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CHAPTER 6

Hidden granitoids from boreholes and seamounts

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6.1 GEOLOGICAL SETTING

In southern Tuscany, the stack of nappes piled up during the Oligocene-Miocene Apennine convergence often has limited thickness, and were intruded by magmas of the Tuscan Magmatic Province since early Pliocene. Numerous traces of igneous activity have been found in boreholes drilled for geothermal or ore mineral exploration in the famous Larderello geothermal field and to the south. The drillings sampled intrusive rocks in many localities (Fig. 1).

The main bodies were found at Castel di Pietra (boreholes S2 and S3), at Monte Spinosa (borehole MS1), and in the area of Larderello geothermal field. In addition an intrusive rock have been sampled on the Seamount Vercelli (Central Tyrrenian Sea; Fig. 2).

6.2 THE INTRUSIVE UNITS

6.2.1 Castel di Pietra

The contact between the intrusion and country rocks is found in two boreholes at depth of 866 and 689 m, and intrusive rocks have been cored for 223 and 48 m, respectively (Franceschini *et al.*, 2000). The host rocks of the intrusive body consist of the quartzitephyllites of the Verrucano unit, the oldest rocks of the Apennine belt, also called «parautochtonous» (cfr. Complex I of Elba Island). The country rocks overlying the intrusive body are thermally metamorphoded across 140-200 m thickness. The intrusion is made up of three different facies (Fig. 3): (1) the main Porphyritic Facies, of monzogranite composition with phenocrysts of K-feldspar (up to 3 cm), plagioclase, embayed quartz and biotite along with igneous muscovite and altered cordierite, all set in a fine-grained groundmass; (2) Leucocratic facies, a medium-grained syenogranite; (3) a monzogranitic-granodioritic grey facies with oscillatory-zoned plagioclase, biotite, orthopyroxene and rare cordierite, along with interstitial K-feldspar and quartz. The overall SiO_2 variation is high, from 65.0 to 71.9 wt%. Sr isotope data, although to be regarded with caution owing to the widespread hydrothermal alteration, point to very different composition for the different facies: $^{87}Sr/^{86}Sr$=0.7165-0.7222 for the main porphyritic facies, against $^{87}Sr/^{86}Sr$=0.7145 for the orthopyroxene-bearing facies. The emplacement age of the Castel di Pietra intrusion is ca. 4.3 Ma.

6.2.2 Monte Spinosa

The contact between the intrusion and country rocks is found in two boreholes at depth

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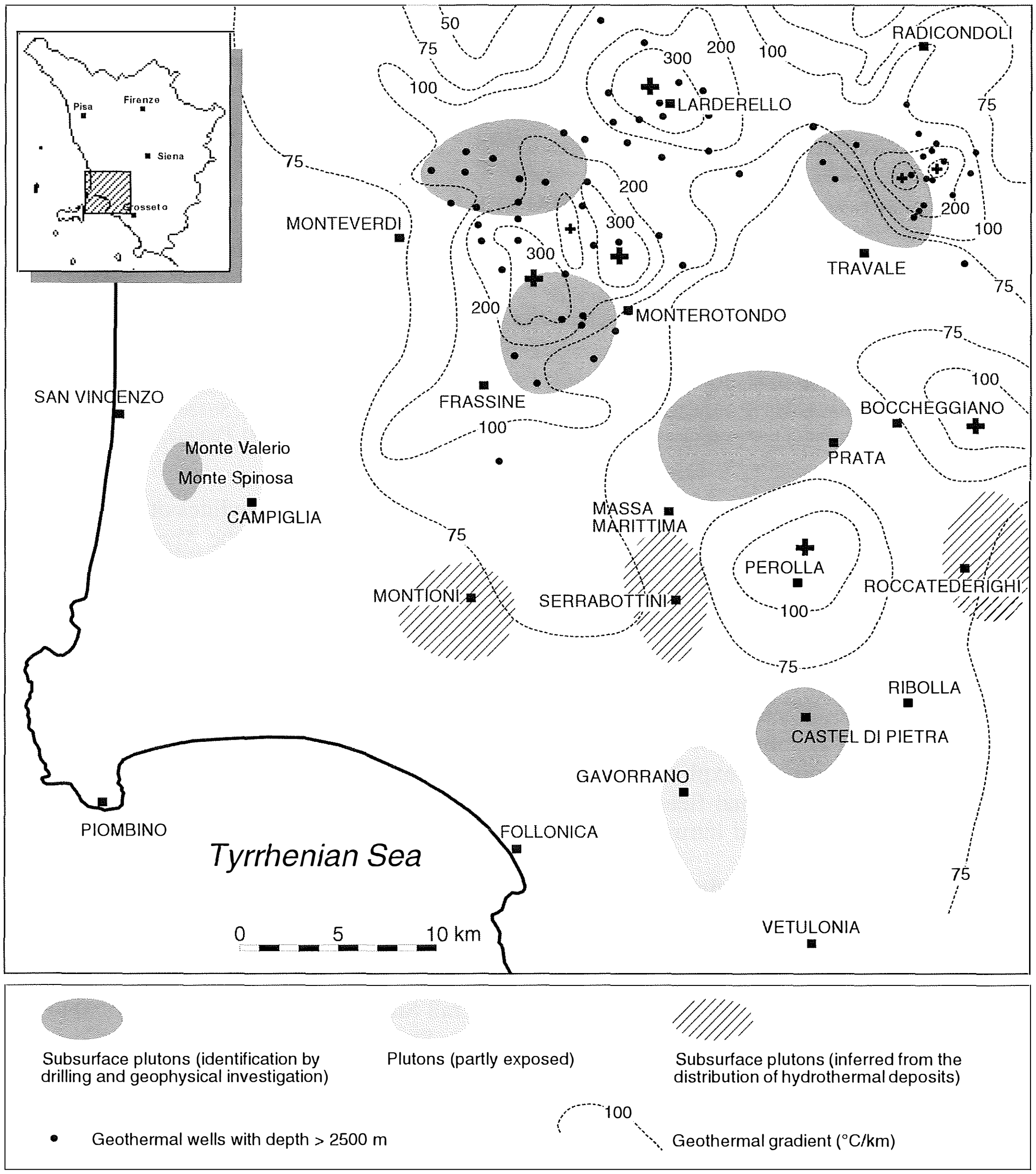


