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Variscan and Alpine metamorphic events in the northern Apennines (Italy): a review

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ABSTRACT. — The Northern Apennines consist of oceanic and continental Mesozoic-Tertiary units thrust over the deepest Tuscan metamorphic units, including Paleozoic successions. Tuscan metamorphic units underwent two Alpine tectono-metamorphic deformation phases, and only pre-Carboniferous ones were subjected to polyphase Variscan metamorphism. For the first Variscan phase with a Sudetian age of 328 ±5.3 Ma, the estimated P-T values are ~0.8 GPa and ~670°C; for the second Variscan phase, P~0.4-0.5 GPa, T~530°C. These P-T conditions were attained only in the Gneiss and Micaschist Complexes. In Larderello Micaschist C. and Gneiss C., pre-Alpine andalusite and muscovite (285±11Ma) might be related to a Late Variscan thermal event (third Variscan phase) with P=0.15-0.25 GPa and T >550 °C. During the first Alpine compressional phase (27-20 Ma), Mesozoic-Tertiary sediments were buried to a maximum depth of 40-55 km. Peak pressure values ranged from 0.8 to 1.2 GPa for Verrucano metasediments (Tuscan metamorphic units), with the exception of those on Giglio Island (1.0-1.5 GPa). The Schistes Lustrés of Gorgona show peak pressure values of 1.3-1.6 GPa, while the same rocks on the Argentario Promontory and Giglio Island are in the range 0.6-0.85 GPa. For both units, temperatures varied from 300° to 420° C (450°- 480°C in the Massa Unit). Extensional tectonics began in the early to late Miocene according to different models, caused very rapid exhumation (rough estimates: 2.0-2.5 mm/yr for the Apuan units and 3.9-4.0 mm/yr for the Schistes Lustrés of Gorgona) up to 10-15 km depth and produced a second main folding metamorphic phase (14-12 Ma) with P=0.3-0.5 GPa and T=300°-370°C. The distribution pattern of Al-silicates reveals that Tuscany is divided into NW-SE trending narrow parallel zones. Metamorphic grade increases from an eastern kaolinite-bearing zone to a central kyanite-bearing zone corresponding to the Massa Unit-Larderello alignment and then shows a westward decrease in the Punta Bianca-Elba areas. Similarly, non-metamorphic rocks show a rough decrease in illite crystallinity (°$\Delta 2\Theta$ increase) from west to east and from the lower to upper tectonic units. In Southern Tuscany and in the Tuscan Archipelago, Tortonian-Quaternary magmatism produced contact metamorphism and hydrothermal alterations.

RIASSUNTO. — L'Appennino Settentrionale è costituito da unità oceaniche e continentali di età mesozoico-terziaria sovrascorse sulle più profonde unità metamorfiche toscane che includono successioni paleozoiche. Le unità metamorfiche toscane hanno subito due fasi deformative Alpine e solo le unità Pre-carbonifere sono state interessate da un metamorfismo Varisico polifasico. Per la prima fase Varisica con età Sudetica di 328±5,3 Ma, sono

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stati stimati valori P-T di 0,85-0,86 GPa e 550°-670°C, per la seconda fase P=0,4-0,5 GPa, T=470°-580°C. Queste condizioni P-T furono raggiunte solamente nei Complessi degli gneiss e micascisti. Per tali rocce a Larderello la presenza di andalusite precedente alle fasi tettono-metamorfiche alpine e associata a muscovite (285 ±11Ma) può essere attribuita ad un evento termico tardo-Varisico con P=0,15-0,25 GPa e T >550 °C. Durante la prima fase compressiva Alpina (27-20 Ma), sedimenti Mesozoico-Terziari furono trascinati ad una profondità di 40-55 km. I valori di pressione di picco variano da 0,8 a 1,2 GPa nei metasedimenti del Verrucano, con l'eccezione di quelli dell'Isola del Giglio (1,0-1,5 GPa). Gli Schistes Lustrés dell'Isola di Gorgona mostrano valori di picco di pressione di 1,3-1,6 GPa, mentre le stesse rocce al Promontorio dell'Argentario e all'Isola del Giglio presentano valori di 0,6-0,85 GPa. Per entrambe le unità le temperature variano da 300° a 420° (450°-480° nell'Unità di Massa). La tettonica distensiva cominciò nel Miocene inferiore o superiore secondo i diversi modelli, causò una rapida esumazione (stima approssimata di 2,0-2,5 mm/anno per le unità Apuane e di 3,9-4,0 mm/anno per gli Scistes Lustrés dell' isola di Gorgona) fino a profondità di 10-15 km e diede origine a una seconda principale fase tettono-metamorfica plicativa Alpina con P=0,3-0,5 GPa T=300°-370°C. La distribuzione su scala regionale dei silicati di alluminio rivela che la Toscana è divisa in sottili fasce con andamento NW-SE. In un transetto da E verso O si passa da una zona orientale a caolinite a una centrale con cianite situata sull'allineamento Unità di Massa- Larderello e poi a una successiva zona nella quale il grado metamorfico decresce (Punta Bianca - Elba). In modo simile le rocce non metamorfiche mostrano una grossolana diminuzione della cristallinità dell'illite (aumento di $°\Delta 2\Theta$) da ovest verso est e dalle unità inferiori a quelle superiori. Nella Toscana meridionale e nell'Arcipelago Toscano, il magmatismo Tortoniano-Quaternario ha dato luogo a un metamorfismo di contatto e ad alterazioni idrotermali

