Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Anatomy of Granite Intrusions in the Travale Geothermal Field (Italy): a First Geochemical-Petrographic-spectral Gamma Ray Log Approach

Rebecca Spinelli[1], Michele Casini[1], Nicola Costantino[1], Geoffrey Giudetti[1], Simonetta Ciuffi[1] and Andrea Dini[2]

1. Enel Green Power, via Andrea Pisano, 120, 56122 Pisa (Italy)
2. Istituto di Geoscienze e Georisorse – CNR, Via Moruzzi 1, 56124 Pisa, Italy

michele.casini@enel.com

Keywords: Granite, Travale, geothermal field, geophysical logs, Spectral Gamma ray log, Th-U minerals

ABSTRACT

Since the 80's, the exploration in the eastern portion of Larderello - Travale geothermal field (southern Tuscany, Italy) has been targeted to depths of 3000-4000 m b.s.l., where the first deep drillings discovered a superheated steam reservoir (temperatures of 300-350°C).

The deep reservoir is hosted within, such as metamorphic and/or intrusive formations. The best productivity seems to be linked to deep fractured levels related directly or indirectly, to the emplacement of granitic bodies.

Most of the deep wells drilled in the eastern portion of the geothermal field reached deep Pliocenic granites finding different characteristics and ages. Granitic bodies permeability is still under investigation.

A long term activity, aimed at the geological/petrophysical/geophysical characterization of these granite bodies has been planned. Core samples analyses (both petrographic and chemical), geophysical logs, seismic and well testing data will be integrated in order to identify a possible correlation with steam production and to provide an update of the geothermal conceptual model.

In this work the first results of this activity are presented. New data regarding chemistry and petrological description are tentatively correlated to spectralog response on 18 wells from Travale area. Mineralogical and chemical data point out to the presence of four different granitic facies which are also autonomously identified by spectra log analyses on the basis of U, Th and K measurement.

Since coring is an high costly and risky operation and most of the drilling is done under total loss of circulation geophysical log shows an optimum capability as a continuous stratigraphic tool to identify different granitic bodies in Travale area and possibly, using geospatial modeling software tool, reconstruct their geometry.

1. INTRODUCTION

Exploration activity and scientific investigation of the Larderello-Travale geothermal field (Tuscany, Italy), indicate that the deeper part of the system (below ca. 2500-4000 m) is constituted by a plutonic complex built up incrementally (between 3.8 and 1.3 Ma) by progressive stacking of several different granite magma batches (Dini et al., 2005; Bertini et al., 2006; Casini et al., 2008). Cooling models for these intrusions imply thermal equilibration with the ambient crust within ca. 10-100 ka, indicating that they cannot be responsible for the active geothermal system. The present day geothermal system and potential supercritical reservoirs detected by geophysics at depth (the so-called K-horizon at 5-6 km depth; e.g., Batini et al., 2003; Bertini et al., 2006) must be related to the emplacement of very recent granite magmas at shallow depth. Currently exploited superheated steam reservoirs are hosted by both granites and their contact metamorphic aureoles. Reservoir productivity is linked to fractured and permeable levels that are rather confined and mostly scattered.

Although most of the geothermal wells have reached the intrusive bodies in total loss of circulation (TLC), a detailed 3D reconstruction of the top of the granite intrusion was reconstructed by means of 3D and 2D reflection seismic prospection, well logs and through the observation of cutting from the wells drilled with return of circulation. Moreover, in spite of the high cost, some granite cores were collected throughout the entire geothermal field. On the basis of petrographic, geochemical and isotopic investigation of few core samples, Dini et al. (2005) provided a preliminary classification of Larderello-Travale buried granites. Major and trace element patterns coupled with isotopic data suggest that in the root zone of the Larderello geothermal field (ca. 20 km depth), P–T conditions for crustal melting were intermittently reached, and low fractions of heterogeneous crustal melts were locally produced and sequentially transferred/emplaced (between 3.8 and 1.3 Ma) at shallow levels (4-6 km depth).

Multiple emplacement of geochemically distinct magma batches characterize also the older granite complexes of the Tuscan Magmatic Province, like those cropping out in Elba Island (8.4-5.9 Ma; Dini et al 2002) and in Campiglia Marittima. In the case of multi-pulse magmatic complexes, several contact metamorphic and hydrothermal effects can overlap through time on a relatively small crustal portion (e.g. Dini et al., 2005). The net result of the described complex evolution is a continuously renewed magmatic system, where exsolution of magmatic fluid, heat flow and triggering of meteoric fluid circuits follow cyclically transient patterns with strong implication on geothermal field lifespan.

Understanding the "anatomy" of such a complex intrusive systems has strong impact on both scientific and industrial sides. In fact, deciphering the story of granite complexes provide crucial knowledge of generation, segregation, transfer and emplacement of granite magmas within the continental crust: i.e. all the distinct stages of crustal recycling/growth, a fundamental process that involves mass and heat transfer from lower-middle crust (and mantle) to the upper crust/surface. On the other hand, defining

physical discontinuities inside the Larderello-Travale granite intrusions (contacts between multiple intrusive units; differentiation boundaries; late magmatic/hydrothermal veins; contractional fractures developed during cooling; etc.) provides pivotal clues for defining 3D geometry of permeability zones in productive reservoir/recharge zones, as well as for inferring potentially productive horizons in new areas/depths of the geothermal field.