Fig. 1 – Location of subsurface intrusive bodies of Pliocene-Quaternary age in southern Tuscany. 1) Subsurface masses recostructed through drillings and geophysical data (in Campiglia and Gavorrano areas intrusive rocks also crop out). 2) Intrusive masse inferred from the location of hydrothermal deposits. 3) Geothermal gradient (°C/km). 4) Bouguer anomaly (mgal). 5) Geothermal wells reaching depth > 2000 m. Redrawn and modified after Franceschini *et al.* (2000).

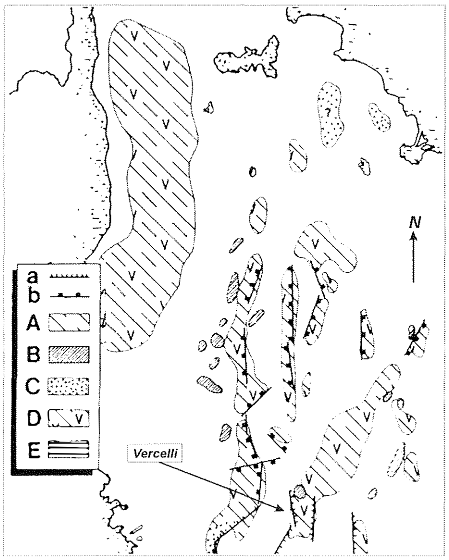


Fig. 2 – Schematic geological map of Central Thyrrenian Sea showing the location of Seamount Vercelli (modified after Zitellini *et al.*, 1986); a) vertical normal fault; b) rotational normal fault; A) extension of preevaporitic middle(?)-Eocene basins; B) apex of magmatic intrusions; C) Messinian basins with clastic sedimentation; D) Messinian basins with evaporitic sedimentations; E) Late Serravallian(?)-Tortonian basins.

of 361, and intrusive rocks have been cored for 180 m with some intrusive facies containing endomorphic phases (Festoso, 1989). The host rocks of the intrusive body are similar to those of Catel di Pietra. The country rocks overlying the intrusive body are thermally metamorphoded across 350 m thickness. The intrusion is made up of an equigranular facies of syenogranite and monzogranite composition with K-feldspar (max 3 mm), plagioclase, embayed quartz, along with igneous muscovite and scarce titanite (Festoso, 1989). The overall SiO_2 variation is high, from 66.0 to 71.2 wt%. MS1 samples are not peraluminous than the S2 and S3 samples (ASI 0.9 and 1.2, respectively). In spite of similar compositions (Fig. 3) MS1 samples have different geochemical characteristics (Fig. 4; data from Festoso, 1989 and Poli *et al.*, 1989). The trend on the SiO_2 versus TiO_2 is different from all the other facies of intrusive rocks from Tuscan Magmatic Province claiming for a different batch of magma. In addition MS1 samples have higher Sr (340 vs 170) content and lower Zr (100 vs 200), Nb (5 vs 20), and La (15 vs 40) contents in respect to the Castel di Pietra samples.

