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Tectono-Metamorphic evolution of the anthracite - bearing Basin of La Thuile (External Briançonnais Zone)

par Andrea VALENTE* et Alessandro BORGHI**

ABSTRACT.– This paper deals with the microstructural and petrographic study of the anthracitiferous basin of La Thuile (Val d'Aosta). Three tectonic units are distinguished from lower to upper structural level: 1) the Versoyen Zone (Brèches de Tarentaise); 2) the Petit St. Bernard Zone; 3) the Houillère Zone. The Houillère Zone (External Briançonnais Zone) represents the lower and the more external tectonic unit belonging to the Briançonnais nappe system. The anthracitiferous basin of La Thuile consists of graphitic schists with minor intercalations of coarse metaconglomerates. These metasediments show two ductile deformation phases. The first tectonic foliation (S_1) has developed under high pressure–low temperature conditions (phengite+chlorite+paragonite+pyrophyllite±chloritoid±rutile). The axes are NE–SW oriented and the axial plane cleavage plunges towards SE. A second pervasive tectonic foliation (S_2) has developed under low P-low T metamorphic conditions. Therefore, metamorphic evidence for a low thermal gradient (ca. 10° C/km), reflecting a subductive tectonic environment, has been detected in the Northern sector of the Houillère Zone. Hence, the tectono-metamorphic history inferred for the anthracitiferous basin of La Thuile, is consistent with the low geothermal gradient displayed by the adjoining tectonic units. Finally, comparing the inferred tectono-metamorphic evolution with other tectonic units of the Briançonnais nappe system a subductive Alpine evolution for both the Internal and the External sectors of the Briançonnais Zone is suggested.

KEY WORDS.– Houillère Zone, metamorphic evolution, mineral chemistry, Western Alps.

Évolution tectono-métamorphique du bassin anthracitifère de La Thuile (Zone briançonnaise externe)

RÉSUMÉ.– La zone Houillère (Briançonnais externe) représente l'unité tectonique la plus externe et la plus profonde de la zone briançonnaise. Cet article rend compte des résultats d'une étude qui a été faite sur la portion de la zone Houillère correspondant au bassin anthracitifère de La Thuile (val d'Aoste).

Dans cette zone, trois unités tectoniques ont été distinguées. De bas en haut ce sont du point de vue structural : 1) la zone du Versoyen (Brèches de Tarentaise) ; 2) la zone du Petit St.-Bernard ; 3) la zone Houillère. Une mince bande mylonitique se trouve le long du cisaillement basal du Briançonnais.

L'étude pétrographique et microstructurale effectuée sur les roches de la zone Houillère a permis de reconstruire l'évolution métamorphique alpine de cette unité. La zone Houillère est composée de schistes graphitiques avec intercalations mineures de métaconglomérats grossiers. Ces métasédiments montrent deux phases de déformation ductile. La foliation tectonique associée à la première phase (S_1) est définie par une paragenèse de haute pression et basse température (phengite + chlorite + paragonite + pyrophyllite ± chloritoïde ± rutile). Les axes sont orientés NE-SW et le plan axial plonge vers le SE. Une deuxième foliation (S_2) s'est développée en conditions métamorphiques de basse P et basse T. Il s'ensuit que la zone Houillère elle aussi a été intéressée

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par un événement de gradient thermique faible (10° C/km) qui reflète un régime tectonique de subduction. Enfin, la confrontation avec l'évolution métamorphique et structurale des unités tectonique adjacentes a mis en évidence certaines ressemblances comme la présence d'un premier événement de même gradient thermique qui a respectivement atteint le faciès schistes bleus de basse T dans la zone Houillère et de haute T dans les unités du Briançonnais interne.

Mots clés.– Zone Houillère, évolution métamorphique, Alpes occidentales.

1. – Introduction

The anthracitiferous basin of La Thuile (Aosta Valley) belongs to the Permo-Carboniferous mono-metamorphic cover of the nappe system of the Briançonnais Zone. The Briançonnais Zone *s.l.* outcrops all along the arc of the Western Alps, from the Valais to the Liguria (fig. 1).

It can be structurally subdivided into two parts bounded by a tectonic contact: 1) the **External Briançonnais Zone,** consisting of the Houillère Zone (Permian to Upper Carboniferous in age) and the classical sequences of the Briançonnais cover (Mesozoic to lower Cainozoic in age), 2) the **Internal Briançonnais Zone**, including various basement units with cover sequences dated from Permian to lower Cainozoic age.

Moreover, the Briançonnais basement can be subdivided into "younger" and "ancient" independent tectonic units according to the definition of Desmons and Mercier [1993]. The younger basement records no trace of pre-Alpine metamorphic imprint and consists of the Mont Fort Nappe, the Mont Pourri-Bellecôte Massif, the "Zona Interna", the Ambin Complex of the homonymous massif, most part of the Acceglio Zone and the Costa Dardarella Massif [e.g. Desmons and Mercier, 1993; Thélin *et al.*, 1993]. On the contrary, the ancient basement shows effects of pre-Alpine metamorphism and includes the Siviez-Mischabel Nappe, the Pontis Nappe, the Ruitor Massif, the Sapey Zone, the Chasseforêt Massif, the Clarea Complex of the Ambin Massif, the Nucetto Massif and the Savona-Calizzano Massif.

The units of ancient basement display relicts of pre Alpine metamorphism superimposed in Alpine time by a first high-pressure event and later events of low pressure and medium to high T/P gradients [Messiga, 1981; Cortesogno, 1984; Desmons and Mercier, 1993; Thélin *et al.*, 1993, Borghi *et al.*, 1999]. The « intermediate slices », located near Briançon and part of the Acceglio Zone are instead of more uncertain attribution. A detailed description of the different units belonging to the Briançonnais Zone is found in Desmons and Mercier [1993, with references].

