THE LARDERELLO PLUTONO-METAMORPHIC CORE COMPLEX: PETROGRAPHIC DATA

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INTRODUCTION

Terranes which have suffered LP-HT metamorphism (De Yoreo et al., 1991 for explication about Low Pressure Metamorphism) are of great interest because they can be related to extensional lithospheric processes (Thompson and Ridley, 1987; Wickham and Oxburgh, 1985,1987) accompanied to magmatic heat advection (De Yoreo et al., 1989; Barton and Hanson, 1989; Jones and Brown, 1990; Haugered and Zen, 1991; D'Lemos et al., 1992). The extensional processes may, for example, be expressed by low-angle normal shear zones (detachments). This type of structures has been widely described, particularly in continental domains which have undergone an earlier orogeny (Wernicke, 1981, 1982; Davis, 1983). The magmatic product often associated to extensional tectonic is due to the partial melting of crustal rocks; the felsic magma rises to the crust and emplaces in high crustal level (Soula, 1982; Castro, 1987). Some field examples of this association have been described from the continental collision in the Variscan belt, especially in the Massif Central area and in the axial zone **of** the Pyrenees (i.e. Saint Blanquat et al., 1990), from high temperature part of paired metamorphic belts related to subduction in the Aegean Sea (Jansen et al., 1976; Lister et al., 1984; Avigad et al., 1991) and Western United States (Cordillera-type LPM; Barton et al, 1988).

In the Larderello-Travalearea, previous studies have show (a) the presence of a LP-HT metamorphism associated with migmatization and young granitoid rocks (b) the frequent superposition of mylonitic textures over magmatic and metamorphic assemblages. The core of metamorphic and magmatic rocks have been named Larderello Plutono-metamorphic Core Complex by Franceschini (1994a).

In this paper I present the result of a petrographic study which complete and confirms data already obtained by Franceschini (1993a, 1993b, 1994a, 1994b, 1994c).

Arguments based on petrology and bibliography for the high temperature metamorphism associated with crustal extension are presented. The age and significance of the crustal extension and magmatic advection are discussed taking into consideration the regional geological framework.

GEOLOGICAL SETTING

The present outcropping structure of the Apennines belt is the result of a strong shortening due to the compressive phase, Miocene in age, which developed overthrusts in both the Paleozoic basement and its sedimentary cover. Main flats in the cover were localized in the Triassic evaporites. In the denudation zone the Ligurian units replaced the detached Tuscan formation.

Starting from Messinian, an extensional tectonic phase took place after the compression accompanied by opening of Neogenic sedimentary basins. These basins were controlled by two faulting systems with orthogonal direction: Apenninic (NW-SE, turning N-S) and antiapenninic (SW-NE, turning W-E).

The igneous activity of the northern Apennine, associated with this extensional tectonic, comprises the 'Provincia Magmatica Toscana' (PMT) and the 'Provincia Magmatica Romana' (Serri et al., 1992). The igneous activity, took place in four phases, progressively younger from west to east.

THE BASEMENT OF SOUTHERN TUSCANY

The studies of the basement in the Southern Tuscany, caused of small and discontinuous outcrops (fig. 1), were developed when more and more depth geothermal drillings affected the buried crystalline basement (Puxeddu et al., 1977; Puxeddu, 1984; Batini et al., 1978, 1985; Elter e Pandeli, 1990; Franceschini, 1994a, b).

Due to the scarcity of extensive outcrops of the crystalline substratum up today the behaviour of the depth structure of the chain has been difficult to understand for what concerning the Apennine orogenic effects and the post-orogenic tectonic delamination. Some new important data about the depth structure of the chain may be inferred by the study of cuttings collected in the geothermal exploration and producing wells inside the "Boracifera" area of Larderello-Travale, Obviously, due to the lack of sampling and the nature self of the samples, the structural analyses **is** really difficult. The depth of investigation of these wells (more than 2500 meters) and the extension of the investigated area (~500 km^2) suggest the importance of carried out the petrographic study of these samples.

