ACTIVE STRESS FIELD IN THE GEOTHERMAL AREAS OF LATLUM AND TUSCANY

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ABSTRACT

We have investigated the present-day stress field in the Tyrrhenian border of Latium and Tuscany using borehole breakout from deep geothermal wells, fault plane solutions of shallow earthquakes, and surface mesostructural data. The study region is a NW-SE elongated belt (200 km by 50 km) bordering the western side of the Apennines, that includes a suite of volcanoes active during Quaternary times. The breakouts have been observed on four-arm caliper dipmeter data, indicating a horizontal minimum stress direction (Sh) that varies from NE to ENE. The earthquake focal mechanisms (M=4) show normal or to a lesser extent strike-slip faulting, with T (tensional) axes predominantly oriented NE-SW. Field studies of fractures and faults also indicate NE extension. These data suggest that the whole area is presently extending in a direction perpendicular to the Apenninic chain, where a similar, probably faster extension, is documented by focal mechanisms of strong (M>5) recent earthquakes and young geologic data.

1. INTRODUCTION

The study region includes several volcanoes of the Tyrrhenian border of the Apennines, mostly active in the last 1.0 Ma. From northwest to southeast, we analysed data from Mt. Amiata, Vulsini, Sabatini, and Albani Mts. (Figure 1). The most recent volcanic activity is dated between 20-30,000 years (Fornaseri, 1985). Most of these Quaternary volcanoes are affected by a frequent and often felt seismic activity, despite the moderate magnitudes of the earthquakes (generally lower than 4). This is due to the small hypocentral depths (<6-7 km) of the earthquakes (Buonasorte *et al.*, 1987; Amato *et al.,* 1994).
Since the mid 70's, some of these volcanoes have been extensively drilled for geothermal research. For this reason, data from deep (2-3 km, sometimes up to 5 km) wells are available for breakout analysis in all the volcanoes, excepting the Alban Hills (Figure 1). In addition, microseismic monitoring of the geothermal fields operated by ENEL for the past 18 years, has recorded several thousands of events. In the Alban Hills, where no geothermal research has been carried out to date (and hence no deep wells and no permanent seismic network data were available), we have microseismic data recorded during a long seismic swarm in 1989 and 1990 by a temporary local network.