The Briançonnais Zone is overthrust to West on the narrow Sub-Briançonnais Zone (Basal Briançonnais Thrust, BBT) or, locally, on the Valais Zone, which in turn are in contact with the external zone of the Alpine

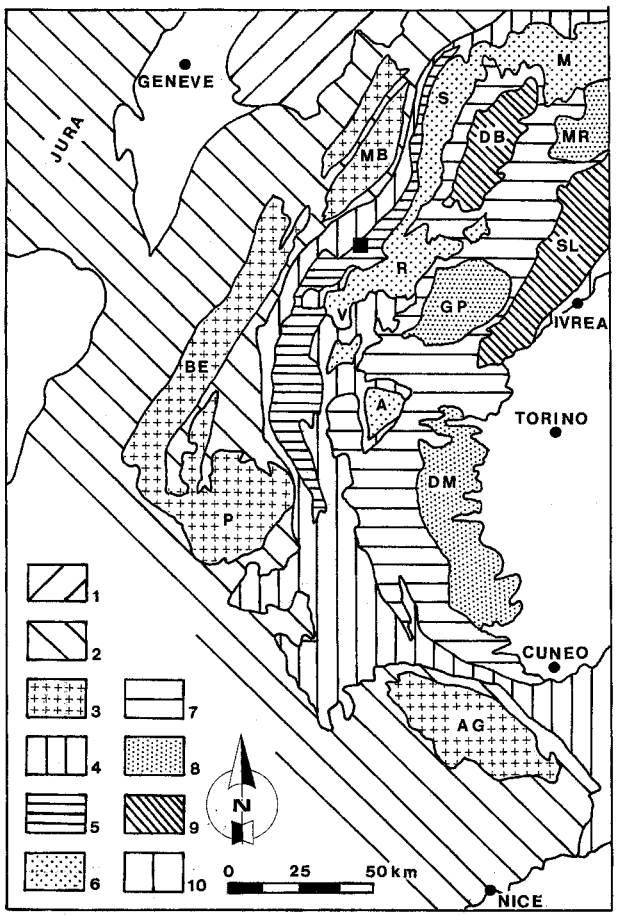

Fig. 1 .– Tectonic sketch map of the Western Alps. **1**: Prealps. **2**: Palaeogenic and Mesozoic Helvetic Nappes, Jura and Dauphinois domains. **3**: External crystalline Massif of the Helvetic Domain (MB = Mont Blanc; BE = Belledonne; P = Pelvoux; AG = Argentera). 4 -6: Briançonnais Zone - **4**: Mesozoic Cover, **5**: Houillère Zone, **6**: Pre-Alpine polymetamorphic basement (M = Mischabel; S = Siviez; R = Ruitor; V = Vanoise; A = Ambin). **7**: Piemont Zone. **8**: Internal Penninic Nappes (MR = Monte Rosa; GP = Gran Pararadiso; DM = Dora-Maira). **9**: Austro-Alpine Domain (DB = Dent Blanche; SL = Sesia Lanzo Zone). The solid square indicates the location of the investigated area.

the East, instead, the contact that originally carried the Piemont Zone to overlap onto Briançonnais units was inverted by the backfolding phase with a vergence directed eastward. The backfolding phase was accompanied by an extensive backthrusting, well developed in Aosta Valley and in Val Savaranche (Entrelor Thrust), which carried the Internal Briançonnais Zone onto the structurally higher Zermatt-Saas Zone [Freeman *et al.*, 1997]. Therefore, the Briançonnais Zone shows a double vergence: toward West in the outer part and toward East in the inner part, forming the so-called "Briançonnais fan" of Bourbon *et al.* [1973], recently interpreted by Butler and Freeman [1996] as a pop-up structure.

The Alpine metamorphic evolution of the Briançonnais Zone is polyphasic. It consists of a first event of high-pressure low-temperature conditions, which reached the epidote - or lawsonite-blueschists facies [according to the classification of Evans, 1980] in the basement tectonic units of the Internal Briançonnais Zone [Dal Piaz and Govi, 1965; Bocquet, 1974; Desmons, 1977; Borghi and Gattiglio, 1997, Desmons *et al.*, 1999]. Instead, in the External Briançonnais Zone this first metamorphic event developed under lawsonite–albite-chlorite facies conditions. Finally, a second metamorphic event, characterized by a generalized greenschist facies overprinting of low pressure developed.

Particularly, in the Houillère Zone the main metamorphic imprint is of greenschist facies. High pressure relics are only reported South of the Isère valley, where volcanic rocks included in the Houillère Zone contain assemblages characteristic of the lawsonite–albite–chlorite facies [Desmons *et al.*, 1999]. Moreover, in the Aosta valley area no trace of high-P metamorphism is reported for the Houillère Zone, likely due to a stronger greenschist overprint.

In contrast, across the French-Italian border close to the Petit St. Bernard Pass, high-pressure conditions are reported in the adjoining units of the Houillère Zone. Indeed, blueschist and eclogite facies conditions were found in various sectors of the Versoyen unit of Valais Zone [Schürch, 1987, with references; Cannic *et al.*, 1996], and in the Petit St. Bernard Zone [Goffé andBousquet, 1997], which represent the tectonic hangingwall of the Houillère Zone. Therefore, the Basal Briançonnais Thrust is considered as the main tectonic contact which separates two sectors that experienced significantly different Alpine geodynamic evolution [Fügenschuh *et al.*, 1999].

This paper reports the metamorphic evolution of the anthracitiferous basin of La Thuile (belonging to the Houillère Zone), where evidence of a high-pressure metamorphic event has been found. Its comparison with the metamorphic evolution of the adjoining units allows to propose a new model which simplifies the geological history of the Petit St. Bernard Pass area.