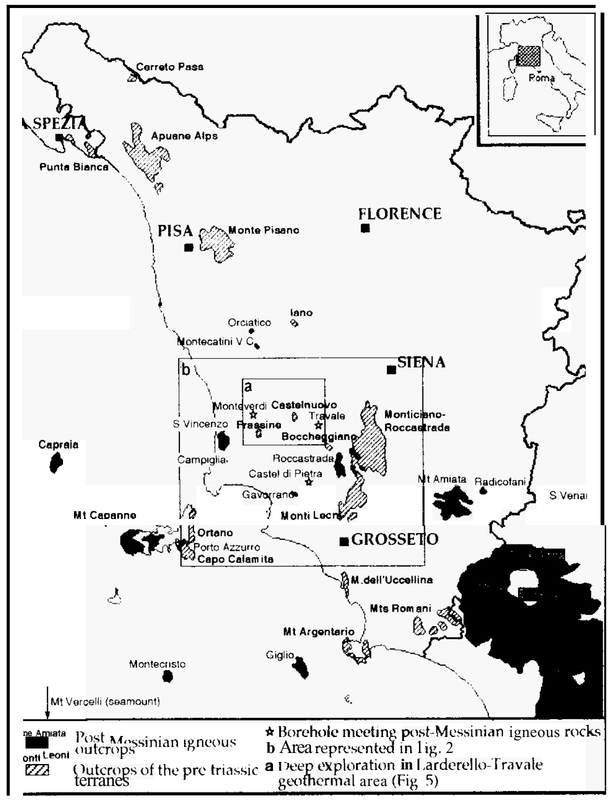
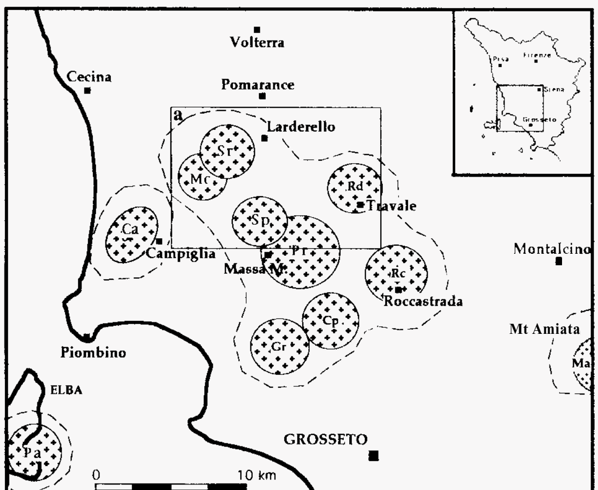


Fig. 1 - Distribution of post-orogenic igneous rocks and basement outcrops in continental and insular Tuscany. In the area interesting to deep drilling and in Campiglia and Capo Calamita areas this magmatism is associated with LP metamorphism (see Fig. 2).

The previous studies interpreted the basement below all of Tuscany consisting of Palaeozoic and Precambrian metamorphic rocks and of Hercynian granite comparable to that of Sardinia (**Del Moro** et al., 1982; Puxeddu, 1984). More recently, based on some structural data, the probable connection between the Larderello depth sequence and the basement of **NE** Sardinia was re-proposed by several authors (Gianelli et al., 1988; Elter and Pandeli, 1990; Pandeli et al., 1992). Franceschini, (1994a,b,c), based on radiometric data on some geothermal wells (Del **Moro** et al., 1982; Batini et al., 1985), petrographic studies of about 15 deep geothermal wells (total depth greater than 3000 m), and geophysical data interpreted the metamorphic effects observed in the deep rocks of Larderello-Travale as plio-quaternary thermometamorphic events on Paleozoic(?) polymetamorphic micaschists (Almandine-amphibolite facies). The thermometamorphic events are found in a domal structure, named Larderello Plutono-Metamorphic Core Complex (LPMC), which is the result of several intrusive upraises of post-Miocene anatectic plutons coupled with extensional tectonics (Fig.2). Large heat flow anomalies occur in the Larderello geothermal area. The estimates of heat flow in the Tyrrhenian Tuscany (Mongelli & Zito, 1991) show values around 4 HFU with a max. of 15 HFU in the Larderello area and 25 in the volcanic areas of the northern Latium. Modern day continental heat flow values in excess of 2.75 HFU (1 HFU = 41.8 mW/m^2) occur only locally and are generally confined to regions of extension such as Basin and Range province in USA (Lachembruch and Sass, 1987), island arc terranes (Sclater et al., 1980), and continental collision zones marked by rapid uplift and erosion such as the Taiwan fold and Thrust belt (Barr and Dahlen, 1989). Each of these settings involves large components of advective heat transfer, either via rising magmas or solid crust (De Yoreo et al., 1991). Therefore, in the Larderello-Travale area, the relationship oh high heat flow with recent volcanic activity (and the presents of shallow magmatic bodies) is very clear.

The LPMC contains (from bottom to top; *see* Fig. 3) (a) a indefinite (crossed only for small hundred of meters) thick of para- and orthogneissose formation metamorphosed in high grade and cordierite amphibolitic LPM faces (b) from 1 to 2 km thick of micaschist characterised, in the bottom part, by metamorphic LPM assemblage (cordierite-andalusite amphibolitic facies) developed progressively above the previous foliation. Available radiometric data suggest a recent age for the low pressure metamorphism in the Larderello-Travalearea. The LPMC is cover by (c) a great thickness of Triassic-Upper Palaeozoic terrigenous formations consisting of quartzitic and phyllitic alternances, complicated by tectonic repetitions of series ("Tectonic Wedges"; Pandeli et al., 1991) (d) a very variable thickness of dolomitic-anhydritic formation of Noric age ("Burano Formation" that in outcrop is named "Calcare Cavernoso") (e) the previous formation can be overlain by (1) a succession ("Falda Toscana") consisting essentially of Mesozoic carbonate ("Calcare Massiccio" and "Calcare Selcifero Formations"), Cretaceous-Paleocenic slate ("Scaglia Formation") and an Oligocene arenaceous series ("Macigno Formation") *(2)* by only the Oligocene arenaceous *series;* in this case the overlain is of tectonic nature. A variable thick of allochthonous flysch (Ligurian Nappes of Cretaceous-Eoceneage) cover tectonically the previous terranes. Neogene clastic formation (Messinian-Pliocene) represent the post-orogenic deposition welding the orogenic structure.