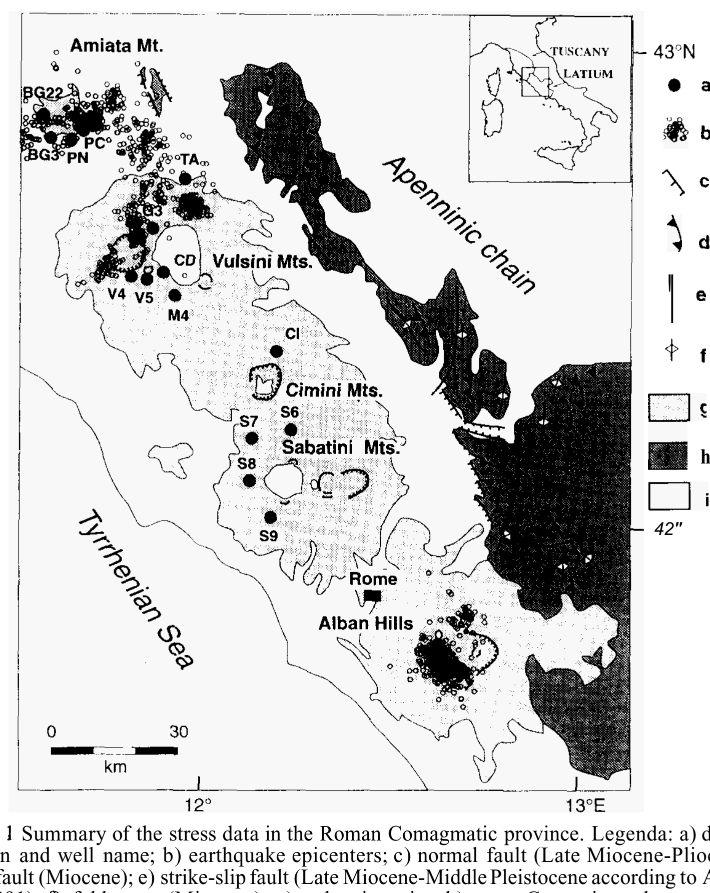

Figure 1 Summary of the stress data in the Roman Comagmatic province. Legenda: a) deep well location and well name; b) earthquake epicenters; c) normal fault (Late Miocene-Pliocene); d) thrust fault (Miocene); e) strike-slip fault (Late Miocene-Middle Pleistocene according to Alfonsi *et al.*, 1991); f) fold axes (Miocene): g) volcanic units; h) meso-Cenozoic carbonate units; i) neoautochtonous units.

The seismicity was studied by Amato *et al.* (1994) who located more than 1100 earthquakes and computed fault plane solutions of the strongest shocks.

2. METHODOLOGY

The orientation of the active stress field can be inferred from 1) focal mechanisms of earthquakes, 2) measurements gathered during the drilling and logging of exploration wells (borehole breakouts), *3)* in situ stress measurements, and 4) young geologic data (Zohack, 1992). In this work, we have analysed data relative to the first two categories of stress indicators, that have been then compared to structural data on recent volcanic rocks.

In our study area, 15 deep wells have been analysed to investigate the active stress field. As known, the minimum and the maximum horizontal stress directions (Sh and SH) inferred from borehole breakouts does not uniquely describe the stress regime.

Other data are needed to constrain the stress tensor, in particular focal mechanisms of earthquakes can yield principal stress directions (Angelier, 1979; Gephart & Forsyth, 1984; Michael, 1987). Fault plane solutions have been computed from P-wave first motion polarities recorded at local distances by microseismic networks (Buonasorte *et al.*, 1987; Amato *et al.*, 1994). In addition, mesostructural data have been analysed from published works (Buonasorte *et al.*, 1987; Faccenna, 1993) and in some regions from originally collected measurements.

2.1 Identification of borehole breakouts

Breakouts are spalled regions on opposite side of the borehole that produce intervals of the well with ellipsoidal cross sections (Cox. 1970; Babcock, 1978). Bell and Gough (1983) suggested that the breakouts are the result of localized shear failure, in response to a concentration of compressive stress at the borehole wall, within an anisotropic stress field. Breakouts are aligned in the minimum horizontal principal stress (Sh) direction. They arc generally identified using four-arm dipmeter (SHDT) designed to measure strike and dip of bedding planes by measuring the conductivity of the rock. The dipmeter is equipped with four orthogonal extendible pad-types electrodes, one of which is magnetically oriented. The two orthogonal calipers measure the long and the short axes of the borehole and their azimuths. The orientation of the long axis recorded by the four-arm caliper is parallel to the direction of the minimum horizontal stress Sh, (see Bell and Gough, 1983; Plumb and Hickmann, 1985; Bell, 1990; Zoback, 1992).

We analysed several wells in a variety of rock types located . Quaternary volcanoes of the Latium and Tuscan province. namely the Amiata, the Vulsini. and the Sabatini Volcanoes (Figure 1 and Table 1). The form of our data include non computed field logs and digital data. We analysed paper lugs identifying ovalization regions according to the criteria listed below:

1) the tool must not rotate in the zone of elongation.

2) the larger caliper curve should exceed the bit-six, the smaller one should not be less than hole gauge and its trace is parallel to the bit-size;

3) breakout elongations coincident (within + - 10°) with azimuth of hole deviation arc discarded, because they may be caused by the tool weight or by erosion of the drill strings;

4) well intervals with deviation >10° arc not considered.

Data (length and azimuth of each ovalized zone) are then input into a Fortran computer code that calculates the breakout preferred orientation (parallel to Sh) and its standard deviation.