KEY WORDS: *Variscan metamorphism, Alpine metamorphism, P-T conditions, radiometric ages, Northern Apennines, Tuscany.*

INTRODUCTION

The Northern Apennines consist of a stack of Alpine tectonic units generated by collision between the Corsica-Sardinia and Adriatic microplates during the last 30 Ma (Vai and Martini, 2001). Most of these units are continental margin Mesozoic-Tertiary sedimentary sequences (e.g. the Tuscan Units), sometimes including at their base syn- to post-Variscan Paleozoic metamorphic sequences, scraped off an underlying Variscan to (?) Pre-Variscan basement (Fig. 1). Other units were generated by subduction of the Jurassic Ligurian-Piedmontese oceanic crust (e.g. the HP-LT metamorphic Schistes Lustrés).

During the last thirty years, various new geological, petrological, geochemical and radiometric data on Tuscan Paleozoic rocks allowed the first organic classification of Tuscan pre-Alpine sequences (Bagnoli *et al.*, 1979; Puxeddu *et al.*, 1984; Conti *et al.*, 1991; Pandeli *et al.*, 1994; Vai and Martini, 2001).

The following Paleozoic Variscan Formations were distinguished by Pandeli *et al.* (1994):

1) Pre-Sudetian Formations, from bottom to top: a) the Gneiss Complex consisting of gneisses, amphibolites and minor calc-silicate rocks (?Proterozoic to ?Early Paleozoic); b) the Micaschist Complex made up of almandine-bearing albite micaschists and amphibolites (?Proterozoic to? Early Paleozoic); c) Variscan epimetamorphic formations including metasiliciclastic rocks with metabasite intercalations, metarhyolites and derived metasediments, Fe-rich and carbonate-rich metasiliciclastic rocks (?Late Cambrian-?Late Ordovician), black phyllites with lydite and Orthoceras dolostone intercalations, calc-schists and nodular limestones (Silurian–Devonian).

2) Post-Sudetian-Asturian Formations consisting of metapelites and overlying turbiditic metasandstones (Late Visean-Late Moscovian).

3) Post-Asturian/ Pre-Saalian Formations: mostly represented by graphite-rich metasediments (Upper Carboniferous-Lower Permian).

4) Syn/Post-Saalian Formations: reddish continental metarudites, porphyritic schists, reddish volcanic-rich metasandstones, locally-