Plutons name	1	2	3	4	5
Gavorrano(Gr)	●	●	●	●	4.3
Radicondoli(Rd)			●	●	?
Porto Azzurro (Pa)	●	●		●	5
Serrazzano(Sr)				●	~4
Mt Canneto (Mc)				●	3.8
Campiglia(Ca)	●	●	●	●	4.5
S. Pompeo (Sp)			●	●	1.5
Prata (Pr)		●		●	3
Roccastrada(Rc)		●			2.5
Castel di Pietra (Cp)		●	●	●	4.1
Mt Amiata (Ma)		●	●	●	1

Plutons (the areal extension is approssimate, being inferred from drilling data)

Extension of thermometamorphic halo (LP metamorphism)

a Area of deep exploration in Larderello-Travale geothermal area (Area in Fig. 5a, b and c).

1) Outcropping; 2) Depth <1000 mt; 3) Geophysical evidences; 4) Petrographic evidence; 5) Age (m.y.).

Fig. 2 - Pliocene and Quaternary deep intrusive igneous activity in Southern Tuscany. The *age* of high level plutonic emplacement ranges between 5 m.y., for Porto Azzurro, and 1 m.y., for Mt Amiata. The K-seismic horizon, which is generally very deep, arises at 3 km below ground level in San Pompeo area where a zone of attenuation of S-waves is present at depths > 8 km (Puxeddu, 1984). Because of its regional extension, the contact metamorphism can be classified of regional extension and interpreted as Low Pressure Metamorphism (De Yoreo et al., 1991; Hansen et al., 1989) of Pliocene - Quaternary age. Below the San Pompeo area the metamorphic and plutonic phenomena are still active at present. The Larderello-Travale geothermal field receives a significant thermal contribution from cooling magmas. Older igneous sources of Pliocene-Quaternary *age* provide further thermal imput to sustain present geothermal activity. In depth, over the anatectic zone (between 5 and 15 km), the plutons probably forms a composite batholith.

PETROGRAPHIC DATA

Gneiss metamorphic unit

These rocks are unknown in outcrop all over Northern and Central Apennines and represents the deepest rocks reached by geothermal (Larderello and Travale area) and mining (southern and insular Tuscany) drilling until today. In this metamorphic unit is possible identified several **rocks** representative of some prograde reactions from medium to **high** grade (Fig.3): (a) Andalusite-cordierite paragneiss (b) Cordierite gneiss (c) Migmatitic gneiss. This unit, mineralogicaly and structurally reconstructed during the magmatic intrusive phenomena, represent the "core" of the LPMC which geometry is reported in Fig. *5.*

Cordierite muscovite -free gneiss (Gc)

Particulars data

The primary assemblage in the cordierite gneiss, that represent the deeper rocks till now meeting in the drilling, is characterized by the occurrence of cordierite, the abundance of k-feldspar with pecilitic fibrolite, and absence of muscovite; in the gneiss of the Travale basement the sillimanite is prismatic. The rocks, coarse and mica-poor, are characterize by a texture of more or less equidimensional, straight sides (polygonal) grains for feldspars; where the biotite is more abundant is present a weakly foliation (S_g) that is the one foliation observed in these rocks and can be interpreted as due to the rise of the plutons in a delamination regime. The biotite, fibrolite and magnetite represent the only one femic minerals. There isn't trace of a previous sedimentary or metamorphic texture. The compositional layering, constituted to biotite-rich and leucocratic millimetric beds, is interpreted as metamorphic differentiated that in some cases can degenerate in a migmatitic facies. The nature of protolite of these gneissic **rocks** is pelitic also if some samples (Biotite-amphibole gneiss) shows a igneous parentage.

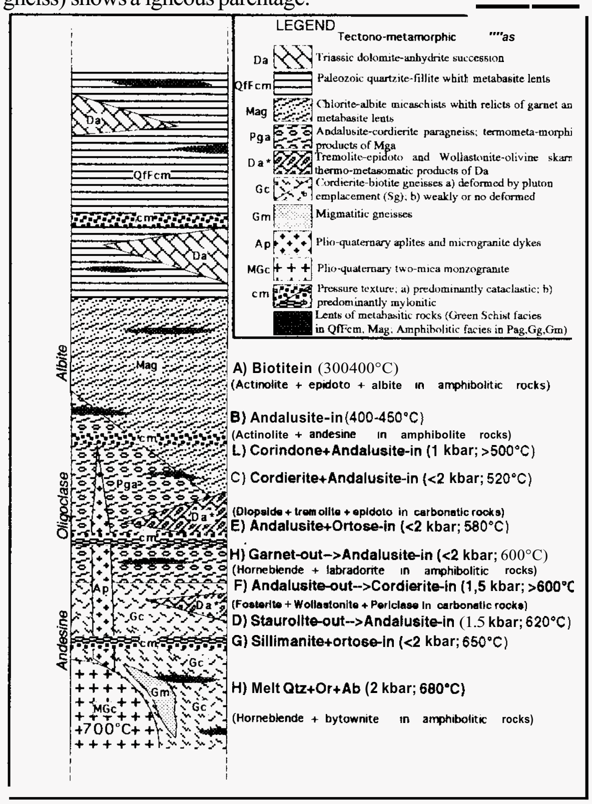


Fig. 3 - Tectono-metamorphic succession reconstructed after the study of more that 15 deep geothermal wells.

