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Strike-slip faulting and block rotation: a possible triggering mechanism for lava flows in the Alban Hills?

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Abstract

It is suggested in this paper that two distinct tectonic triggers, tapping different depths of a magma reservoir, may be the cause of nearly contemporaneous eruptions of lava flows and ignimbrites in the Alban Hills. The area between the Alban Hills and Rome underwent alternating regional extensional and strike-slip faulting during the Middle Pleistocene. The geometries of the main structural dislocations in Quaternary strata, combined with a statistical analysis of drainage network trends, show a structural pattern that is consistent with local strain partitioning in transpressive zones at strike-slip fault bends, superimposed on regional extension. Based on this analysis, it is suggested that local clockwise block rotation between parallel N–S strike-slip faults might have generated local crustal decompression, allowing relatively volatile-free magma to rise from deep reservoirs beneath the Alban Hills, triggering peripheral fissure lava flows. In contrast, the main ignimbrite eruptions appear to tap shallow, volatile-rich magma reservoirs and are controlled by extensional processes.

1. Introduction

Rome is located on the margin of the Central Tyrrhenian Sea, at the convergence of a series of major structural lineaments (Fig. 1). The Latium Volcanoes (Vulsini, Cimini, Monti Sabatini and Alban Hills) are aligned along the strike of extensional structures which formed at the rear of the Apennine fold-and-thrust belt (Funiciello et al., 1976; Locardi et al., 1977; Funiciello and Parotto, 1978). The continuity of the Central Apennines is interrupted along the Olevano–Antrodoco line, a N-striking thrust front across which the Umbria-Marche Basin is thrusted eastward over the Latium-Abruzzi Carbonate Platform (Parotto and Praturlon, 1975; Salvini and Vittori, 1982). A few kilometers west of this line is the Sabina Fault, a N10–20° shear zone described by Alfonsi et al. (1991). The southern end of the Sabina Fault had strike-slip activity from Pliocene through middle–late Pleistocene time, developed through a series of N-striking right-lateral en echelon fault segments (Faccenna and Funiciello, 1993; Faccenna et al., 1994a). N-striking right-lateral strike-slip faulting has been proposed as the most recent tectonic style for the area of Rome, implying a NW-striking σ_3 (Faccenna and Funiciello 1993; Faccenna et al., 1994a).

In contrast to this scenario, recent seismicity, including a $M_L = 3.6$ earthquake (June 12, 1995) in the Cecchignola area south of Rome (Figs. 1 and 2), is consistent with seismic activity associated with the Alban Hills volcano (Amato et al., 1994; Amato and Chiarabba, 1995), which has a present-day stress-field characterized by a NE-trending σ_3 (Montone et al., 1995). The Cecchignola earthquake showed right-lateral oblique slip and occurred at a depth of 11.5 km on an E–W striking fault located 15 km west of the central caldera of the Alban Hills (Basili et al., 1996). It was therefore interpreted as a tectonic earthquake that re-activated a pre-existing strike-slip fault with oblique slip under NE–SW extension (Marra, 1999).

The common northeast orientation of the tension (T) axes of the Cecchignola and Alban Hills earthquakes suggests that back-arc extension along the Tyrrhenian margin controls Roman seismicity (Marra, 1999). Alternatively, tectonic activity responsible for the E–W structures has been proposed to be linked with N-striking right-lateral faulting that generated localized transpression around Rome (Marra, 1999). The transpressive feature of the N–S shear zone associated with the Sabina Fault is due to a major restraining bend that occurs in the area of Rome (see Fig. 1b). These strike-slip features are superimposed on regional extension, possibly due to the northeast escape of the Northern Apennines relative to the Central Apennines along the Sabina Fault (Marra, 1999).

The fault geometry that affects the sedimentary and

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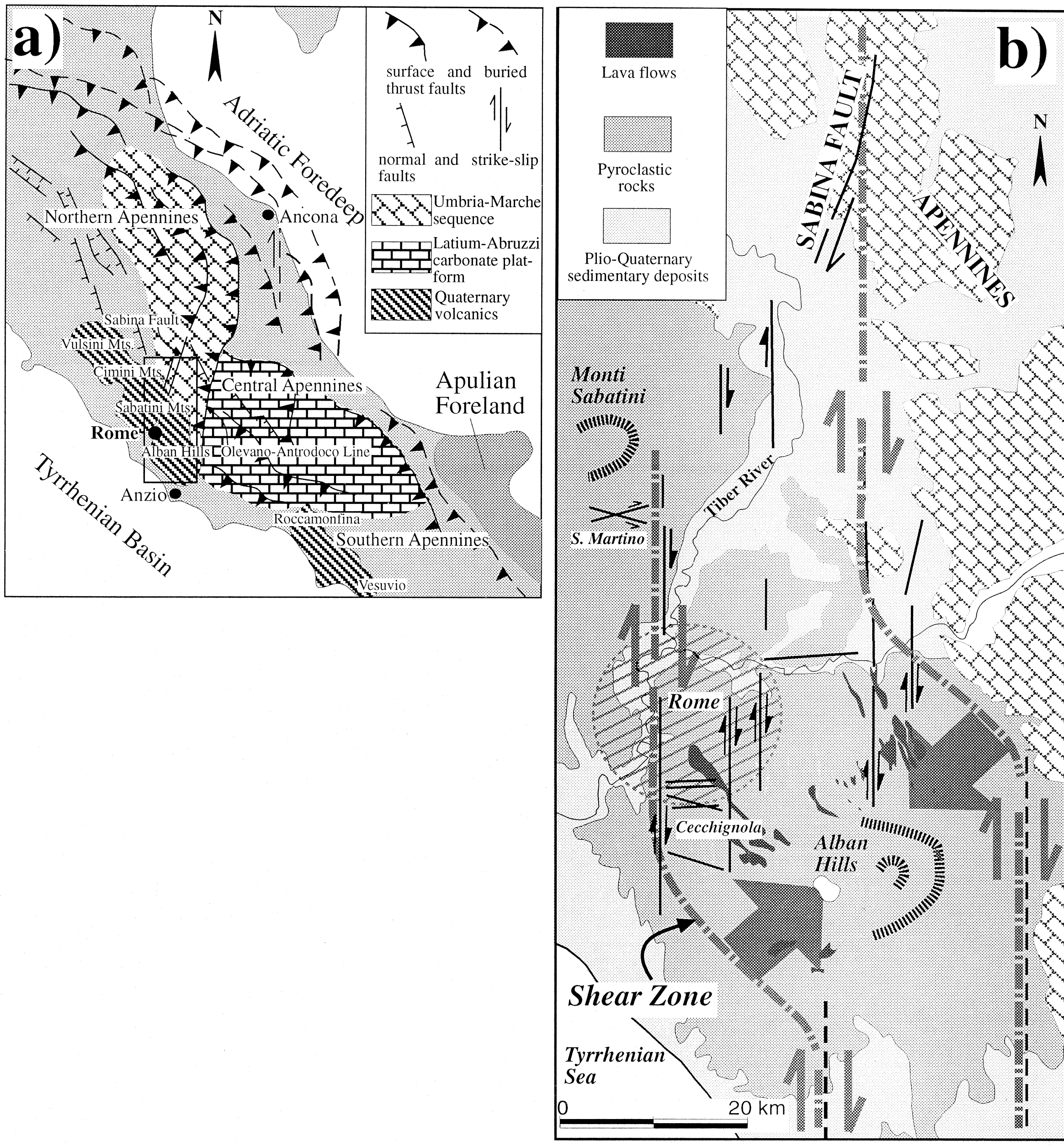

Fig. 1. (a) Structural sketch map of Central Italy. (b) Geologic map of the investigated area: the mechanism capable of generating local transpression in the area of Rome is shown.

volcanic strata and drainage network around Rome is investigated here and reinterpreted in order to reconstruct the deformational history between Rome and the Alban Hills and to evaluate possible relationships between tectonism and volcanism. The aim of this work is to understand emplacement mechanisms for nearly contemporaneous lava and pyroclastic eruptions, since these volcanics cannot be explained as the simple evolution of a common magma source.

2. Geological, volcanological and structural setting

The geology consists of a Plio-Pleistocene marine clay substrate (Marra et al., 1995) which fills extensional basins that formed at the rear of the Apennine fold-and-thrust belt. Middle Pleistocene age alluvial sediments (Karner and Renne, 1998; Karner and Marra, 1998, Marra et al., 1998) lie above the substrate and interfinger with volcanic rocks from the Monti Sabatini and Alban Hills. Thick tuff horizons form most of the outcrops around Rome, except where they are incised by Holocene cut-and-fill alluvial valleys of the Tiber and Aniene Rivers and their tributaries (Fig. 1b).