The automatic analysis is performed on the digital curves of the borehole geometry (azimuth of pad1, hole azimuth, deviation, calipers length), sampled at 0.1 m **or** less. **A** computer program identifies the breakout zones, according to a series of cutoff criteria set "a priori". This gives a more objective estimate of which elongation is a breakout and which is not, compared to the analysis of paper logs. The results obtained with the two methods generally give the same results. Following the quality ranking system described by Zohack (1992) we have assigned a quality factor to each well, ranging from **A** (the highest quality) to D (the lowest quality). Quality E has been assigned to wells that do not contain any reliable stress field direction. All young (Quaternary) geological joint and fault slip data found in previous works have been considered to better constrain the stress field. In addition, new analyses of joint systems have been performed on pyroclastic formations of the Vulsini Volcanic Complex.

	stratigraphy	bottom	breakout length	analysed interval	breakout azimuth	Q.
PC (d)	L-**M**	3552m	109m	2540-3300	N16°+-9.9°	D
BG22 (d)	L-**M**	2310m	110m	1801-2259	N99°+-23.6°	D
BG3 (d)	V-L-**M**	3216m	301m	2610-3041	N47°+-8.1°	B
PN (d)	**L-M**	3262m	36m	300-1010	N51°+-14.6°	D
TA (d)	V-L-**ST**-SU	4826m	195m	2200-2810	N13°+-30.9°	D
CD (d)	**V**-M	2527m		670-2310		E
M 4 (c)	V-**L-ST**	2228m	151m	1238-2191	N60°+-10°	C
G 3 (c)	**V-L-M**	3040m	40m	610-1229	N58°+-18°	D
V 4 (d)	V-L-**ST-L**	3497m	303m	1573-2814	N88°+-20.7°	C
V 5 (c)	V-L	3501m	212m	467-2269	N66°+-5°	C
CI (c)	**V-N-L-ST**	3000m		1200-2600		E
S7 (d)	V-**L**-SU	1380m		186-785		E
S6 (c)	V-**L**-SU	2518m	179m	305-1854	N177°+-24°	D
S 9 (c)	V-**N-L**-SU	2300m	225m	393-1180	N130°+-7.6°	D
S 8 (c)	V-N-**L**-SU	2370m	60m	410-1580	N32°+-1.6°	D

Table 1 Legenda: V= volcanic rocks; N= neoautocthonous; L= allochthonous; ST= Tuscan sequence; SU= Umbrian sequence; M=metamorphic sequence. Bold letters indicate in which units the breakouts were detected; (d)= digital data; (c)= paper log data.

3. RESULTS

All the volcanoes of the Tyrrhenian margin between Southern Tuscany and Latium have at least one available group of reliable stress indicators, either focal mechanisms of earthquakes, as the Alban Hills, or deep wells for breakout analysis, as the Sabatini volcano, or both, as the Vulsini and Amiata volcanoes (Figure 1). In these latter two regions, both types of stress indicators can he used to characterize the stress state in the upper 5 km of the crust. The analysis of both fault plane solutions of earthquakes and borehole breakouts, with the aid of structural data on young rocks, can lead to a more reliable estimate of the whole stress tensor. In this paper we show directions of P and T axes of earthquake focal mechanisms. Although these arc indicators of strain, they lie close to the $\sigma 1$ and 03 axes of the stress tensor and are thus used here in comparison with breakout inferred **SH** and Sh stress directions. **A** formal inversion of the stress tensor using focal mechanisms is presently in progress.

3.1 Alban Hills volcano

The Alban Hills are Quaternary volcanoes that developed between 0.6 and 0.020 Ma, during three main eruptive, predominantly explosive phases. This area has experienced many earthquakes since historical times. In April 1989, the ING in cooperation with the **U.S.** Geological Survey, installed a temporary microseismic network that recorded more than 3000 earthquakes (**M<4**) in one year of operation (Amato *et al.*, 1994). The earthquakes are located in the 3-6 km depth range, with normal to strike-slip focal mechanisms with NE trending T-axes. Figure 1 shows that the seismicity is clustered in the western flank of the volcano, site of the youngest phreatomagmatic eruption (around the 0.020 - 0.030 Ma). In the absence of wellbore breakout data, both fault plane solutions of the strongest earthquakes and composite solutions of clustered microearthquakes show that in the Alban Hills volcano 03 is horizontal and is oriented approximately NE-SW (Figure 2). The predominance of normal faulting earthquakes also suggests that in this area $\sigma 1$ is vertical.