Assemblage

The most common assemblage is quartz-plagioclase (An_{35-40})-K feldspar-fibrolitic sillimanite-biotite-cordierite. The XMg of cordierite is in range 0.40 (**SA** 3671 mt)-0.50. Small isolated andalusite grains which are surrounded by cordierite are optically continuos with nearby grains, showing that they were once part of a larger **grains.** Frequently porphyroblasts of andalusite are surrounded by a prograde cordierite and never by sillimanite. These evidence indicate that in these **rocks** cordierite grew via the following reaction:

biotite + andalusite + quartz = cordierite + K-feldspar + H2O (1)

The muscovite is entirely consumed at reaction **8,** leaving the assemblage **Qtz** + Cdr + K-feld + Sill + Bt and the distinctive

fibrolitic pekiloblastesis in the K-feldspar.
Near the microgranite dikes in the Monteverdi area is present corundum and rare green spinel growing on andalusite and associated with biotite and K-feldspar. The white mica occumng in corundum-bearing rocks is usually ***secondary*** but in some instances corundum coexisting with a white mica interpreted to be primary. In muscovite-absent specimens the corundum is associated with andalusite and biotite. Therefore the inferred reactions that introduces corundum is:

muscovite = k-feldspar + corundum + H_2O (2)

biotite + andalusite = cordierite + corundum + ***k-feldspar*** + H_2O (3)

Corundum associated with biotite is also present in the thermometamorphic micaschist in the Travale wells. Further Occurrence of corundum and green spinel are sparsely developed close to less deep supposed igneous contacts.

Ultrametamorphism phenomena: migmatitic gneiss (Gm)

The aplitic melt observed in the VC/11 well (Serrazzano area) is interpreted as a product of migmatization phenomena (Franceschini, 1993a). The assemblage of this leucosome is quartz-plagioclase (An_{21-24})-**perthitic** K **feldspar-fibrolite-cordierite**. The XMg of cordierite is in range 0.28-0.27. The surrounding melanocratic gneiss can be representative of the melanosoma facies. This rock present a rare k-feldspar assemblage of Crt - abundant Bt - Qtz - Pl which texturally and compositionally appears to be restitic residue from the extraction of a melt. In this case quartz-feldspar aggregate don't show granoblastic-polygonal characterize but the 'mosaic' texture is granular and some crystal of the plagioclases possesses a face. The thickness of granulitic-migmatitic gneiss isn't known but I think that this rocks represent the proximal igneous contact facies (Serrazzano pluton).

Resuming the main characteristics in the leucosoma rock are:
(a) absence of biotite; (b) abundance of microperthitic k-feldspar; (c) rare plagioclase; (d) abundance of cordierite; (e) presence of fibrolite. Similarly leucosomic melt *can* be observed in Lumiera 1bis well, ubicate in southern geothermal area near the culmination of Prata pluton. Millimetric aplitic dykelets of leucosome nature is enclosed in biotite ortogneiss with amphibolitic lens (Hbl + Pl) characterized from a Bt+Pl+Py assemblage. Here host rock present textural continuity with dykelet and some crystals may remain lying across the contact. The planar fabric of host rock is roughly comformable with the contact of the aplite dykelet. In this dyke are absent the alumino-silicate (cordierite and sillimanite) caused (a) difference between the wall rock here characterize to low contents of aluminium (ortogneiss) (b) low degree of melt show from near eutectic quartz-feldspar of dykelet assemblage (Qz + K-feld + Pl).

For melting of the cordierite gneiss a substantial volume of water was required. Based on leucosoma assemblage we can be supposed two possible sources, one internal to metamorphic rocks, one external coming to crystallizing granite. The internal source, since the reaction responsible of muscovite-out isn't connected to the migmatization phenomenous, was the dehydration melting of biotite in the matrix subassemblage **Bt-**Al_2O_5**-Qtz**, by reaction

biotite + andalusite + quartz = cordierite + k-feldspar + melt **(4)**

observed both in the cordierite gneiss and in leucosoma melt. In cordierite gneiss, in fact, biotite occurs only as **coarse** rare flakes; in leucosoma melt the biotite is absent. This suggest that biotite **was** partially consumed during prograde metamorphism possibly through melting reaction **(4)**. The total water content of a typical high-grade, muscovite absent metapelite is usually less than 1 wt%, residing in biotite and less importantly cordierite. Based on the experiments at 3 kbar and 800°C of Van der Molen and Paterson (1979), 1% water translates to a maximum volume of granitic melt of 15% of the **rock** volume. This is well below the critical melt fraction value of 30-35% requisite for melt segregation. The second and most important source of water is believed to have been derived externally from the underlying crystallizing granite. Vapour-saturated melting in the semipelite proceeded by the reaction:

K-feldspar + ***quartz*** *+ plagioclase +* H_2O ± *biotite* ± *cordierite = melt* (5)

This reaction occurs between 650-680°C at 3 kbar and H_2O activity of 1.0, depending upon the exact mineralogy (Thompson, 1982).