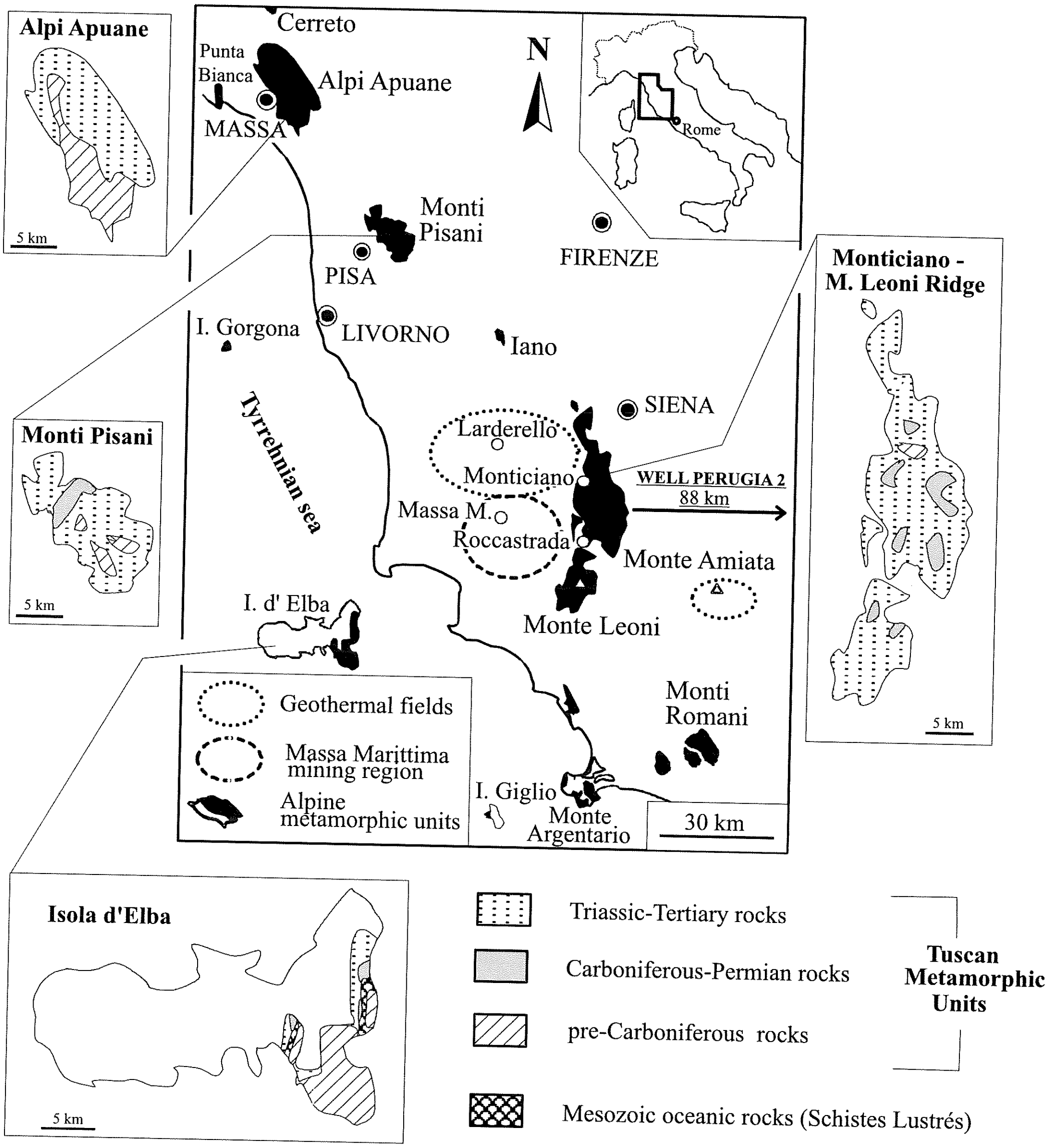

Fig. 1 – Location of the main Variscan and Alpine metamorphic units in the Northern Apennines and in the Tuscan Archipelago. The location of the geothermal area of Larderello and Monte Amiata and the mining area of Massa Marittima (Massa M.) are also shown.

graphitic marine metasiliciclastic rocks, sometimes with carbonate intercalations (middle-Upper Permian).

Most information about Variscan events is provided by Micaschist C. and Gneiss C.. The micaschists and amphibolites were found in the outcrops of Passo del Cerreto (Molli *et al.*, 2002) and in deep drillings of the Larderello-

Travale geothermal region (Pandeli *et al.*, 1994 and references therein). Gneisses were found below Micaschist C. only in the same geothermal drillings.

Studies on these rocks (Del Moro *et al.*, 1982; Elter and Pandeli, 1990, 1996; Molli *et al.*, 2002) revealed the overlapping of three Variscan metamorphic phases: two regional deformation events and a late thermal event. Only traces of these events are still recognizable due to the strong overprint exerted by the two Alpine deformation phases of Oligocene-Miocene age and by the Late Tortonian to Quaternary thermal event.

The two Variscan deformation phases can be better distinguished in the Cerreto micaschists and amphibolites, owing to a weaker Alpine overprint. In Larderello-Travale micaschists, Alpine phases, particularly the first one, almost completely erased the evidence of pre-Alpine events, leaving only traces of Variscan textural features and mineral assemblages (Elter and Pandeli, 1990, 1996; Bertini *et al.*, 1994). Evidence of a Late Variscan thermal event was found only in Larderello micaschists and gneisses (Del Moro *et al.*, 1982; Pandeli *et al.*, 1994).

Alpine deformation phases are better recognizable in the Tuscan metamorphic units of the Tuscan Metamorphic Ridge from the Alpi Apuane to the Argentario Promontory (Fig. 1). Traces of the Late Alpine thermal event are ubiquitous around Late Tortonian to Quaternary granite intrusions: the best evidence of this event was found in the San Pompeo 2 well at Larderello (Batini *et*, 1983) and in wells crossing the contact aureole around the buried Castel di Pietra pluton (Franceschini, 2000).

The mineral abbreviations used in this paper are those suggested by Kretz (1983).

VARISCAN METAMORPHIC EVENTS

In the Larderello-Travale geothermal region, micaschists show grano-lepidoblastic to porphyroblastic texture, two Alpine schistosities (S_1 and S_2), relics of pre-Alpine schistosity, e.g. Ms and Bt fishes, pre-S_1 (i.e. Variscan) fractured garnet, partly replaced by chlorite (Fig. 2a), plagioclase and rare pre-Alpine andalusite porphyroblasts (Fig. 2b) with helicitic inclusions. Plagioclase is often zoned with an oligoclase core and an albite syn-D_1 rim; albite also occurs in the pressure shadows around plagioclase crystals (Del Moro *et al.*, 1982; Elter and Pandeli, 1990; Conti *et al.*, 1991; Pandeli *et al.*, 1994; Gianelli, 1998). The core shows inclusion trails, mainly discordant as to S_1. The mm- to cm-thick mafic intercalations show typical amphibolite facies assemblages (Hbl+Pl-An_{28-39}+Spn), transposed and retrogressed to low-grade assemblages by overprinting of the tectono-metamorphic Alpine phases.

Gneisses display fine-to medium grain size, gneissic layering and amphibolite facies assemblages (Qtz+Bt+Ms+Pl+Kfs+Hbl). Plagioclase with helicitic sillimanite inclusions, almandine and rare staurolite relics (Puxeddu, personal communication in Elter and Pandeli, 1990; Bertini *et al.*, 1994) suggest a pre-Alpine evolution for the gneisses similar to that of the micaschists (Elter and Pandeli, 1996). According to Elter and Pandeli (1990), gneissic layering was only weakly overprinted by Alpine crenulations. Cataclastic to milonitic textures were also found.