The explosive activity of the Alban Hills started 557 ± 14 ka and lasted until 353 ± 3 ka (Karner and Renne, 1998). It was followed by an effusive period that emplaced

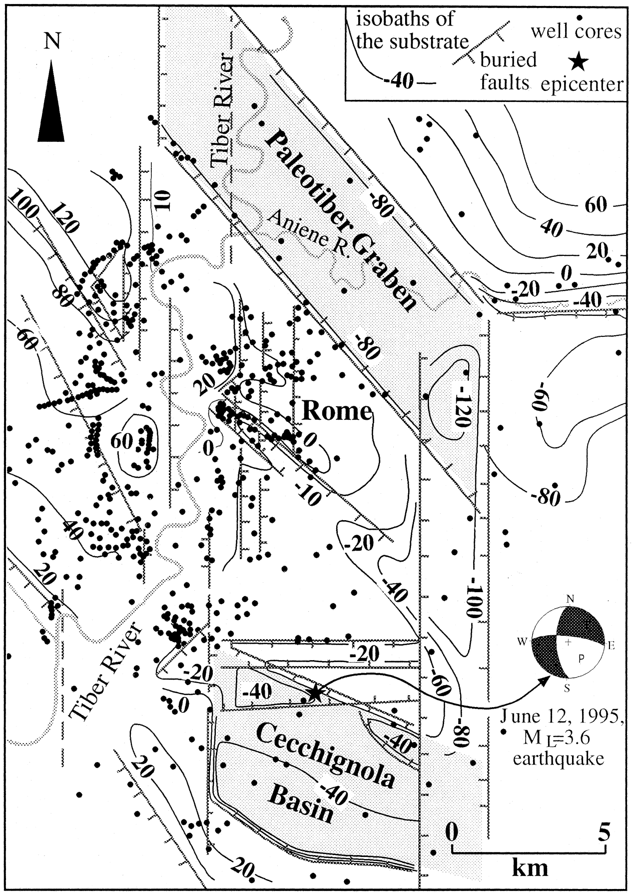

Fig. 2. Structure of the top of the Plio-Pleistocene substrate, reconstructed from well core data (modified from Marra, 1999). Isobaths of the top of the Plio-Pleistocene substrate are in meters above sea level. Shaded areas are the Paleotiber Graben and Cecchignola Basin. Epicenter location of the June, 12, 1995 Cecchignola earthquake with focal mechanism from Basili et al. (1996) is also shown.

several lava flows, and by a late hydromagmatic phase that took place in more recent time (De Rita et al., 1988, 1995).

Several large pyroclastic flows (ignimbrites) were emplaced during the explosive phase, whereas only minor effusive activity is associated with this phase and was interpreted to occur in the final stages of the eruptive cycles (De Rita et al., 1988). The pyroclastic flows which are important for this paper include the Pozzolane Rosse ('pozzolana' is a term used to describe a scoriaceous ash-flow, 455 ± 8 ka, Karner and Renne, 1998), and the Pozzolanelle–Tufo Lionato (353 ± 4 ka, Karner and Renne, 1998). The Pozzolanelle and Tufo Lionato are interpreted as products of two phases of the same eruption (Villa Senni Eruption, Marra and Rosa, 1995). Volumetrically less significant lava flows are associated with these ignimbrite eruptions. Marra (1999) has shown that all the outcrops of lava to the south of Rome that were previously attributed to different eruptive cycles of early Alban Hills volcanism are one single lava flow (hereafter the Vallerano Lava, 457 ± 8 ka by Karner and Renne, 1998), erupted from a local fissure field rather than from the central edifice of the Alban Hills. Previously, different outcrops of this lava (at Selcetta, Acquacetosa, Cecchignola and Vallerano) were interpreted as different flows (De Rita and Rosa, 1990; De Rita et al., 1995), some supposedly below the Pozzolane Rosse (Selcetta, Acquacetosa and Cecchignola), and at Vallerano above the Pozzolane Rosse. However, Marra (1999) shows that the Vallerano Lava was erupted just prior to the Pozzolane Rosse pyroclastic flow, consistent with its $^{40}Ar/^{39}Ar$ age. Marra (1999) also indicates that at least some of the Pozzolane Rosse erupted from a N140°-striking fissure cut through the Vallerano Lava. This indicates that the Pozzolane Rosse postdates the Vallerano Lava, thus the eruptive sequence is from effusive (Vallerano lava) to explosive (Pozzolane Rosse), contrary to the more common sequence of pyroclastic eruption followed by lava emission after de-gassing.

One possible mechanism for eruption of lava prior to pyroclastic rocks is a separate tectonic trigger for lava flows versus ignimbrites. A detailed analysis of the structural setting of the source area of the Vallerano Lava and Pozzolane Rosse has been performed, but the flat topography and the high degree of human disturbance have hindered the possibility to find good exposures. Additionally, the prevailing surface lithology is loose ash-tuff, which is easily eroded and rapidly weathered, preventing preservation of outcropping structural elements. Indeed, much of the tectonic displacement in the area of Rome has been investigated by means of borehole data which showed the geometric pattern of the major dislocations (Fig. 2), but not the kinematic indicators (Marra and Rosa, 1995; Marra et al., 1998).

In order to overcome the paucity of structural elements, the structural dataset has been supplemented with a comparative geomorphological study of the direction of the fluvial channels. This is based on the assumption of a strict structural control of the local hydrographic network, as was previously suggested for this area (Marra, 1999).

In addition to the few faults that have been observed in the area (Fig. 3), a larger dataset of fractures has been compared to other stress indicators for this area (Fig. 4). Since these fractures are mostly sub-vertical, they have been represented in rose diagrams in order to be readily comparable with the drainage directions.

Paleostress indicators identified in the Cecchignola area are homogeneous and support the previous interpretation that deformation is generated by strain partitioning in a transpressive tectonic style (Marra, 1999). Such conditions are favourable for generating local rotation of crustal blocks in between strike-slip faults (Freund 1970, 1974; Dibblee, 1977; Christie-Blick and Biddle, 1985; Nur et al., 1986; Nicholson et al., 1986). Since small angles of rotation are not detectable by means of independent methods like paleomagnetic analysis, geometry and kinematics of the dislocations affecting the Cecchignola area have been reconstructed in detail in order to compare them with those predicted by a block-rotation model capable of relieving lithostatic pressure at depth and triggering an effusive