Considering the large area (ca. 400 km2) and the high costs and risk for recovering cores we tested the possibility to unravel internal units and structures of Larderello-Travale granite intrusions by application of Spectralog analyses (40K; 232Th, 238U) in parallel with a petrographic, mineralogical and geochemical study of granites samples. Geochemical comparison and characterization of U and Th mineral carriers were performed on few selected wells where Spectralogs, cuttings and cores of granites were available. Then, the calibrated sections were used for comparing other granite intersections drilled and sampled during the last decade

Petrographic-mineralogical (SEM-EDS) and geochemical analysis (major and trace elements) have been performed on seventeen new core samples and three cuttings samples from sixteen different wells. Thanks to the larger dataset, the classification of Larderello-Travale granites proposed by Dini el al. (2005) was significantly improved.

Petrographic and chemical analysis (major and trace elements) have been performed on new seventeen core samples and three cuttings samples in sixteen different wells in Travale area. Spectralog data are available on the same wells. In this work the first result of data crossing are described.

2. GEOLOGY OF THE GEOTHERMAL AREA

The Travale geothermal field is the southern east portion of the main Larderello-Travale geothermal system, in Southern Tuscany (Figure 1), The geological and structural characteristics of the Travale area (Bertini et al., 2009) result from the tectonic evolution of the Northern Apennine chain.

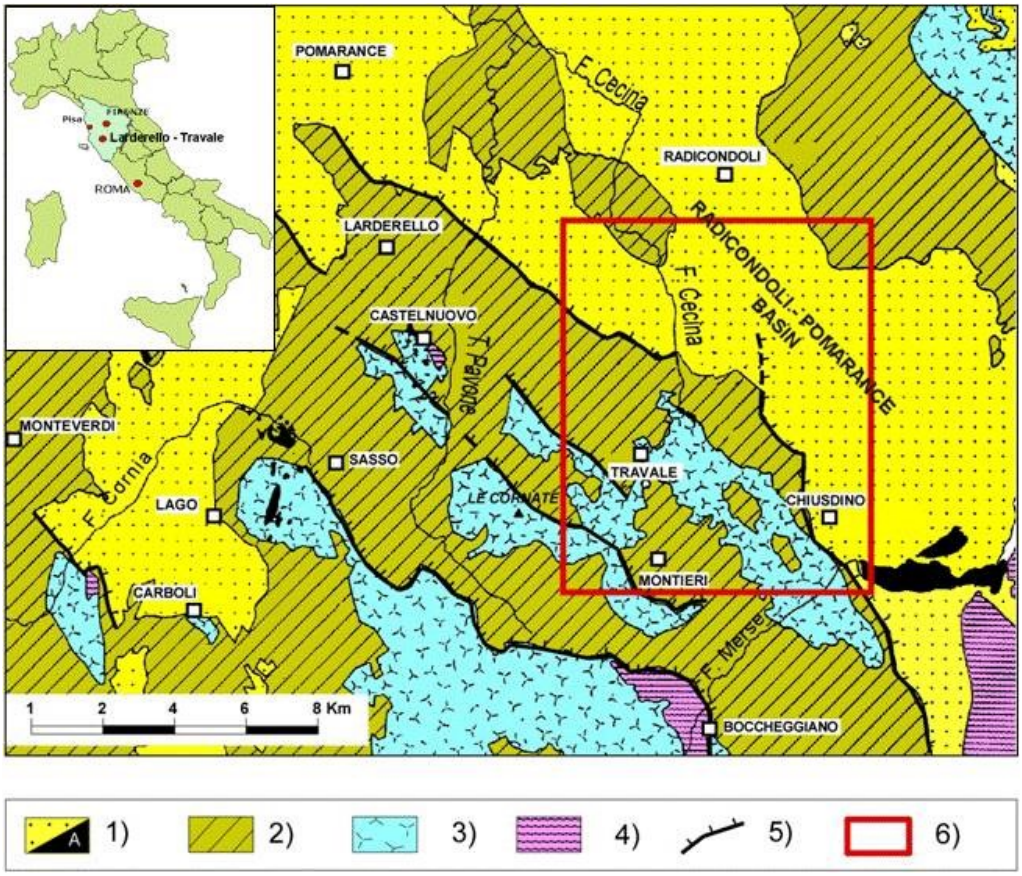

Figure 1: Location of the Travale field and schematic geological map of the Larderello-Travale area. 1) Neogenic Sediments (A=Hydrothermal deposits); 2) Flysch facies Formations of the Ligurian Unit (Lower Cretaceous - Eocene); 3) Sandstones and Limestones of the Tuscan Nappe (Upper Trias - Lower Miocene); 4) Metamorphic Basement (Palaeozoic); 5) Normal fault; 6) Travale study area (From Casini et al. 2008).

The structural setting of the Travale site involves, from top to bottom, the following geological sequence:

a) Neogene marine and continental sediments deposed in the structural depressions due to the Upper Miocene extensional phase

b) Ligurian Unit - flysch facies formation, composed of remnants of Jurassic oceanic crust and its related Jurassic–Cretaceous cover

c) Tuscan Nappe - sandstones and limestones (U. Trias – L. Miocene)

d) Tectonic Wedge - anhydrites, quartzites and phyllites (L. Permian – U. Trias)

e) Metamorphic Basement - phyllites and micaschistes (L. Palaeozoic)

f) Contact metamorphic rocks (skarn and hornfels) in the lower part of the basement can represent the aureole of the underlying granitic intrusions.

g) Quaternary pliocenic granites deriving from mixing of crustal and mantle sources (Serri et al., 1993).