Andalusite-cordierite paragneiss (Pga)

This faces is meet in many deep drilling between the micaschist metamorphic unit and high-grade cordierite muscovite-free gneiss.
In this litotipe the cordierite and andalusite develop replace interely the lepidoblastic matrix of micaschist. In the new gneissose texture the S2 is preserved only as hematite and quartz inclusion in the cordierite and andalusite porphiroblasts. The gradual passage between the andalusitecordieritemicaschist and andalusite-cordierite gneiss is accompanied by increasing of metamorphic HTLP grade (passage from andalusite facies to andalusite + cordierite facies) and decreasing in the lepidoblastic portions. Practically the difference between andalusite-cordierite micaschist and andalusite-cordierite gneiss can be represented to abundance of muscovite.
In several samples, andalusite porphyroblasts have pink core surrounded by colourless rims. This zoning is quite common in porphyroblastic andalusite (Okrusch and Evans, 1970). Electron-microbe analysis (Kerrick and Speer, 1988) shows that the cores contain higher concentrations of Fe compared to the rims.
Relicts of garnet and staurolite, belonging to barrovian regionally metamorphism (Medium-T/ Medium-P) of micaschist, *can be* occur as inclusion within andalusite porphyroblasts. The following reactions are responsible for these coronitic structure:

muscovite + staurolite + quartz = andalusite + ***biotite*** + H_2O **(6)**

garnet + muscovite = andalusite + biotite + quartz + H_2O (7)

The other important reaction that ***start*** to occur in this sub-unit is the muscovite-quartz breakdown.

muscovite + quartz = andalusite (fibrolite) + K-feldspar + H_2O (8)

The apparence of K-feldspar in addiction to andalusite produces an further loss of fissility, due to the loss of muscovite. The reaction is texturally manifested by the intergrowth of andalusite with K-feldspar. Minor sillimanite is present as fibrolite, which often grows in cordierite or nucleates on biotite. Texturally, andalusite appears to be in equilibrium with the rest of assemblage.

Micaschist metamorphic unit (Mga)

Muscovite-chlorite-albite-garnet-quartz schist

Particulars data

Where the HT/LP Pliocene-quaternary metamorphism is present only as biotite facies (<350°C) the barrovian texture and assemblage is well preserved. The dominant texture is the alignment of sheet-silicates, in an almost perfect planar preferred-orientation (S2). Frequently, due to the process of solution transfer, the schistosity is spaced *so* that planes rich in oriented sheet-silicates alternate with layers rich in quartz (metamorphic segregation layering). An important porphyroblastesis of albite, like that observed in the bottom of quartzo-feldspathic schist, develop over lepidoblastic beds. Albite porphyroblasts often present an S-shaped (elicitic) internal fabric and, more seldom, simple twin. **Garnet** porphyroblasts follow often albite porphyroblasts into the lepidoblastic beds of the micaschist. Garnet often present **a** well developed elicitic texture probably due to D1 represented from a earliest S1. In the lower grade **part** (chlorite and biotite zone) of the micaschist the inclusion trail of albite porphiroblasts are curved, with development of a pronounced "S" form commonly continuos with external main scistosity S2. This characteristic is indicative to develop synchronous with main deformation S2.

Assemblage

The texture indicate that the chlorite was the stable minerals in the rock during the Almandine-amphibolitic facies. Actually, below the biotite-isograde, the biotite of recent LPM is developing over chlorite. The presence of almandine associate with chorite is indicative of the lower **part** of almandine-amphibolitic facies (chlorite zone, with temperatures lower that 450°C). **Garnet** is a almandine and show a normal zoning with core relatively rich in Ca and Mn and the rims richer in Fe and Mg. More in depth **can** be observed staurolite associated with almandine. The almandine-staurolite association indicate the reaching of Staurolite-almandino amphibolitic facies (with temperature higher that 450°C) for the regional metamorphism that interested the micaschist units. Age of this regional MT/MP metamorphism is probably indicate from the muscovite age of 285 m.y. (Del Moro et al. 1982). The garnet-biotite geothermometer of Ferry and **Spear** (1978), taking T= 500°C (garnet-chlorite zone; higher temperature part of low-grade metamorphism) for the **micaschist** in the Travale area (where these rocks are less affected to the recent thermal events) gives P=9 kbar.