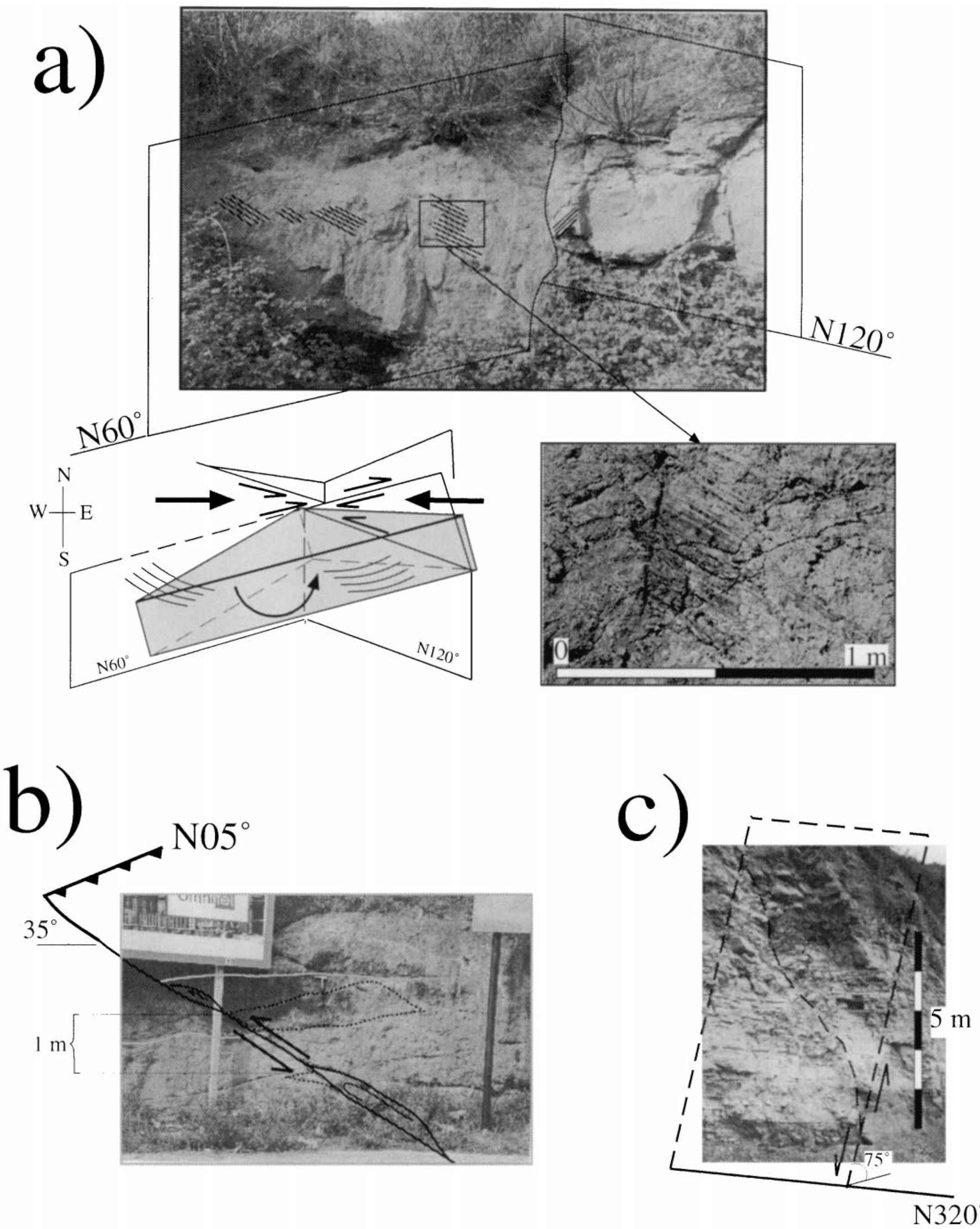

Fig. 3. Field evidence for transpressive and extensional faulting affecting rocks younger than approximately 300 ka. (a) Conjugate strike-slip faults cutting the Tufo Lionato ignimbrite at Perna Stream Valley (Fig. 5 spot d for location). A principal fault plane strikes N60° and shows several oblique (pitch = 30°) striae (close-up picture); a secondary fault plane strikes N120° and has striae with a pitch of 35°. Oblique, divergent striae with respect to a pure strike-slip theoretical faulting are probably linked with uplift and rotation of the faulted blocks. (b) Reverse fault striking N05° and dipping 35E in the Pozzolanelle ignimbrite (Fig. 5, spot b). (c) N320°, 75NE° normal fault in lacustrine deposits of the Aurelia Formation (Fig. 5 spot a).

lava eruption. This mechanism is here attributed to episodic strike-slip faulting, superimposed on larger scale extension, the latter being responsible for triggering the main ash flow eruptions of the Alban Hills.

Well data from previous work (Marra et al., 1998; Marra, 1999) have been integrated to identify dislocations affecting the substrate (Fig. 2) and to compare the attitudes of these dislocations with trends of the hydrographic network throughout the area, presumed to reflect in part more recent tectonic movements (Fig. 5). The subsurface of Rome is strongly controlled structurally by N- and NW-striking faults, which have formed two principal basins (Fig. 2). The first is the Paleotiber Graben, a ~N140° trending, 12×5 km wide basin, filled with approximately 100 m of fluvial-lacustrine sediments. The second is the Cecchignola Basin, a rhomb-shaped depression bordered by N-, and

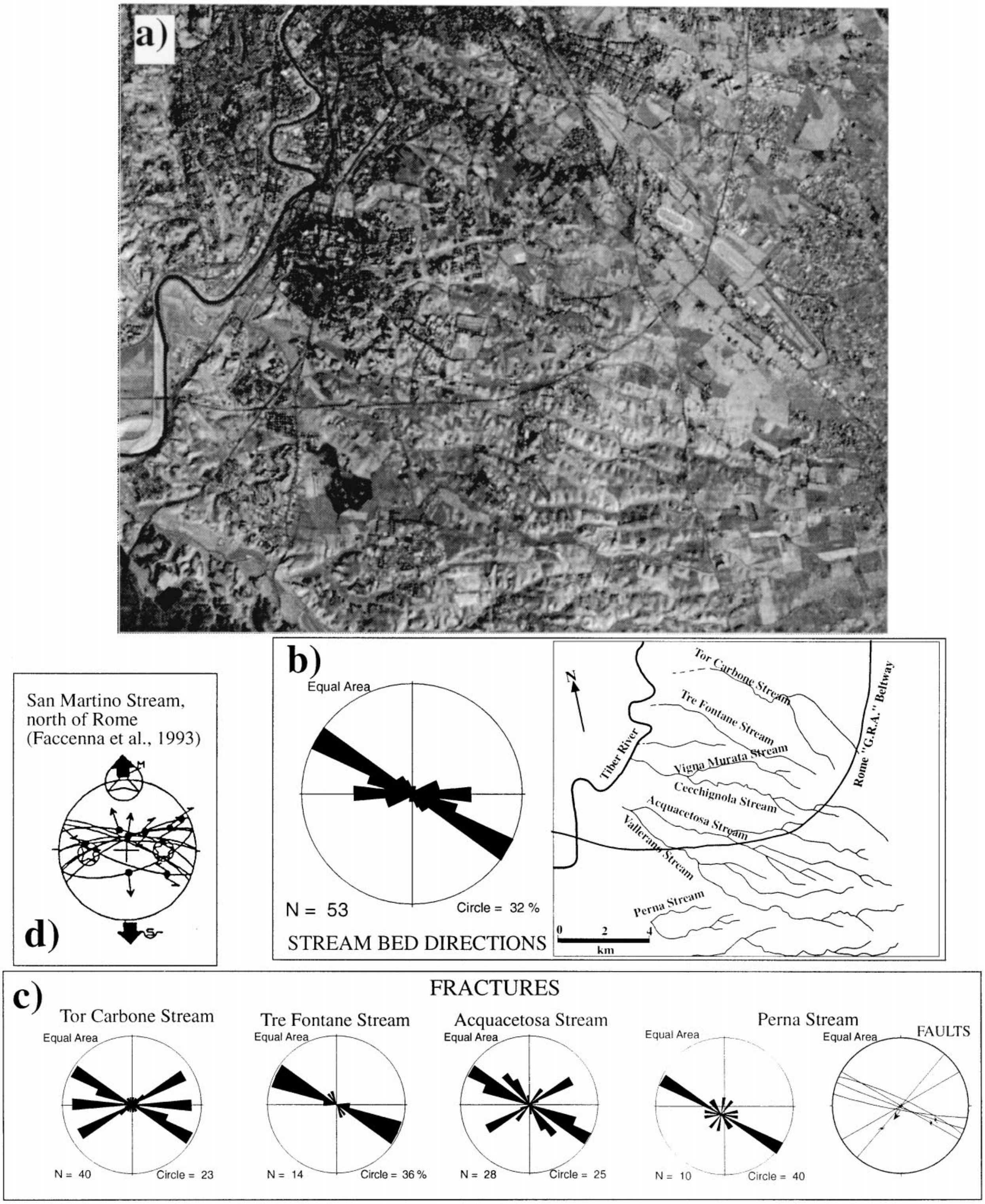

Fig. 4. Landsat image of the Cecchignola area. Rectilinear trends of the hydrographic network are particularly visible in the southern zone. Rose diagrams with fracture directions collected along the major stream valleys are shown and compared to rose diagram of rectified streambed directions. A conjugate fault system observed by Faccenna et al. (1993) near the San Martino Stream north of Rome is also shown for comparison with the small dataset from the Perna Stream valley.

