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Alpine and Hercynian orogenic phases in the basement rocks of the Northern Apennines (Larderello geothermal field, southern Tuscany, Italy)

By Franco Marco Elter[1]) and Enrico Pandeli[2])

ABSTRACT

A microstructural – petrographic study was carried out on core samples from several deep wells of the Larderello geothermal field (southern Tuscany, Italy). This paper aims to outline the structural-metamorphic framework of the buried Palaeozoic – Middle Triassic sequences during Hercynian and/or Alpine times.

A "cover" ("Tectonic wedges Complex", "Phyllitic-Quartzitic Group" and "Micaschist Group"), with a strong Alpine overprint, is detached from a Hercynian basement ("Gneiss Group"), weakly affected by Alpine events.

The imprint of the Hercynian orogeny (a late Hercynian HT-LP event, the Sudetic phase, and, sometimes, relics probably belonging to the Breton phase) is clearly recognizable in most of the Palaeozoic sequences.

Correlation between the Larderello buried Palaeozoic sequences and the ones outcropping in northeastern Sardinia is pointed out.

RIASSUNTO

È stato condotto uno studio microstrutturale e petrografico su campioni di carote e di cuttings appartenenti a numerosi sodaggi del campo geotermico di Larderello (Toscana meridionale, Italia). Lo scopo di questa nota è la ricostruzione del quadro deformativo – metamorfico delle successioni paleozoiche – medio triassiche «sepolte» durante gli eventi tettonici ercinici e/o alpini.

Sono state identificate Unità di «copertura» («Complesso a Scaglie Tettoniche», «Gruppo Filladico-Quarzitico» e «Gruppo dei Micascisti»), caratterizzate da un forte imprinting deformativo-metamorfico alpino, che risultano scollate rispetto al sottostante basamento ercinico, blandamente interessato dalla tettonica alpina.

I segni della tettonica ercinica (fasi bretone e sudetica alle quali si sovrappone un evento di HT-BP) sono spesso ben identificabili in gran parte delle successioni paleozoiche.

Vengono infine confermate le strette analogie tra le successioni paleozoiche «sepolte» di Larderello e quelle affioranti nella Sardegna di Nord-Est.

Introduction

The surface geology of the Northern Apennines (e.g. Abbate et al. 1970; Giannini et al. 1972; Dallan Nardi & Nardi 1972) consists largely of the "Ligurian", "Tuscan" and "Umbrian" Meso-Cainozoic and the U. Miocene-Pliocene cover sedimentary sequences. Palaeozoic and Middle Triassic rocks, which constitute the deepest tectonic units (e.g. "Massa Unit" and "Tuscanid I" Auct.) of the structural pile of the Northern Apennines, are scattered throughout Tuscany (Fig. 1).

[1]) Earth Sciences Department, University of Siena, Via delle Cerchia 3, Siena (Italy).

[2]) ENEL – National Geothermal Unit, Via A. Pisano 120, Pisa (Italy).

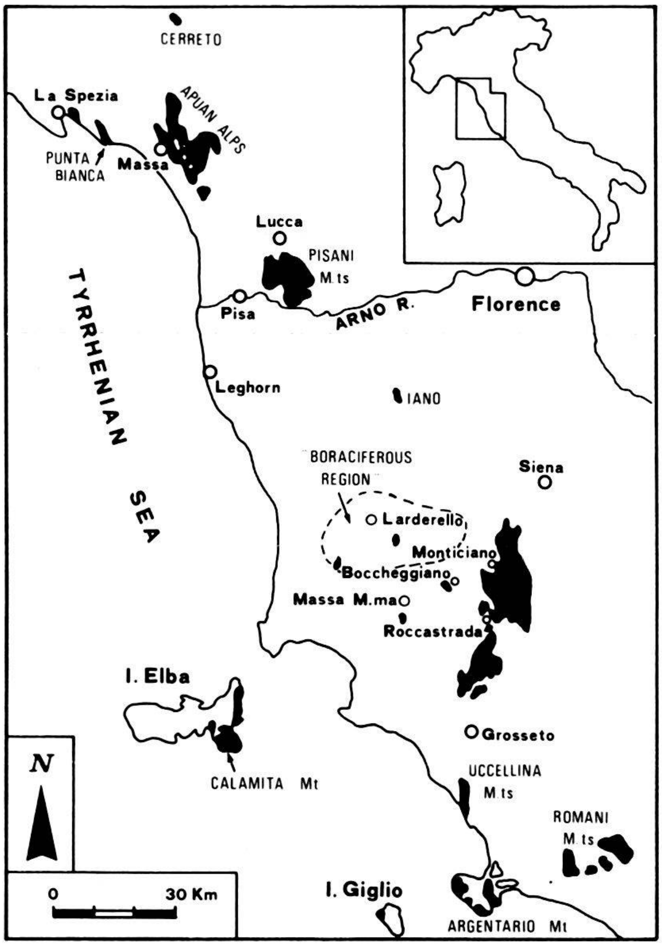


Fig. 1. Location of the Tuscan Palaeozoic–Middle Triassic outcrops (in black).

Because of the scarcity of outcrops, the data obtained by deep geothermal drillings, carried out by Enel (Italian Electricity Board) in southern Tuscany are very interesting; these boreholes reach horizons deeper than 3,500–4,000 m B.G.L. and cross a remarkable thickness of the Palaeozoic basement. In the last few years, several authors have presented new data on the stratigraphy, petrography, structural framework and mineralization of the buried Triassic-Palaeozoic metamorphic sequences in the Larderello-Travale ("Boraciferous region") and M. Amiata areas (Batini et al. 1983, 1984; Bertini et al. 1985; Franceschelli et al. 1984; Gianelli et al. 1988; Pandeli et al. 1988a). However, there are only scarce data available about the relations between deformation and metamorphism for these rocks during the Hercynian and/or Alpine tectonic phases. Therefore, we have carried out a series of petrographic and microstructural investigations on the Triassic "Verrucano" and the Palaeozoic sequences in most of the Larderello deep wells.

Geological Framework

Many papers have dealt with the surface and subsurface geology of the "Boraciferous region" (Mazzanti 1966; Lazzarotto 1967; Lazzarotto & Mazzanti 1976;

GIANELLI et al. 1978; BATINI et al. 1983; FRANCESCHELLI et al. 1984; PANDELI 1988; PANDELI et al. 1988b). The geological setting of this area (Fig. 2) is defined by the following stratigraphic-structural units (from top to bottom):

– post-orogenic Upper Miocene – Middle Pliocene and Quaternary sedimentary sequences;

– *Ligurid Units:* the "Ophiolitic Complex" (Upper Jurassic-Lower Cretaceous); the "Flysch Calcareo-Marnoso Complex" (Lower/Upper Cretaceous – Paleocene); the "Canetolo Complex" (Paleocene – Eocene);

– *Tuscan Nappe,* made up of carbonate and carbonate-siliceous Formations (Upper Trias – Lower Cretaceous) and terrigenous Formations (Upper Cretaceous – Lower Miocene). It is often imbricated or completely missing ("Reduced Tuscan sequences" in DALLAN NARDI & NARDI 1972; GIANNINI et al. 1972);

