PALEOMAGNETIC EVIDENCE OF NON ROTATIONAL TECTONISM IN THE TUSCAN-LATIUM GEOTHERMAL PROVINCE (ITALY)

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Key words: Geothermal anomaly; Tuscany; Paleomagnetism; Tectonics.

ABSTRACT
New paleomagnetic data, referring to the Late Miocene-Pliocene "Neo-Autocthonous" sedimentaty sequences in the extensional basins of the Tuscan-Latium Tyrrhenian margin, demonstrate that no significant rotations affected this region since the Late Messinian-Early Pliocene time. These data suggest an evolution in the area hetween the Amo River and Rome that is different from that in the southern Apennines, where diffuse Plio-Pleistocene rotations were previously recognized. This geodynamic feature can better explain some different hehaviour between volcanic areas to the north and south of Rome: - the strong crustal influence in Neogene-Quaternary magmatic activity and volcanism to the north of Rome that attenuates southwards; - the presence to the north of Rome of a strong and large positive thermal anomaly that decreases sharply southwards, only partially due to widespread outcrops of permeable carbonatic platform units. The Neogene-Quaternary anatectic events of Tuscany and north to the Latium regions could be influenced by the non-rotational geodynamic feature. The inferred continuity between the lower and upper parts of the lithosphere, since the Messinian to the present, allowed the persistence of thermal processes at various depths: these peculiar conditions produced a different tectonic hehaviour and greater heat flow density with respect to the neighbouring areas.

1. INTRODUCTION
The northern Tyrrhenian margin is one of the better known and studied geothermal regions, and the understanding of its precise tectonic evolution is a main goal of geothermal research. Large amounts of geophysical and geological data have hecn collected in recent years, hut the geodinamic processes which concern this region are still heing debated.
In particular some authors have suggested that geodynamic processes responsible for the post-middle Miocene opening of the Tyrrhenian basin, and the consequent extension of the Tuscan Tyrrhenian margin. were connected with a homogeneous counterclockwise (CCW) rotation of the entire Italian peninsula (Boccaletti et al., 1974; Patacca and Scandone, 1987; Sartori, 1990; Doglioni, 1991: Castellarin et al., 1992). This hypothesis was hased on paleomagnetic data carried out in allochthonous sedimentary sequences of Early Jurassic-Oligocene age in the Northern Apenninic chain, which recorded a CCW rotation that was largely extrapolated both in space and time (Lowrie and Alvarez, 1975; Channell and Tarling, 1975: Channell et al., 1978; VandenBerg et al., 1978; Hirt and Lowrie, 1986).
In order to define the precise rotational pattern of the northern Tyrrhenian margin, we performed a paleomagnetic analysis in the "Neo-Autochthonous" Upper Messinian-Pliocene sedimentary sequences outcropping in the Tuscan region. The results obtained show that in the Tuscan geothermal province extensional tectonics did not accompain significative regional rotations. These results are discussed in terms of tectonic evolution and geophysical characters of the region.