~N120°- to N90°-striking faults. Agreement between the N120°- and N90°-striking faults and the trends of the fluvial channels inside the Cecchignola Basin was noted by Marra (1999). Five meters of vertical displacement is seen in the Pozzolanelle ignimbrite, generating an E–W fault scarp that controls the course of the Vigna Murata stream (Figs. 4, 5

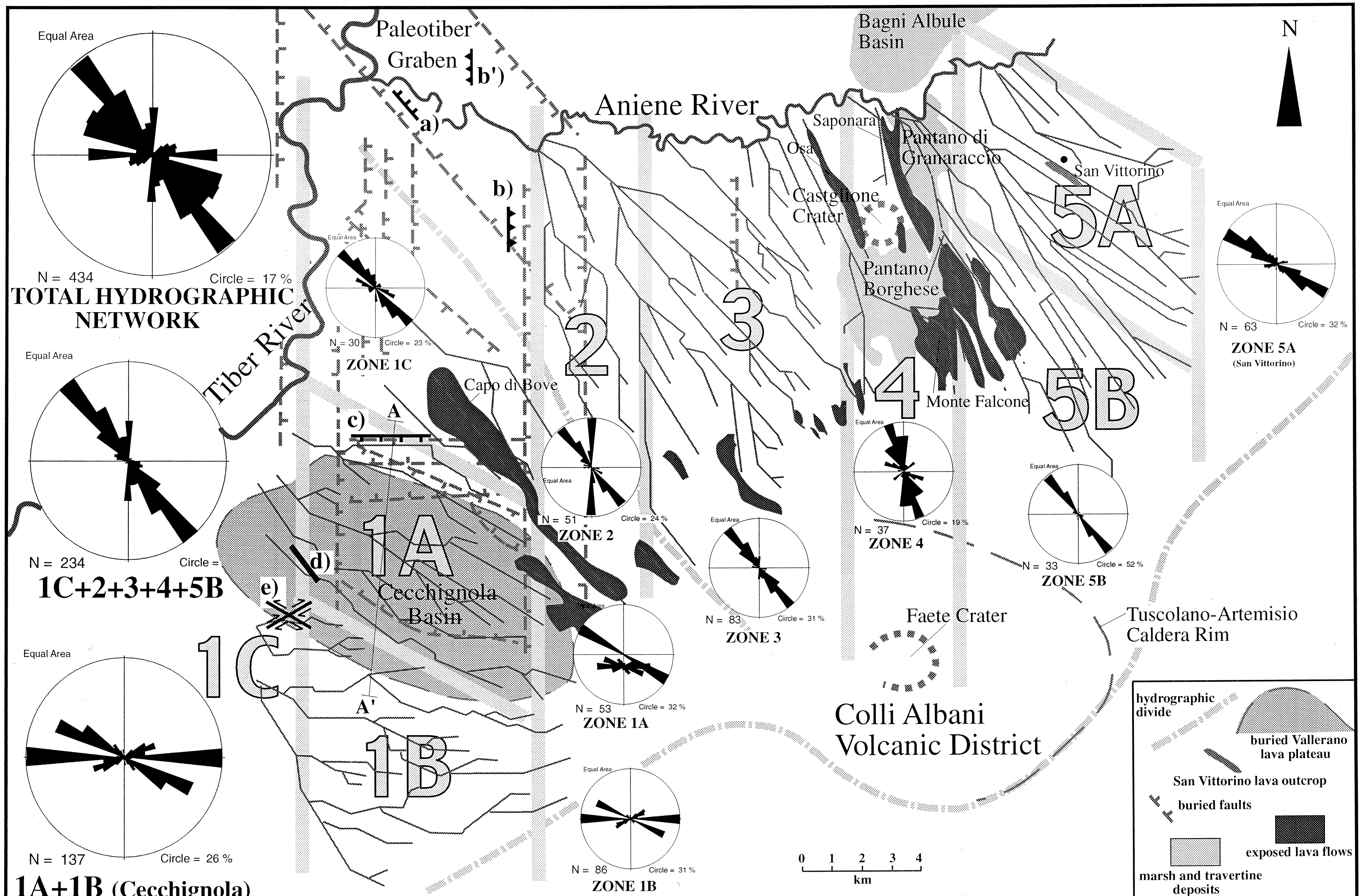

Fig. 5. Rectified drainage network and main faults affecting the Plio-Pleistocene substrate. Rose diagrams show the results of the statistical analysis of the drainage trends. Light gray lines trace the major structural lineaments that border the discrete zones. Structural elements described in this paper are shown: (a) normal fault affecting the Aurelia Formation, (b–b') reverse faults offsetting the Pozzolanelle ignimbrite, (c) fault scarp offsetting the Pozzolanelle ignimbrite along the Vigna Murata stream valley, (d) Pozzolane Rosse ignimbrite feeder dike, (e) conjugate faults affecting the Tufo Lionato ignimbrite.

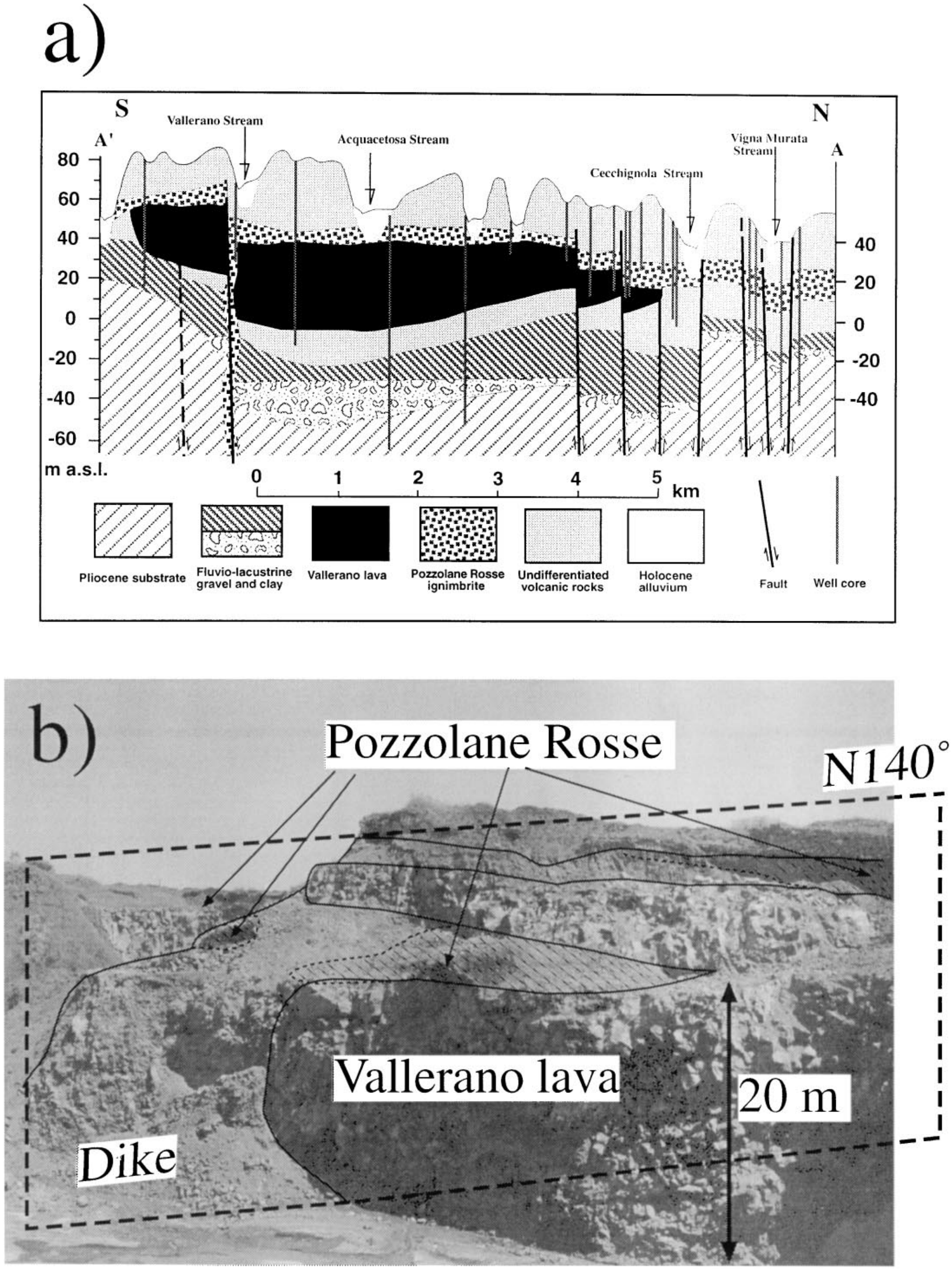

Fig. 6. (a) N–S cross-section of the Vallerano lava plateau (see line of section in Fig. 5). (b) Feeder dike of the Pozzolane Rosse ignimbrite at Vallerano (see Fig. 5 spot d for location).

spot c, and 6). Moreover, several other tectonic displacements occur in correspondence with the stream valleys, as shown in the cross-section of Fig. 6.

