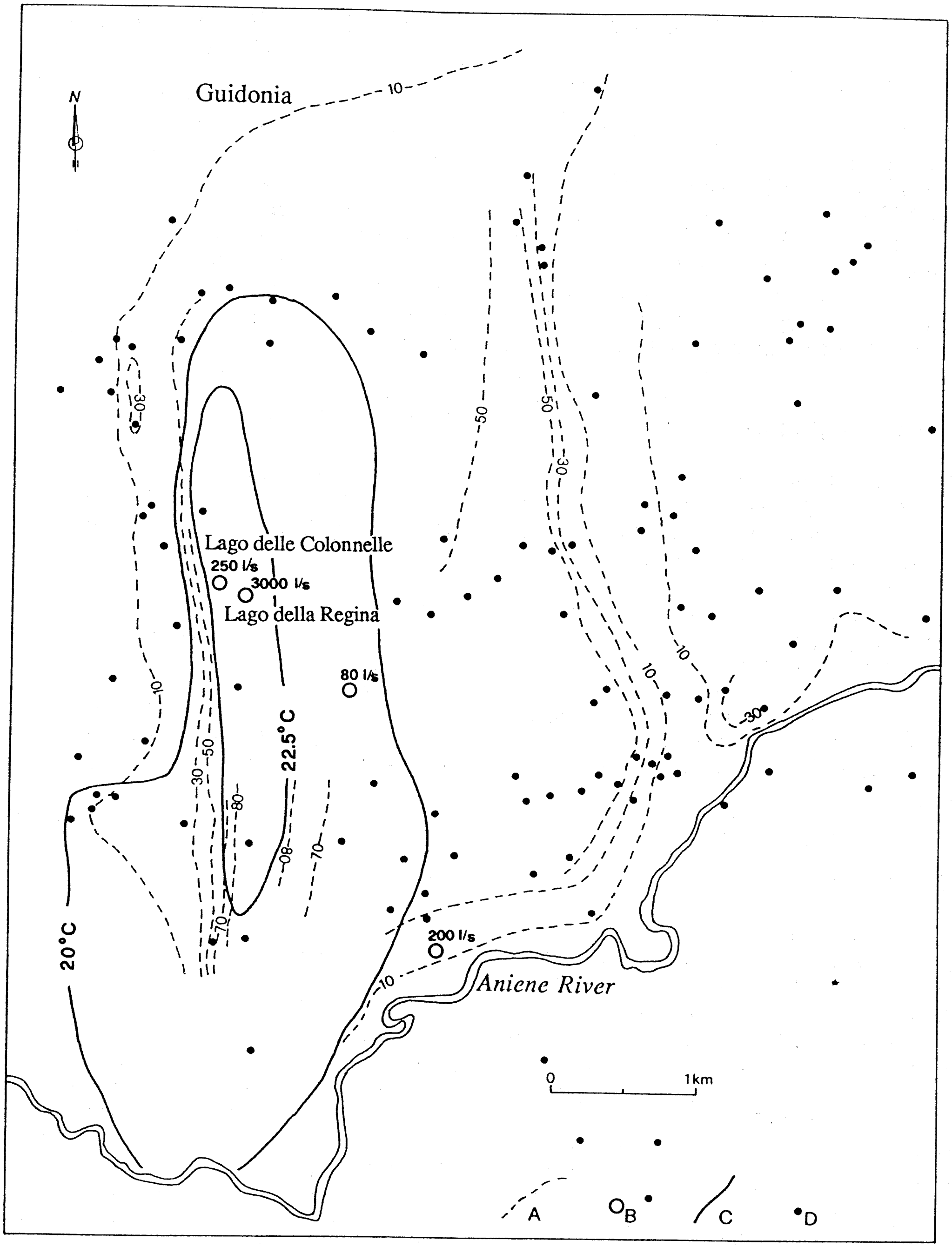

Fig. 6. Isopach map of travertine deposits. Legend: A) contour-lines of travertine deposits; B) main springs (> 80 l/s); C) water table isotherms; D) drillings.

calcite inside oblique faults and of the joints filling calcite, sampled two km north of the travertine body (Guidonia area, fig. 6), are respectively 178 ka (+44; −66) and 49 ka (±8) (radiometrical dating has been performed by M. Voltaggio and is in Faccenna *et al.*, 1994). The result of these analyses, the geometry of the brittle deformations and the shape of the travertine *plateau*, suggests a link between the faulting event (~170 ka) and the travertine deposition. It is worthy pointing out that around 180 ka began the hydromagmatic phase of the Colli Albani volcanic district, located just south of the Acque Albule area (De Rita *et al.*, 1992).

The Fiano Romano travertines, north of the Acque Albule area, on the right river bank of the Tiber valley, are located at the tip of a strike-slip N-S oriented fault, related to the Soratte Mt. transtensive shear zone (fig. 3); chronological data indicate that deposition started at the same time as the one observed in the Acque Albule area (Funiciello *et al.*, 1992). Finally, the Cisterna di Latina travertine deposits, southward of the Acque Albule area, (fig. 1) seem to be also related with the southernmost strike-slip shear zone of the Lepini Mts. area.