The Sudetian phase may be related to the $^{40}Ar/^{39}Ar$ plateau ages of 328.1±5.3 and 312.4± 3.7 Ma found by Molli *et al.* (2002) for the M_1 phase they recognized in the Cerreto amphibolite. These authors, using various geothermobarometers, estimate P~ 0.8 GPa and T~650°C for the Sudetian phase and P~ 0.4-0.5 GPa and T~ 530°C for a second retrogressive phase producing pervasive milonitic deformation. According to Molli *et al.* (2002), some textural evidence, such as pre-kinematic garnet porphyroblasts, might record an early metamorphic event under amphibolite to eclogite facies conditions older than M_1 (?Bretonian phase). For Larderello gneiss, Bertini *et al.* (1994) identified a first Variscan metamorphic event (M_1) with P= 0.7 GPa,

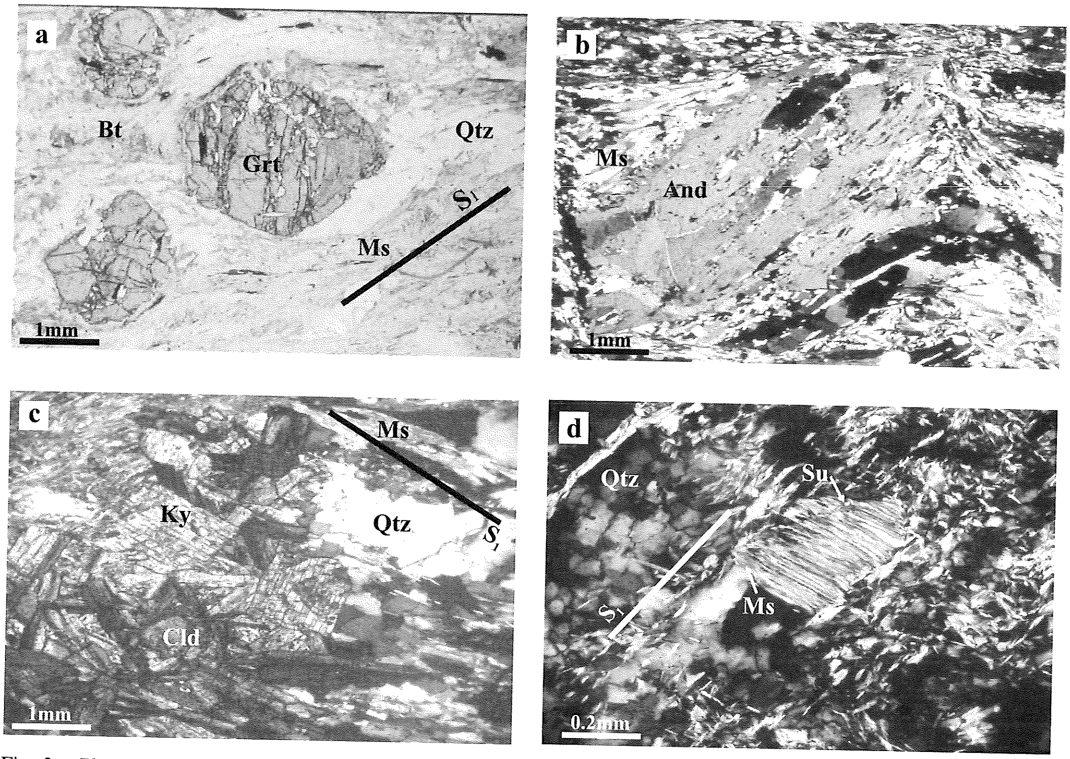

Fig. 2 – Photomicrographs of Variscan and Alpine metamorphic rocks. A) Variscan garnet- bearing micaschist from a Larderello well. S_1 = first Alpine schistosity; b) Sample from the Micaschist Group of Larderello showing pre-Alpine andalusite with helicitic inclusions enveloped by Alpine schistosity; c) Kyanite- and chloritoid- bearing metapsammite Verrucano sample from the Massa Unit, Alpi Apuane; d) Sudoite-bearing rock from the Verrucano of Monticiano-Roccastrada ridge. The sudoite (Su) is interlayered with white mica. S_1 = first Alpine schistosity

T=500°-600° C and a second LP one M_2 with P=0.20-0.35 GPa, T= 550°-600°C (Fig. 3).

For all the Variscan epimetamorphic units overlying the Micaschist and Gneiss Complexes, in spite of the Alpine overprint, pre-S_1 Variscan schistosity is defined by the preferred orientation of the Qtz + Ab + Chl + Ms mineral assemblage. Elter and Pandeli (1996) noted a close analogy between tectono-metamorphic Variscan evolution in Tuscany and that described for the Calabrian–Peloritan Arc, NE Sardinia, the Massif Central, France, and the Bethic Rifean Belt, Spain.

In Micaschist C. and Gneiss C., the probable original coexistence of garnet, staurolite and biotite points to Variscan crystallization at $T \geq 550$ °C (Elter and Pandeli, 1990; Bertini *et al.*, 1994). The X_{Mg} of the biotites is higher than 0.3 in contact metamorphic samples containing cordierite, andalusite, quartz and muscovite. This indicates a minimum pressure of 0.15-0.25 GPa, depending on the thermodynamic data set and the presence or absence of graphite in the system (Pattison *et al.*, 2002). These P values are significantly higher than the estimate of 0.085-0.125 GPa obtained for the lithostatic pressure in the Larderello late Alpine contact aureole. The latter values were obtained taking into account, from drilling data, the thickness of each lithotype, measured rock densities and an estimated thickness of 800 m of eroded light