2. – Houillère Zone

The Houillère Zone, defined by Gignoux and Moret [1934], includes Upper Carboniferous and Permian continental metasediments and magmatic rocks, interpreted as molassic deposits of the Variscan chain. The Upper Carboniferous series has been intruded by subvolcanic, porphyritic rocks, which show cross-cutting relationships. This tectonic unit outcrops almost continuously from the Cottian Alps to the Swiss Alps. The Alpine thrusting phases uncoupled the Carboniferous series from its primary basement, which remains unknown. On the basis of tectonic and sedimentary evidence, the Houillère Zone can be divided in two series, separated by a major discontinuity corresponding to the Asturian phase of Feys [1963]:

1) a very thick **lower series** which consists of sandstones and pelites, rich in coal and dated from Namurian to lower Stephanian times [Greber, 1965];

2) an **upper series** constituted by conglomerates and sandstones, characterized by gradually more arid climate. The presumed age range from middle Stephanian to Lower Triassic [Desmons and Mercier, 1993].

At the base of the **lower series** monotonous clastic deposits, more than 2500 m thick, of Namurian up to lower Stephanian age occur [Feys, 1963]. The clasts are mainly represented by polycrystalline quartz, paraschists and gneiss displaying a polyphasic pre-Alpine metamorphic imprint, possibly derived from the Briançonnais basement. From the lower part toward the top, this series can be divided into four levels: Westphalian A, B, C, which represents the more anthracitiferous-rich sediments of the whole Houillère Zone, and Westphalian D. Inside this series a level 100-200 m thick containing fossil flora of Namurian age is present [Feys and Greber, 1952]. These sediments represent the most ancient sedimentary terranes discovered and dated in the Western Alps. In the whole Houillère Zone the Upper Carboniferous series has been intruded by sub-volcanic rocks, showing a calc-alkaline trend [Debelmas and Kerckhove, 1980; Piantone, 1980].

The **upper series** consists of highly colored continental clastic or volcaniclastic sedimentary rocks, strongly contrasting with the underlying monotonous Upper Carboniferous series. A major regional unconformity defines a lower and an upper complex [Fabre and Feys, 1966; Fabre *et al.*, 1987]. On the internal border of the Houillère Zone, the lower complex (middle Stephanian) is represented by conglomeratic formation bearing crystalline basement clasts, which lies unconformably on the coal measures. On the external border, the lower complex is mainly volcaniclastic, containing conglomerates, tuffaceous sandstones and pelites. The upper complex (Permian-Lower Triassic) is represented by the

Verrucano conglomerates and by variegated pelites near Briançon, while it is represented by ankeritic sandstones and sericitic schists in the Arc and Isère valleys. These facies, attributable to Neopermian [Feys, 1963], gradually change to Werfenian quarzites [Caby, 1964].

In the Internal Briançonnais Zone the Upper Carboniferous cover is missing, while the Neopermian levels lie with a depositional contact directly on the monometamorphic basement [Gay, 1970; Guillot and Raoult, 1984].

By the end of the Permian the Houillère Zone, together with the more internal basement units, formed a wide subsiding platform which was flooded during the Lower Triassic.

3. – Geological setting

A new geological map of the anthracitiferous basin of La Thuile was established. The studied area is located on the orographic right of the Dora of Verney and outcrops from Petit St. Bernard Pass as far as to the S. Carlo pass, located at the NE corner of the Geological Map (fig. 2). The anthracitiferous basin of La Thuile was object of intense industrial exploitation in the period ranging between the two wars [Clerici and Clerici, 1980]. The mining cultivations were definitely closed in 1966.

In the mapped area three different structural units are present, bounded by tectonic contacts (fig. 3). They consist from the lower to the upper structural level by 1) the flyschoid terranes (Brèches de Tarentaise) and the Versoyen complex of the Roignais-Versoyen Unit; 2) the calcareous slates of the Petit St. Bernard Zone; 3) the Upper Carboniferous graphitic schists of the Houillère Zone.

The **Roignais Versoyen Unit** [Cannic *et al.*, 1996] belongs to the Valais Zone which forms a thin unit bounded to the East and the West by two major thrusts: the Basal Briançonnais Thrust and the Penninic Front, respectively. The Brèches de Tarentaise (or Valais flysch) are composed by the following succession from bottom to top: the « Couches de l'Aroley », the « Couches de Marmontains » and the « Couches de Saint-Christophe » [Antoine, 1972; Fudral, 1973]. The age of the Brèches de Tarentaise is still debated, it could be Senonian to Campanian [Antoine, 1972] or Priabonian [Gely, 1989].

The Versoyen complex is composed of an alternation of oceanic metabasites and sediments. The age of the Versoyen complex is not determined. The presence in the metabasites of high-pressure metamorphic assemblages is reported [Lassere and Laverne, 1976; Cannic *et al.*, 1996; with references].

In the mapped area the Roignais Versoyen Unit consists of a narrow portion of the inverted limb of a large isoclinal synform verging toward NW, on the basis of S-type asymmetric folds looking toward NE. The prevailing lithology consists of the basal carbonate sequence of the « Valais flysch ». The rocks show a prominent tectonic foliation, which corresponds to the axial plane foliation of isoclinal folds of metric-decimetric dimensions. However, the original sedimentary texture is still well preserved.

The **Petit St. Bernard Zone** has a limited extension and is tectonically interposed between the other two units [Elter and Elter, 1965]. It is composed of Liassic calcareous slates and black shales [Antoine, 1972] which are attributed to the Sub-briançonnais Zone [Fudral, 1980].