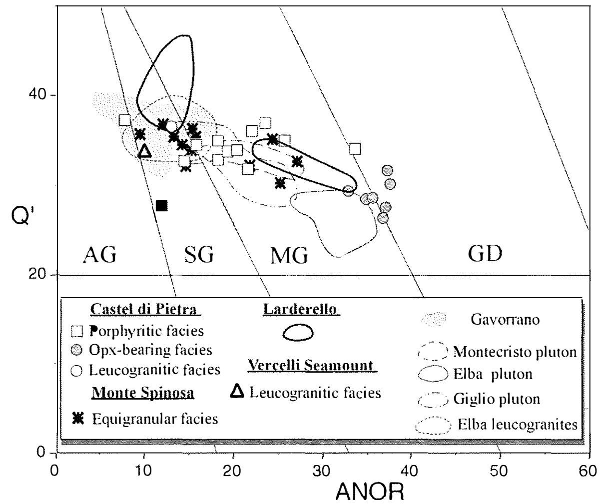
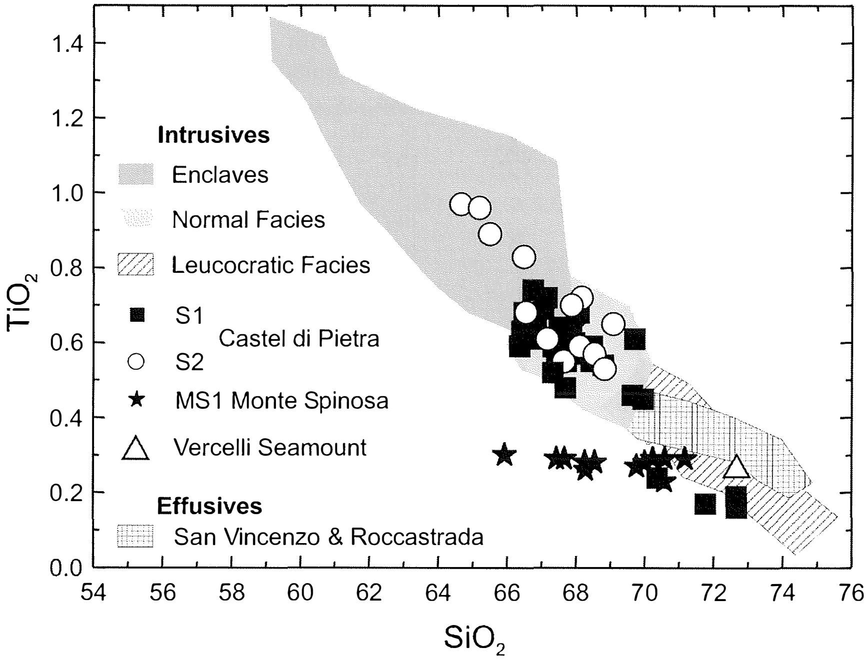


Fig. 3 – Q'-ANOR diagram for the Castel di Pietra, Monte Spinosa, and Vercelli Seamount intrusions. AG: alkali feldspar granite; SG: syenogranite; MG: monzogranite; GD: granodiorite. Data Giglio pluton from (Westerman *et al.*, 1993) for Montecristo pluton from (Innocenti *et al.*, 1997), for Monte Capanne pluton from (Dini *et al.*, 2002), for Larderello granites from (Gianelli and Laurenzi, 2001). Redrawn and modified after Franceschini (2000).



Fig, 4 – SiO_2 vs TiO_2 diagram for Castel di Pietra, Monte Spinosa, and Vercelli Seamount intrusions. AG: alkali feldspar granite. Data from Poli, 1992; Festoso, 1989; Pinarelli *et al.*, 1989.

6.2.3 Larderello

At Larderello granites have been found in wells reaching 2 to 4.5 km below the ground level. Furthermore, the presence of intrusive bodies can be inferred from different geophysical data such as: heat flow, gravity and seismic data, magnetotelluric surveys (see Gianelli and Laurenzi, 2001 for a brief review). The granites intrude Palaeozoic basement rocks (micaschists, gneiss and amphibolite) that suffered multiphase regional metamorphic history (both Hercynian and Alpine). Granite emplacement produced thermometamorphic aureoles dominated by a biotite, plagioclase, andalusite, cordierite, tourmaline assemblage.