3. PETROGRAPHY

3.1 Lithological Log and petrographic analysis

Lithological log of about 60 meters of granite cores (from 20 wells intercepting granite at depth) and petrographic analysis of 250 thin sections allowed us to improve the characterization introduced by Dini et al. (2005). Travale granites display significant textural and mineralogical variation easily recognizable in the hand specimen and under the microscope. They can be classified in 4 petrofacies that were named on the base of their Th/U ratio (Figure 2 and Figure 2Figure 3; see next chapters on geochemistry and spectral gamma ray):

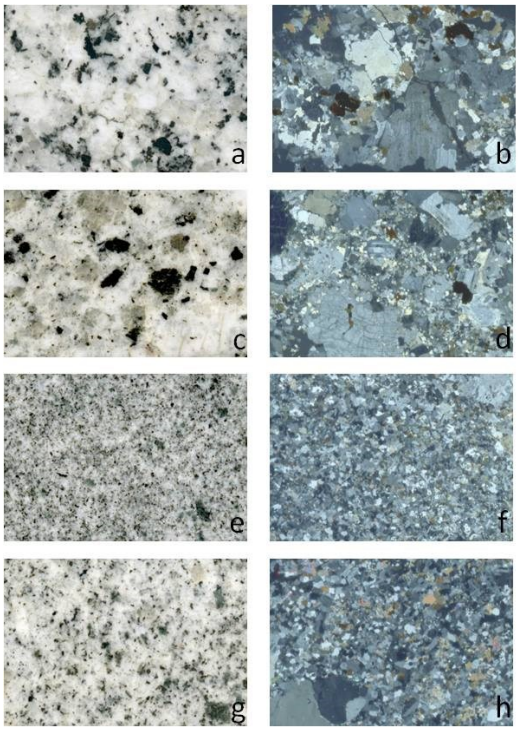

Figure 2: Travale granite samples: a), b) petrofacies A, c), d) petrofacies C1, e), f) petrofacies C2 and g), h) petrofacies B. a) c) e) g) polish surface scanned (image size 45x30mm); b) d) f) h) microphotograph on thin section (cross polarized image size 22x15mm).

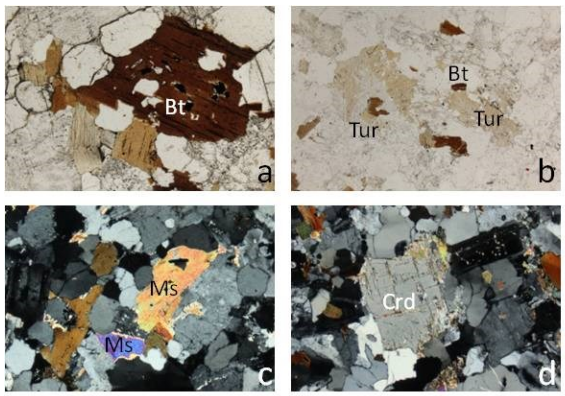

Figure 3: Thin sections photograph of travale granite showing mineralogical primary parageneisis: Bt, Tur, Ms and Crd. Qz, Kfs and Pl are widespread. a), b) and c) are from facies B, while d) is facies C2 granite (a and b plain polarized, c and d cross polarized images - size 3x2mm).

Petrofacies A:

K-feldspar megacryst-rich coarse grained monzogranite, with ipidiomorphic, inequigranular texture. Plagioclase, quartz, biotite and cordierite occur as large subhedral crystals; muscovite has not been observed. Tourmaline frequently occurs as interstitial aggregates. Ilmenite is ubiquitous, especially hosted by biotite.

Petrofacies C1:

Medium grained porphiric monzogranite, with large plagioclase, K-feldspar, quartz, biotite and cordierite phenocrysts set in a fine-grained quartz-feldspar matrix. Rare muscovite has been observed. Tourmaline occurs as interstitial aggregates and small rounded spots. Ilmenite is ubiquitous, especially hosted by biotite.

Petrofacies C2:

Microgranitic monzogranite, ranging from fine-grained, equigranular, with rare K-feldspar, quartz, plagioclase, biotite and cordierite phenocrysts up to fine-medium-grained, inequigranular. The microgranular matrix is made up by the same mineral assemblage associated with muscovite. Tourmaline occurs as interstitial aggregates and local concentrations of small rounded spots. Ilmenite is ubiquitous, especially hosted by biotite.

Petrofacies B:

Medium grained monzo-syenogranites, with ipidiomorphic texture, poorly inequigranular, with quartz, sodic plagioclase, K-feldspar, biotite, cordierite and abundant muscovite. Tourmaline is locally abundant as interstitial grains and rounded spots. Ilmenite is ubiquitous, especially hosted by biotite.

3.2 SEM petrographic analysis of accessory minerals

Eight representative thin sections, two for each petrofacies of Travale granites, were selected from a large set available at the petrographic laboratory of ENEL Green Power (Larderello) for the characterization of Th- U-rich accessory minerals. In order to compare accessory mineral assemblages with geochemical data and spectral gamma ray logs, samples were chosen from well characterized boreholes (cores and geophysical logs). The petrographic and chemical investigation of accessory phases was carried out by SEM with backscattered imaging and EDS. Backscattered imaging and EDS qualitative and semiquantitative analyses were carried out by means of the Philips XL30 equipped with EDAX DX4 housed at Dipartimento di Scienze della Terra, Pisa University (Italy).