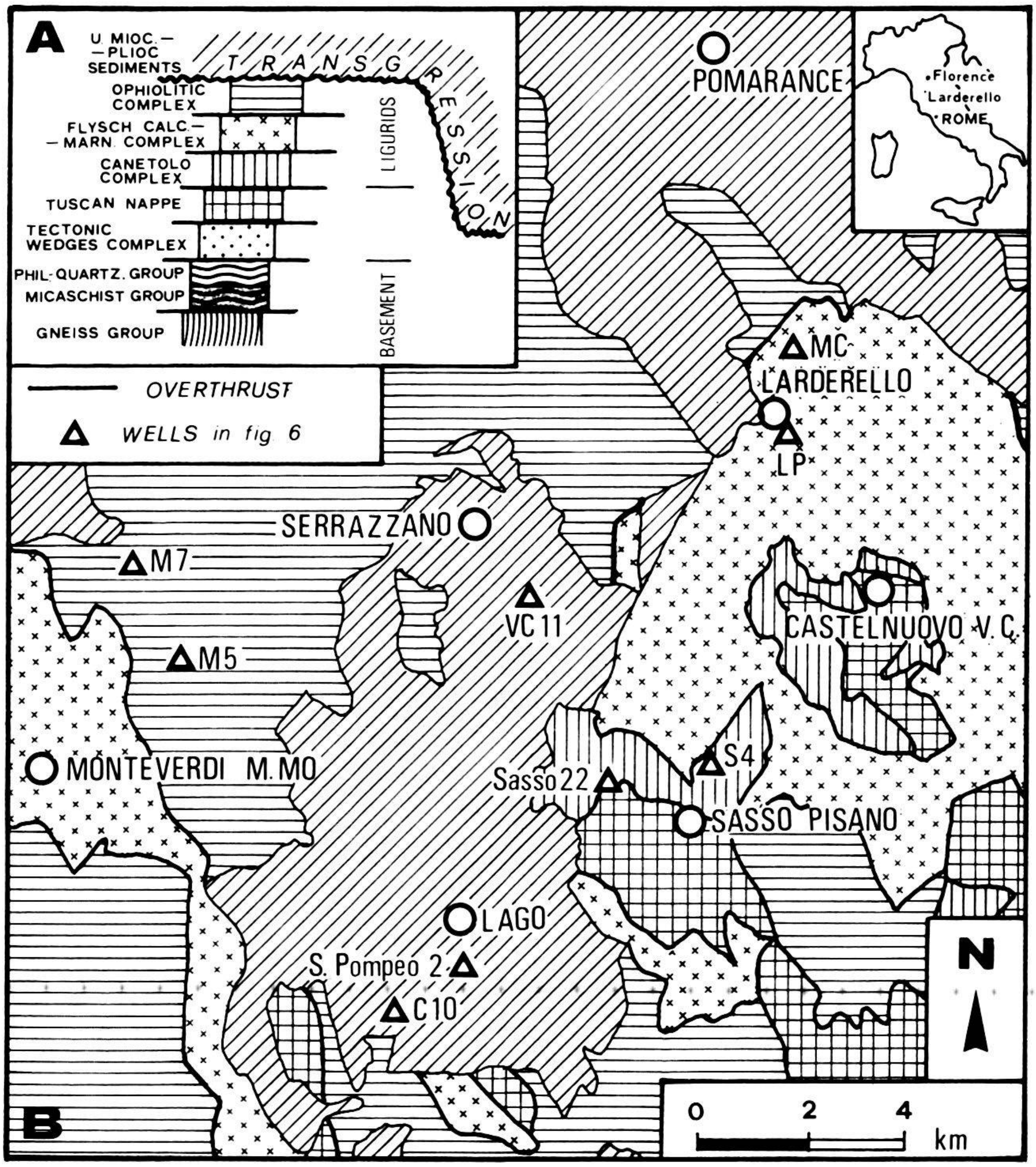


Fig. 2. Geology of the Larderello geothermal region: A) Structural setting of the main tectonic units. B) Geological sketch-map (legend in Fig. 2A).

– *Tectonic Wedges Complex,* these are generally thrusted stacks of Upper Trias dolomitic/evaporitic sequences (Anidriti di Burano and Calcare Cavernoso formations) and of metamorphic Middle – Upper Triassic Verrucano and Palaeozoic formations;

– *Basement* composed of Palaeozoic (Ordovician? – Silurian?/Devonian?) and/or pre-Palaeozoic (?) polymetamorphic rocks. These rocks show traces of Hercynian metamorphism (low to medium grade regional metamorphism, followed by a high temperature-low pressure phase of medium to high-grade) and Alpine metamorphism (low-grade regional metamorphism with locally superimposed contact metamorphism phenomena, related to the emplacement of Pliocene acidic anatectic stocks: e.g. Batini et al. 1983).

Petrographic and structural data

The lithologic, petrographic and micro-structural features of the metamorphic rocks belonging to the Tectonic Wedges Complex and to the Basement are summarized here:

Tectonic Wedges Complex

Middle-Upper Triassic rocks of the Verrucano Group are the dominant lithology in the metamorphic sequences belonging to this Complex.

Two Verrucano sequences can be distinguished (Franceschelli et al. 1984) based on different metamorphic grade (low to high greenschists facies, for petrographic details see Table 1):

– *Verrucano "A".* It consists of lithotypes, already described by Rau & Tongiorgi (1974) in the Verrucano, of the Pisani Mountains, affected by very low-grade metamorphism (the pyrophyllite zone in Franceschelli et al. 1984). These lithotypes include: whitish and pinkish, poorly sorted quartzitic meta-conglomerates and metasandstone with a quartzose-micaceous matrix ("Anageniti"), green-whitish to red-violet, often quartzose, phyllites ("Scisti violetti" e "Scisti verdi"), and minor well sorted greenish quartzites with a sericite-chlorite matrix ("Quarziti verdi").

In addition, alternating grey to pinkish microcrystalline impure dolomitic limestone, anhydrite levels, green to violet phyllites and quartzites (sometimes with anhydrite cement) can be referred to the uppermost part of the Verrucano Group in southern Tuscany ("Tocchi Formation": Costantini et al. 1980).

– *Verrucano "B".* These rocks, peculiar to the western wells in the Larderello field, show much less lithologic variation than those described for the Verrucano "A". They contain quartzites, phyllitic quartzites, quartzose meta-conglomerates together with variegated sericitic-chloritic phyllites, which include scattered white and pink quartz grains, and sometimes are rich in hematitic pigment. However, the granoblastic and granolepidoblastic textures and the occurrence of kyanite (sometimes coexisting with chloritoid) indicate higher metamorphic grade for the "Verrucano B" (the kyanite-pyrophyllite zone and kyanite zone in Franceschelli et al. 1984). Moreover, grey-whitish, often impure marble intercalations have been found.

TABLE 1 - "TECTONIC WEDGES COMPLEX"

LITHOLOGY	TEXTURE	MINERALS	PARTICULAR REMARKS	STRUCTURAL FEATURES
Meta-Conglomerates and meta-sandstone	Blasto-psefitic to blasto-psammitic Granoblastic to granolepidoblastic(*)	Quartz + Muscovite/Sericite ± ±Chlorite (±Chloritoid) Accessories: Tourmaline, Zircon, Apatite, Fe and Fe Ti oxides ± Kyanite (*)	Hematite - rich matrix and Hematite inclusions in quartzose clasts. Lithics: abundant quartzitic clasts and occurence of Lydites, Quartz + Tourmaline aggregates ("Tourmalinits"), Triassic-Paleozoic phyllitic lithotypes and acidic volcanites (magmatic quartz and red porphyries).	
Phyllites	Lepidoblastic to blasto-psammitic Lepidoblastic to granolepidoblastic (*)	Muscovite ± Chlorite ± Quartz ± Hematite (± Chloritoid) Accessories: Rutile, Fe Ti oxides, Pyrite, Tourmaline, Zircon, Apatite ± Kyanite (*)	Hematite-rich levels and occurrence of carbonatic concretions ("Caliche")	SA1 (MA1), CA2, CA3 (*) SA1(MA1),SA2(MA2), CA3
Quarzites	Blasto-Psammitic Granoblastic (*)	Quartz ± Sericite ± Chlorite Accessories: Tourmaline, Zircon, Pyrite, Feldspar		
Dolomitic Limestone	Granoblastic	Calcite ± Dolomite ± Quartz ± ± Sericite ± Albite (rare) ± ± Hematite ± Anhydrite	Ghosts of sedimentary textures (Mudstone with Algae and micro-Forams; Oolitic Grainstone and Packstone)	
Sulphatic Levels	Granoblastic	Anhydrite ± Gypsum		
Phyllite and Quartzite	Lepidoblastic to blasto-psammitic	Muscovite, Quartz ± Chlorite (± Anhydrite) ± Hematite Accessories: Rutile, Zircon, Tourmaline, Fe Ti oxides, Pyrite		
Marble (*)	Granoblastic	Calcite ± Quartz ± Sericite		

(*) VERRUCANO "B"

Such sequences could be related to the Verrucano of the "Massa Unit" sensu strictu (e.g. Franceschelli et al. 1986) outcropping near Massa in the Apuan Alps area (Fig. 1).

In addition to the Verrucano sequences, tectonically intercalated Palaeozoic sequences were recognized in the Tectonic Wedges Complex. In decreasing order of frequency, we find (for petrographic details see Table 2):

a) Dark grey to black phyllites with grey quartzitic intercalations. These lithotypes are similar to the Upper Carboniferous deposits outcropping elsewhere in Tuscany ("S. Lorenzo Group" in Bagnoli et al. 1979).

b) Poorly sorted reddish polymictic meta-conglomerates and coarse meta-sandstones with abundant Palaeozoic clasts (often bearing a pre-Alpine foliation) in a hematite rich phyllitic matrix. These rocks closely resemble the Lower Permian to Middle Trias (?) Asciano breccia and conglomerate in the Pisani Mountains (e.g. Rau & Tongiorgi 1974).

c) Grey-yellowish to greenish quartzose phyllites rich in lithoclasts of acidic volcanics and of minor Palaeozoic phyllites. This lithology is identical to the "Iano porphyric Schists" (e.g. Bagnoli et al. 1979), of probable Permian – Lower Trias age.

d) Red quartzites with clasts of acidic volcanics in a hematite-rich quartzose-sericitic matrix (Permian Castelnuovo red Sandstone in Bagnoli et al. 1979).