In the mapped area the **Houillère Zone** is represented by a monometamorphic sequence of meta-conglomerates of Stephanian - Eopermian age [Elter, 1960; Greber, 1965; Fabre, 1989] at the top and of pelitic-psammitic schists with abundant anthracitiferous lenses of Westphalian-Stephanian age [Elter, 1960] at the bottom. The limit between the two sedimentary lithotypes is always gradual and marked by repeated intercalations of both lithologies. Finally, limited portions of the Triassic cover lying in discordance on the continental Permo-Carboniferous metasediments are present (M. Touriasse). This cover consists of quarzites attributable to the Lower Triassic and by dolomitic limestones, attributable to the Middle-Upper Triassic.

The tectonic contact which represents the external and lower limit of the Houillère Zone corresponds to the Basal Briançonnais Thrust (BBT), to which an age between 27 and 32 Ma has been recently attributed by Freeman *et al.* [1998]. The BBT is sub-parallel to the Penninic Front, which defines the limit between the high-pressure Penninic Domain from the low-pressure Helvetic Domain. The BBT dips moderately toward the East, generally with down-dip stretching lineations and top-to-northwest shear sense [Freeman *et al.*, 1998].

In the investigated area the BBT is outlined by a discontinuous mylonitic belt (fig. 2). In the Petit St. Bernard Pass area it consists of tectonized carbonate rocks (cargneule) which outcrops along the limit between the Houillère Zone and the Petit St. Bernard Zone. In the S. Carlo Pass area the tectonic contact between the Houillère Zone and the Versoyen unit is marked by a large (ca. 100 m) belt of gypsum, which enabled the tectonic displacement. Minor internal thrusts in the Permo-Carboniferous unit are also present (fig. 3).

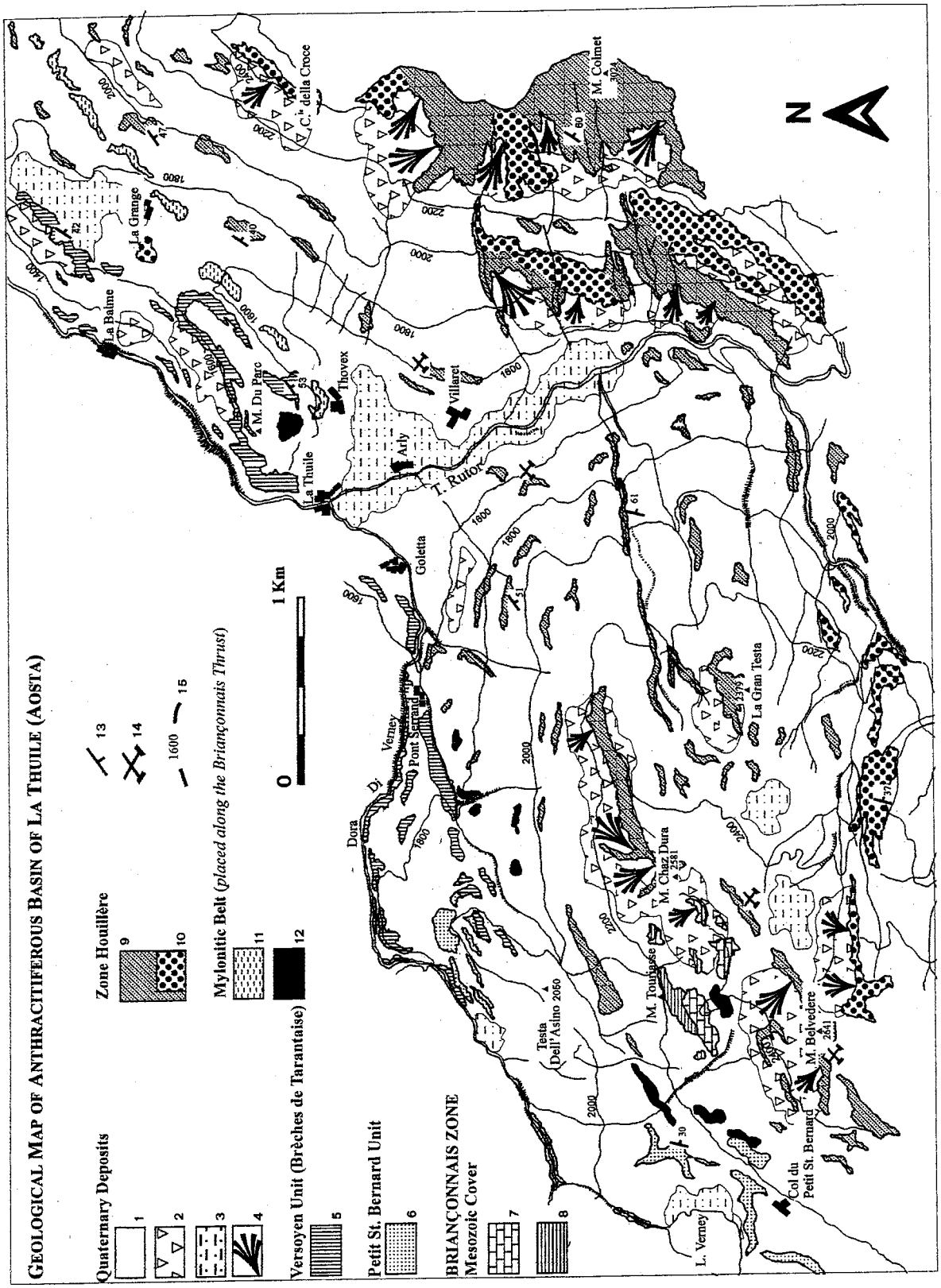

FIG. 2 – Geologic map of the Anthracitiferous Basin of La Thuile (Aosta Valley).