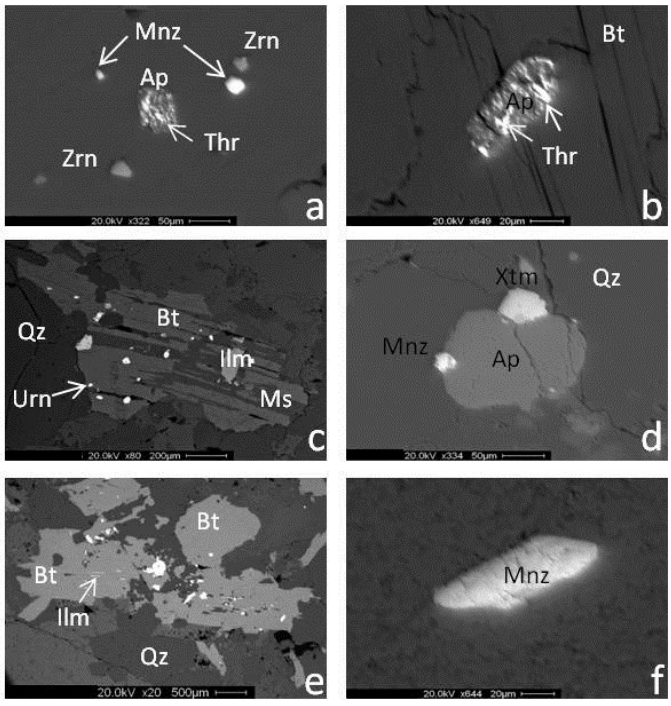

Figure 4: Backscattered SEM image of selected Travale granites. a)and b) show Thr in facies A granite; c) and d) Urn and Xtm as accessories minerals in facies B granite; e) and f) facies C1 mineral paragenesis with Bt, Ilm, Qz and Mnz.

The four petrofacies are characterized by very similar accessory mineral assemblages dominated by ubiquitous apatite and zircon, followed in abundance by monazite-(Ce). These minerals form small euhedral crystals (10–200 μm) preferentially hosted in biotite. Monazite-(Ce) shows a significant content of thorium (several percent) and detectable amount of uranium.

Worth to note is the presence of peculiar Th-U minerals in petrofacies A and B: U-rich thorite is common in petrofacies A, while uraninite, thorite-coffinite solid solution and xenotime-(Y) are ubiquitous only in petrofacies B.

4. GEOCHEMISTRY

Chemical analyses on 20 samples from the Travale granites were performed at the ActLABS facilities, Ancaster (Canada) through ICP emission (major and some trace elements) and ICP-MS for trace elements. Representative analyses for the four petrological facies recognized are reported in Table 1.

Table 1: Selected chemical analyses for Travale granites

sample	SiO2	TiO2	Al2O3	Fe2O3(T)	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	ASI
3	70.61	0.506	14.71	3.59	0.049	0.94	2.2	2.71	4.95	0.17	0.44	1.08
19	75.15	0.232	13.42	2.48	0.045	0.39	0.96	2.72	5.03	0.17	0.4	1.17
15	70.74	0.452	14.84	2.9	0.03	0.72	1.59	3.01	4.65	0.18	0.49	1.17
10	71.84	0.406	14.6	2.91	0.056	0.75	1.44	2.72	4.71	0.19	0.38	1.22

Major elements (%wt)

sample	Sc	Be	V	Cr	Co	Ni	Cu	Zn	Ga	Ge	As	Rb
3	8	6	39	60	6	< 20	< 10	40	20	2	6	280
19	5	10	26	40	3	< 20	< 10	60	21	3	27	426
15	6	7	31	30	4	< 20	< 10	30	23	2.2	< 5	283
10	6	8	36	40	4	< 20	< 10	60	22	2.3	24	378

sample	Sr	Y	Zr	Nb	Mo	Ag	In	Sn	Sb	Cs	Ba
3	159	35.3	248	10.5	2	1.9	< 0.1	4	< 0.2	20.6	510
19	55	22.4	104	10.4	< 2	< 0.5	< 0.1	18	< 0.2	45.2	161
15	147	20.4	195	9.9	< 2	1.3	< 0.1	10	< 0.2	27.3	441
10	98	20.9	175	11.9	< 2	1.3	< 0.1	11	< 0.2	41.8	313

sample	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm
3	125	14.6	52.3	9.58	0.946	7.39	1.09	6.07	1.14	3.31	0.512
19	41.3	5.02	18.7	4.17	0.37	3.11	0.6	3.7	0.73	1.96	0.281
15	85.7	10.2	36.8	7.03	0.808	5.37	0.79	3.9	0.71	1.89	0.271
10	75	8.87	33.9	6.5	0.692	4.47	0.7	3.78	0.69	1.94	0.301

sample	La	Yb	Lu	Hf	Ta	W	Tl	Pb	Bi	Th	U
3	62.5	3.27	0.44	5.7	1.51	4.6	1.75	39	0.2	38.2	7.19
19	19.8	1.88	0.259	2.8	1.83	20.6	1.01	33	0.1	15	29
15	41.4	1.73	0.244	4.4	1.32	2.2	1.4	28	0.3	25	7.65
10	35.6	1.99	0.265	4.5	2.18	3.9	2.3	32	0.2	18.1	14.3

Trace elements (ppm)

Travale granites range in composition from monzogranites, with SiO_2 from 69 to 74 wt.% (petrofacies A, C1 and C2) to monzo-syenogranites (petrofacies B) characterized by a more acidic composition, with SiO_2 between 73% and 79% (Figure 5).