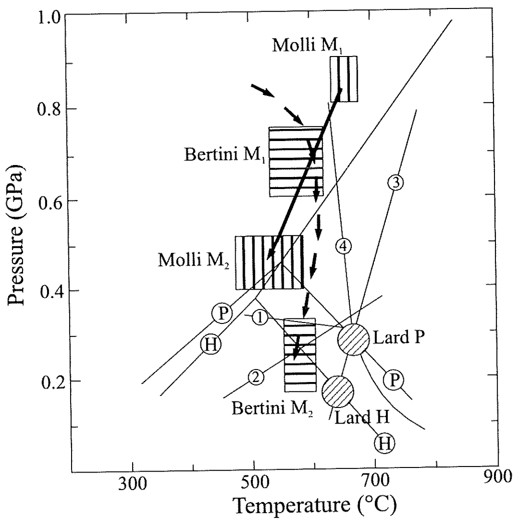

Fig. 3 – Petrogenetic grid for Variscan metamorphism in micaschists and gneisses. Stability boundaries of Al-silicate polymorphs are plotted using the data base of Berman (1991) based on the Al-silicate polymorph triple point datasets of Holdaway (1971) (H) and Pattison (1992) (P), as proposed by Larson and Sharp (2003). (1) Grt + Ms+ V= And + Bt + Qtz (Vielzeuf, 1984); (2) Fe-St +Qtz = Crd + And + V (Richardson, 1968); (3) Ms + Qtz = Sil + Kfs + V (Holdaway and Lee 1977); (4) Ms + Ab + Kfs + Qtz = L (Thompson, 1982). Dashed arrow: Variscan P-T path deduced from the gneisses by Bertini *et al.* (1994). Full arrow: Variscan P-T path according to Molli *et al.* (2002) for the Cerreto micaschists and amphibolites; Lard H, Lard P: P-T conditions for inferred Late Variscan contact metamorphism in Larderello gneisses using Holdaway's and Pattison's data respectively.

sediments (see Del Moro *et al.*, 1982; Cathelineau *et al.*, 1994). This pressure discrepancy may indicate that the Larderello thermometamorphic system did not reach equilibrium conditions for the 2Ms + 3Crd = 2 Bt + 8 Als +7Qtz + $3H_2O$ reaction, perhaps because one or more minerals are relics inherited from an older, possibly Variscan thermal event. The existence of a Late Variscan thermal event for Tuscan Paleozoic rocks was suggested by the discovery of pre-S_1 deformed andalusite blasts (Fig. 2b). This hypothesis was strengthened by a Rb-Sr age of 285±11 Ma yielded by a muscovite coexisting in equilibrium conditions with poikilitic andalusite porphyroblasts in a micaschist sample of the Serrazzano Sperimentale well at 2076 m depth b.g.l. at Larderello (Del Moro *et al.*, 1982). This HT-LP event is coeval with the magmatism of the Variscan belt (Lorenz and Nicholls, 1984), and in particular with that of NE Sardinia (Del Moro *et al.*, 1975). The coexistence of muscovite, andalusite, sillimanite and K-feldspar under equilibrium conditions, as clearly indicated by textural relationships in the depth range of 3.5-3.6 km below ground level in the Sasso 22 well (Del Moro *et al.*, 1982), constrains P-T conditions for the inferred Late Variscan thermal event to those identified by the intersection between the sillimanite-in isograd and sillimanite/andalusite boundaries (Fig. 3), i.e. P=0.18-0.22 GPa and T=600°-650°C (according to Holdaway, 1971) or P=0.27-0.32 GPa and T=630°-670°C (according to Pattison, 1992). Estimations of P-T conditions for the Late Variscan thermal event are completely different from those for Late Apine ones (see below).

ALPINE METAMORPHIC EVENTS

During the Oligocene-Miocene collision between the Corsica-Sardinia and Adriatic microplates, the Ligurian-Piedmontese oceanic successions and those of the Adriatic margin (i.e. Tuscan Domain) suffered polyphased metamorphism. In particular, two main Alpine tectono-metamorphic phases took place in the Tuscan Domain (D_1 and D_2 in Carmignani and Kligfield, 1990), dated at 27-20 Ma and 14-12 Ma ago respectively (Kligfield *et al.*, 1986). Recent papers have supplied evidence that the Northern Apennines were formed by means of an initial burial phase of Triassic siliciclastic sediments (Verrucano) and metabasite-bearing Schistes Lustrés to 40-55 km in depth (Fig. 13 in Brunet *et al.*, 2000) and a successive phase of rapid exhumation up to a depth of 10-15 km (Azzaro *et al.*, 1977; Di Sabatino *et al.*, 1977; Theye *et al.*,1997; Franceschelli *et al.*, 1997, 1998; Giorgetti *et al.*, 1998; Jolivet *et al.*,1998; Brunet *et al.*, 2000). Estimates of P-T conditions were based on the presence or lack of carpholite, chloritoid, pyrophyllite, sudoite (Fig. 2d) and kaolinite, on the X_{Mg} of carpholite and chloritoid and the Si^{4+} content of phengite.

Table 1 provides a synoptic view of the various P-T estimates proposed in the literature for different localities. In short, three main Alpine phases characterized the history of the Northern Apennines. During an early HP-LT burial phase, peak pressure values ranged from 0.8 to 1.2 GPa for Verrucano metasediments (Tuscan metamorphic units), with the exception of those on Giglio Island (1.0-1.5 GPa). The Schistes Lustrés of Gorgona show peak pressure values of 1.3-1.6 GPa, while the same rocks on the Argentario Promontory and Giglio Island are in the 0.6-0.85 GPa range. For both units, temperatures varied from 300° to 420°C, with the sole exception of the Massa Unit (a Tuscan metamorphic unit), in which temperatures of 450°- 480°C were attained.