1-4 = QUATERNARY DEPOSITS 1: Eluvium - colluvium and glacial deposits; 2: Detritic deposits; 3: Alluvional deposits; 4: Detrital fans; 5: VERSOYEN UNIT; 6: PETIT ST. BERNARD ZONE; 7-12 = BRIANÇONNAIS ZONE. 7: Dolomitic limestones; 8: Quarzites; 9: Graphitic schists; 10: Metaconglomerates; 11: Gypsum; 12: Cargneules. SYMBOLS: 13: plunging of S_2 foliation; 14: Coal mines (derelict); 15: altitude countour lines.

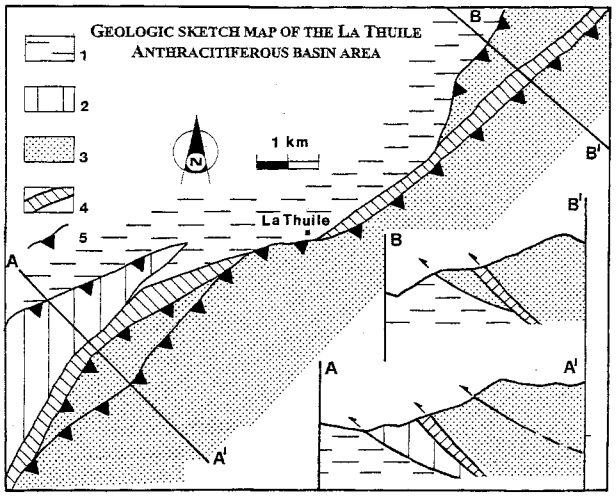

FIG. 3. – Interpretative sketch map of the La Thuile anthracitiferous basin area and cross sections (A-A' and B-B'). **1**: Versoyen unit (Valais Zone); **2**: Petit St. Bernard Zone; **3**: Permo-Carboniferous graphitic metasediments (Houillère Zone) **4**: mylonitic belt along the BBT (Basal Briançonnais Thrust); **5**: tectonic contacts.

3.1. Houillère Zone

The prevailing lithology is represented by graphitic schists of grey dark colour and very fine and homogeneous grain, bearing coal matter in varying quantity. The graphitic phyllites are very abundant. The amount of the organic portion can increase to the point that the rock becomes constituted almost exclusively of coal matter. It forms numerous lenses and measures of limited extension and thickness, with very irregular sharp, interbedded in the graphitic schists. The anthracite has a typically granular structure. It is constituted of very fine (100 μ) grains with rounded edge.

Graphitic schists show an obvious fissility determined by the presence of a tectonic foliation closely spaced and very pervasive. The peculiar character of these rocks is the presence of abundant lenses of quartz elongated parallel to the foliation planes. According to the fossils recovered by Peola [1903], these graphitic schists were attributed to the Westphalian.

To their inside, numerous lenses and intercalations of meta-sandstones and metaconglomerates occur. The limit between these different metasediments is generally gradual and often two or more lithological varieties repeatedly alternate. For this reason, in the geologic map of figure 2 only the bodies and the lenses of greater dimensions of metaconglomerates are distinguished.

They are monogenic in prevalence, and show a quartz-feldspathic matrix with a fine and homogeneous grain. The pebbles show dimensions of 2-5 cm and are rounded in shape. They are slightly deformed and oriented according to the direction of maximum extension, which in this area is oriented ESE-WNW. They are constituted in prevalence by quartz, but there also are pebbles that, according to their composition, could derive from the dismantlement of the graphitic schists. The anthracitic lenses are not found in the metaconglomerate intercalations.

3.2. Triassic cover

A limited slice of the autocthonous Mesozoic cover of the Permo-Carboniferous complex is preserved near Mt. Touriasse (fig. 2). The original stratigraphic contact between the Mesozoic cover and the underlying continental metasediments is now obliterated by the tectonic regional foliation. This sequence is tectonically truncated at the top by an internal thrust, by which the Permo-Carboniferous metasediments lie over their Triassic cover (fig. 3).

The most ancient term of the sequence is represented by Lower Triassic quarzites. On the surfaces of fracture, they show a granular texture and a grey clear color. The schistosity is hardly visible on the outcrop and is underlined by rare and submillimetric mica levels. The quarzites grade into conglomeratic quarzites with pebbles of rounded quartz, slightly iso-oriented according to the extensional direction. The matrix is carbonatic of yellowish colour and fine grain. Dolomitic limestones of Upper Triassic age follow. They show a grey clear colour, the foliation is not visible and the grain is fine.

4. – STRUCTURAL EVOLUTION

The structural evolution displayed by the rocks forming the anthracitiferous basin of La Thuile is relatively simple. It is characterized by two folding phases whose distribution has strongly affected the form and the spatial distribution of anthracite lenses [Borghi *et al.*, 1994].

The first phase of deformation (F_1) developed under high pressure - low temperature metamorphic conditions (Qtz+Ph+Chl+Prl±Cld; mineral symbols according to Kretz, 1983). It is characterized by the occurrence of a pervasive tectonic foliation (S_1) which displays the morphological characters of a slaty cleavage. The first phase deforms the original sedimentary surface, defined by the boundary between the different kinds of metasediments previously described. At this phase relict isoclinal folds of varying dimensions (from millimetric to metric) can be assigned, whose axial plane cleavage corresponds to the regional foliation. The axes of this folding phase are subhorizontal and oriented NE-SW (fig. 4a), while the axial plane surfaces are characterized

by a regional attitude almost monoclinal, plunging toward SE of 30°-40° (fig. 4c). Finally, a mineral lineation oriented WNW-ESE was recognized.