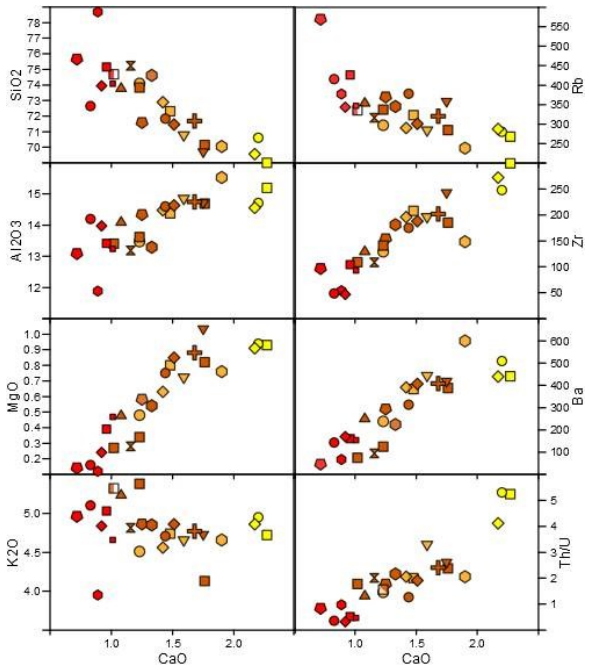

Figure 5 Variation diagrams (Harker's diagram) of SiO2, Al2O3, MgO, K2O (%wt), Ba, Zr, Rb (ppm), Th/U vs CaO (5wt) for Travale granites. Symbols as in figure 3

All the Travale granites are peraluminous with ASI between 1.08 and 1.26. Sr and Nd isotopic data from Dini et al. (2005) indicate they do not belong to a single differentiated igneous intrusion; therefore the distribution patterns in the Harker's diagrams are only

apparent differentiation trends, not related to fractional crystallization processes. Petrofacies A is characterized by the highest CaO, MgO, Fe2O3, Ba. The very high Th/U ratio (>4) is particularly relevant for this study and it is correlated with the observed occurrence of thorite. Petrofacies B displays a reverse geochemical pattern (lowest CaO, MgO, Fe2O3, Ba) coupled with a Th/U < 1 that is coherent with the common presence of U minerals like uraninite and thorite-coffinite solid solution and the ubiquitous occurrence of xenotime-(Y). Finally, major and trace element composition of petrofacies C1 and C2 overlap the general fields of granites from Tuscan Magmatic Province, showing normal Th/U ratios (in the range 1-3).

The chondrite-normalized REE patterns for Travale granites are shown in Figure 6 (normalizing values after McDonough and Sun, 1995). Travale granites exhibit moderate LREE fractionated patterns, comparable with those reported by Dini et al. (2002; 2005) for the Larderello and TMP granites. They can be divided in two main groups on the basis of HREE pattern (Figure 6). A first group (petrofacies A, C1 and C2), shows slightly fractionated HREE pattern (GdN/ YbN=1.59–2.51) and moderate Eu anomaly (Eu/ Eu*=0.40–0.63) matching the patterns of LAR1 and other TMP granites (Dini et al., 2005). A second group (petrofacies B) shows flat HREE patterns (GdN/YbN=0.83–1.36), and deeper Eu anomalies (Eu/ Eu*=0.05–0.21) that overlap the REE patterns of LAR2 type granites described by Dini et al. (2005). The two contrasting patterns can be explained by the dominance of monazite-(Ce) in petrofacies A, C1 and C2, while xenotime-(Y) probably represents the main REE carrier in petrofacies B.

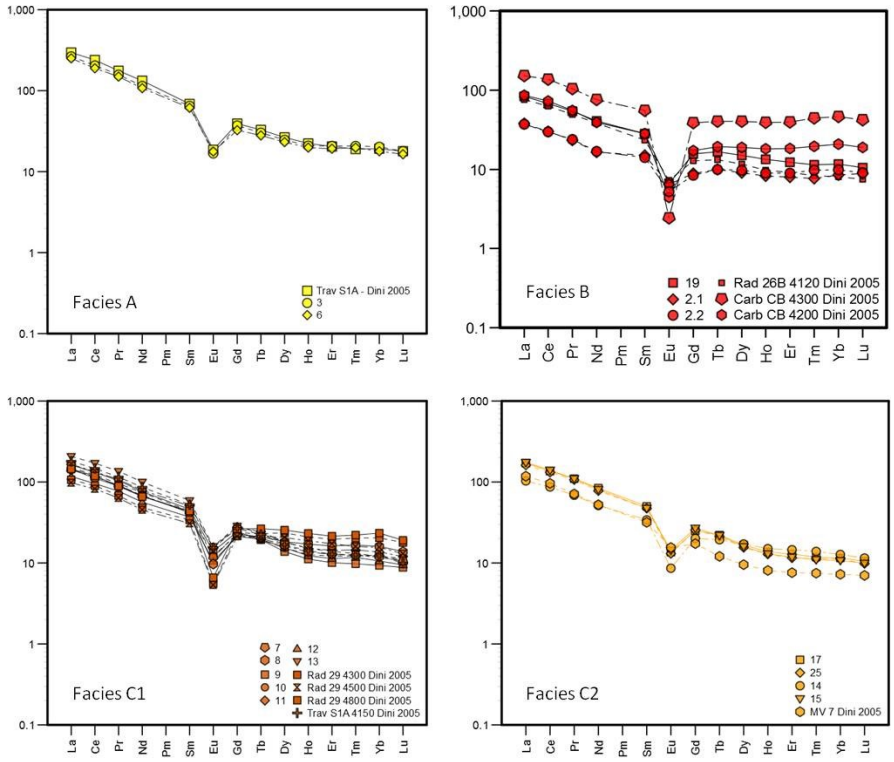

Figure 6: Chondrite normalized REE patterns for Travale granites.