The Cecchignola Basin contains the buried Vallerano Lava plateau, an $\sim$2.25 km^3 flow that accumulated in the Basin and subsequently has been dislocated by normal faults (Fig. 4a). The chemical composition of this lava (Trigila et al., 1995) is in the K-foidite field of the total-alkali-silica (TAS) classification of Le Bas et al. (1986). Directly above the Vallerano Lava is the Pozzolane Rosse pyroclastic flow. Scoria clasts of the Pozzolane Rosse are in the Tephrite field of the TAS diagram (Trigila et al., 1995), thus have a higher silica content than the Vallerano Lava. Additionally, a geochemical study of phlogopite in the Vallerano Lava and Pozzolane Rosse, as well as in other volcanic products from the Alban Hills (Gaeta et al., 2000) shows that there is a systematic difference between phlogopite compositions in lavas and those in pyroclastic rocks. Gaeta et al. (2000) interpret the composition of groundmass phlogopite in the lavas as evidence of rapid magma ascent from a deep reservoir. In contrast, they interpret the composition of phlogopite in the pyroclastic rocks to be from a more shallow magma source, consistent with the depth of the magma chamber beneath the Alban Hills, which a tomographic study indicates is at a depth of 5–6 km (Amato and Chiarabba, 1995). These geochemical differences suggest that the Vallerano Lava and Pozzolane Rosse may have tapped different magma bodies, or at least different portions of the same body.

At Vallerano, a lava-pyroclastite transition is seen in the feeder dike of the Pozzolane Rosse (Fig. 6b). Here, an aggregate of rounded dark gray scoriae with dense cores and vessiculated rinds are at the top of the dike, and grade outwards into an ash-flow tuff. These textural features are the same as those described by Locardi and Mittempergher (1967) who describe ‘foam lavas’ as the rounded scoria blocks that are observed in Vallerano. They interpret foam lavas to be the transition from lava to ‘ignimbrite’, in accordance with the observations at Vallerano. Laterally, a reddish ash matrix develops away from the mouth of the feeder dike. A 5-m-thick ‘sill’ of pozzolana horizontally extends several tens of meters into the Vallerano Lava (Fig. 4b) showing that this dike is the eruptive conduit of the Pozzolane Rosse in this area. It is clear that the magma decompressed upon reaching the surface, forming a fissure ash flow. The initial, volatile-rich phase also intruded a horizontal fracture in the Vallerano lava producing the observed ‘sill’, whereas the final, de-gassed phase filled the feeder conduit and spilled out of the eruptive mouth and onto the surface.

Field observations provide evidence for both transpressive and extensional faulting in the area of Rome. In particular, a large set of structural elements associated with a principal right-lateral N–S fault zone has been documented in the northern area of Rome (Faccenna and Funiciello, 1993; Faccenna et al., 1993, 1994a,b). Local transpression associated with this fault zone has been suggested by Marra (1999) on the basis of its regional trend which forms a restraining bend and justifies the presence of several E–W°- and N120-striking faults in this area as the result of strain partitioning between the principal N–S fault segments (Fig. 1b).

Few structural elements with clear kinematic indicators have been found in the Cecchignola area. Even though they fit the proposed model of strain partitioning, they should be considered together with the stream channel direction data in order to evaluate a reliable local stress tensor for this area. Several N100°–120° oblique faults affect the lithified Tufo Lionato along the Fosso della Perna valley (Figs. 3 and 4). Well defined oblique striae have generally poorly preserved slickensides, the exception being two large fault planes shown in Fig. 3. These two conjugate vertical faults with oblique striae are at the west border of the Cecchignola Basin in a stream valley that flows E–W (Fig. 5, spot e). This stream channel is fragmented into a series of N90° segments, connected by N60°–70° and N120° bends. The faults strike N60° and N120°, and both have vertical dip. Pitch of the striae is 30° and 35°, respectively; slickensides indicate left-lateral motion. Strikes and dips of these faults correspond to those expected for a conjugate system generated by pure shear under E–W compression, as predicted in a model of strain partitioning by Marra (1999) for this area. Incompatible left-lateral motion on both fault planes is explained in Fig. 3 as the effect of the extrusion of a compressed block. It is likely that the lack of lithostatic pressure that affects the near surface stress field caused upward displacement of the compressed blocks, which resulted in an oblique rake for the faults rather than the theoretical horizontal pitch (Fig. 3a).

Evidence for E–W compression is also 10 km north of Cecchignola, along the two N-striking faults that border the Cecchignola Basin (Fig. 5, spot b). A reverse fault striking N05° and dipping 35°E displaces the Pozzolanelle vertically by 1 m, with no detectable strike component (Fig. 5b). Another N–S reverse fault affects the volcanic rocks in Rome, north of the Aniene River (Fig. 5, spot b’).

Extensional faulting also affects rocks younger than the Pozzolanelle pyroclastic unit. A dip–slip normal fault, striking N320° displaces sediment of the Aurelia Formation (Figs. 3c, 5 spot a), the approximate age of which is 300 ka (Karner and Renne, 1998). According to seismic data, the presence of NW–SE-trending normal faults affecting terrains as young as 300 ka suggests, that NE–SW extension overprinted the trascurrent regime again in recent time.

3. Geomorphological analysis

Preferential drainage alignments with left steps in fluvial channels in the Cecchignola Basin (Figs. 4 and 5) are interpreted as structural control on the present-day hydrographic network (Marra, 1999). A quantitative analysis of drainage trends in a larger area is made here for a 10-km-wide band southeast of the Tiber and Aniene Rivers. Results from this analysis are plotted on rose diagrams and compared with the regional deformation pattern of the northwest half of the Alban Hills (Fig. 5). A common technique that rectifies directions of stream beds is applied (e.g. Ciccacci et al., 1987; Buonasorte et al., 1991; Caputo et al., 1993). The assumption is made that each rectified portion of a fluvial bed may represent the direction of a fault controlling its course. While it is possible that rectifying drainage patterns can introduce directionality that is unrelated to structural control, it still does indicate preferential directions of river flow. In the case that these preferential directions of river flow are statistically significant and are different from those expected from non-structural controls (e.g. topographic and

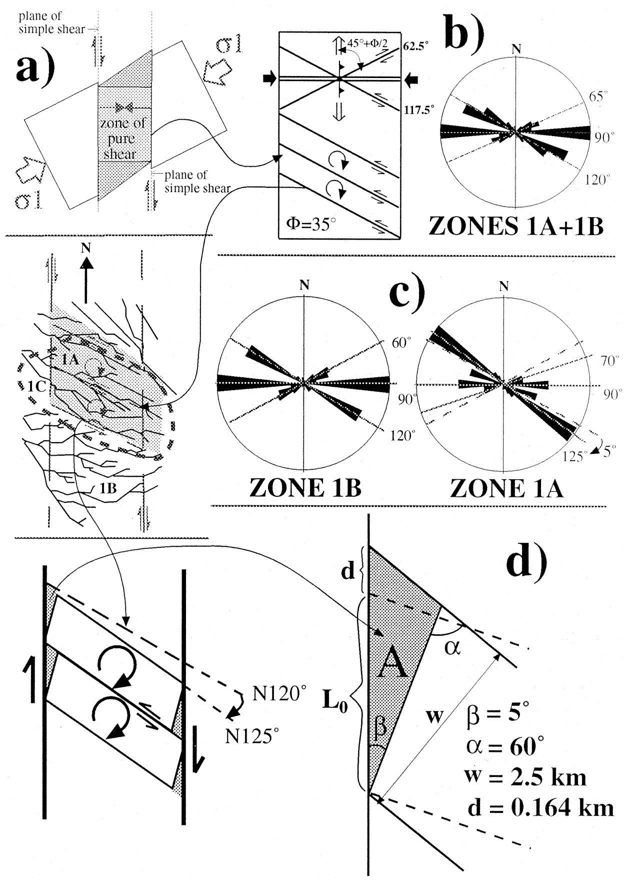

Fig. 7. (a) Transpression model to generate localized pure-shear between planes of simple shear (after Jones and Tanner, 1995). (b) Conjugate set of vertical transcurrent faults, reverse faults and fractures expected inside the pure shear zone (after Sylvester, 1988) and induced block-rotation (after Nur et al., 1986). (c) Clockwise rotation of rigid blocks inside the Cecchignola Basin interpreted from fluvial channel directions (Fig. 5 zone 1A). (d) Decompression model (after Nicholson et al., 1986; Christie-Blick and Biddle, 1985) at the corner of the rotated blocks in the Cecchignola Basin.

geographic trends), they are interpreted to be diagnostic of the structural setting.