Therefore, the anthracitiferous basin of La Thuile displays a first deformation phase showing folding axes oriented transversally with respect to the main tectonic displacement of the Western Alps which is directed toward West [Choukroune *et al.*, 1986] and generally is marked by the development of an extensional lineation. This structural setting implies that in the Houillère Zone the progressive simple shear component of the deformation was absent or very low.

Subsequently, a second phase of ductile deformation (F_2) developed. The intensity of his development is varying and increases toward the lower structural levels of the Zone Houillère, where it becomes the prevailing tectonic foliation. Here the F_2 phase deforms the regional early-Alpine foliation (S_1) drawing mesoscopic folds from closed to isoclinal with sub-horizontal axes oriented NE-SW (fig. 4b). The S_2 foliation developed under low pressure - low temperature metamorphic conditions. The F_2 phase shows axial plane surfaces weakly plunging toward SSE, which progressively transpose the previously S_1 foliation. This latter is preserved inside structural relics as intrafolial hinges or microlithons separated by spaced cleavage surfaces or is still recognizable as lineation of intersection.

The two folding phases display a strong parallelism of the axes and the axial planes, which cross cut at a low angle. Therefore, in the metasediments of the Houillère Zone the typical structures of interference of type 3 according to the classification reported by Ramsay ANDHuber [1987] are developed, arisen by the geometrical intersection of F_1 and F_2.

In particular, the tectonic surface S_1 deformed by the F_2 phase shows a sense of asymmetry of S-type looking toward NE, implying a tectonic transport directed towards NW.

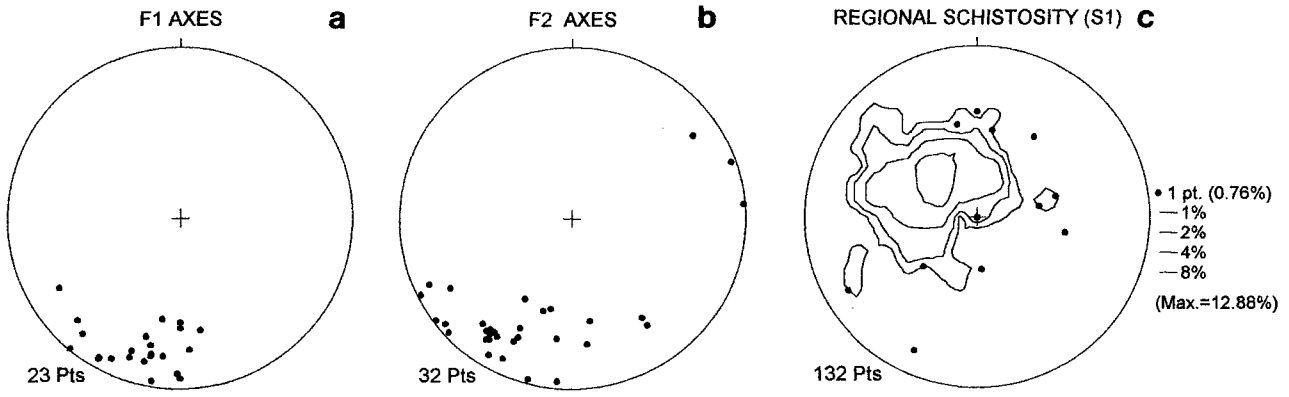

FIG. 4. – Structural data from the anthracitiferous basin of La Thuile plotted on the Lambert equal area net. **a:** fold axes of the first Alpine folding phase; **b:** fold axes of the second Alpine folding phase; **c:** poles of the high-pressure regional schistosity (S_1). The two phases are co-axial and the axes are both transversal to the direction of Alpine tectonic emplacement.

Concerning the kinematics along the BBT different interpretations have been proposed. Cannic *et al.* [1995] argued for top to the SE directed ductile normal faulting along the BBT, in order to allow exhumation of the high-P rocks of Valais Zone. Instead, Freeman *et al.* [1998] reported WNW directed thrusting of the Houillère Zone onto the more external units. According to structural evidence, we suggest that the described second deformation phase can be connected with the overthrusting of the External Briançonnais Zone, here represented by the Permo-Carboniferous metasediments of the Houillère Zone, onto the Valais Zone or the Petit St. Bernard Zone during the later ductile Alpine evolution. Moreover, along this tectonic contact, the presence of cataclastic rocks suggests that the BBT was then reactivated under brittle deformation conditions, which can be related to normal faulting top to SE directed at about 5 Ma, based on the fission – track ages reported by Fügenschuh *et al.*, [1999].

5. – PETROGRAPHY

5.1. Microstructural relationships

The petrographic study was performed on around fifty thin sections of representative samples of graphitic schists, graphitic phyllites and metaconglomerates of the Houillère Zone. In Table 1 selected chemical compositions of the minerals analyzed with the electronic microprobe are reported.

The graphitic schists are mainly constituted by quartz, albite, white mica, chlorite, pyrophyllite, graphite, carbonate and chloritoid. In accessory quantity are present: apatite, rutile, zircon and ilmenite.

The first tectonic foliation (slaty cleavage) is defined by the preferential dimensional and crystallographic orientation of white mica and chlorite, beside a preferential orientation of the quartz lenses. Quartz forms fine-grained granoblasts homogeneously scattered in the foliated matrix. Sometimes they show phenomenons of intracrystalline deformation (undulated extinction). Albite is associated to quartz and it also forms regular granoblasts. Elonged lepidoblasts of white mica constitute generally thin continuous layers. Chlorite and pyrophyllite occur in the same microstructural position as white mica. Chloritoid has grown under syn-kinematic conditions as regards the development of the S_1 foliation and was then deformed by the S_2 cleavage and replaced by white mica.