5. SPECTRAL GAMMA RAY LOG ANALYSES (SGR)

The measure of formation natural radioactivity intensity along the wellbore, and that of the major radio-isotopic sources such as Potassium (^{40}K), Uranium (^{238}U) and Thorium (^{232}Th) give an indication on rock type occurrences. Therefore, spectral gamma ray log analysis is a suitable tool for stratigraphic reconstruction.

In the Travale area, the highest radiation levels are associated with igneous rocks, in particular with granites, due to the geochemical behaviour of K, U and Th, which, during the magmatic processes of partial melting and/or fractional crystallization, are concentrated in the liquid phase and incorporated into the related products of solidification.

In the Travale area, considering the wells that have reached the intrusive bodies, SGR has been analyzed in 14 wells, for a total of about 10350 logged meters.

On the basis of Th and U content, three main granite facies have been identified: the Facies A with high Th contents and high Th/U ratios (>4), Facies B (uranium-enriched) with high U contents and low Th/U ratios (<1) and a Facies C, granites characterized by similar U and Th content and with Th/U ratio that ranges from 1 to 4. The K content is the same in all the A, B and C facies and ranges around 5%. In Figure 7 the most representative cases for the three granite facies are shown.

For the wells in which both SGR and chemical analysis on core/cuttings are available, the cross-plots U vs Th, have been compared with U and Th content determined by chemical analysis.

The cross-plots show that the three different facies fall in distinct and characteristic areas of the diagrams, as evidenced in the most representative cases: A Facies well30 in Figure 8a), B Facies well 2 in Figure 8b) and C Facies well 17 in Figure 8c). For all wells, the cumulative cross-plots U vs Th are shown in Figure 8d).

The three granite facies distinguished by SGR are strongly correlated with different granite petrofacies distinguished by the petrographic observation and chemical analyses.

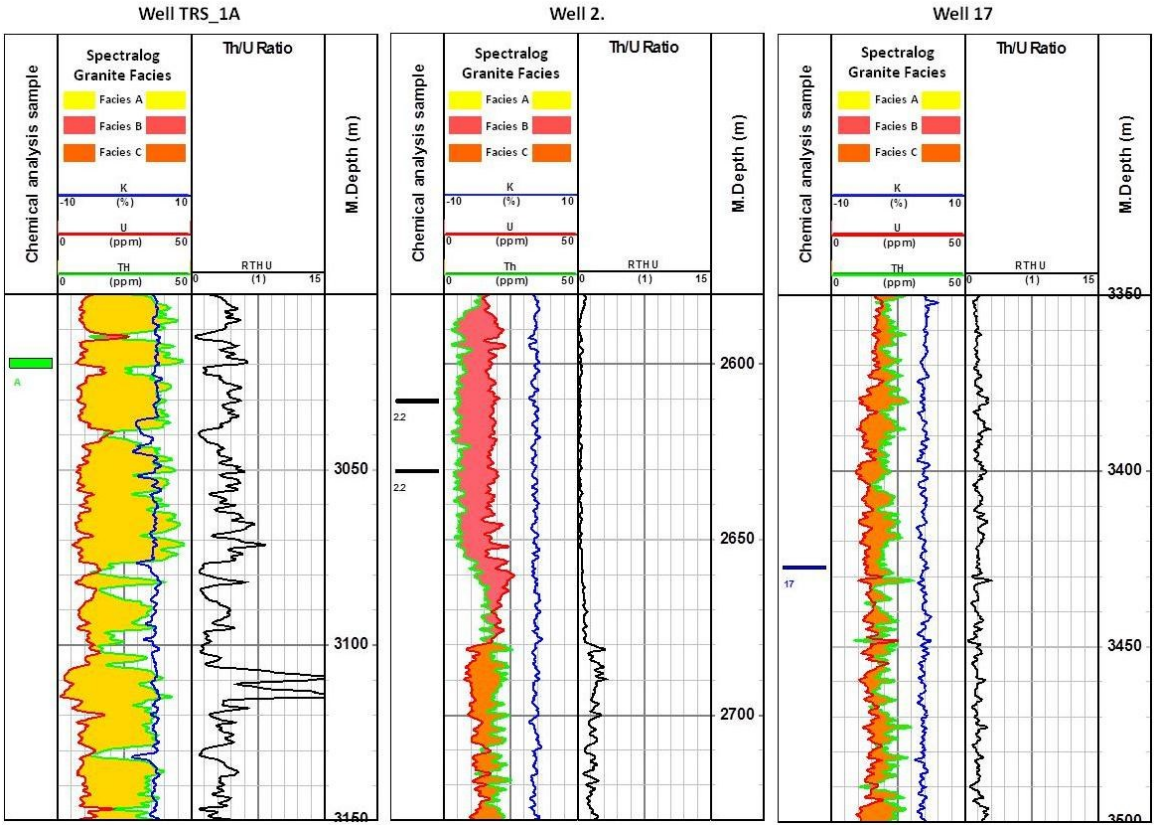

Figure 7: Display of actual SGR logs for A, B , and C granite facies, as from the TRS_1A, 2 and 17 wells. Yellow fill is for the A facies, red fill is for the B facies and orange fill is used for the C facies.