3.2 Sabatini volcano

The Sabatini volcano, similar in composition and age to the Alban Hills is located about 40 km to the northeast (Figure 1), and is seismically inactive. During the 15 years that the ENEL has operated, the microseismic network has never detected any seismic activity. However the long established geothermal exploration program has provided an abundance of information on the upper crustal structures. We analysed four wells drilled by ENEL, for which data from four-arm calipers were available. Three of these wells provided valuable results. These are located in the western and northern sector of the volcanic area (Figure 2), drilling a thin (150 to 390 m) volcanic cover overlying allochthonous sedimentary units (marls and limestones) down to about 2-2.5 km depth. The breakout intervals were between 300 and 1800 m.

The breakout analysis was done using both paper logs and digital data. The two methods yield similar results, showing different directions of elongations: N-S for Sabatini 6, NE-SW for Sabatini 8, NW-SE for Sabatini 9 (Figure 2). According to the quality ranking system proposed by Zoback (1992) we have assigned quality D to all the three wells, mainly due to the low number of breakout intervals detected or to the large scatter in the data. It seems that the breakout directions are locally influenced by existing tectonic structures as observed in other studies (Castillo & Zoback, 1994). This may indicate the presence of a nearly isotropic stress field, in which local sources of stress can modify the regional field, consistently with the observed absence of seismicity.

3.3 Vulsini volcano

In the Vulsini volcano, deep wells for breakout analysis and local seismicity for fault plane solutions are available. Six wells were analysed for breakout preferred orientations, of which five were suitable. Four wells are located in the western side of the volcanic complex, between Lake Bolsena and Latera caldera (Figure 2). Similarly to the Sabatini wells, they have drilled a thin volcanic cover overlying allochthonous sedimentary units above Meso-Cenozoic marls and limestones of the Tuscan Nappe. Another well (Alfina 15, TA in Figure 1) is located north of the lake, in the geothermal area of 'Torre Alfina and is the deepest well ever drilled in this region (more than 5 km) (Ruonasorte *et al.*, 1991). The four wells of the western sector give comparable results (Figure 2), indicating that Sh is oriented between E-W (well V4) and N60E (well G3). The northern well (TA) yielded an Sh direction N15E, but is of D quality, due to the strong dispersion of the breakout data (+- 30.9°) and to the short depth interval (2200m-2800m) available for breakout analysis.

Furthermore, we have analysed data collected by a microseismic network managed by ENEL since 1977 (Buonasorte *et al.*, 1987). The seismicity is concentrated in three main clusters located to the north and to the west of Lake Bolsena (Figure 1). Fault plane solutions computed for the strongest earthquakes (M~4) reveal T axes preferentially oriented between NE and ENE, parallel to the Sh inferred from the breakout data. The focal mechanisms show mostly normal and subordinately strike-slip motion.