In rose diagrams, stream channel directions are plotted according to length and subdivided into three groups as a function of their length, independent of hydrographic order. The highest hydrographic orders corresponding to the shortest fluvial channels have not been considered for this work, in order to avoid the introduction of bias into the data set. Total trends for the 10-km-wide band are compared to local trends within discrete zones, corresponding to the areas bounded by the main structural lineaments (Figs. 2 and 5). Three large zones (1, 3 and 5) are divided by two N–S fault zones (zones 2 and 4), the latter of which contain a series of structural basins. In zone 2, the top of the Pliocene substrate and the base of the volcanics are significantly lowered (Marra and Rosa, 1995). In zone 4 are the recent tectonic basins of Bagni Albule, Pantano di Granaraccio and Pantano Borghese, and the Castiglione and Faete volcanic craters. Two unique zones (1A and 5A) are noted also for their common geological and structural features.

The analysis of the total area shows that the average directions of the stream channels are dominated by NW–SE alignments (Fig. 5, upper left corner). This is in good agreement with a previous statistical analysis for the whole hydrographic network around the Alban Hills (Caputo et al., 1995), which showed two preferential northwest and north trends, attributed by those authors to regional structural control. However, the N–S trend in Caputo et al. was based chiefly on analysis of the highest hydrographic orders, which have not been included in this study.

4. Discussion of geomorphological data

The hydrographic network has developed by cutting through the Pozzolanelle ignimbrite, the top of which forms a flat surface that now constitutes the 'Campagna Romana'. Without structural control, a radial drainage trend would be expected leading away from the Alban Hills, but the plot in Fig. 5 shows a maximum concentration of fluvial channel directions oriented N145°. This direction matches the strike of extension-induced faults and fractures and agrees with the present day stress field determined from focal mechanisms in the Alban Hills region (Montone et al., 1995).

A radial drainage trend is detectable in the western area, where stream bed rotation from E–W to NW–SE occurs (Fig. 5, zones 1A, B, 2, 3). In the eastern area, the superposition of a preferential NW–SE direction on the trends of the hydrographic network is recognizable (Fig. 5 zones 2, 3, 4, 5B). Finally, N–S trending fluvial beds are parallel to N-striking fault zones in zones 2 and 4.

Drainage in the Cecchignola Basin is characterized by a unique concentration of the trends. Prevalent ~N120° and N90° and minor ~N60° lineaments characterize the drainage network between the two principal N-striking border faults (Fig. 5 zones 1A, B; Fig. 7b). In particular, ~N120° and a secondary conjugate ~N60°, together with a N90° set of lineaments, are present to the south (Fig. 5 zone 1B; Fig. 7c). A similar pattern of major ~N125° and relatively minor N90° trends is present inside the Cecchignola Basin (Fig. 5 zone 1A; Fig. 7c), while a ~N70° trend is very poorly defined. While N145°-striking lineaments are predominant immediately outside the two border faults (Fig. 5 zone 1C), they are nearly missing in zones 1A and 1B.

While a unimodal distribution of the trends would have been a strong indication of a control by the first order topographic gradient in the investigated area, the observed concentration around three different maxima in the two subzones of the Cecchignola Basin (Fig. 8) is not consistent with topographic control.

In agreement with a previous study (Marra, 1999), the presence of 120° and N90° and lack of N145° drainage

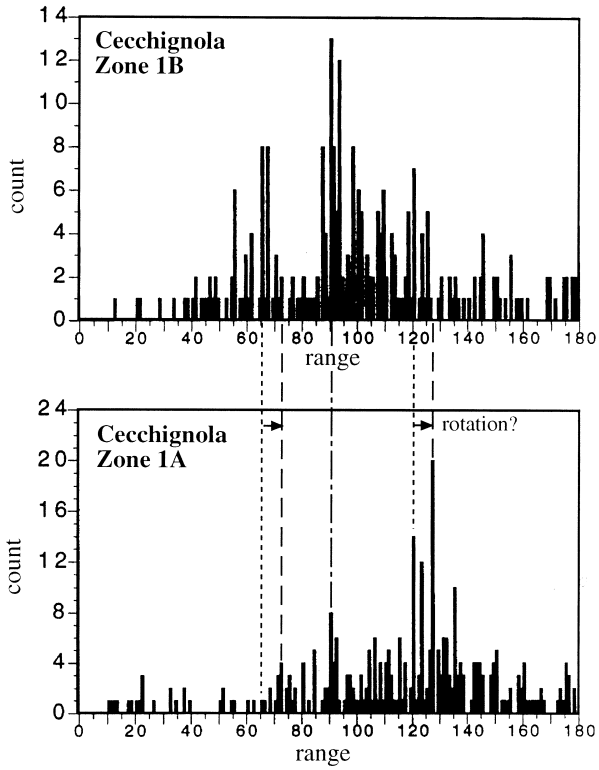

Fig. 8. Histograms showing frequency distributions of stream channel directions inside the Cecchignola zones A and B.

trends in the Cecchignola area is here interpreted to be related to unique structural control of this area. These N120° and N90° drainage trends are found in discrete zones around Rome. E–W trends are still evident in zone 1A, where the existence of a fault controlling the E–W course of the Vigna Murata stream valley has been shown (Marra, 1999). Four E–W-trending faults have been identified from well data, which also allow us to recognize a ~N120°-striking fault bordering the south of the Cecchignola Basin. Additionally, several ~N120°-oriented fluvial channels inside zones 1A and 1B have left steps which constitute the N60–70° secondary concentration on the rose diagrams (Figs. 4 and 5). A very similar set of conjugate strike-slip faults is found in the northen area of Rome, near the N–S-striking San Martino stream valley (Faccenna et al., 1993), and it is here compared to the smaller dataset from the Cecchignola area (Fig. 4).

Fig. 5 shows another zone (5A) north of the Alban Hills which has a structural setting similar to the Cecchignola area. Principal ~N120° and secondary ~N90° bends of the left tributaries of the Aniene River are recognizable near San Vittorino. This area mimics the stratigraphic, structural, volcanological and seismological characteristics of the Cecchignola (Marra, 1999), and thus has been treated separately in the statistical analysis. The only other outcrop of lava that occurs in the same stratigraphic position and has probably the same age as the Vallerano Lava lies here at San Vittorino (Fornaseri et al., 1963; see Fig. 5).

5. Block-rotation model

The N90°-, N120°- and N60°-striking faults controlling fluvial valleys and dislocating the volcanics suggests a common tectonic origin for these trends. These fault orientations have been predicted by a theoretical model for strain partitioning in transpressive zones (Marra, 1999). Transpression around Rome is caused by a left step in the right-lateral strike-slip Sabina Fault (Marra, 1999). A mechanism capable of generating localized areas of pure shear between parallel strike-slip faults in transpressive zones was proposed by Jones and Tanner (1995) (Fig. 7a). In this model, when a north strike for parallel strike-slip faults is considered, approximately N60° and N120° conjugate strike-slip faults are expected, together with E–W tensile fractures (Fig. 7b).

It is here proposed that after formation, the conjugate sets of faults rotated in response to transpression (Fig. 7b), a mechanism that has been suggested for other areas (Nur et al., 1986; Freund 1970, 1974; Dibblee, 1977; Nicholson et al., 1986). Rotation of rigid blocks around a vertical axis can result in the discharge of lithostatic pressure at the corners of the blocks (Christie-Blick and Biddle, 1985; see Fig. 7d). In a volcanic region, the corners of such blocks may be likely sites for decompression melting, and the faults could provide preferential magma conduits. De Rita et al. (1995) suggested a similar mechanism for eruptions of the major pyroclastic flows from the Alban Hills central edifice.

An ~5° clockwise rotation in the Cecchignola Basin is interpreted in Fig. 7. The lineaments inside the rhomb-shaped zone, corresponding to the buried lava plateau, strike ~N125° and ~N70° (zone 1A, shaded in Fig. 7c), whereas to the south they strike close to N120° and N60° (Fig. 5 zone 1B; Fig. 7c). Further statistic treatment of the trends of the fluvial channels in zones A and B has been performed in order to better define a possible systematic rotation. The complete hydrographic network including the channels of the highest orders has been subdvided into rectified segments. Each of the resulting directions has been weighted as a function of the segment length. The resulting distribution of stream channel directions is shown in histograms in Fig. 8.