TABLE 2 - "TECTONIC WEDGES COMPLEX"

LITHOLOGY	TEXTURE	MINERALS	PARTICULAR REMARKS	STRUCTURAL FEATURES
a)Black phyllites and gray quartzites	Lepidoblastic to blasto-psammitic	Muscovite, Quartz ± Chlorite ± Graphite ± green Biotite (static) Accessories: Pyrite, Zircon, Rutile, Tourmaline	Lithics of graphitic phyllites	
b)Polymictic meta-conglomerates and meta-sandstone	Blasto psefitic to blasto psammitic	Quartz, Muscovite ± acidic Plagioclase ± Chlorite ± Hematite Accessories: Zircon, Tourmaline, Apatite, Titanite, Fe Ti oxides	Abundant lithics of Paleozoic rocks	SA1 (MA1), CA2, CA3 In some samples of e) sequences: SA1(MA1),SA2(MA2), CA3
c)Quartzose phyllites	Blasto psammitic	Muscovite/Sericite, Quartz ± Chlorite Accessories: Zircon,Tourmaline	Abundant lithics of acidic volcanics (embayed magmatic quartz, welded scoriae, vitrophyric lavas) and of Paleozoic sericitic phyllites (often rich in Rutile and sometimes with Hematite rich millimetric bands)	
d) Red quartzites	Blasto psammitic	Quartz, Muscovite/Sericite ± Hematite ± Fe Ti oxides Accessories: Tourmaline, Rutile, Zircon	Occurrence of acidic volcanics (rhyolites and welded scoriae) and phyllitic lithics	
e)Quartzitic pyllites and quartzites	Granolepidoblastic to granoblastic	See Phyllitic-Quartzitic Group lithotypes of the basement		

e) Quartzitic phyllites and quartzites, petrographically similar to the Phyllitic-quartzitic Group lithologies described in the following notes on the Basement rocks.

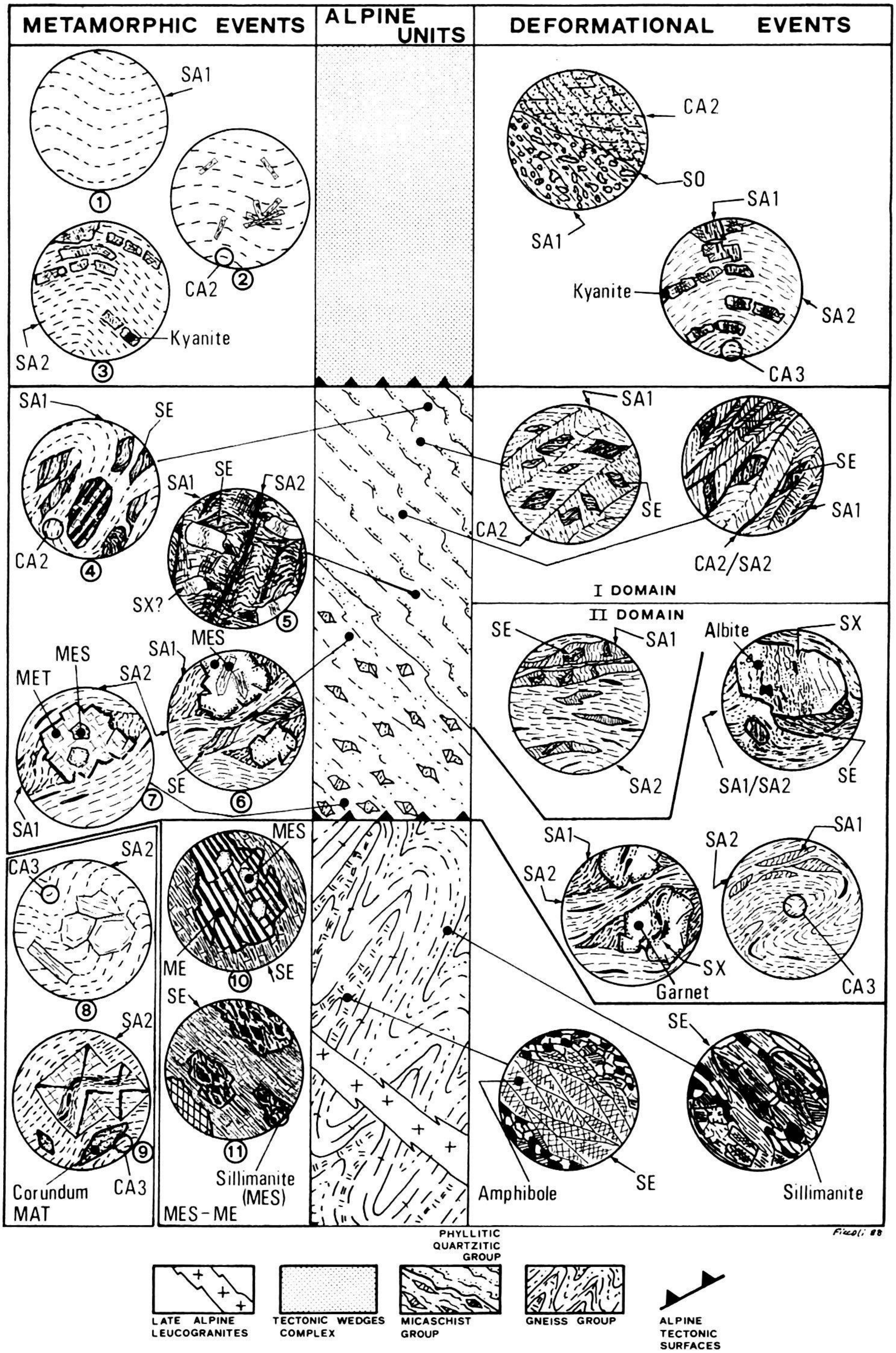
Microstructural aspects: (Fig. 3)

Two Alpine deformation events are clearly recognizable (DA1 and DA2). The DA1 deformation event is associated with a planar penetrative anisotropy (SA1), which is usually sub-parallel or slightly inclined to the sedimentary layering, and whose intensity is related to the lithology. The subsequent event (DA2) produced a crenulation cleavage (CA2). The CA2 in the Verrucano "B" and, locally, in the Palaeozoic quartzitic phyllites and quartzites (sequence e) described above), may become an axial plane schistosity (SA2). In some cases a later deformation event (DA3) produced local gentle crenulations (CA3).

Metamorphic events: (Fig. 3 and Table 3)

A syn-DA1 blastesis (MA1 event) is characterized by fine-grained muscovite + pyrophyllite + quartz + chlorite. The blastesis of fine-grained muscovite + chlorite +

Fig. 3. Scheme of the blastesis-deformation relationships during Alpine-Hercynian events: 1) Fine-grained Alpine muscovite; 2) Alpine chloritoid (post-CA2); 3) Alpine kyanite (post-SA1/pre-SA2); 4) Fine-grained Alpine muscovite, coarse-grained Hercynian muscovite (SE) and acidic plagioclase blasts; 5) Fine-grained Alpine muscovite (SA1, SA2), coarse-grained Hercynian muscovite and albitic porphyroblasts with helicitic inclusions (SE, SX?); 6) Hercynian garnet with chloritoid inclusions (both belonging to MES); 7) Hercynian andalusite (MET) with garnet inclusions (MES); 8) Late Alpine static biotite (MAT); 9) Late Alpine static chiastolitic andalusite and corundum (MAT); 10) Hercynian andesine (ME) with garnet inclusions (MES); 11) Hercynian andesine (ME) with prismatic (black rombohedra) and fibrolitic sillimanite inclusions (MES).


METAMORPHIC EVENTS
ALPINE UNITS
DEFORMATIONAL EVENTS
SA1
CA2
Kyanite
SA2
SE
SX?
MES
MET
ME
SO
CA3
I DOMAIN
II DOMAIN
Albite
SX
SA1/SA2
CA2/SA2
Garnet
Corundum
MAT
Sillimanite (MES)
MES-ME
Amphibole
Sillimanite
PHYLLITIC QUARTZITIC GROUP
LATE ALPINE LEUCOGRANITES
TECTONIC WEDGES COMPLEX
MICASCHIST GROUP
GNEISS GROUP
ALPINE TECTONIC SURFACES

oxides (MA2 event) is associated with the SA2 schistosity. In the Verrucano "A", the development of chloritoid is post-DA1/pre-DA2 (MAS1). There is also a local static post-DA2 (MAS2) crystallization of chloritoid.

In the Verrucano "B" the blastesis of kyanite ± chloritoid is post-DA1/pre-DA2 (MAS1).

In some Verrucano and Palaeozoic sequences (sequence a) above) there is also evidence of late static crystallization of green biotite (MAT) locally connected with the intrusion of late-Alpine igneous dykes.

TABLE 3 - "TECTONIC WEDGES COMPLEX"

	ALPINE EVOLUTION					
DEFORMATIONAL EVENT	DA1		DA2	DA3		
METAMORPHIC EVENT	MA1	MAS1	MA2		MAS2	MAT
QZ	========					
MS	========	=========	========	==?==?=		
*KY		=========				
CHL	========		========			
OX	========		========	==?==?=		
CLD		=========			=======	
G.BIO						=======

(*) VERRUCANO "B"

Legend for the Tables 3; 5; 7; 9a, b.