The following decompression phase was characterized by T=300°-370°C and P=0.3-0.5 GPa, and the last hydrothermal phase by T=200°-300°C and P=0.1-0.4 GPa. The anomalous value of P >0.5 GPa attributed by Jolivet *et al.* (1998) to the last phase in the Apuan Autochthon is suggested by the occurrence of aragonite in some marbles (Di Sabatino *et al.*, 1977).

The Alpi Apuane and Gorgona and Elba Islands merit further comment.

Alpi Apuane- After the HP phase, uplift and thrusting placed the Massa Unit above the Apuan Autochthon. Using the calcite-dolomite geothermometer, Di Pisa *et al.* (1985) found metamorphic zonation in the Alpi Apuane, with a max T of 380°C in the eastern part, 420°C in the central part and 460°C in the western part. According to Di Pisa *et al.* (1985), peak temperature was attained after or at the end of the D_1 phase. Günther and Wallbrecher (1977), taking into account the coexistence of kyanite (Bonatti, 1938; Wachsmuth, 1966), Fe-rich chloritoid, biotite and muscovite, estimated T=400°-430°C for the Massa Unit. Moreover, the possible presence of staurolite in the Massa Unit (Wunderlich, 1960) led Günther and Wallbrecher (1977) to hypothesise the attainment of medium-grade metamorphism with T=520°-540°C.

Gorgona Island- According to Jolivet *et al.* (1998) and Pandeli *et al.* (2001), the marble-calcschist phyllite-serpentinite association in Gorgona is very similar to the HP Schistes Lustrés Unit in Corsica, whose most reliable $^{40}Ar/^{39}Ar$ plateau ages cluster in the 30-40 Ma range (Brunet *et al.*, 2000 and references therein). For the Gorgona sequence, a phengite sample yielded a plateau age of 25.5± 0.3 Ma (Brunet *et al.*, 2000).

Elba Island - No HP/LT mineral assemblages have been found to date, probably because the intensive heating and recrystallization around the Late Tortonian-Pliocene granites completely obliterated any evidence of a previous HP/LT deformation phase. However, according to Pandeli *et al.*(2001, with references therein), the Acquadolce Unit appears very similar to the HP-LT Schistes Lustrés sequences in Gorgona and Corsica. Deino *et al.* (1992) dated the main schistosity of the Acquadolce Unit at 19.68 ± 0.15 Ma ($^{40}Ar/^{39}Ar$ plateau age).

Franceschelli *et al.* (1986) defined the regional distribution pattern of metamorphic minerals all over Tuscany through a regional study on Al-silicates from low grade Verrucano metasediments. The main result was the discovery of a metamorphic zonation in the inner part of the Northern Apennines, parallel to the main NW-SE trending thrust fronts. Four metamorphic zones were distinguished (from east to west):

1) Kaolinite zone, represented only by the Verrucano samples from the Perugia 2 well; the temperature is lower than 290°-300°C, corresponding at 0.2-0.6 GPa to the onset of the Kln+Qtz = Prl + H_2O reaction.

2) Kaolinite-pyrophyllite transition zone, characterized by the coexistence of the two minerals for T= 300°C (some samples from Monte Argentario, Monte Leoni and Monticiano Roccastrada Ridge).

3) Pyrophyllite zone, in which the complete disappearance of kaolinite testifies to the

TABLE I

Synoptic view of the P-T conditions for the Alpine metamorphic units of the Northern Apennines.

LOCALITY	LITHOLOGY	T (°C) peak	P (GPa) peak	REFERENCE
Monte Argentario (first phase)	Verrucano metasediments	350 – 360 350 – 420	0.8 – 1.0 1.0 – 1.2	Theye *et al.* (1997) Jolivet *et al.* (1998, p. 12,138)
Monte Argentario (first phase)	Metabasites (Schistes Lustrés)	340 – 370	0.65 – 0.85	Theye *et al.* (1997, Fig. 7)
Monte Argentario (second phase)	Verrucano metasediments	340 – 370	0.3 – 0.4	Theye *et al.* (1997)
Monte Argentario (third phase)	Verrucano metasediments	< 300	0.1-0.2	Theye *et al.* (1997)
Giglio island (first phase)	Verrucano metasediments	310 – 350 < 350	1.0 – 1.5 1.2 – 1.4	Rossetti *et al.* (1998) Jolivet *et al.* (1998, p. 12,138)
Giglio island (first phase)	Metabasites (Schistes Lustrés)	340 – 360	0.6 – 0.8	Biancone and Tucci (1984)
Monte Leoni subunit (first phase)	Verrucano metasediments	400 – 420 380	0.8 – 1.0 0.8 – 1.0	Giorgetti *et al.* (1998) Jolivet *et al.* (1998, p. 12,145)
Monte Leoni subunit (second phase)	Verrucano metasediments	330 – 350 330 – 350	0.4 – 0.5 0.4	Giorgetti *et al.* (1998) Jolivet *et al.* (1998, Fig. 10)
Monte Leoni subunit (third phase)	Verrucano metasediments	280 – 300 280 – 300	0.3 – 0.4 0.2 – 0.3	Giorgetti *et al.* (1998) Jolivet *et al.* (1998, Fig. 10)
Montepescali subunit (first phase)	Verrucano metasediments	360	0.8 – 0.9	Giorgetti *et al.* (1998)
Montepescali subunit (second phase)	Verrucano metasediments	300 – 320	0.4 – 0.5	Giorgetti *et al.* (1998, Fig. 9)
Larderello subsurface (first phase)	M.Pisani-type Verrucano metasediments Massa-type Verrucano metasediments	400 470 - 480	0.85-0.95 0.9-0.95	Franceschelli *et al.* (1986, Fig. 5) Franceschelli *et al.* (1986, Fig. 5)
Monti Pisani (first phase)	Verrucano metasediments	400	0.85-0.95	Franceschelli *et al.* (1986, Fig. 5)
Apuan Autochthon (first phase)	Triassic metapelites Brecce di Seravezza Fm.	390 - 410 340 – 380	0.8 0.8	Jolivet *et al.* (1998, p. 12,145) Franceschelli *et al.* (1998)
Apuan Autochthon (last phase)	Triassic metapelites	200 – 220	0.5 – 0.6	Jolivet *et al.* (1998, Fig. 10)
Apuan Massa Unit (first phase)	Verrucano metasediments	450 – 480 480 - 490	0.9 0.9-0.95	Jolivet *et al.* (1998, p. 12,145) Franceschelli *et al.* (1986, Fig. 5)
Apuan Massa Unit (last phase)	Verrucano metasediments	260 – 280	0.1	Jolivet *et al.* (1998, fig. 10)
Gorgona island (first phase)	Metapelites – metabasites (Schistes Lustrés)	300 – 350	1.3 – 1.6	Jolivet *et al.* (1998, p. 12,143)
Gorgona island (second phase)	Metapelites – metabasites (Schistes Lustrés)	300 – 320	0.3 – 0.4	Jolivet *et al.* (1998, Fig. 10)