The conjugate set of lineaments predicted in the theoretical model is still well reproduced in zone B, where it is possible to recognise the three concentrations around 60°, 90°, and 120°. A less defined distribution is obtained for zone A, where a strong maximum concentration peaks at 127° and a secondary peak is at 120°. Only two other peaks can be distinguished in zone A, corresponding to 90° and 135°. With the exception of the lack of any relevant concentration at 60–70°, the distribution of stream directions in zone A mimics that of zone B as it shows a relative peak at 90° and a great dispersion between this value and a maximum at 127°. This is something expected in the case we assume that most lineaments in the zone A underwent rotation through time. In particular, the second maximum at

120° in zone A is possibly interpretable as the indication of the existence of some unrotated (or newly generated) lineaments with that strike. It is here proposed that a maximum 7° clockwise rotation of zone A with respect to zone B in the Cecchignola area occurred as a consequence of transpressive tectonics. This 7° of rotation within the Cecchignola Basin should be considered the cumulative effect of several 100 kyr of displacement on the N–S border faults.

Even though this interpretation based on geomorphic observations is not unique and is far from being definitively proved, it is a supporting indication of local block rotation when considered in the light of the reconstructed geometry of dislocations and the recognised transpressive tectonic style. The sense of rotation, interpreted as unrelated to the hydrographic trend, is indicative of a right-lateral sense of shear on the N-striking faults, which is the same as observed at the Sabina to Alban Hills shear zone (Alfonsi et al., 1991; Faccenna and Funiciello 1993). Slickensides on the striated fault planes in Fig. 5a indicate left-lateral motion on the plane that strikes N60° and on the N120° fault plane as well. This is in agreement with the expected sense of motion for the N120° faults to accommodate clockwise block rotation by dextral N–S strike-slip faulting (Fig. 7d).

Different from the other faults, the E–W lineaments appear to be generated more recently as tensile fractures induced by E–W compression inside the pure-shear zone, when the rotation of the faults among the blocks was complete. These E–W lineaments, as well as the ~N120° ones, represent possible discontinuities which may act as oblique to normal faults under NE–SW extension, thus they likely underwent a re-activation in recent time as proposed in order to explain the focal mechanism for the June 12, 1995 Cecchignola earthquake (Marra, 1999).

Based on these data, it is here suggested that the eruption and emplacement of the Vallerano Lava could be the result of local block rotation. This mechanism would cause tensile fractures to extend through the upper crust, reaching to the decollement level of the rotating blocks. It has been shown that volcanism and geothermal potential could be associated with local extension induced by strike-slip faulting (Weaver and Hill, 1978/79; Bacon et al., 1980; Aydin et al., 1990). The Vallerano Lava is within the zone of ~5° clockwise rotation of fluvial beds (Fig. 7c), suggesting a direct linkage between block-rotation and lava eruption.

The horizontal displacement necessary to induce a rigid block rotation of 5° (considered as an average realistic value) in the Cecchignola Basin is estimated as follows (Fig. 7d). Assuming $\beta = 5°$, blocks dimension width (w) = 2.5 km and $\alpha = 60°$ (from originally N120°-striking faults among the rotating blocks), the simplified model in Fig. 7d allows us to estimate a horizontal displacement (d) = 0.164 km. The area (A) of potential decompression is given by: $A = (L_0 + d)H/2$ where $H = w\sin\beta$ and $L_0 = w/(\cos 90\text{-}\alpha)$. The induced decompression is given by: $AZ\rho$ where Z is the decollement depth and ρ the rock density.

6. Discussion

Evidence for alternating extensional and strike-slip faulting are found throughout the area. The NW–SE strike of the feeder dike of the Pozzolane Rosse indicates that NE–SW extensional faulting probably triggered this ash-flow eruption. It is therefore questionable whether another type of displacement, namely strike-slip faulting, triggered the eruption of the lava flow.

A possible early utilisation of the N–S discontinuity under the NE–SW extensional regime seems unlikely, because no substantial difference in the eruptive mechanism and its products would be expected in this case. Moreover, the N–S discontinuities are regional faults that are less favourably oriented with respect to the NW–SE ones in order to act as better pathways for the magma during NE–SW extension, even more in the early stages of the eruptive phase.

During transpressive tectonic phases instead, the NW–SE faults are completely sealed and decompression can occur only through NE–SW oriented fractures and as a consequence of local rotation of crustal blocks around a vertical axis between strike-slip faults.

Horizontal displacement induced by strike-slip faulting has been estimated at a minimum of 40 m over the past 500 kyr in the Bagni Albule pull-apart basin northeast of Rome (De Rita et al., 1995; Fig. 5). This equates to a horizontal slip rate of 0.08 mm/yr. In contrast, a horizontal slip rate of 0.47 mm/yr is required in order to provide ~5° of rotation in the Cecchignola area, assuming that all rotation postdates the emplacement of the Pozzolanelle ignimbrite (350 ka).

A possible explanation for this discrepancy is that the ~5° rotation of the Cecchignola Basin interpreted from stream channel trends overestimates the true rotation over the last 350 kyr. Two factors could contribute to an overestimation: 1) radial drainage could cause a different rectified drainage direction for the Cecchignola Basin with respect to the adjacent areas, resulting in an apparent clockwise rotation of the fluvial beds; and 2) the trends of the stream channels in the Cecchignola Basin might reflect the strike of buried faults that have been reactivated several times either as strike-slip faults under transpression, or, more recently, as normal-to-oblique faults under extension. Regarding point 1), clockwise rotation in the Cecchignola Basin is not observed for the E–W drainages. This suggests that changes in the regional hydrographic trend (i.e. radial drainage) are not the cause of the apparent rotation of the stream channels. An argument that favors point 2) is that strike-slip tectonics have been active on the Tyrrhenian margin at least since the late Pliocene (Alfonsi et al., 1991), thus the block-rotation in the Cecchignola area is a process that might have been active for a long time. Assuming a constant horizontal slip of 0.08 mm/yr over the last 2.5 Ma from the value estimated in Bagni Albule, we obtain 200 m of total horizontal slip for the area of Rome, which is consistent with the amount of slip predicted by the block rotation model proposed here for

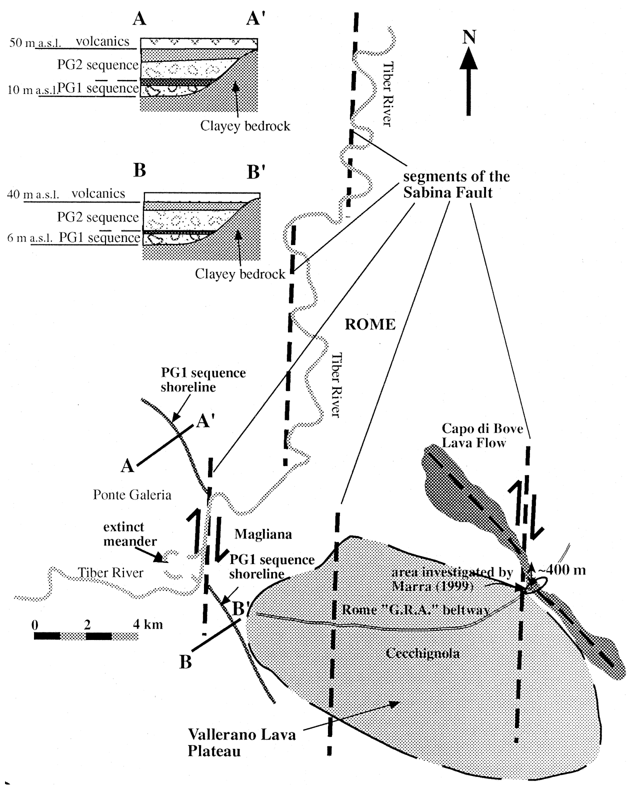

Fig. 9. Geomorphological evidence for right-lateral displacement along two segments of the Sabina Fault. In the Magliana area, south of Rome, the paleo-shoreline of the first depositional sequence of the Ponte Galeria Formation (PG1 sequence, Marra et al., 1998) shows an approximately 3.5 km offset. No significant vertical displacement is inferred from the two cross-sections (A–A', B–B') west and east of the fault segment, respectively. Northeast of the Cecchignola area, the course of the Capo di Bove lava flow shows approximately a 0.4 km offset, although only two small strike-slip fault planes have been observed in the road cuts along the Rome 'G.R.A.' beltway (Marra, 1999).

the Cecchignola Basin. Moreover, the presence of the un-rotated E–W faults inside the rotated Cecchignola zone suggests that significant block-rotation related to trans-current activity on the N–S faults has not occurred in recent times, when stress was released through compressive faulting induced by strain partitioning between the locked N–S faults under transpressive regime.