QZ: quartz; MS: muscovite; KY: kyanite; CHL: chlorite; OX: oxides; CLD: chloritoid; G. BIO: green biotite; BIO: biotite; APL: acidic plagioclase; ILM: ilmenite; PY: pyrite; TR-ACT: tremolite-actinolite; SPH: sphene; IPL: intermediate plagioclase; GR: garnet; HBL: hornblende; AND: andalusite; CRD: cordierite; COR: corundum; KF: K-feldspar; PSIL: prismatic sillimanite; FSIL: fibrolitic sillimanite; BPL: basic plagioclase.

Basement

The typical sequence of the Larderello Basement can be divided, from top to bottom, into three broad lithologic groups: Phyllitic-quartzitic Group, Micaschist Group and Gneiss Group.

Phyllitic-quartzitic Group

This group consists of lead-grey to green and blackish quartzitic phyllites and quartzites (see textures and petrographic composition in Table 4).

In the lower part of this sequence are locally present:

– horizons rich in albite porphyroblasts (sometimes zoned and with evident graphitic or, more rarely, quartz + muscovite helicitic inclusions, similar to the underlying Micaschist group);

– granoblastic metabasitic intercalations (composition in Table 4) related to "within-plate basalts" (Gianelli & Puxeddu 1979; Puxeddu et al. 1984).

TABLE 4 - "PHYLLITIC-QUARZITIC GROUP"

LITHOLOGY	TEXTURE	MINERALS	PARTICULAR REMARKS	STRUCTURAL FEATURES
Quartizitic Phyllites and quartzites	Granolepidoblastic to granoblastic	Quartz, Muscovite/Sericite, Chlorite, acidic Plagioclase (often with polysynthetic twinning) ± Graphite (locally abundant) ± Calcite ± Fe Ti oxides (leucoxene) ± Pyrite Accessories: Zircon, Tourmaline, Apatite	In the lower part: -Granoblastic metabasitic levels with intermediate plagioclase (often albitized and calcitized/sericitized), Tremolite-Actinolite, Titanite ± Chlorite ± Fe Ti oxides ± Quartz -Albite porphyroblasts rich levels similar to ones of the Micaschist Group	DOMAIN 1 (superficial) SA1(MA1), CA2,CA3 DOMAIN 2 (deeper) SA1(MA1),SA2(MA2), CA3 Relics of pre-Alpine foliations (SE, SX?)

The rocks of the Phyllitic-quartzitic Group show the same petrographical features as the Quarziti e Filladi inferiori Formation described by Barberi & Giglia (1965) in the Apuan Alps. An Ordovician-Silurian age is proposed on the basis of petrographical correlation with the Sardinian, Provençal and Spanish Palaeozoic sequences (Bagnoli et al. 1979; Tongiorgi & Bagnoli 1981).

Microstructural aspect: (Fig. 3)

Three Alpine deformational events are recognizable as in the Tectonic Wedges Complex.

The event DA1 is associated with a highly penetrative planar anisotropy (SA1).

The subsequent event DA2 shows different features depending on the depth of burial: in a more superficial structural domain (*Domain I* in Figs. 3 and 4a) DA2 is characterized by a crenulation cleavage CA2, while, towards the bottom CA2 increases in intensity to become a schistosity SA2 (*Domain II* in Figs. 3 and 4b). The DA2 phase deforms SA1 into isoclinal folds and locally SA2 obliterates SA1 completely. Sometimes also a deformation event DA3 produced a discontinuous crenulation cleavage (CA3), which deforms SA2 (Figs. 4a, b). In the phyllitic lithologies the SA1 transposes an earlier foliation, which is correlated with pre-Alpine Phases (DE) (Fig. 4a). The SE schistosity is defined by aligned coarse grained white mica (muscovite) ± quartz ± opaques ± albite, mica-fish and quartzose rods.

The albite porphyroblasts sometimes contain helicitic inclusions (graphite ± muscovite aligments) probably related to a pre-DE event.

Metamorphic events: (Fig. 3 and Table 5)

The DA1 alpine event is characterized by synkinematic crystallization (event MA1) of quartz, albite, fine-grained muscovite, chlorite and oxides. In the deepest structural domain (Domain II), blastesis (MA2) of quartz ± fine-grained muscovite ± opaques occurred during the DA2 event. Moreover, static post-DA3 crystallization of green and/or brown biotite (MAT) has been observed in some samples.

A synkinematic blastesis of coarse grained white mica + quartz + albite characterized the pre-Alpine DE event. The same muscovites show reaction rims with new fine grained mica, similar to that associated with the DA1 event.

The presence of pre-DE helicitic inclusions in the albite porphyroblasts is indicative of an earlier metamorphic event, which is synkinematic to a deformation phase (DX).

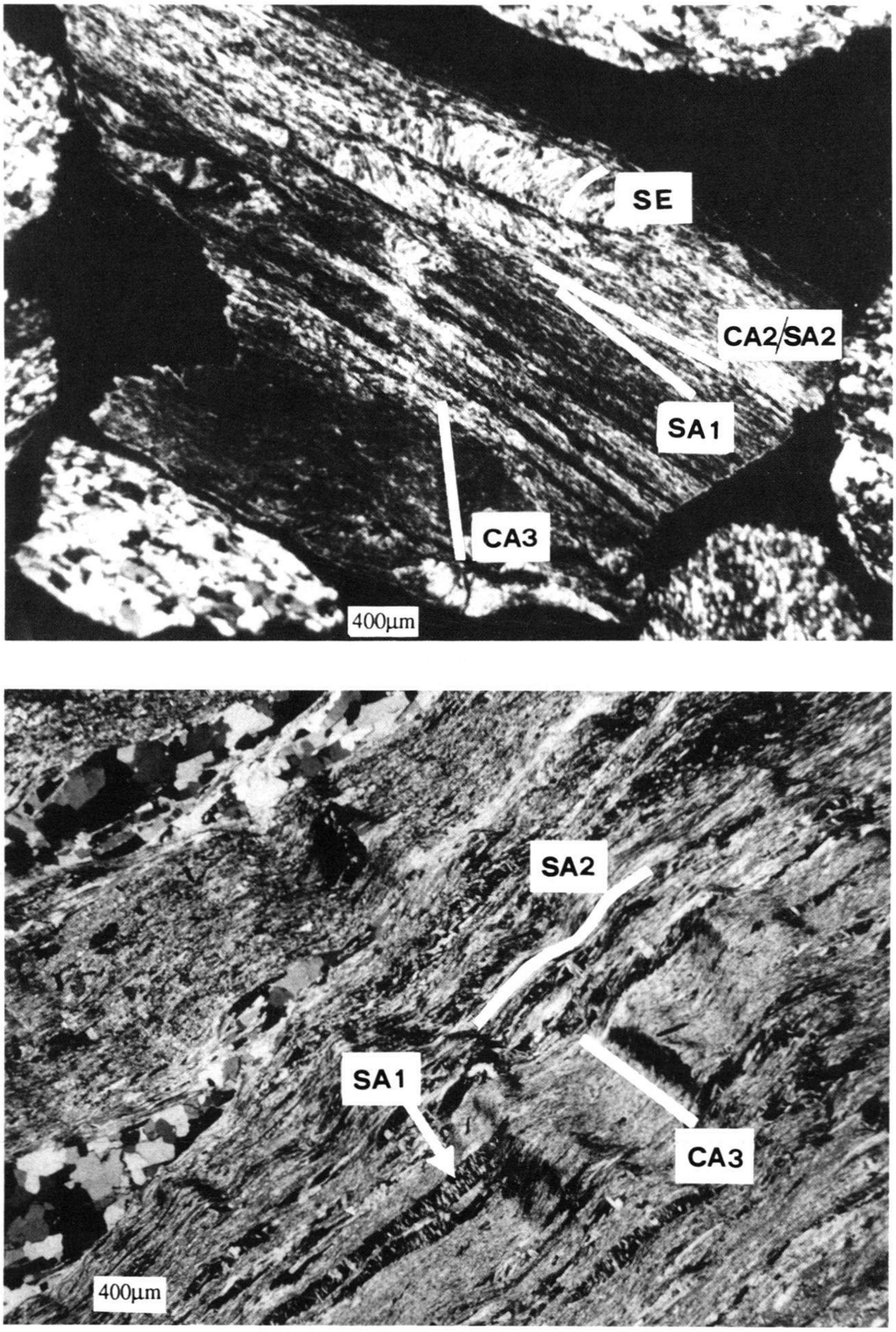


Fig. 4. Microphotographs of the structural features in the "Phyllitic-quartzitic Group". a (top): SE, SA1, CA2/SA2 and CA3 (I Domain). Crossed polars. b (bottom): SA1, SA2, and CA3 (II Domain). Polarized light.