Larderello granites are peraluminous (ASI between 1.10 and 1.22) and range in composition from monzogranite to syenogranite (Fig. 3). They are constituted by quartz, Kfeldspar, plagioclase, biotite, muscovite, cordierite (up to 7 modal wt%), ilmenite, apatite, monazite, xenotime and uraninite. Boron minerals like tourmaline (common) and dumortierite (rare) also occur. The available geochemical and geochronologic data (Villa *et al.*, 2001; Gianelli and Laurenzi, 2001 and reference therein) indicate that the geothermal wells have reached distinct bodies, emplaced in the range of 3.8-1.3 Ma.

Recently, geochemical and isotopic investigations were carried out on granites cored during drilling exploration activity on the Larderello–Travale geothermal field (Dini *et al.*, 2003 a, b). On the basis of major and trace elements, as well as REE patterns, two groups of granites were proposed: LAR–1 granites (3.8–2.3 Ma) originated by biotite breakdown, and LAR–2 granites (2.3-1.3 Ma) generated by muscovite dehydration melting. At least three main crustal sources (Fig. 5), characterized by distinct $\varepsilon_{Nd}(t)$ and $^{87}Sr/^{86}Sr$ values, were activated at different times, and the magmas

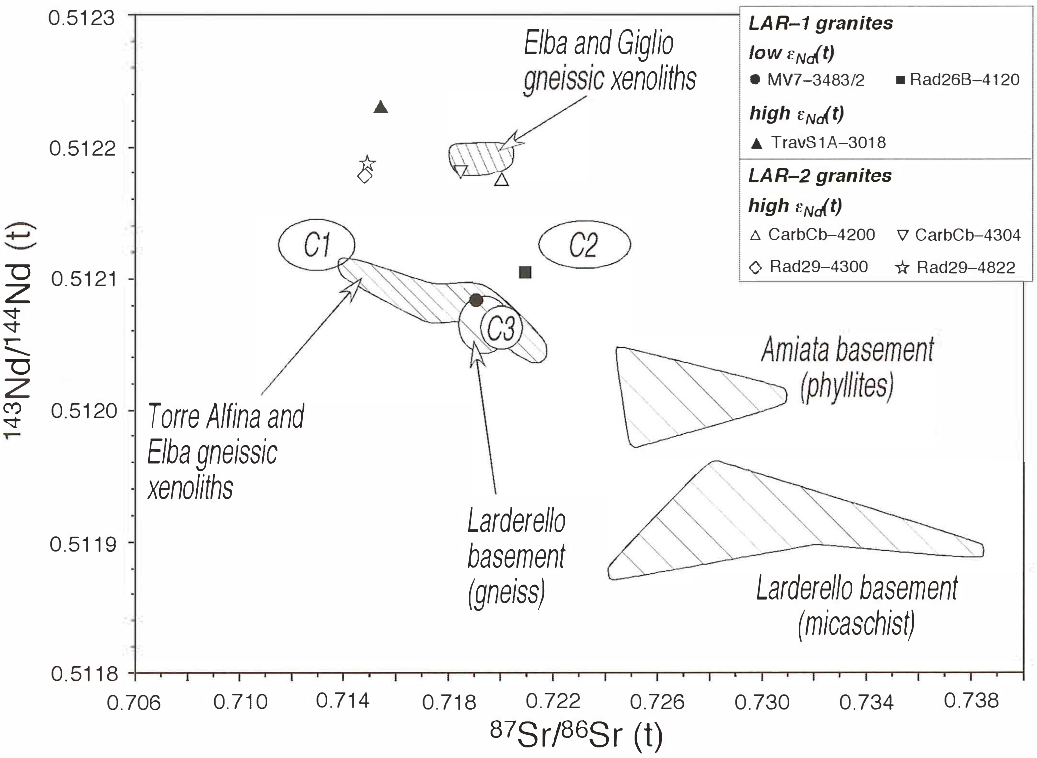


Fig. 5 – Comparative $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram showing the isotopic compositions of: 1) LAR granites, 2) some fertile metamorphic lithologies from the Tuscan basement and xenoliths, 3) crustal components involved in Tuscan Magmatic Province. C1 is the crustal source for the early crustal product of Elba Island; C2 is the main crustal end-member for hybridism processes in TMP (Elba Island, San Vincenzo); C3 is the crustal source for the youngest Giglio leucogranites (see more details in Dini *et al.*, 2002).