It is therefore suggested here that 5° of rotation in the Cecchignola area may be the cumulative effect of several transcurrent phases that occurred since the late Pliocene, with a climax at 450 ka that triggered the eruption of the Vallerano lava.

In contrast with the limited macroscopic surface evidence of strike-slip faulting, other geomorphic observations suggest that significant horizontal displacement may have occurred in middle Pleistocene times along N–S segments of the Sabina Fault. It is possible that significant horizontal displacement along a N–S segment of the Sabina Fault in the Magliana area south of Rome occurred in the last 800 kyr, based on geomorphic observations (Fig. 9). Here, a paleo-shoreline deposit correlated to marine oxygen isotopic stage 19 (roughly 800 ka) (PG1 sequence in Marra et al., 1998) undergoes a sharp dextral bend or break of roughly 3.5 km across the Tiber River Valley. The Tiber River here trends N185, as do a number of sections of the Tiber valley in Rome. These N–S sections of the Tiber valley are disposed with a regular right-stepping geometry and are probably controlled by segments of the Sabina Fault (see Figs. 1B, 2 and Fig. 9). The correspondence of this straight portion of the Tiber River course with a right step of the paleo-shoreline suggests a recently active underlying segment of a right-lateral strike-slip fault. It is likely that erosion during the marine oxygen isotopic stage 20 sea-level low stand would have smoothed any pre-existing sharp bends of the paleo-shoreline, as the substrate below the PG1 sequence is unconsolidated clay. Based on this notion, it is likely that the offset of the paleo-shoreline is a tectonic effect. Based on the approximate age of 800 ka for the PG1 sequence, an average horizontal slip rate of 4.4 mm/yr is inferred. This is much more than that calculated in order to justify 5° of rotation in the Cecchignola Basin (0.47 mm/yr). These data suggest that horizontal slip on segments of the Sabina Fault may increase to the west, or that a significantly higher slip-rate characterised the transcurrent activity in the area of Rome between 800 and 450 ka.

Other surface features suggest dextral offset. The Capo di Bove lava flow (Fig. 9) has a dextral bend of about 400 m, a displacement larger than that predicted for the Cecchignola Basin. However, structural analysis of the Capo di Bove flow in a road cut at this bend reveals little evidence of strike-slip faulting. Based on this lack of surface evidence, the apparent offset of this lava flow has been attributed mainly to the pre-existing drainage network (Marra, 1999). This fact supports the hypothesis that no significant transcurrent activity occurred after the emplacement of the Pozzolanelle–Tufo Lionato ignimbrite (350 ka), whereas the locked N–S faults re-oriented the stress within the confined sectors causing the origin of compressive structures and E–W tensile fractures.

Presently, the possibility of significant horizontal displacement on N–S segments of the Sabina Fault in the last 350 ka can neither be confirmed nor excluded. The few available structural data suggest that transpresson occurred in the Cecchignola Basin in this time span, and this could have generated local block rotation. Regardless of whether the inferred ~5° of rotation occurred in the last 350 ka at a significantly higher slip-rate than that proposed by De Rita et al. (1995) or is the cumulative effect of block-rotation in a much longer period of time, this mechanism seems the most plausible to explain the eruption of the Vallerano Lava flow shortly before emplacement of the Pozzolane Rosse.

7. Conclusions

It is here suggested that transpressive tectonics linked

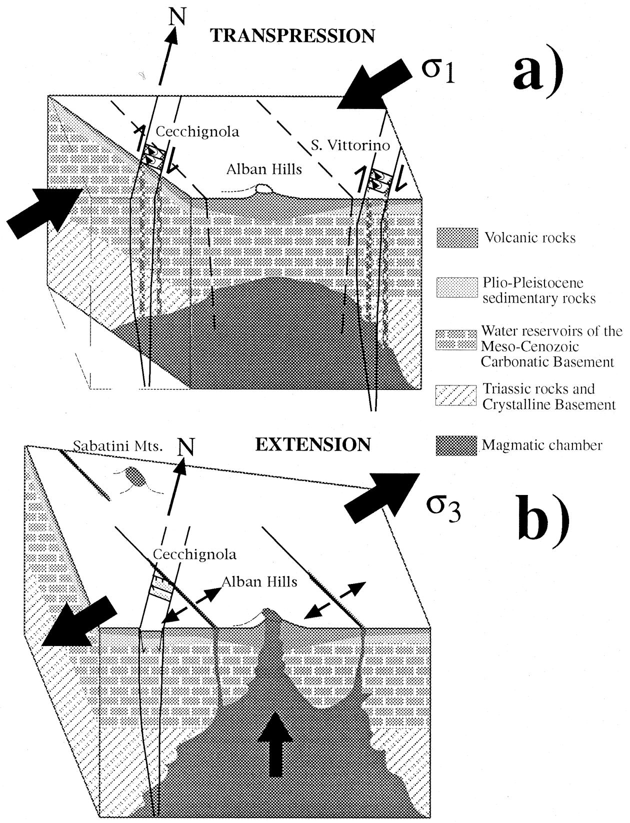

Fig. 10. Block diagram proposed to explain the two tectonic triggering mechanisms capable of generating: (a) Lava by transpression-induced block-rotation. Localized, narrow conduits originate by lithostatic discharge at the corners of rotating crustal blocks: magma can rise along these fractures to produce volumetrically small lava flows. (b) Pyroclastic flows by regional extension. Regional extension causes the rupture of NW-striking normal faults that allow large amounts of magma to interact with water reservoirs in the substrate, causing explosive volcanism simultaneously in the Alban Hills and Monti Sabatini volcanic areas.

with major N–S right-lateral strike-slip faults have generated the lineaments that control the hydrographic network in the Cecchignola Basin. Extension appears to be the controlling mechanism on a regional scale, as shown by the hydrographic network in the greater area of Rome, and by the geometry of the Latium volcanoes and major basins like the Paleotiber Graben. Because extension has been active in this area since the early Pliocene (Montone et al., 1995; Marra, 1999), the compressional structures are interpreted as the result of minor transpression along strike-slip fault bends, superimposed on regional extension. The presence of a crustal discontinuity along the Sabina Fault has been suggested as the causal mechanism for concurrent regional strike-slip and extensional tectonics (Marra, 1999). If not explained as a kinematic effect of differential movement of two adjacent extending crustal blocks, the right-lateral strike-slip faulting would be dynamically incompatible with NE–SW extension.

Geologic data from recent literature (Faccenna and Funiciello, 1993; Faccenna et al., 1993, 1994a,b) and those discussed here suggest that the local stress field underwent several changes that produced alternating extensional and transcurrent features in the area of Rome. In particular, a recent switch from a mainly transpressive regime that was active after 350 ka and a present-day NE–SW extensional regime is inferred by comparison of geologic and seismic data. This recent switch is the plausible reason for the contrast in previous interpretations of the trascurrent regime as the most recent tectonic phase that occurred in this area. Indeed, the scarcity of significant tectonic structures and their low level of organization, combined with available geodetic data, suggest very low strain rates in this region: this is a condition that favours fast changes or permutation of the stress tensor.

It is here proposed that the emplacement of the Vallerano Lava in the Cecchignola Basin shortly before eruption of the Pozzolane Rosse ignimbrite was a consequence of local decompression caused by block-rotation induced by transcurrent activity on N–S oriented faults. Sudden decompression combined with fracture opening may have tapped a deep magma source, consistent with the different chemical compositions (lower silica content) of the Vallerano lava with respect to the Pozzolane Rosse, and a rapid and volumetrically limited magma rising through narrow conduits might allow limited magma-host rock interaction, causing a relatively volatile-free eruption (Fig. 10). Additionally, the extensional NW–SE faults would be sealed during transpression, further reducing magma-host rock interaction, and allowing only small amounts of magma to ascend through localized conduits.

In contrast, ignimbrite eruptions which characterize most activity of the Latium volcanoes (Locardi et al., 1977; Funiciello and Parotto, 1978) are possibly due to magma injection along NW–SE extensional faults, which would allow for greater hydration of magma through interaction with carbonate host rocks along open fracture systems (see Fig. 10). The NW–SE strike of the feeder dike of the Pozzolane Rosse suggests that eruption was triggered by NE–SW extension. Identical ages for several of the major pyroclastic flows from the Alban Hills and nearby Monti Sabatini volcanoes (Karner and Renne, 1998) also suggest a common triggering mechanism for these large ignimbrite eruptions.

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