attainment of temperatures higher than 300°C and a maximum temperature of 360°- 400°C for diaspore-fertile rock compositions (Brecce di Seravezza Fm, see above) or 380°- 420°C for the 0.3-0.6 GPa range, defining the onset of the Prl = Ky + Qtz + H_2O reaction; this zone includes the Verrucano samples of the Apuan Autochthon (Di Pisa et *al.*, 1985), Monticiano-Roccastrada ridge, Monte Leoni, Monti Pisani, Iano, Rio Marina (Elba Island: Deschamps, 1980) and Larderello (Franceschelli *et al.*, 1984).

4) Kyanite zone, characterized by the complete disappearance of pyrophyllite, which implies temperatures higher than 380°-420°C. Only the Verrucano in the Massa Unit (Fig. 2c) and part of the Larderello samples belong to this zone (Franceschelli *et al.*, 1986). The Massa-Larderello alignment was characterized by the highest P-T conditions.

Further to the west of the Kyanite zone, a significant decrease in P-T conditions was observed (Punta Bianca-Elba alignment). The Late Alpine distribution pattern of metamorphic P-T values arising from the study of Verrucano samples substantially agrees with the present distribution pattern of heat flow values (Cataldi *et al.*, 1978; Mongelli *et al.*, 1998), and this observation is consistent with the hypothesis that the metamorphic zonation described mainly reflects the early-middle stage of exhumation. This tectono-metamorphic phase is linked to the upwelling of the astenosphere, which produced a rapid rise in isotherms, enhanced extensional tectonics and opened an easy pathway for the late post-metamorphic ascent of granitic melts, particularly below the hottest central Larderello region (Villa and Puxeddu, 1994; Gianelli *et al.*, 1997).

Regional temperature zonation has also been found for non-metamorphic Ligurian and Tuscan-Umbrian, Mesozoic–Tertiary Units. Reutter *et al.* (1980), by means of vetrinite reflectance, and Venturelli and Frey (1977) and Cerrina Ferroni *et al.* (1980, 1983, 1985), using illite crystallinity data (°Δ2Θ, Kübler, 1984), found an eastward increase in °Δ2Θ from the Tyrrhenian coast to Val di Lima. They also observed a vertical increase in °Δ2Θ from the lowest epimetamorphic units to the uppermost diagenetic ones and, in greater detail, an increase in °Δ2Θ and decrease in the degree of coalification within each unit from west to east. Less distinct or more complex zonation was found by Franceschelli *et al.* (1994) for the same Ligurian Units south of the Arno River. As compared to northern °Δ2Θ values, southern ones are significantly lower both for the group of units taken as a whole and for each single unit. However, remarkable overlapping of values among different units generates less distinct vertical and horizontal zonation as compared to northern Tuscany. The °Δ2Θ decrease south of the Arno was attributed by Franceschelli *et al.* (1994) to a higher geothermal gradient and crustal extension of greater magnitude in southern Tuscany. The late Alpine thermal event destroyed the original zonation, which is still preserved, on the contrary, in northern Tuscany.

Contact aureoles around granites are ubiquitous in southern Tuscany. For the Monte Amiata aureole, van Bergen (1983) distinguished outermost pyroxene hornfels facies rocks with And + Crd + Crn + Spl and innermost sanidinite facies rocks with Crn + Spl + Sil + An + grandidierite. For this contact aureole, Gianelli *et al.* (1988) estimated P=0.15-0.25 GPa, T=550°-650°C.

Franceschini *et al.* (2000) described a 100-200 m thick contact aureole around the buried granite of Castel di Pietra, with an outer Bt + Ms + Crd + Crn assemblage and an inner Grt+ Spl+ Kfs one, suggesting P-T conditions of 0.28-0.33 GPa, T 600°C.