2. GEOLOGICAL FEATURES
The Northern Italian peninsula is characterized by a set of thrust units separated by several elongated Neogene basins produced hy late extensional tectonics. The thrust nappes have progressively embricated toward the Adriatic foreland since Tortonian time. These nappes define arcuate structures with a prevalently east to northeastward vergence (Elter et al., 1975; Boccaletti et al., 1987; Bigi et al., 1988). The nappes are composed of metasedimentary sequences, which formed the metamorphic basement of the area, and sedimentary sequences deposited on both oceanic and continental crust, which are superimposed to constitute the Apenninic chain (Figure 1). Detachment layers are mainly concentrated within Triassic evaporites which form the base of the sedimentary sequences. The crystalline Paleozoic "basement" is also organized in thrust sheets as inferred by geophysical research and demonstrated by recent geothemal exploration (Pandeli et al. 1988; Elter and Pandeli, 1994).
During Late Miocene the Tuscany was affected by extensional tectonics which followed migrating compressional phases. This extension was accompanied by the formation of large, mainly NW-SE oriented, sedimentary hasins filled with continental, brackish and marine sequences (Neo-Autochthonous Tuscan cycle) which unconformably covered the compressive Apenninic structures. This general extension progressively affected the Tyrrhenian basin and the Italian peninsula reaching the axis of the Apenninic chain where is presently active. Several authors (Carmignani and Kligfield, 1990; Bertini et al., 1991), also suggest that an earlier (Middle Miocene) extensional phase affected the Tuscan margin. This extension formed anomalous "reduced sequences" and denudation processes well recognisable in the metamorphic Apuane Alps and southern Tuscany.
Extensional tectonics was also characterised by diffuse magmatic processes from the eastern coast of Corsica island to the inner part of the Apenninic chain. The western part of this magmatic area shows the oldest (13-6 Ma) (Serri et al., 1991). more crustally contaminated plutonic bodies (Sisco, Montecristo, Mt. Capanne, Giglio). The volcanics get progressively younger toward the Tuscan Tyrrhenian coast. **An** associated Pliocene rhyodacitic volcanism is also recognised from S.Vincenzo-Monticiano-Roccastrada to Ciniini, Tolfa-Ceriti Mts.. The magmatic processes continued with the formation of alkaline-potassic volcanoes (Roman Comagmatic Province, RCP) that started in Pleistocene tunc.

3. THE GEOTHERMAL ANOMALIES AND FIELDS OF THE TUSCANY AND LATIUM
The western belt of Tuscany and Latium and the Tyrrhenian Sea show a large, nearly continuous positive heat flow anomaly of 100 mW/m^2 coinciding with an equally large and important absolute positive gravimetric anomaly in the Tyrrhenian Sea and with a gravity anomaly gradient zone in the internal western sector of the Apenninic range. This situation is clearly explained by the reduced thickness of the crust and the lithosphere, which are less than 25-30 km and 50 km, respectively.
The thinning of the crust and lithosphere explains the heat flow anomaly on the regional scale. It does not account for the wide zones of high heat flow anomaly (200 mW/m^2), which characterize the pre-Apennine belt of central Italy (Figure 2).These zones correspond, from the north to the south, to the areas of Larderello-Travale, Amiata Volcano, Volsini Volcanoes, Vico-Cimini and Sabatini Volcanoes. The Italian geothermal fields of Larderello-Travale, Bagnore, Piancastagnaio, Alfina, Latera, Cesano are located in these areas (Baldi et al., 1982). For these anomaly zones in particular it is necessary to consider further causes of heat flow which are consistent with the geological and geophysical features of the fields.
The Larderello-Travale and Mt. Amiata fields are structural highs as evidenced both at the level of the top of the carbonate formations of the Tuscan Units and at the level of the metamorphic complexes, to which gravimetric positive anomalies