TABLE 5 - "PHYLLITIC-QUARZITIC GROUP"

	HERCYNIAN EVOLUTION				ALPINE EVOLUTION					
DEFORMATIONAL EVENT	DX		DE		DA1		DA2	DA3		
METAMORPHIC EVENT	MX	MES	ME	MET	MA1	MAS1	MA2		MAS2	MAT
PHYLLITES AND QUARTZITES										
QZ	===?===		========		========		========			
MS	===?===		========	==?==	========		========	==?==?=		
CHL					========	==				
APL		==?==	========	==?==	========					
ILM			===?====		========		========			
PY			===?====		========		========		=======	
BIO										= ===
G.BIO										=== =
OX	===?===		========	==?==	========		========	==?==?=		
METABASITES										
TR. - ACT					========	== =				
SPH			========							
IPL			========							

LEGEND IN TABLE 3

Micaschist Group

The Micaschist Group is essentially represented by granolepidoblastic/porphyroblastic grey to dark grey-green micaschists and, sometimes, by grey granoblastic quartzites (see composition in Table 6). Noteworthy is the abundance of biotite and the presence of albite (Figs. 5a, b), garnets (Fig. 5c) and andalusite (Fig. 5d) porphyroblasts.

Locally greenish hornblende – bearing amphibolitic horizons have been found ("Ocean-floor basalts" in Puxeddu et al. 1984).

TABLE 6 - "MICASCHIST GROUP"

LITHOLOGY	TEXTURE	MINERALS	PARTICULAR REMARKS	STRUCTURAL FEATURES
Mica-schists and quartzites	Granolepidoblastic-porphyroblastic to Granoblastic	Quartz, Muscovite, Chlorite, Biotite (altered/kinked and static with triple boundaries), Albite (often Albite law twinned), Garnet (Almandine ± fractured and altered to Chlorite ± Quartz ± Ilmenite ± ± Epidote) ± Graphite (locally abundant) ± Ilmenite. Rare Chloritoid Accessories:Zircon, Tourmaline, Apatite, Titanite Towards the bottom occurrence of HT-BP Associations: - Pre-Alpine Cordierite (largely pinnitized) + andalusite - Late Alpine (chiastolitic Andalusite ± blue Corundum with Sanidine rims)	- Widespread occurrence of Albite and, locally, Garnet porphyroblasts with helicitic textures (opaque minerals and sometimes Quartz+Muscovite alignments) and Albite-Quartz pressure shadows. - Local nematoblastic amphibolitic levels with Hornblende (± altered to Tremolite -Actinolite), intermediate Plagioclase (± Albitized or calcitized/sausurritized), Titanite ± Ilmenite ± Quartz ± Apatite.	SA1 (MA1),SA2(MA2), CA3 Relics of pre-Alpine foliations: - Muscovite + Biotite ± Quartz ± Opaques alignments "Rods" and "Mica fish" (SE) - Helicitic textures (SX), within Garnet and Albite porphyroblasts,discordant with SA1 and locally, with SE

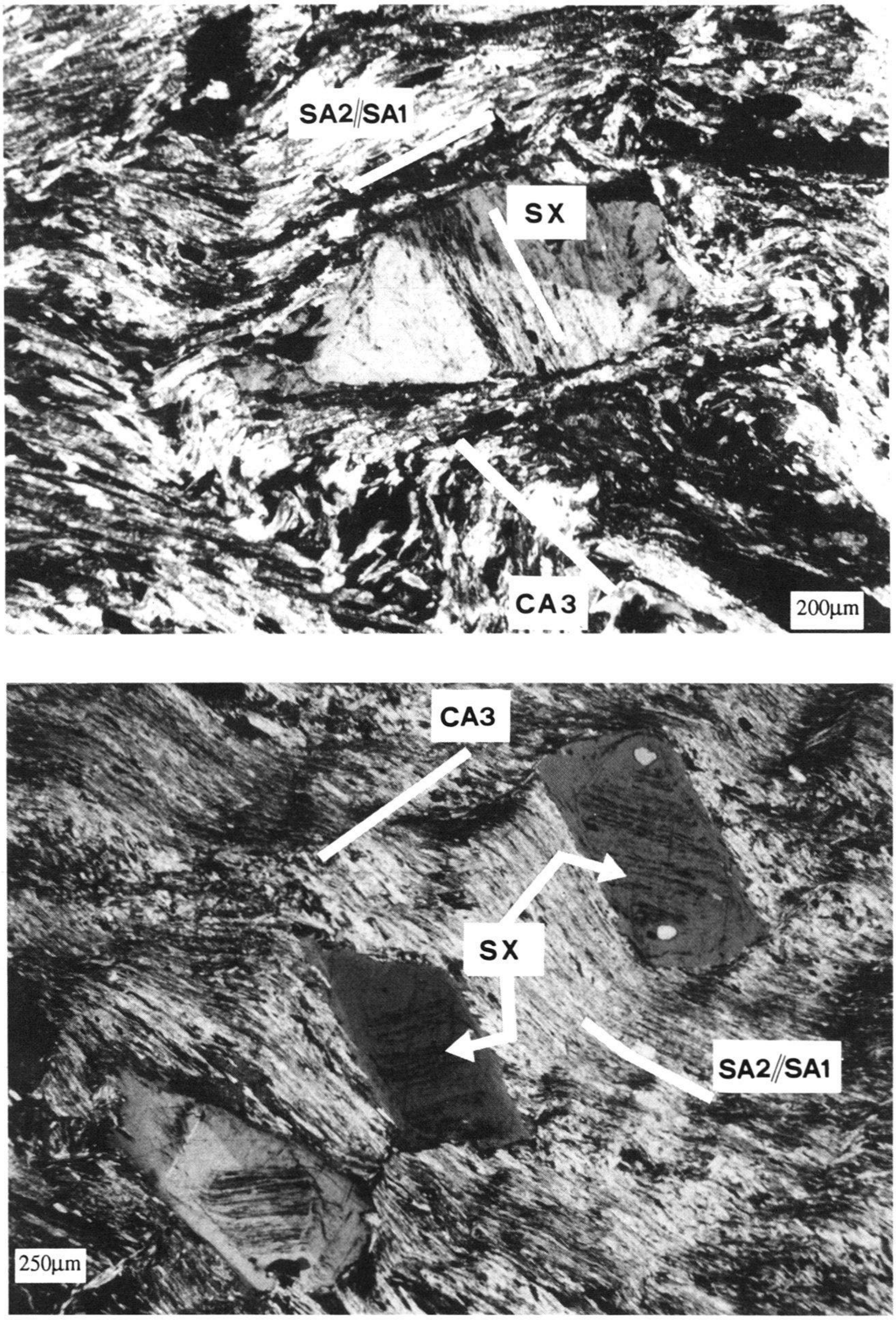


Fig. 5. Microphotographs of the structural features in the "Micaschist Group". a (top)–b (bottom): SA1/SA2, CA3 and SX (within zoned albite porphyroblasts). Crossed polars.