Andalusite-cordierite micaschist

The andalusite isograde represent an important replace for the micaschist texture. The first mineral change that most clearly and consistently delineated the boundary of the thermal metamorphism in the Larderello-Travale area is the **first** apparence of andalusite in the micaschist. The andalusite first appears as 1-4 mm idioblastic porphyroblast scattered on lepidoblastic **beds.** The andalusite porphiroblasts grew essentially via the following reaction:

muscovite + clorite = andalusite + biotite + ***quarm*** **(9)**

The cordierite isograde is located immediately below the andalusite isograde (Fig.3); cordierite appears as strongly poikiloblastic growths on the lepidoblastic beds and it usually have their long axis (C-axis) oriented parallel to schistosity. The cordierite is packed with fine inclusions of muscovite, quartz and matrix accessories and is always associated spatially with biotite. Cordierite **most** probably grew via the following reaction:

chlorite + muscovite + quark = cordierite + biotite + H_2O (10)

There is also evidence that cordierite formed in the univariant reaction:

chlorite + muscovite + quartz = cordierite + andalusite +
biotite + H_2O (11)

Develop of andalusite and cordierite replaced the foliation micas and preserved the S2 foliation as aligned hematite and quartz inclusion. **As** one proceeds upgrade, the andalusite and cordierite increase in size and abundance, and the micaschist became gneissose rocks **(Pga).**

PHYSICAL CONDITIONS OF METAMORPHISM

Figures 3 and 4 summarises the available P-T data for reactions observed in the LPMC. Area labelled **(A)** refer to biotite-in zone, (B) to the early formation of andalusite (C) to the formation of andalusite + cordierite, (D) to andalusite and biotite after regional staurolite, (E) to andalusite + ortose, (F) cordierite + ortose after andalusite + biotite, (G) to fibrolite sillimanite, (H) melt + fibrolite sillimanite, (L) to andalusite + corundum. The preferred P-T range for the LPMC, 2.5-0.5 kbar and 350-700°C, is the shaded line. Striped areas represent the hydrothermal and metasomatic phenomena following the metamorphic effects. These phenomena are distributed into the LPMC rocks and their sedimentaq and weakly metamorphic covering.

Fluid pressure and composition will affect inferred conditions during the LPM. The stability of hydrous phases is a function of P_{H_2O}, which is in turn affected by fluid composition and its distribution in the rocks. The main component reducing the activity of H_2O in metamorphic rocks is CO_2, which is likely to have played a major role in the carbonate-free pelitic gneiss (rare calcsilicate associated with the amphibolites may originally have contained carbonate). Moreover, boron is present in accessory tourmaline and carbonaceous matter is abundant in micaschist. Fluid pressure can be reduced relative to total pressure and that shifts the dehydration

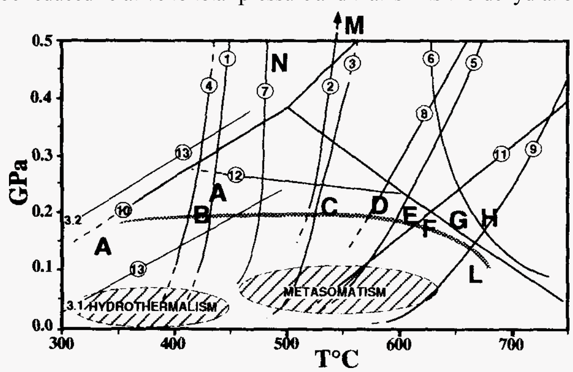


Fig. 4 - Paragenetic assemblages in the P-T path for the deep rocks in the Larderello-Travale area. The diagram shows the tennometamorphic assemblages related to metapelitic and metapsammitic rocks (Mga, Pga and Gc in Fig. 4) observed in the micaschist and gneiss metamorphic units..

The tbermobarometric conditions suggest that the extensive termometamorphic effects (LPM, Low Pressure Metamorphism) result characterize by pressure lower to 2.5 kbar and upper temperature around 700°C. Comparable values can be deduced by wollastonite + fosterite + periclase assemblage observed in deeper metacarbonatic rocks (Da* in Fig. 3) tectonically interposed to Pga.

PLIO-QUATERNARY LOW PRESSURE METAMORPHISM (see also Fig. 3): A) Biotite-in; B) Andalusite-in; C) Cordierite+Andalusite-in; D) Staurolite-out-->Andalusite-in; E) Andalusite+Ortose-in (2kbar; 600°C); F) Andalusite-out-->Cordierite-in (1,5 kbar; >600°C); G) Sillimanite+ortose-in (2kbar; 650°C); H) Fuso Qtz+Or+Ab (2kbar; 680°C); L) Corindone+Andalusite-in (lkbar; >600°C).

PRE-INTRUSIVE BARROWIAN METAMORPHISM. M) Staurolite-in; N) Granato-in.

REACTIONS REFERENCE 1) presumed, Stp + Ms-out-->Bt + Mu-in (Nitsch, 1970); 2) presumed, Cld --> St; (Hoschek, 1969; Ganguly e Newton, 1969); 3) observed, Chl + Ms + Qtz-->Crd + Bt + Al_2SiO_5 (And) + H_2O (Hischberg e Winkler, 1968); 4) observed, Prl->Al_2SiO_5 (And) + Qtz + H_2O (Hemley, 1967; Kerrick, 1968; Wall e Essene, 1972); 5) observed, Ms + Qtz-->Kfs + Al_2SiO_5 (Sill) + H_2O (Althaus et al., 1970); 6) observed, Ab + Or + Qtz + H_2O--> melt (Tuttle e Bowen, 1958; Merrill et al. 1970); 7) observed, Alm87-Sps13-in (Hsu, 1968); 8) observed, St + Ms + Qtz-->Al_2SiO_5(And) + Bt + H_2O (Hoschek, 1969); 9) observed, Mu-->Kfs + C + H_2O (Winkler, 1976); 10) calcolata, Campo Al_2SiO_5 (Johnson et al., 1991); 11) observed, Bt + And + Qtz-->Crd + Kfs + H_2O (Pattison e Tracy, 1991); 12) observed, Gt + Ms->And + Bt + Qtz (Vielzeuf e Holloway, 1988); 13) isoplete of Si4+ in fengite (Massone e Scbreyer, 1987).