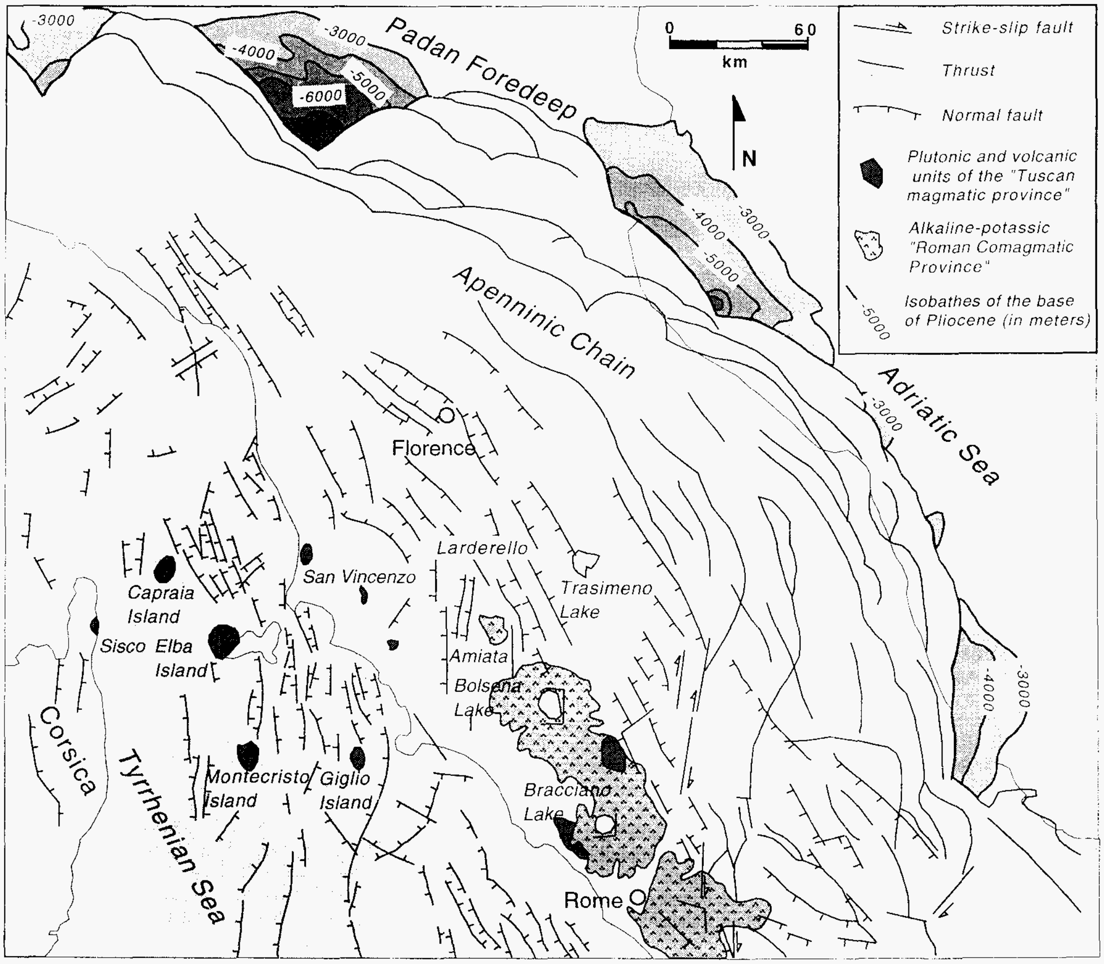

Figure 1. Schematic structural map of the main Neogene tectonic features of Northern Apennines (from CNR, 1989, modified).

should correspond. However, the structural highs correspond instead to large relative gravimetric minima. The two areas are also characterized by a considerable uplift (Marinelli 1975; Barberi et al., 1993; Marinelli et al., 1993), revealed by the present-day elevation of the most recent marine sedimentary formation (Middle Pliocene-Quaternary). They reach in the case of Tolfa-Cimini and Larderello-Travale, respectively, elevations of 400 m and 600 m, and exceed 800 m in the case of Mt. Amiata (Figure 2). These uplift zones can only in part be connected to the regional isostathic adjustment of the Apenninic chain; they are likely linked to intrusive bodies at relatively shallow depth.

Microseismicity data indicate that the earthquake hypocenters are generally situated at shallow depths almost always less than 7 km. Seismic topographic modelling for the Larderello area indicate the presence at depth of about 5 km of a considerably thick "body" characterized by low velocity of the P seismic waves, which wide towards the bottom and is shown to be still partially melted intrusions (Batini et al., 1995). A rough extrapolation of the temperature from the maximum depth reached by the Larderello area wells, based on the deep thermal gradient reconstructed in impermeable deep levels, lead to the temperature of roughly 700" C at this depth.

Moreover some wells have met microgranitic dikes and the top of a granitic body at depth between 3000 and 4200 m. Radiometric data available on a sample of microgranite give an age of 3X Ma (Villa et al. 1987). In addition, in neighbouring areas, magmatic intrusions are present, whose age is in accordance with that (4.7-2.1 Ma; Ferrara et al., 1989; Villa, 1988).