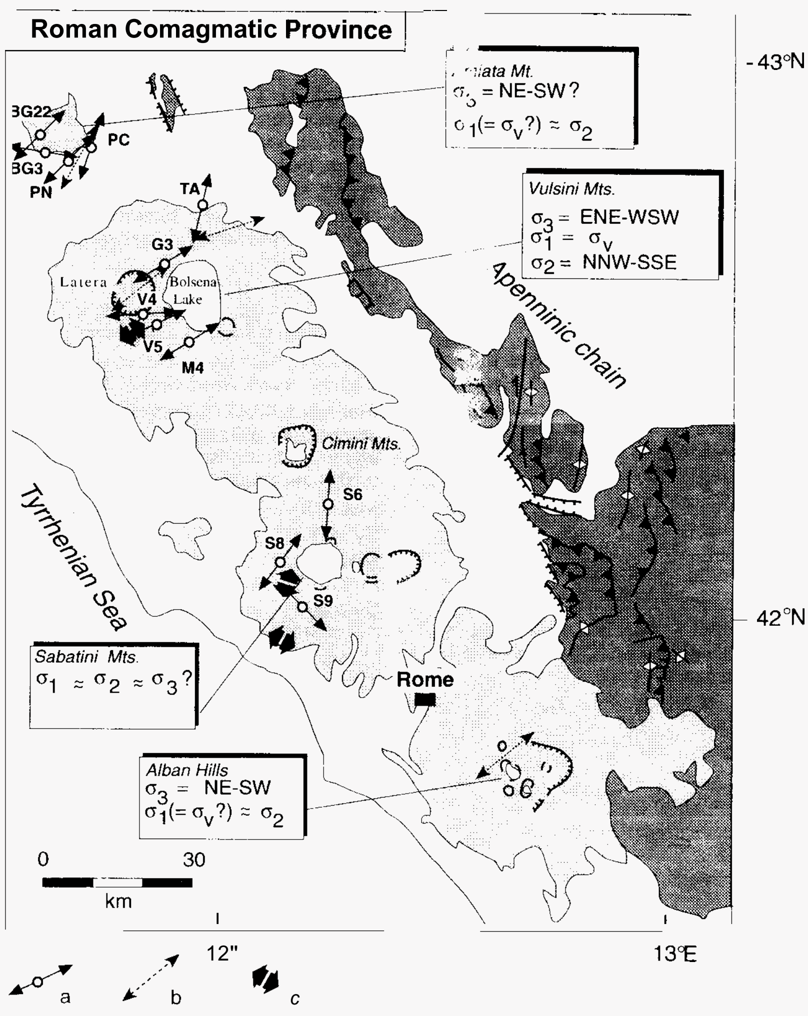

Figure 2 horizontal stress indicators for the Roman Comagmatic Province. Legenda: a) breakout azimuth; b) average T-axes of focal mechanisms (horizontal projection); c) direction of extension from mesostructural data. For the other symbols see Figure 1

Therefore, we suppose that the stress field in the Vulsini region has a vertical σ1, and a horizontal σ3, oriented around N60E-N90E.

3.4 Amiata volcano

The Amiata volcano formed around 0.3 Ma, composed of alkaline-potassic rocks. The seismic activity in this region is concentrated in the southern and eastern flanks of the volcano, close to the areas where the deep geothermal wells are located.
Four wells were analysed to get breakout directions. Similarly to what we find in the adjacent Vulsini volcano, the preferred directions of breakouts (and hence of Sh) range between E-W (well BG22, quality D because most of the breakout direction are close to the hole deviation azimuth) and NE-SW for the other three wells (Figure 2), indicating NE-SW extension.
Focal mechanisms of earthquakes also show tensional (T) axes preferably oriented around NE-SW. and subordinately N-S (Montone *et al.*, 1994). Both breakout data and fault plane solutions of earthquakes indicate that the Amiata region is undergoing NE-SW extension.

4. DISCUSSION AND CONCLUSIONS

Our investigation of the active stress field in the Quaternary volcanoes of Latium and Southern Tuscany reveals a common stress regime presently acting in the region. Both borehole breakouts and focal mechanisms of earthquakes indicate that the region is extending, with σ3 oriented between NE-SW and ENE-WSW, and σ1 most likely parallel to σv (vertical load). The only exception to this general trend is the Sabatini volcano, where the three analysed wells show different orientations of Sh at close distances. It is not clear why the stress variability is high, but one possibility would be local perturbations due to borehole intersecting or close to a fault. It is interesting to note that the Sabatini volcano is the only region of the Roman Comagmatic Province where no seismic deformation is observed (Figure 1).
In the remaining volcanic regions, rather uniform orientation of the stress field is observed, based on borehole breakouts and focal mechanisms of earthquakes. Where available (Vulsini and Amiata) the two types of stress indicators show consistent results. In these regions, a NE-SW to ENE-WSW direction of extension is revealed. In the Alban Hills, where well data is not available, the focal mechanisms of the strongest earthquakes and composite solutions of clustered microearthquakes, also show NE-SW to ENE-WSW extension.
We therefore hypothesize that in the whole region from Mt. Amiata to the north up to the Alban Hills to the south, a uniform stress field is active, with a horizontal, NE-trending σ3 and vertical σ1. Local sources of stress related to the magmatic systems (as possibly in the Amiata region) or to pre-existing tectonic features (as maybe in the Sabatini) can then deviate the regional stress field.

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