reactions to lower T (Spear, 1993). In the high grade LPMC rocks dehydration reactions involving biotite are in progress, and this water is presumably incorporated into the melt forming simultaneously in the leucosomes. Isobaric prograde path show in Fig. 4 is typical of contact metamorphic terranes. The inferred P-T conditions for LPMC require a geothermal gradient on the order of 300°C/km that suggest abnormally large thermal perturbations brought about by relatively shallow emplacement of multiple granitic intrusions (High Level Plutons).

DISCUSSION AND CONCLUSION

Low-pressure metamorphism (LPM) in many Precambrian and Phanerozoic orogens is associate with abundant migmatites and granitoids. This close spatial relationship between igneous rocks and regional metamorphism has been for a long time recognized (for example, Barrow, 1893). This has been interpreted in terms of two broad alternatives: first, that magmatism and metamorphism *effect* are closely related to an underlying thermal (and/or mechanical) event (Turner, 1981, p.455-468), or second, that metamorphism directly reflects the advection of magmatic heat and is thus caused by magmatism.

Whereas there is general agreement on the cause of high- and medium-pressure regional metamorphism, the origin of high temperature in low-pressure terranes remains controversial. Mechanism for high temperatures to low pressure includes (1) a rapid uplift during extension or following crustal thickening (2) many deep heat sources (including magmas). Production of LPM requires that the geothermal gradient in the upper 15 km of the crust exceeds 35°C/km. Regional low-pressure metamorphic gradients commonly exceed 50°C/km and *can exceed* 100°C/km (De Yoreo et al., 1989; Turner, 1981; Wickham and Oxburgh,1987). The metamorphic thermal gradient may be 80°C/km or higher, strongly suggesting a local magmatic control. Heat flow measurements in many areas of regional extension (for example Base and Range Province, USA) and reconstructions of petrological features of the crust in ancient magmatic arcs indicate that the *crust* remains below temperatures required for LPM much of the time (Blackwell et al., 1982; Gill, 1981). For this reasons many investigators have suggested that advection of heat by magmas may be important in the generation of LPM (DeYoreo et al., 1989; England & Thompson, 1984; Lachenbruch & Sass, 1978; Lux et al., 1985; Wickham and Oxburgh,1987; Thompson and Ridley, 1987; Oxburgh & Turcotte, 1971). Low-pressmihigh -temperature regional metamorphism terranes are the subject of particular interest in metamorphic petrology because they require the existence, during prograde metamorphism, of abnormally high upper crustal and mid-crustal thermal gradients (>35-40 °C/km). In recent years, several models have been proposed to explain the development of these high thermal gradients in different low-P-high-T metamorphic terranes. These models are based on observation of the relative timing of deformation, metamorphism, and plutonism, and of the P-T evolutionary paths followed by rocks in these terranes.

Hanson & Barton (1991) have demonstrated that magmatic heat advection is sufficient to produce low-pressure metamorphic belts in many areas where intrusion forms>50% of upper crust. Their numerical models indicate that the coalescence of thermal aureoles from multiple felsic intrusions can produce regionally extensive LPM. Moreover the sequential intrusions can produce brief (<1 m.y.) high-grade events after several million years of lower-grade metamorphic conditions, providing a mechanism for homfelsic textures to overprint schistose textures formed during the same event. This model of relatively cool crust punctuate by local, short lived thermal events differs significantly from the image of a broad, uniform thermal maximum that might be drawn from the spatial distribution of LPM.

In the Larderello area the widespread distribution of intrusive rocks of roughly concordant age (Fig. 2) can be considered to be a strong evidence that the entire area is underlain in the shallow subsurface by a broad coeval plutonic mass (Fig. 5). Pluton emplacement probably served as a volume-compensating mechanism for dilation of the upper crust. As the superficial rocks were stretched and thinned (distended) over the zones of dilation (spreading plutons), they presumably responded by brittle fracture near the surface and plastically nearer to the plutons.

Diapiric ascent is often considered to be linked to models of forceful emplacement, where buoyancy-driven ascent of the pluton induces ductile deformation of the wall rock. Thus, rock fabrics in and around plutons are attributed to the rise and the emplacement of magma (Holder, 1979; Bateman, 1985; Ramsay, 1989).

Resuming, in the southern Tuscany the lithospheric extension produce significant volumes of anatectic magma that arise as plutons and emplace in high crustal level. These magmas, combined with the elevated heat flow due to extension, generate LPM on a regional scale (Fig. 2). At present, uplift of LPM and granitoids rocks complex is active (Fig. 6).