All the anomalies and elements which characterize the Tuscan geothermal anomalies and fields mentioned lead to the conclusion that their "roots" are attributable to magmatic intrusions of essentially acid-anatectic type. These intrusions gave rise to strong and wide thermometamorphic mineralization characterized by post-kinematic biotite, andalusite and cordierite in the metamorphic host rocks of the regional basement (Franceschini, 1995). Presently only a small part of the thermometamorphic dome is in equilibrium with the presently measured temperature (350 - 450 °C)

On the basis of the available data it is not possible to make definite conclusions about the beginning and the duration of this magmatism. However, the very high rock temperatures measured at relatively shallow depth, together with the above considerations on the deep extrapolation temperature, gravity anomaly, seismic tomography and the trend of the seismicity lead us to believe that there is recent active magmatism; moreover, on the basis of the granitic intrusion found by the wells and their age, it is possible to say that this magmatism has been active for the last 3.8 Ma.

The Latium geothermal fields are related to the extensive Late Quaternary alkaline-potassic volcanism of northern Latium. The structural and phenomenological characteristics of the geothermal fields are substantially different from those of the Tuscan fields. The geothermal anomalies of these fields are clearly located in areas of volcano-tectonic activity, where the calderas of Bolsena, Vico and Bracciano have collapsed. The peaks of the main Latian geothermal anomalies are located, in particular, to the north and west of Rolsena Lake (Alfina and Latera), and to the east of Bracciano Lake (Cesano), in con-espondence with the structural highs of the geothermal field.

4. PALEOMAGNETIC RESULTS

Paleomagnetic sampling was carried out in the main Upper Miocene-Pliocene sedimentary sequences of the Tuscan area between Pisa and the Mignon; basin (Figure 3).

A total of 38 paleomagnetic sites were sampled in the sedimentary rocks of western Tuscany: Upper Messinian sites have been sampled in blue clays interbedded with evaporitic deposits, in the Volterra, Val di Fine and Orcia valley basins and Pliocene sites have been sampled in blue clays sediments mainly located in the Volterra, Siena-Radicofani and Mignone basins. Ten to fifteen cores, well distributed both horizontally and vertically, were taken from each site. A total of340 cores, each of than giving 2 to 3 specimens have been sampled for this study. Natural Remanent Magnetization (NRM) values range from 5.10^{-6} A/m to 0.2 A/m with a great majority between 10^{-4} and 10^{-3} A/m.

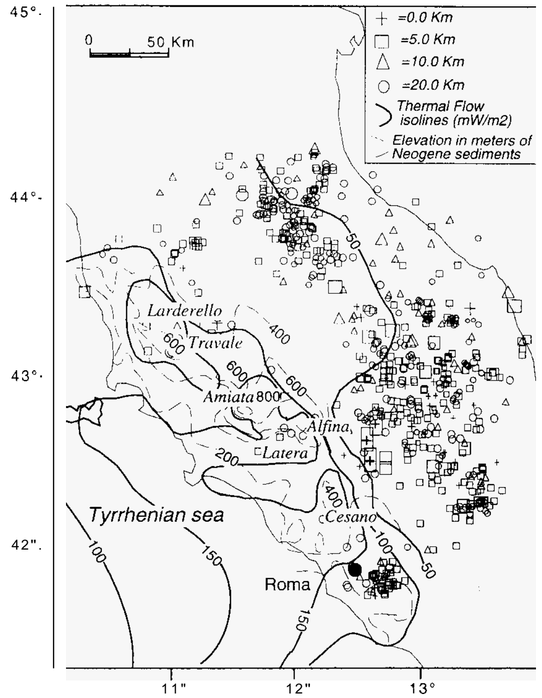

Figure 2. Schematic map showing the distribution of the earthquakes, thermal flow and Pliocene sediment elevations in Northern Apennines. Crosses, squares, triangles and circles represent different depths hypocenter distributions (Selvaggi and Amato. 1992). Thick lines represent thermal flow isolines. Thin lines represent the elevation of Neogene sediments (Mongelli et al. 1991).