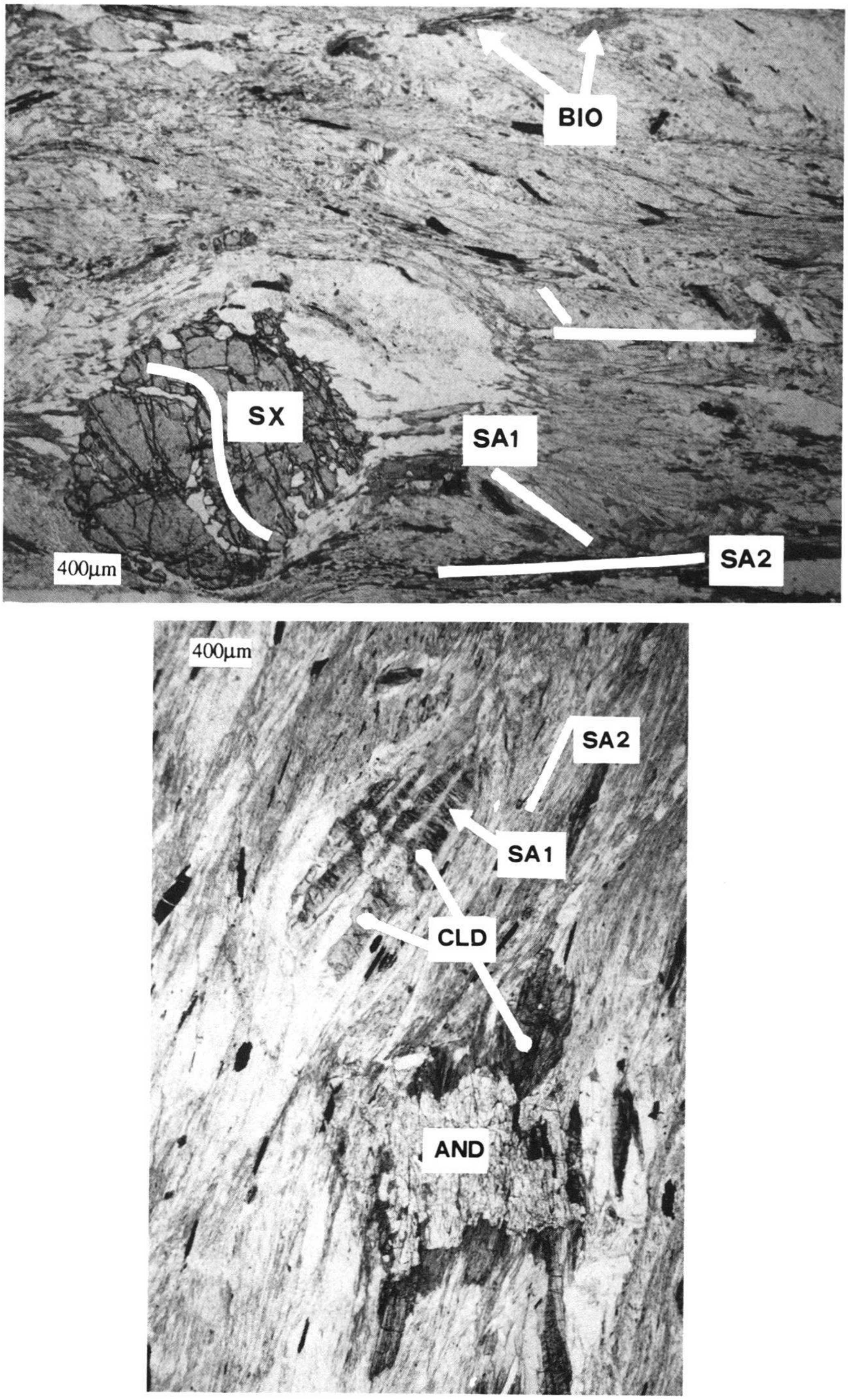


Fig. 5c (top): SX bearing garnet, SE biotite (BIO), SA1 and SA2. Polarized light. d (bottom): Post-SA1/pre-SA2 chloritoid (CLD) and post-tectonic andalusite (AND). Polarized light.

The thickness of the Micaschist Group varies from about 50 m to more than 800 m over the Larderello area (Fig. 6).

According to BAGNOLI et al. (1979) the Micaschist Group, of probable early Palaeozoic or even older age, has characteristics similar to the "M. Calamita Schist", on the island of Elba, and to the Palaeozoic rocks outcropping near the Cerreto Pass (e.g. BAGNOLI et al. 1979; location on Fig. 1).

Microstructural aspects: (Fig. 3)

The Alpine (DA1, DA2, and, locally, DA3) and probable Hercynian (DE, DX) events reveal features similar to those observed for the immediately overlying Domain II of the Phyllitic-Quartzitic Group. A noteworthy difference is the presence of biotite in the SE foliation and the growth of quartz parallel to the SX foliation (Fig. 5c).

SX-bearing garnet and albite porphyroblasts are often clearly rotated during the DA1 event (Figs. 5a, b, c).

Metamorphic events: (Fig. 3 and Table 7)

The helicitic inclusions (Figs. 5a, b, c) display a blastesis of quartz + muscovite + oxides (MX ?), which is older than the static crystallization of albite and garnet porphyroblasts (MES). Moreover, the chloritoid crystallization that took place locally preceded the formation of garnet. The synkinematic crystallization (ME) of quartz + coarse grained micas (muscovite ± biotite) + acidic plagioclase + oxides and hornblende (amphibolitic horizons) + intermediate plagioclase + titanite, is associated with the next deformation event (DE). The static blastesis of cordierite and andalusite occurred during a post-DE/pre-DA1 HT-LP event (MET).

During the Alpine phases, a synkinematic blastesis DA1 (MA1) of fine grained muscovite + quartz + albite + opaques + chlorite occurred, as well as retrograde metamorphism of some Hercynian minerals (chloritization of biotite and garnet, pinitization of cordierite, transformation of hornblende into tremolite-actinolite and/or chlorite, albitization of intermediate plagioclases). This was followed during event DA2 by the crystallization of fine-grained muscovite + opaques ± quartz.

Locally post-DA1/pre-DA2 chloritoid blastesis (MAS1) can be noted (Fig. 5d).

The late Alpine thermal event caused the static crystallization (MAT) of brown biotite (K-Ar age=2.9–3.8 MA, BATINI et al. 1985), chiastolitic andalusite (Fig. 4c), corundum and K-feldspar (BATINI et al. 1983).

Gneiss Group

These rocks, which are unknown in outcrop all over the Northern Apennines, are the deepest and, probably, the oldest metamorphics (Lower Palaeozoic? – Precambrian?) of the Tuscan Basement, that have been reached by drilling until today.

The Gneiss group (Fig. 6) is mainly represented by grey-brown to grey-green coarse-grained quartzitic rocks, characterized by a typical "differentiated layering" with granoblastic, leucocratic (quartz and plagioclase rich), and lepidoblastic melanocratic (biotite rich) millimetre-scale bands. Most of these rocks can be petrographically referred to as gneiss s.l., others to amphibolites/amphibolitic gneiss with widespread occurrence of hornblende ("Ocean-floor basalts" in PUXEDDU et al. 1984) or to ortho-

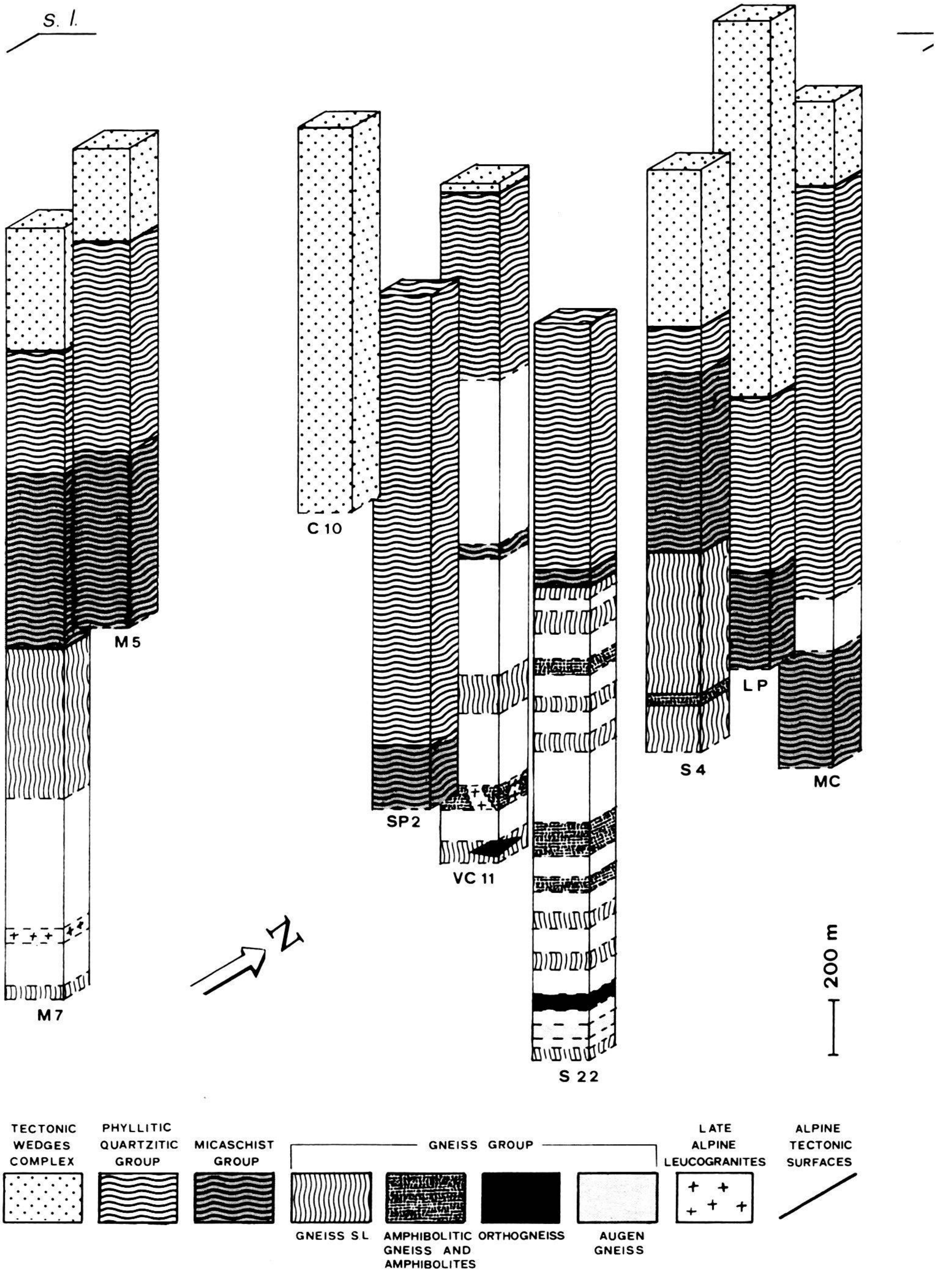


Fig. 6. Series of depth profiles including the "Tectonic Wedges Complex" and basement sequences, found in the studied drill samples in the Boraciferous region (see from the SE; dashed areas indicate portions of basement which were not sampled because of loss of circulation).