produced were randomly emplaced throughout the entire field. A biotite-rich source with low $\varepsilon_{Nd}(t)$ value (about -10.5) was activated during the early magmatic phase producing the oldest intrusions (about 3.8–2.5 Ma). During the second part of this magmatic phase (2.5–2.3 Ma) another biotite-rich source having a distinctly higher $\varepsilon_{Nd}(t)$ value (-7.9) was activated. Subsequently, a muscovite-rich source with high $\varepsilon_{Nd}(t)$ (about -8.9) was activated and the younger group of granites emplaced (2.3-1.0 Ma). Crustal melting probably was a fast process as indicated by the significant Sr isotope disequilibrium recorded by granites belonging to the same group. Moreover, the preservation of Sr isotopic disequilibrium inside the same intrusion is a further evidence of the short magma residence time in the source region and its rapid transfer to the emplacement level. The isotopic compositions of LAR granites do not fit the variation field for the fertile Larderello micaschist as well as the Amiata-Farma Phyllites (Fig. 5). Isotopic data from a single sample of Larderello gneiss fit the isotopic composition of the low $\varepsilon_{Nd}(t)$ granite group, but further investigation on this formation, and other potential fertile lithologies from the Tuscan basement, is needed in order to characterize the anatectic protoliths.

In summary, in the root zone of the Larderello-Travale geothermal field (14–23 km), P-T conditions for crustal melting were intermittently reached, and low fractions of heterogeneous crustal melts were locally produced and sequentially transferred to shallow levels (4-6 km). This behaviour could be controlled by multiple, small-sized mafic intrusions, distributed over the last 3.8 m.y. that allowed temporary overstepping of biotite- and muscovite-dehydration melting reactions into an already pre-heated crust. Dilution in time of the magmatic activity probably prevented melt mingling and homogeneization at depth, as well as the formation of a single, homogeneous, hybrid pluton at the emplacement level. Moreover the high concentrations of volatile elements (B, F) estimated in the LAR granites were able to modify melt properties by reducing solidus temperatures, decreasing viscosity and increasing H_2O solubility in granite melts. In turn, these consequences influenced magma mobility and crystallization, allowing a more efficient, fast, extraction and transfer from the source, and a prolonged time of crystallization at the emplacement level. All these characters can be regarded as the key-factors explaining the long-lived hydrothermal activity recorded in this area by both fossil (Plio-Quaternary ore deposits) and active (Larderello-Travale geothermal field) systems.

6.2.4 Seamount Vercelli

During the geological and geophysical expedition of the R/V Vityaz in the Thyrrenian Sea (August 1984) a large sample of fresh intrusive rock was recovered from the top of Vercelli seamount (Fig. 2). On the basis of K/Ar method the intrusive rock have an age of 7.2 Ma (Barbieri *et al.*, 1986) quite similar to Elba and Montecristo. The rock has a syenogranite composition (Fig. 3) and a mineral assemblage consisting of plagioclase, quartz, perthitic K-feldspar, and biotite plus accessory amounts of tourmaline, apatite, zircon and monazite. The rock resemble, hence, the leucocratic facies of the Tuscan archipelago pluton (Fig. 4). $^{87}Sr/^{86}Sr$ data points to 0.71140, that is at the lower end of the Sr isotopic composition of the TMP plutonic rocks. It is to note, however, that only a single rock sample has been analyzed and therefore cannot be representative of the petrographic and geochemical variation that occur throughout the granitic intrusion. It is noteworthy that several buried granitoids have been interpreted on the basis of seismic reflection studies. They should occur along a ridge south of Elba and Montecristo islands (Fig. 2).

6.3 REGIONAL CONSIDERATIONS

It is worth noting that, from west to east: the Tuscan Archipelago granites intruded the ophiolite-bearing Ligurian nappe, the highest in the Apennine pile; the Tuscan coastal granites intruded the Tuscan nappe, structurally located below the Ligurian nappe; the innermost borehole granites intruded the deepest Palaeozoic Basement. That is, from west to east, progressively younger granites intruded units that are progressively structurally deeper, although emplacement depth did not vary significantly. As yet reported for Elba magmatic system, such a behaviour cannot be explained by neutral buoyancy, and a delicate linkage between magma driving pressure, extensional tectonics and availability of structural traps has to be hypothesized. Activation of exploitable magma traps by migration, in space and time, of extensional tectonics, seems to be a process mainly controlled by depth.