Seven of the sites were too weakly magnetized to he measured even using a cryogenic magnetometer. Four other sites, characterized by multidomain magnetite, exhibit an unstable behaviour during demagnetization. No reliable results were obtained from these sites. The remaining 27 sites show good magnetic behaviour and statistical parameters. Normal and reversed polarities have been found and the site mean directions group in two antipodal clusters. Thus the ohtained results are able to he used to define the tectonic evolution of the area.

The details of the laboratory analyses and paleomagnetic results will be published elsewhere (Mattei et al. submitted), in Figure 4 are shown the paleomagnetic results ohtained from the well measured sites. Averaging these 27 produced a mean direction of D=357; I=57.

5. DISCUSSION AND CONCLIJSIONS

Paleomagnetic data from Upper Messinian-Pliocene sedimentary sequences of the Tuscan "neo-autochthonous" units confirm the results ohtained by Lowrie and Alvarez (1979) in the San Vincenzo rhyolite and by Sagnotti et al. (1994) in Lower Pliocene-Pleistocene clayey units of the adjacent Latium Tyrrhenian margin. The paleomagnetic data obtained Prom this study better define the tectonic evolution of the Tuscan Tyrrhenian margin and demonstrate that no significative homogeneous regional rotations affected the Northern Tyrrhenian margin since at least Late Messinian-Early Pliocene times. Paleomagnetic evidences of **no** regional tectonic rotations are confined in the Northern Tyrrhenian margin and contrast with the large angles of rotations which have hcen documented previously all along the Apenninic chain, Calabrian arc and Sicily from Cretaceous to Pleistocene sequences.

Paleomagnetic data confirm that the Northern Tyrrhenian margin represents an area with a distinct tectonic evolution respect with the large part of the Italian peninsula as already suggested by other geological and geophysical data. In particular the stable region seems to he confined, in northern Italy, in areas characterized by extensional tectonics while contemporaneously, the east verging units of the Apenninic chain were thrust and rotated over the Adriatic foredeep (Dela Pierre et al. 1992; Mattei et al., 1993).

This difference in tectonic evolution is also evidenced by the present day distribution of intermediate and deep seismicity that, in northern Italy, is mainly concentrated in the Apenninic chain and Adriatic foredeep suggesting the existence of an active "subduction" of the Adriatic lithosphere beneath the Northern Apenninic chain (Spakman, 1990; Amato et al., 1992; Selvaggi and Amato, 1992, Serri et al., 1993).(Figure 2). The Tuscan region at the contrary, is almost not seismically active and corresponds with the region characterized by positive anomalous heat flow (Pasquale et al., 1993). The subduction processes would cause severe shortening and rotations in the Apenninic thrust sheets followed by post-collisional extension accompanied by anomalous thermal flow and no major rotations in the Tuscan Tyrrhenian margin.