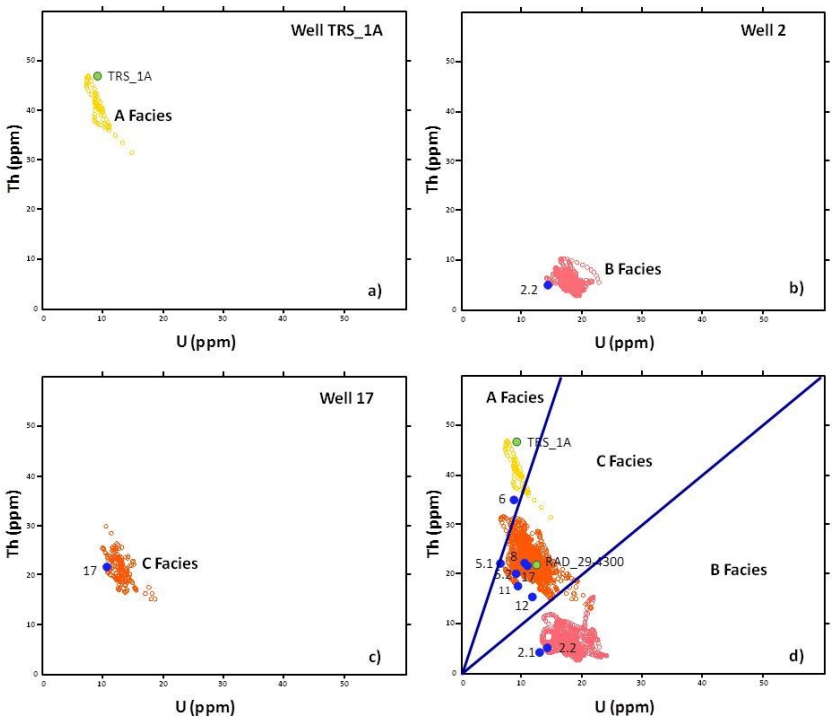

Figure 8: Cross-plots U vs Th for the tree different granite Facies. In a), b), c) separate single cases (TRS_1A, 2 and 17 Well respectively), d) is the cumulated diagram for all wells. Empty circles are the Th and U data from SGR, while blue dots are the Th end U content obtained from new chemical analyses; green dots are Th and U content obtained from chemical analyses already published in Dini et al., 2005..

6 DISCUSSION AND CONCLUSIONS

In Figure 9 the cumulative cross-plots U vs Th from SGR is compared with U and Th content determined by chemical analysis in all samples.

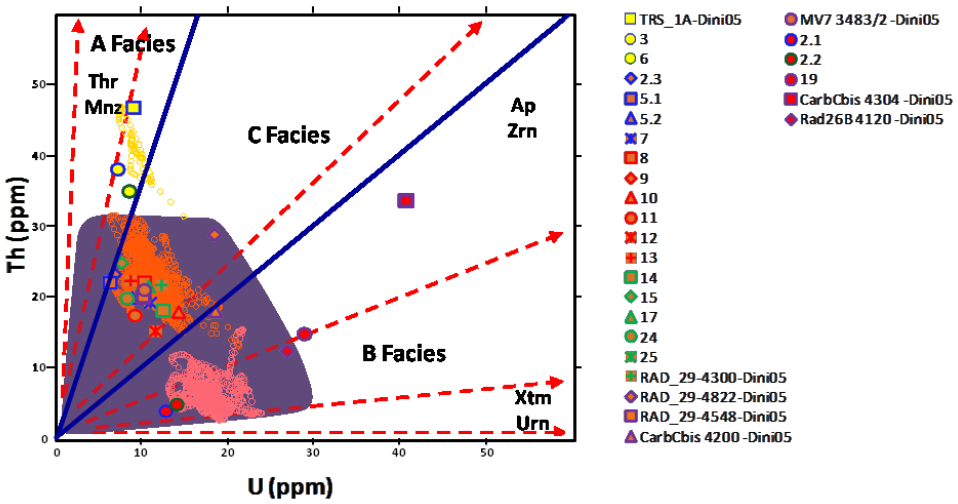

Figure 9: The cumulative cross-plot U vs Th from SGR is compared with U and Th content derived from chemical analysis for all samples available. The grey area highlight the Th U content of the granites from TMP .

The A Facies corresponds to K-feldspar megacryst-rich coarse-grained monzogranite, in which the high Th content and Th/U ratio is controlled by the common occurrence of thorite and monazite-(Ce).

The B Facies includes the most silicic, medium-grained, monzo-syenogranites The characteristic high U enrichment (very low Th/U ratio) is mainly due to the presence of uraninite and thorite–coffinite solid solution coupled with the ubiquitous occurrence of xenotime-(Y).

The C facies includes two textural types (C1: porphyritic; C2: microgranitic) showing monzogranitic composition. The Th and U content is comparable with the values already measured in other granites from the TMP.

A preliminary spatial distribution of the three facies is proposed in Figure 10, in which the complexity of the geometric relationships between the different facies is evident. The Facies C is the most widespread and is found in almost all the wells. Facies A is recognized in wells n° 3, 30, 31 and 6 with thicknesses ranging from 50 to 600m, mainly in the south-west area. Facies B is found in wells n° 11, 12, 30, 32 and 33, with thicknesses up to 250m, but without a preferential spatial distribution.