4.2. *Sinkholes*

The sudden formation of sinkholes, which are small size morphological depressions, is due to the breakdown of carbonate bedrock cave vaults, below a thin cover of slightly cohesive deposits. The formation of the cave vaults is linked to a chemical dissolution process mainly due to the fluids, rich in CO_2 and in H_2S, which migrate through major tectonic fractures and their intersections (Brook and Allison, 1986); for this reason the sinkhole occurrence gives information about the preferential conduits for the upwelling of deep fluids.

As observed for the travertine deposits, natural sinkholes mostly form along the border between Mesozoic-Cenozoic carbonate units and Plio-Quaternary sedimentary and volcanic deposits, where a branching between an epidermic and a deeper circuit is likely to occur (fig. 1). The distribution of sinkholes along the Latium carbonate platform border is mostly controlled by the described shear zones (Faccenna *et al.*, 1993). Particularly, sinkholes are present along the Acque Albule shear zone, north of the Colli Albani volcanic district; along the northern and western border of the Lepini Mts. shear zone and along the central segments of the Soratte Mt. shear zone, in the Fosso di San Martino stream valley (Rome) (fig. 1). In this area, where a detailed structural analysis has been carried out (Faccenna *et al.*, 1993), repeated intense soil subsidence occurred during the last two centuries. Systematic analysis of sinkholes suggests that these karstic features display common characteristics:

1) they mostly occur in slightly cemented sediments, where a carbonate bedrock is found from 50 to 100 m below the surface;

2) they are linked to an upwelling of aggressive fluids related to deep circulation (mainly waters with high CO_2 and minor H_2S contents).

3) they are placed along recent N-S shear zones, or at their intersection with fracture zones.

4.3. *Deep circuits*

Figure 1 illustrates the location of the main hydrothermal springs and gas emissions, as mapped by Boni *et al.* (1988). The main active hydrothermal springs in Latium are located along the Acque Albule shear zone (figs. 1, 3 and 6). In this area, the underground water table is characterised by the mixing of the superficial carbonate circuit, which flows from the Lucretili-Tiburtini-Cornicolani (Capelli *et al.*, 1987) with a deeper one characterised by hydrothermal fluids (CO_2 and minor H_2S rich) and gas. The mixed water upwells in two main springs (Lago delle Colonnelle and Lago della Regina) with a discharge of 3250 l/s, and in other minor ones (fig. 6). Along the western border of the travertine body the isotherms of the mixed fluid are N-S elongated and reach a maximum of 22.5 °C. This means that the deep hot hydrothermal fluids upwell along a N-S master fault which displays a strike-slip component of motion and bounds the basin.

Other minor springs are located nearby the travertine deposits of Viterbo (Bullicame) on the northern prosecution of the Bracciano shear zone and along a N40°E normal fault in the Ardea basin area (fig. 1). Particularly, this last site represents one of the less contaminated discharge of deep endogenous fluid in all the Latium area (Governa *et al.*, 1989).

Finally, soil total helium anomalies in all the western Sabatinian area, are elongated in a N-S direction (De Rita *et al.*, 1991).

5. Discussion

A regional discontinuous strike-slip shear zone has been recognized from the Sabina chain to the Colli Albani area. This fault zone developed during middle-upper Pleistocene, at the border between the volcanic morphologically depressed area and the westernmost part of the Apennine carbonate chain. Moving to the west and to the north-west, along the N-S shear zones, a transition from strike-slip to normal, throughout oblique motion, exists. Moreover, the surface pattern of faulting indicates that each shear zone developed as a reactivation of a buried pre-existing structure. Gravimetric data (Di Filippo and Toro, 1980; Di Filippo *et al.*, 1991) confirm that surface faulting corresponds to deep crustal structures, outcropping on the Meso-Cenozoic units in the Sabina area.

The strike/oblique-slip shear zones (Acque Albule – Soratte Mt. – Lepini Mts.), located at the border of the Apennine chain, display a very high permeability. In this area, upwelling of deep fluids and travertine depositions occur along releasing or overstepping zones or at the tip of the strike-slip faults, where «fault normal dilatation» mechanism (Aydin *et al.*, 1990) could be present. Moreover, radiometric dating, performed on travertine deposits and on faults and joints calcite filling, suggests that a rapid discharge of fluids could occur after the main tectonic event.

Finally, all these data indicate that an intensive fluid circulation along deep fracture zones exists: these fluids are produced mostly by the mixing of a hydrothermal perivolcanic deep circuit with a shallower karstic one. Hence. we propose that huge travertine deposits, hydrothermal springs and even huge Apennine karstic springs could be indicators of recent tectonic activities.

We suggest that the described fault zones act as an impermeable barrier for lateral flow and as preferential way of migration for deep fluids. These processes could influence the kinematics of the recent observed tectonic features:

— high pore pressure zone inside buried pre-existing crustal discontinuities could favour reactivation mechanisms and consequently a partitioning of the strain, as deduced from the surface pattern of faulting;

— high fluid pressure inside these fault zones could induce a local drop in shear strength. A decrease in shear strength and in frictional parameters could cause a local re-orientation of the «near-field stress» (Mount and Suppe, 1987; Zoback and Zoback, 1991; Ben-Avraham and Zoback, 1992; Byerlee, 1992). Hence, following these authors, we propose that the transition between a N-S trending strike-slip zone towards an extensional one, showing a contemporaneous activity and the same orientation, could be better explained by a rotation of the stress axes along weak crustal discontinuities, rather than by an inversion of the principal stress axes.

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