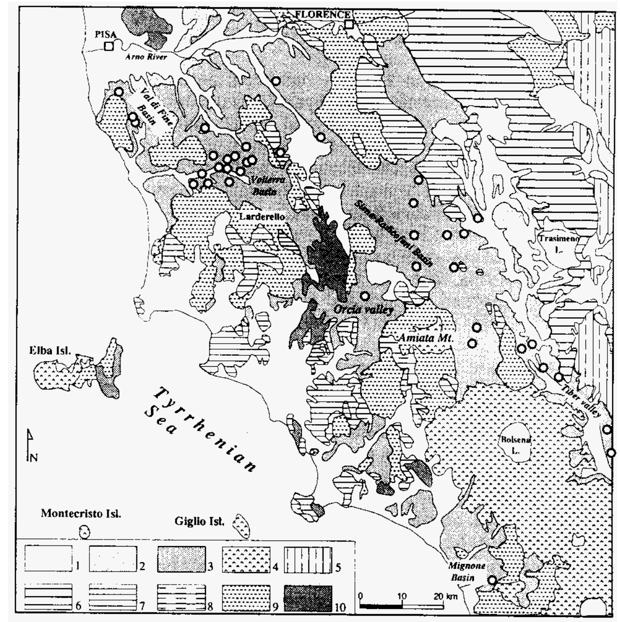

Figure 3. Geological map of the Tuscan Tyrrhenian margin. Open circles represent the distribution of the paleomagnetic sites. Sedimentary sequences of the "Neo-Autochthonous Tuscan cycle" unconformably overlying the Apenninic chain: 1) undifferenciated continental and subordinate marine deposits (Quaternary); 2) lacustrine sediments (Villafranchian); 3) evaporite and marine terrigenous deposits, lacustrine deposits (Messinian-Pliocene). 4) Neogene-Quaternary magmatic rocks. Apenninic units: 5) Umbria-Marche units (Upper Triassic-Tortonian); 6) Modino-Cervarola units (Upper Oligocene-Middle Miocene); 7) Tuscan units (Lower Triassic- Lower Miocene); 8) Sub Ligurian units (Triassic- Lower Miocene); 9) Ligurian units (Jurassic-Eocene); 10) Tuscan low-grade metamorphic units.

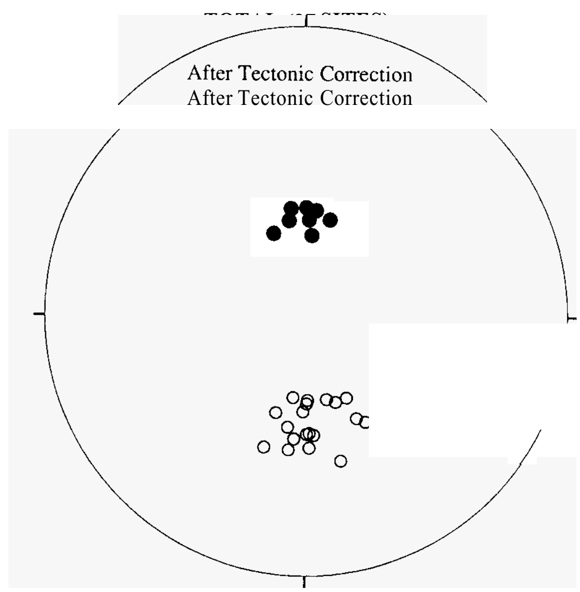

Figure 4. Equal-area projection of site mean directions from all the measured sites. Open and full symbols: upward and downward directions respectively.

The absence of regional rotations in Tuscany may also better explain the geothermal evolution of the Tuscan area respect with the region to the south of Rome. The existence of long living geothermal fields in Tuscany has been largely recognized by means of radiometric ages, hydrothermal minerals and fluid inclusions analyses (Del Moro et al., 1982; Mongelli et al., 1991) and has been connected with the existence of large granitic bodies which should be present below the main geothermal region and that have been recognized, by seismic observations, in the Larderello field (Faley et al. 1992).

A continuous feeding of the crust by hot, deep fluids, is thus necessary to entertain the observed anomalous thermal flow over longer periods, to avoid the thermal energy dissipation which should happened, for isolated granitic bodies, over a very short period of 10.000 to 100.000 years (Mongelli et al., 1991). At the same time the persistence of the thermal processes in the metamorphic and sedimentary sequences which cover the plutonic bodies, testifies a continuity of the geologic units inside the upper part of the lithosphere that is well explained with the detected no rotation pattern.

The absence of regional rotation of the Tuscan margin since Late Messinian-Early Pliocene times explain the main geological and geophysical features of the Tuscan region. This relationship clarify some of the still open debate about the geodynamic evolution of the Italian peninsula and represents an interesting case history for the geothermal research in the world.

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