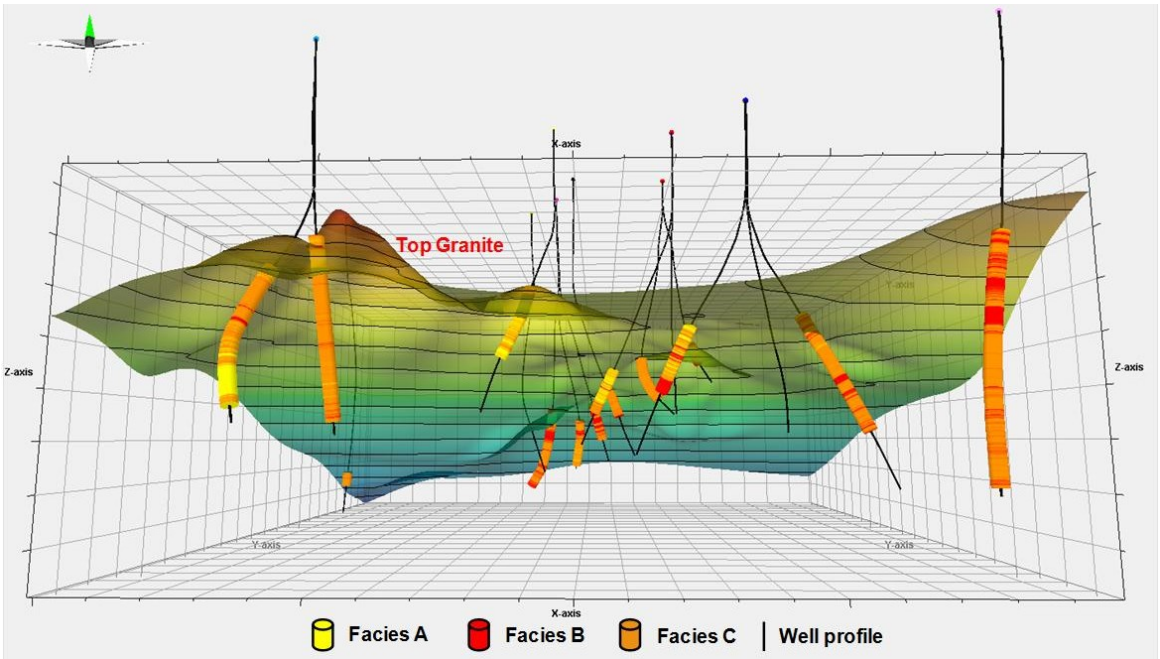

Figure 10: Granite facies spatial distribution. The color code is based on the Th/U ratio from SGR as in figure 9. The contoured surface represents the top of the granite complex, as reconstructed by means of 3D and 2D reflection seismic prospections and geophysical logs.

The result of this integrated study shows that the SGR is a valuable tool for the identification of the different granite types and permits, once calibrated, to discriminate also geochemical and mineralogical variations.

This study is preparatory to a long term activity, aimed to the geological/petrophysical/geophysical characterization of these granite bodies. Deciphering of the architecture of the Larderello-Travale intrusive complex could provide a crucial information to develop correlations between different granite types and hopefully permeability, that will potentially allow to set a basis for future development of the granite reservoir and the reduction of the mining risk.

REFERENCES

Barelli, A., Cappetti, G. and Stefani, G.:. Results of deep drilling in the Larderello-Travale/Radicondoli geothermal area. In: *Proceedings of the Geothermal Congress 1995, 18–31 May, Florence, Italy* (E. Barbier, ed.), (1995) pp. 1275–1278. Published by IGA, Rome

Batini, F., Brogi, A., Lazzarotto, A., Liotta, D., Pandeli, E.: Geological features of the Larderello-Travale and Mt. Amiata geothermal areas (southern Tuscany, Italy). *Episodes,* (2003) **26**, 239–244.

Bertini G., Casini M., Gianelli G., Pandeli E.: Geological structure of a long-living geothermal system, Larderello, Italy. *Terra Nova*, **Vol 18**, (2006), No. 3, 163–169

Brogi A., Lazzarotto A., Liotta D., Ranalli G.: Extensional shear zones as imaged by reflection seismic lines: the Larderello geothermal field (central Italy). *Tectonophysics **363*** (2003), 127– 139.

Casini, M., Ciuffi S., Fiordelisi A., Mazzotti A., and Stucchi E.: Results of a 3D seismic survey at the Travale (Italy) test site, *Geothermics*, **39**, (2008), 4-12.

Dini A., Innocenti F., Rocchi S., Tonarini S. and Westerman D. S.: The magmatic evolution of the late Miocene laccolith–pluton–dyke granitic complex of Elba Island, Italy. *Geol. Mag.* **139** (2002), , 257-279

Dini, A., Gianelli G., Puxeddu M., Ruggieri G.: Origin and evolution of Pliocene-Pleistocene granites from the Larderello geothermal field (Tuscan Magmatic Province, Italy). *Lithos* **81**, (2005) 1 – 31.

Marinelli, G.: Genèse des magmas du volcanisme Plio-Quaternaire des Apennines. *Geol. Rundsch*. **57**, (1967) 127.– 141.

Peccerillo, A.: Multiple mantle metasomatism in centralsouthern Italy: geochemical effects, timing and geodynamic implications. *Geology* **27** (1999), 315–318.

Serri, G., Innocenti, F., Manetti, P.: Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism in central Italy. *Tectonophysics* **223**, (1993) 117 – 147.