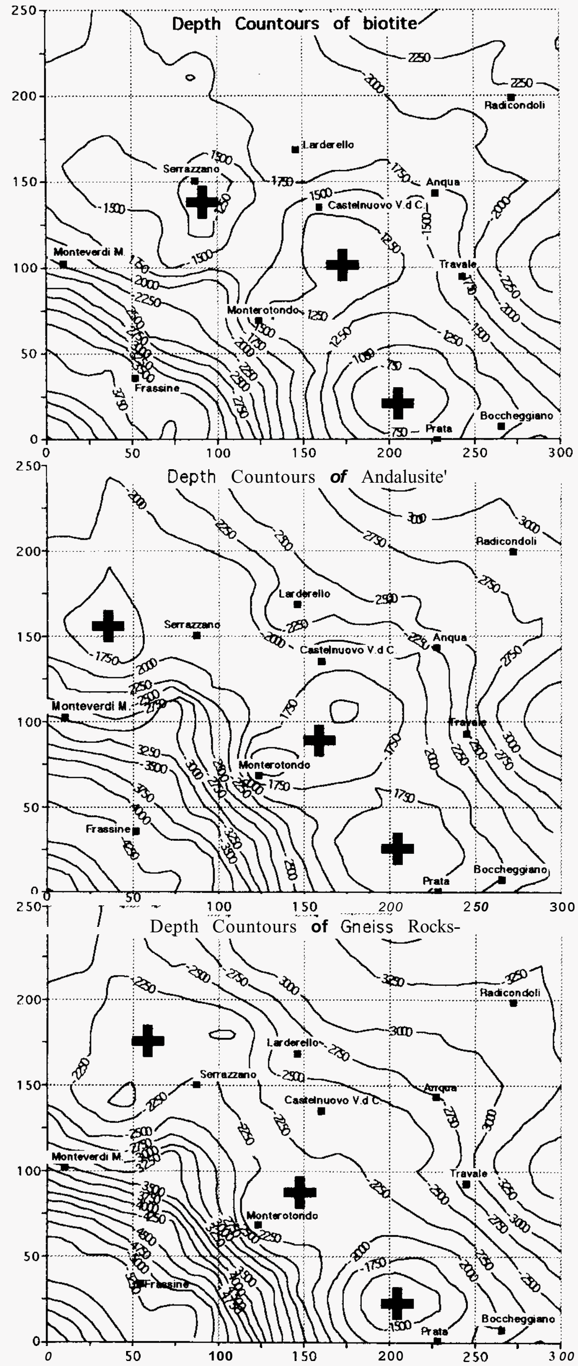


Fig. 5 - Reconstruction of the plutono-metamorphic core complex in the Larderello-Travale geothermal area. There is an excellent overlap between the distribution of thermometamorphic assemblages and the structural high. in the gneiss dome.

Uplift of core compexes has been described in terms of isostatic rebound but may be also the direct result of plutonic activity beneath the gneiss domes that typify these enigmatic geological structures. If the magma pulses are localized in one zone, then the uplift will also be concentrated. If the magma pulses are distributed, as in Southern Tuscany, then uplift will be broad. In contrast to all previous hypotheses concerning the origin of metamorphic core complexes, the plutonism hypotheses produces an elegant and specific explanation for the relative uplift of the gneiss dome present below Larderello-Travale area and more in general below the Southern Tuscany.

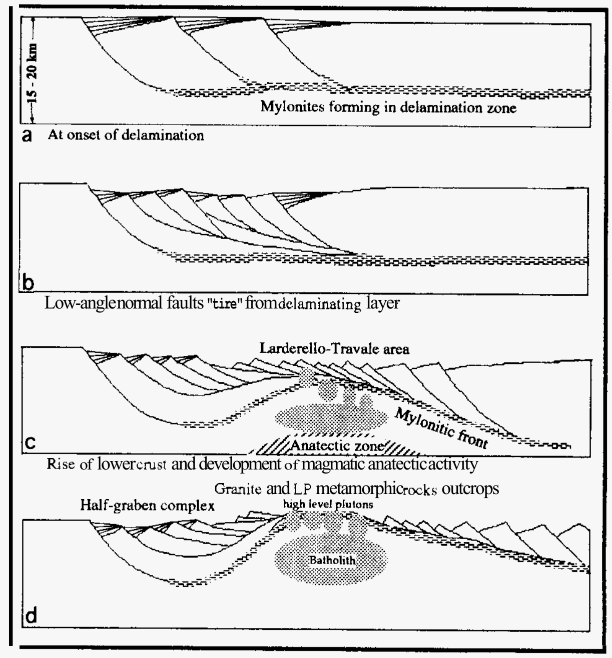


Fig. 6 - Model of development of the Larderello Plutono-metamorphic core complex. In the picture c) is represented the actual situation. As the result of unloading, and as the result of the isostatic effects of granite intrusion at depth (due to the decompressional phenomena), the lower plate bowes upward, with multiple detachment faults splaying from the development culmination. The picture c) represent the actual situation where the plutono-metamorphic body is also buried. In picture d) is represented the future situation where the metamorphic core complex and granitoid rocks are exposed underneath relatively young detachment faults (after Lister and Davis, *1989).*

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