From the association of muscovite with post-tectonic blue corundum, sanidine and chiastolitic andalusite in a micaschist core sample from San Pompeo 2 well, Del Moro *et al.* (1982) estimated P=0.1 GPa, T=600°-620°C for the late Alpine contact aureole at Larderello. Deep drilling data reveal that B and F metasomatism greatly affected country rocks (Gianelli and Ruggeri, 2002 and references therein), causing pervasive crystallization of biotite and tourmaline up to 600m from inferred granite contact (Cavarretta and Puxeddu, 1990).

On Elba Island, the contact aureole around La Serra-Porto Azzurro and Monte Capanne monzogranites shows a prograde zonation from low to high grade for ultramafic rocks (diopside + antigorite to olivine + talc), metapelites (biotite + chlorite + muscovite to cordierite + biotite + andalusite) and metacarbonates (calcite + biotite to wollastonite + clinopyroxene ± scapolite ± garnet ± vesuvianite) (Barberi and Innocenti, 1965, 1966; Barberi *et al.*, 1967; Dimanche, 1971; Duranti *et al.*, 1992).

During and /or soon after the peak of the thermal event, the fluid supply from buried granites to country rocks triggered vigorous convective circulation that gave rise to both present and fossil geothermal fields (Cathelineau *et al.*, 1994; Petrucci *et al.*, 1994) and to the Fe-rich deposits of the Massa Marittima mining region (Benvenuti *et al.*, 2001). The Larderello system was divided into two parts separated by an intermediate barrier: 1) in the deeper one, fluids were characterized by T=425°-670 °C, lithostatic P= 0.095-0.130 GPa and two main compositional types: a) LiCl-NaCl-rich magmatic brines; b) H_2O-CO_2-rich aqueous fluids from contact metamorphism; 2) in the shallower part, only fluids with low salinities, hydrostatic pressures and T=200°-400°C were present (Cathelineau *et al.*, 1994).

EVOLUTION OF THE NORTHERN APENNINES: FINAL REMARKS

Two prevailing models have been proposed in the last thirty years to explain the complex tectono-metamorphic evolution of the Northern Apennines. According to the first one (Carmignani and Kligfield, 1990 and references therein), the Northern Apennines underwent the following formation phases: 1) Rapid underplating of the continental crust due to microplate collision produced wedge thickening through imbrication of metamorphic and sedimentary tectonic units. This phase (D_1), starting about 27 Ma ago (Kligfield *et al.*,1986), was active up to at least Burdigalian times (~ 20 Ma) (Carmignani *et al.*, 1995), marking the end of microplate collision and the consequent rapid collapse of the wedge. 2) In a second phase (D_2), large scale-extensional tectonics developed from about 12 Ma in the Northern Apennines and was followed by denudation, uplift and erosion. This tectono-metamorphic evolution produced the present structure of the Alpi Apuane antiformal stack, characterized by an underlying metamorphic core overlaid by non-metamorphic Mesozoic-Tertiary units. Carmignani and Kligfield (1990) consider the Alpi Apuane as a typical core complex comparable to the evolved system of the Basin and Range Province in North America.

The second model (see Jolivet *et al.*, 1998, and related bibliography; Brunet *et al.*, 2000) envisages the following evolution:

1) An early compressional phase leading to rapid crustal thickening up to 45 km below the Alpi Apuane and remarkable burial at depths generally around 40 km, with a peak of 55 km for Gorgona HP/LT rocks (Brunet *et al.*, 2000, Fig. 13);

2) When the gravitational potential energy stored during wedge accretion and thickening overcame horizontal stress due to microplate convergence (Rossetti *et al.*, 1998, Jolivet et *al.*, 1998), very rapid (rough estimate of 2.0-2.5 mm/yr for the Apuan units, of 3.9-4.0 mm/yr for the Schistes Lustrés of Gorgona), cool (very low geothermal gradient) exhumation took place, bringing HP rocks to depth values <15 km along a nearly-isothermal decompression path;

3) Late HT post-orogenic extension was caused by asthenospheric upwelling, large crustal melting and shallow (4-10 km in depth) emplacement of granitic plutons.

Integrating the two evolutional models just described, the following synthesis may be proposed:

Phase 1 – An early collisional phase produced wedge thickening and rapid burial of the oceanic and continental crust down to a depth of at least 40-50km, with attainment of P-T conditions typical of blueschists to eclogitic facies metamorphism; rocks were then heated in regional metamorphism conditions and reached peak temperatures at the end of this phase and/or in the time interval between the first and the second phase (e.g. kyanite in the Massa Unit);

Phase 2 – The following ascent of HP-LT rocks up to a depth of 10-15 km along a nearly-isothermal decompression path was very rapid and probably due to a «serrage» event which started soon after the end of the previous phase and was also characterized by syn-tectonic extension triggered by gravitational collapse;

Phase 3 – Finally, regional (post-tectonic) extension took place, triggered by asthenospheric upwelling which produced crustal thinning, large crustal melting and shallow emplacement of huge volumes of crustal and/or hybrid magmas. The last thermal event generated, on a regional scale, HT-LP and hydrothermal metamorphism around Late Tortonian to Quaternary volcano-plutonic shallow systems and is still active in Tuscan geothermal areas.

Summing up, the Northern Apennines reproduce, in only 20-25 My, the complete evolution of an orogenic-type collisional belt, from an early HP-LT stage to the final shallow emplacement of granitic plutons.

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