TABLE 7 - "MICASCHIST GROUP"

	HERCYNIAN EVOLUTION				ALPINE EVOLUTION					
DEFORMATIONAL EVENT	DX		DE		DA1		DA2	DA3		
METAMORPHIC EVENT	MX	MES	ME	MET	MA1	MAS1	MA2		MAS2	MAT
MICA-SCHIST										
QZ	===?====		========	= =	========		========			====
MS	===?====		========	== =	========		========			
CHL					========	= =				
BIO		====	===?====	====						======
APL		==?===	========		========	= ==				
GR		===								
CLD		====				=========				
OX	===?====		========	= =	========		========			
ILM			====?===		========		========			
AND				=====						=======
CRD				======	- PINITIZATION -					
COR										=======
KF										=======
METABASITES										
HBL			========							
SPH			========							
IPL		=?=	========							
TR-ACT					========	= ==				

LEGEND IN TABLE 3

gneiss/augen gneiss (characterized by K-feldspars, sometimes perthitic, and andesine, sometimes with myrmekitic textures: see Fig. 7a and, for more compositional details, Table 8).

The plagioclase (andesine) locally shows the following peculiarities:

– local coexistence with other plagioclase of more basic composition and, frequently, poikiloblastic;

– rare inverse zoning (rims An > 50%);

– many types of inclusions (frequently discordant with respect to the rock foliation) such as helicitic textures (opaques + muscovite and, rarely, aligned quartz), static fibrolitic/prismatic sillimanite and small garnets (almandine) (Fig. 7b), locally superimposed on the helicitic textures.

HT-LP mineral associations are very frequent in these rocks in particular cordierite (frequently pinitized) + andalusite but, in the deeper levels, andalusite seems to disappear and fibrolitic sillimanite ± K-feldspar (sanidine type and, sometimes, perthitic microcline) are locally observed.

These associations always overprint the typical "layering". Moreover, crenulated mylonitic quartz textures (ribbon quartz) have been locally recognized in the upper part of this Group (Fig. 7c).

Fig. 7. Microphotographs of the structural features in the "Gneiss Group". a (top): Myrmekitic texture (MY) in orthogneiss. Crossed polars. b (center): Syn-SE andesine with inclusions of garnet (GR). Crossed polars. c (bottom): Post-SE ribbon quartz in amphibolitic gneiss. Crossed polars.

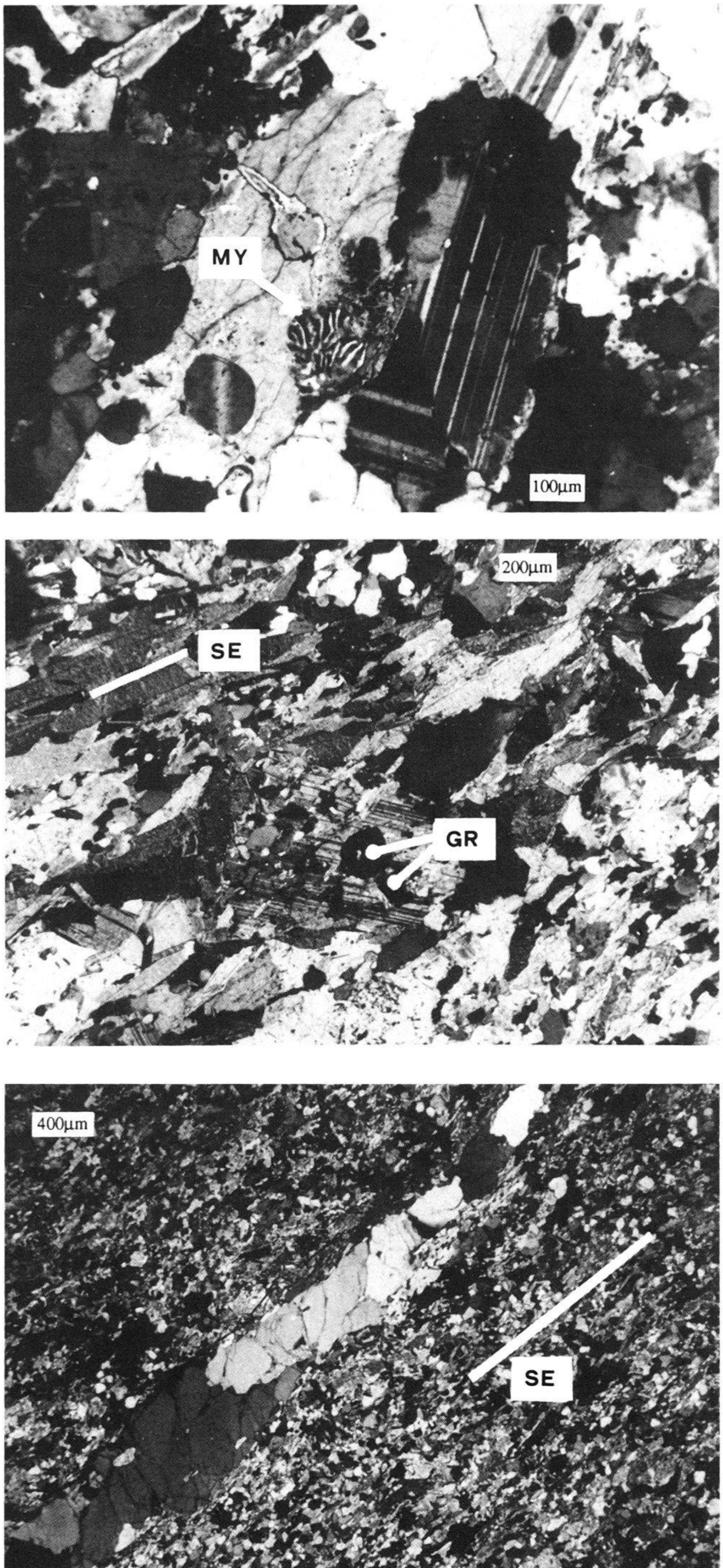

MY
100μm
200μm
SE
GR
400μm
SE

TABLE 8 - "GNEISS GROUP"

LITHOLOGY	TEXTURE	MINERALS	PARTICULAR REMARKS	STRUCTURAL FEATURES
Coarse to medium grained gneiss	Alternating granoblastic (Quartz + Plagioclase) and Lepidoblastic (Biotite rich) levels	Quartz, intermediate Plagioclase (An 30-50%, with polysynthetic/Albite-Carlsbad twinning), Biotite (altered/ /kinked and static with triple boundaries) ± Muscovite ± Chlorite ± Garnet (Almandine) Accessories: Zircon, Titanite, Ilmenite, Apatite, Tourmaline, Pyrite (Gneiss L.S.)	Occurrence of inclusions in the Andesine Plagioclase: - Helicitic textures (opaque minerals + Muscovite ± Quartz) - Fibrolitic/prismatic sillimanite - Garnet (post-dates Helicitic textures) In the upper part, mylonitic horizons (ribbon quartz textures)	Only one coarse grained pervasive schistosity, made up of minerals attributed to a pre-alpine foliation (SE) in the Phyllitic-quartzitic Group and in the Micaschist Group, is recognizable; this foliation predates the HT-BP associations (clearly pre-alpine in the Micaschist Group). They are followed by a mylonitic event and a later weakly crenulated one (Alpine phases?) Relics (helicitic textures in the Plagioclase and garnet) of a pre-SE foliation (SX) are also present
	Nematoblastic to Granoblastic	Hornblende (often altered to Tremolite-Actinolite), An 45-50% Plagioclase, Titanite, Biotite ± Chlorite ± Quartz (Amphibolitic gneiss and Amphibolites)		
	Granoblastic to Porphyroblastic/Augen	Quartz, K-Feldspar (often perthitic; sometimes it includes Quartz, Biotite and Plagioclase), Andesinic plagioclase (local myrmekitic textures), Biotite ± Garnet ± Chlorite (Orthogneiss and Augen Gneiss)		
		Widespread occurrence of HT-BP Associations: - Cordierite (± pinnitized) + Andalusite ± Biotite - Cordierite (± pinnitized) + fibrolitic Sillimanite ± ± K-Feldspar (deeper levels)		

Microstructural aspects: (Fig. 3)

The rocks of the Gneiss Group preserve out only one well-defined penetrative schistosity, represented by the layering described above. This foliation may be attributed to a pre-Alpine deformation event (DE), because of the presence of only coarse grained micas (analogous to the relics of SE in the other groups of the basement) and its existence before the HT-LP MET metamorphic event. Relics of an older foliation event (DX) can, however, be recognized as rare helicitic inclusions of opaques and muscovite + quartz within garnets and syn-SE andesine.

In several core samples, there is also evidence of a slight crenulation of SE. Because it also deforms the post-SE HT-LP associations (MET), this event may have occurred later (Alpine deformation?). The same can be said for the origin of the mylonitic textures described above, which are generally parallel or at low angle in respect to the foliation and the MET minerals, but, at the same time, are crenulated by the later deformation event.

Metamorphic events: (Fig. 3 and Table 9a, b)

A blastesis (ME), synkinematic with respect to DE, can be recognized with crystallization of quartz + andesine plagioclase + biotite + oxides ± muscovite ± hornblende (amphibolitic horizons) ± K-feldspar (orthogneiss). Sillimanite and garnet occurring within plagioclase indicate the existence of a static blastesis event (MES) before DE. The rare occurrence of staurolite (Puxeddu, pers. comm.) may be connected with the MES event. Moreover, the helicitic inclusions of opaques ± muscovite ± quartz (in plagioclases and garnet) could indicate a metamorphic-deformation event (MX, DX) prior to ME.