Within the second phase cleavage planes, a differentiated distribution of mineralogical phases according to the microstructural site is obvious (fig. 5). The cleavage planes are enriched in white mica, pyrophyllite and graphite, which are minerals difficult to be destroyed due to their peculiar crystallographic properties. Conversely, quartz and albite, which represent the minerals that preferentially enter into solution along highly strained rock portions, are transferred by grain boundary fluids and concentrated into sites of deposition such as microlithons. Furthermore, albite and quartz show a rounded shape in the microlithons, whilst they show an elongated habit along the cleavage planes, due to intracrystalline deformation.

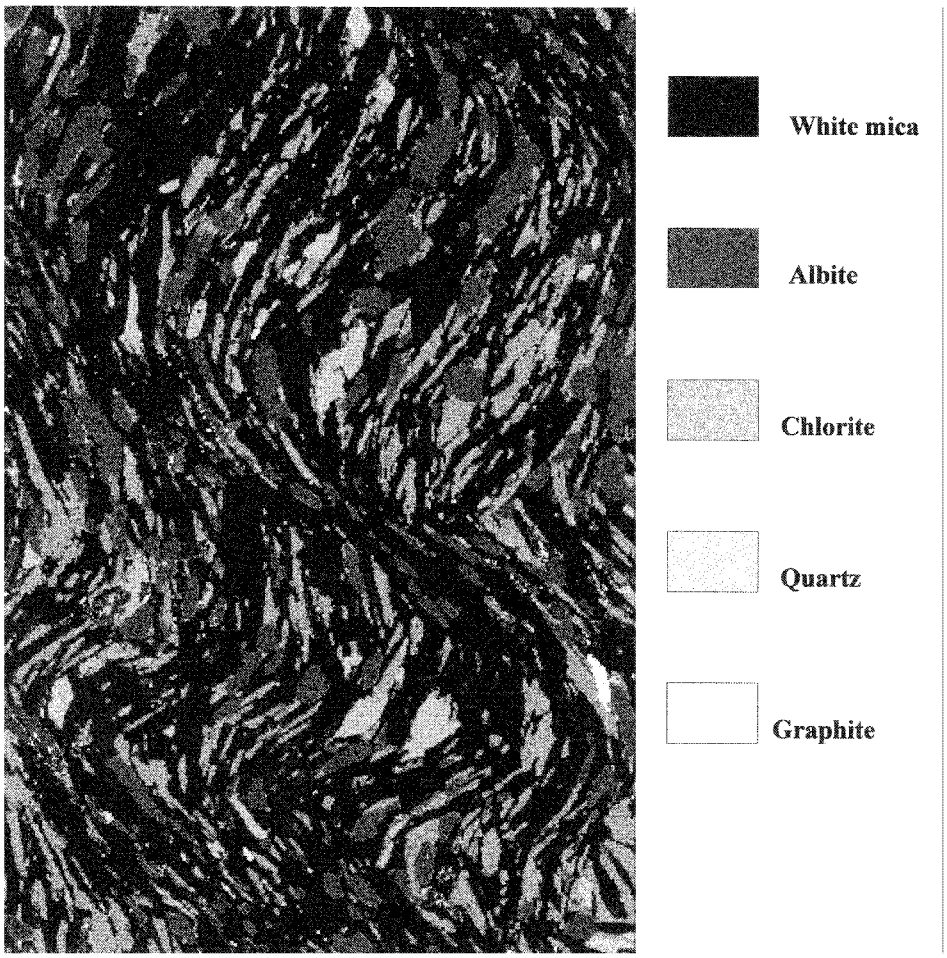

FIG. 5. – Gray level pictures showing the modal distribution of the mineral phases with respect to S_1 microlithons and S_2 cleavage planes.

An. n.	1	2	3	4	5	6	7	8	9	10	11	12
	MB S1	MB S1	MB S1	MB S2	MB S2	MB S2	CHL S1	CHL S1	CHL S2	CHL S2	CLD	CLD
SiO2	45.4702	45.9689	46.2876	48.79	51.345	50.5128	24.2771	23.6496	25.2	25.0716	23.43	23.74
TiO2	0.5656	0	0	0.32	0.225	0.0936	--	--	--	--	--	--
Al2O3	34.4713	35.2672	34.9758	27.11	26.1	26.4264	20.9193	22.0168	21.99	22.1136	37.68	38.62
FeO	1.1514	0.927	0.8874	3.63	4.032	4.5656	32.4141	32.7288	26.63	28.0296	28.97	26.44
MnO	0.0303	0	0.0612	0	0	0.052	0	0	0.03	0.0714	0.03	1.53
MgO	0.5353	0.4326	0.3876	2.15	2.295	2.0488	10.2691	9.7448	13.82	12.8214	1.24	1.48
CaO	0.1717	0	0	0	0	0	--	--	--	--	--	--
Na2O	1.4039	1.4729	1.4076	0.41	0.36	0.4992	--	--	--	--	--	--
K2O	9.2718	9.4348	9.0168	10.74	9.972	10.2336	--	--	--	--	--	--
	---	---	---	---	---	---	---	---	---	---	---	---
Total	93.0614	93.5137	93.024	93.15	94.338	94.432	87.8796	88.1504	87.67	88.1076	91.35	91.81
Si	6.176	6.198	6.251	6.73	6.944	6.868	5.313	5.167	5.339	5.323	1.9954	2.002
Al IV	1.824	1.802	1.749	1.27	1.056	1.132	2.687	2.833	2.661	2.677	3.7819	3.8382
Al VI	3.694	3.803	3.819	3.137	3.103	3.102	2.707	2.839	2.828	2.859	--	--
Ti	0.058	0	0	0.033	0.023	0.01	--	--	--	--	--	--
Fe	0.131	0.105	0.1	0.419	0.456	0.52	5.932	5.982	4.718	4.978	2.0631	1.8644
Mn	0.003	0	0.007	0	0	0.006	0	0	0.005	0.013	0.0022	0.1093
Mg	0.109	0.087	0.077	0.443	0.463	0.415	3.35	3.176	4.366	4.059	0.1574	0.1861
Ca	0.025	0	0	0	0	0	--	--	--	--	--	--
Na	0.369	0.385	0.369	0.11	0.094	0.131	--	--	--	--	--	--
K	1.606	1.624	1.553	1.89	1.721	1.775	--	--	--	--	--	--
Xmg	0.453	0.452	0.437	0.514	0.503	0.444	0.361	0.347	0.481	0.449	0.071	0.091