The HT-LP mineral assemblages and plagioclase with An>50% belong to a post-DE thermal event (MET dated 285±11 Ma by Del Moro et al. 1982). Alpine syn-

TABLE 9a "GNEISS GROUP"

	HERCYNIAN EVOLUTION				ALPINE EVOLUTION					
DEFORMATIONAL EVENT	DX		DE		DA1		DA2	DA3		
METAMORPHIC EVENT	MX	MES	ME	MET	MA1	MAS1	MA2		MAS2	MAT
GNEISS L.S.										
QZ	========		========							
IPL		===?===	========	===						
BIO		===?===	========	====						======
MS	========		========	====						
GR		===	== =							
AND				====						
CRD				=====	- PINITIZATION -					===?===
CHL					========	== =				
P SIL		===								
F SIL		==		=====						
KF				====						
BPL				====						
OX	========		========							
APL		===								

LEGEND IN TABLE 3

TABLE 9b - "GNEISS GROUP"

	HERCYNIAN EVOLUTION				ALPINE EVOLUTION					
DEFORMATIONAL EVENT	DX		DE		DA1		DA2	DA3		
METAMOPHIC EVENT	MX	MES	ME	MET	MA1	MAS1	MA2		MAS2	MAT
AMPHIBOLITES AND/OR AMPHIBOLITIC GNEISS										
HBL			========							
IPL		=?=	========	===						
SPH			========							
TR-ACT					========	= ==				
CHL					========	= ==				
BIO		==?==	========	==== =						======
QZ			========							
ORTHOGNEISS/AUGEN GNEISS										
QZ		== =	========							
XF		== =	========	=====						
IPL		== =	========							
CHL					========	= ==				
BIO		==?==	========	====						======
GR		==?==								
MS			========	====						

LEGEND IN TABLE 3

deformational blastic phenomena are not observed; on the contrary, static retrograde metamorphism is evident and similar to that observed in the Micaschist Group.

The late Alpine HT-LP event (MAT) is represented by the widespread static neo-crystallyzation of biotite (2.5–3.8 Ma in Del Moro et al. 1982; Batini et al. 1984; Villa et al. 1987) and, locally, also of rare cordierite idioblasts.

Results

The Palaeozoic to Middle Triassic rocks in the Larderello region show evidence for several phases of metamorphism and deformation. The "Basement" rocks largely preserve pre-Alpine textures and mineral associations. A preliminary schematic pattern can be outlined, which considers both pre-Alpine and Alpine deformation and crystallization phases.

The Alpine events can be easily recognized both in the Tectonic Wedges Complex and in the Phyllitic-Quartzitic Group/Micaschists Group of the basement. An earlier deformation phase (DA1–MA1) is always characterized by the development of a penetrative schistosity (SA1), that obliterates older foliations in the basement rocks. A static metamorphism (MAS1) that follows this phase is frequently observed (e.g.: chloritoid in Verrucano "A"; kyanite ± chloritoid in Verrucano "B"; chloritoid in Micaschist Group). A later deformation phase (DA2) results in a crenulation of SA1; with increasing depth, this phase is more clearly developed producing a schistosity surface (SA2) associated with blastesis. A still later deformative event (DA3), which weakly crenulates SA2, as well as a subsequent static blastesis of chloritoid (MAS2), can locally be observed (ex. in the Verrucano rocks). All these events occurred under greenschist metamorphic conditions (Franceschelli et al. 1984).

During these phases (and in particular during DA1), retrograde metamorphism of pre-Alpine relics took place in the basement rocks (e.g. chloritization of biotite and garnet, pinitization of cordierite, etc). Finally a HT-LP metamorphism event followed, locally reaching high-grade conditions (andalusite + corundum ± K-Feldspar: $T > 600$ $P \sim 1$ Kb, in Del Moro et al. 1982), linked to the emplacement of Tuscan anatectic magmatic bodies.

It is very difficult to reconstruct the pre-Alpine metamorphic-deformation events in the basement rocks, because of the strong DA1 transposition. In the Phyllitic-Quarzitic Group and in the Micaschist Group, however, there are relics of a pre-SA1, probably Hercynian, schistosity (SE) that precedes the static HT-LP event (MET, presumably of late Hercynian age). Moreover, the albitic and garnet porphyroblasts (rotated and deformed by SA1 but, perhaps even by SE) and their inclusions can be referred to a pre-DE static event (MES) superposed on an older schistosity (SX).

From the Micaschist Group to the deeper Gneiss Group, the deformation framework changes quite abruptly. In the Gneiss Group, Alpine deformation produced only weak crenulations of the schistosity which is defined by large blasts of mica (biotite ± muscovite) + quartz + plagioclase + hornblende. The superposition of HT-LP minerals (referred to the late Hercynian thermal event-MET) suggests that this schistosity (SE) is related to a pre-Alpine deformation-blastic event (DE-ME). Moreover, the garnet and sillimanite inclusions and the helicitic textures in the syn-SE plagioclase indicates the presence of the MES and DX events, such as in the Micaschist Group.

Therefore, in the basement rocks a Hercynian deformation-blastic event (DE-ME), which reached amphibolitic grade and a following HT-LP event (MET), are clearly recognizable. In addition, there is evidence for an older foliation event (DX-MX), on which phenomena of a pre-DE "Barrovian" static metamorphic event (MES) were superimposed.

Concluding remarks

The most important results of this study, are:

– In most metamorphic sequences of the Larderello geothermal field there are two Alpine blastic-deformation phases (DA1 and DA2) comparable with those described throughout Tuscany by previous authors (Moretti 1986; Carmignani et al. 1987: Costantini et al. 1987), as well as evidence for a later crenulation event (DA3).

– The emplacement of the Tectonic Wedges Complex has occurred at least during/ after the Alpine DA2 deformation phase. This complex includes sequences of different metamorphic grade and variable deformation acquired during Alpine deformation (e.g. Verrucano "A" and Verrucano "B"). Moreover, the similarity in metamorphic-deformation features of the Verrucano and of the Upper Palaeozoic sequences to those observed in the Phyllitic-Quartzitic Group suggests that they may represent the same original cover of the basement reached by drilling in the Larderello area.

– For the basement, the following conclusions can be summarized:

a) There are relics of two systems of foliations, which are both demonstrably pre-Alpine in age, as well as a HT-LP late Palaeozoic metamorphic event (e.g. 285±11 Ma radiometric data in Del Moro et al. 1982);

b) The gradual passage between the Phyllitic-Quartzitic Group and the Micaschist Group is accompanied by increasing metamorphism (from low-grade greenschist facies to low-grade amphibolitic facies) and gradient in the deformational fabrics (e.g. with depth the DA2 turns from a crenulation into a transposed schistosity);

c) A sharp change in metamorphic grade with a drastic decrease in the effects of Alpine deformation characterizes the contact between the Micaschist Group and the Gneiss Group (in the latter the Hercynian foliations result at the most to be weakly crenulated by Alpine events, possibly DA2 or DA3 phase). Moreover the highly variable thickness of the Micaschist Group and the mylonitic textures in the upper part of the Gneiss Group, could support the hypothesis of a tectonic detachment of the whole Phyllitic-Quartzitic Group + Micaschist Group from the underlying Gneiss Group during the main compressive Alpine phase (DA1 phase). This suggests that important thrusts also affected the deeper horizons of the Tuscan Palaeozoic basement during the Northern Apennines tectongenesis. If this is the case, the name "basement" should only be retained for the Gneiss Group rocks.

d) The evolution of the Hercynian metamorphism and deformation appears to be similar to that of the Sardinian Basement. In fact, the latter shows a Barrovian metamorphism (M_1 in Franceschelli et al. 1982, dated at 344±7 Ma in Ferrara et al. 1978) which is diachronous in relation to the Breton deformation phase (D_1 in Elter et al. 1985, 1986); a subsequent retrograde metamorphism (M_2 in Franceschelli et al. 1982), syn-kinematic with respect to the sudetic D_2 deformation phase (Elter et al.

1986), took place before widespread late Hercynian magmatic intrusions (dated 310–240 Ma by Ferrara et al. 1978).

The same tectonic-metamorphic framework characterizes other European Hercynian sequences, such as the Maures Massif (Ricci & Sabatini 1978; Vauchez & Buffalo 1988; Matte 1986; Elter 1987; Elter et al. 1989), the Central Massif-Montagne Noire (Bodinier et al. 1986), the Armorican Massif (Berthe et al. 1978), the Vosges (Wichert & Eisbacher 1988) and the W and S-SW areas of the Iberian Peninsula (Burg et al. 1981).

On the basis of these relationships, we suggest a probable connection between the Larderello Hercynian sequence and the basement of NE Sardinia (the Moldanubian Migmatitic Complex in Elter & Sarria 1989) and the southern-western European ones, as also proposed by previous authors (e.g. Bagnoli et al. 1979; Pandeli et al. 1988; Elter et al. 1989).

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