TABLE. 1. – Representative microprobe analyses and number of cations per formula unit (p.f.u.) for white mica (22 O.), chlorite (28 O.) and chloritoid (10 O). An. 1-3 = phengites oriented along the S_1 foliation; an. 4-6 = muscovites oriented along the S_2 cleavage, 7-9 = chlorites oriented along the S_1 foliation. 10-12 = chlorites oriented along the S_2 foliation. 13-14 = chloritoid.

5.2. Mineral chemistry

White mica grown along the S_1 foliation shows a phengitic composition with a Si content ranging between 6.6 and 7.0 atoms for unit formula (p.f.u) on the basis of 22 Oxygens (fig. 6). The paragonite content ranges from 2 to 10%, while the Ti content is always very low (<0.5% in weight). The white mica grown along the tectonic foliation of the second generation is instead characterized by a muscovitic composition (Si=6.1-6.4 atoms p.f.u) (fig. 6). The content of paragonitic molecule is higher (8-20 %), while the Ti content is low (<1% in weight). Chlorite shows a chamositic composition according to the classification of Bayliss [1975]. Particularly, the chlorite oriented parallel to the S_1 foliation displays a Si content ranging between 5.15 and 5.45 atoms (p.f.u) on the basis of 28 Oxygens, a Fe content between 5.6 and 6.3 atoms (p.f.u) and a X_{Mg} value between 0.34 and 0.38. The chlorite oriented along the S_2 cleavage shows a Si content comparable (between 5.20 and 5.40 atoms p.f.u.), while the Fe content is lower (4.7-5.5 atoms p.f.u) and the X_{Mg} value higher (0.31-0.48). Considering that chlorite becomes Mg-richer with increasing temperature, the second tectonic foliation probably developed at lower P but slightly higher T with respect to S_1 foliation (fig. 7). In addition, the S_1 high-P chlorite is marked by a higher Tschermak substitution in agreement with the behaviour of white mica. Finally, the chloritoid displays a X_{Mg} values ranging between 0.06 and 0.11, which points to normal Fe-chloritoid.

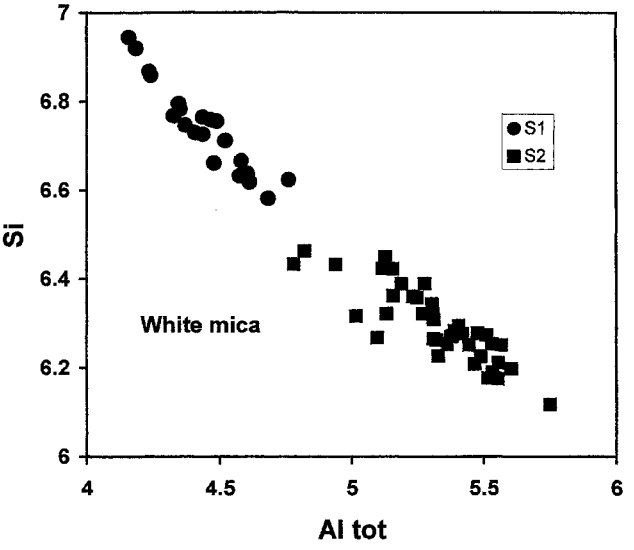

FIG. 6. – Al_{tot} /Si classification diagram for the di-octahedral micas. Data plot along the tie line muscovite-celadonite. The mica oriented along the S_1 foliation (square) shows a phengitic composition, while the mica oriented along the S_2 cleavage (circle) is muscovite.

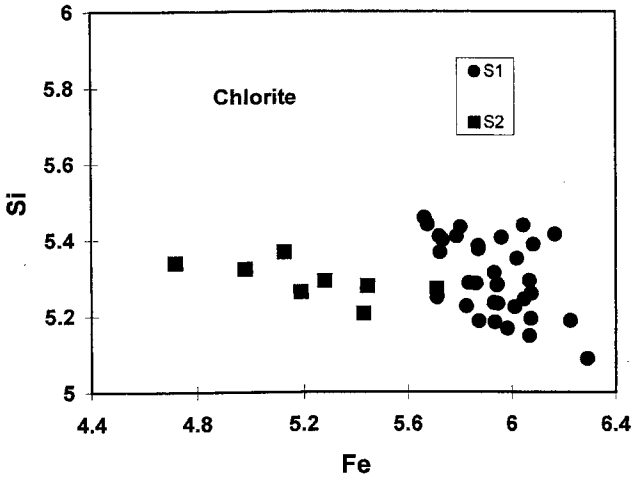

FIG. 7. – Fe /Si classification diagram for the chlorites. The chlorite oriented along the S_1 foliation shows a lower Fe content.

5.3. Metamorphic evolution

The metamorphic Alpine evolution of the Houillère Zone in the La Thuile area was polyphasic. Both previously described Alpine foliations (S_1 and S_2) occurred under low-grade metamorphic conditions, but the first developed under pressures notably higher than the second. Particularly, the paragenesis crystallized syn-kinematically with respect to the first tectonic phase is marked by the AFM association chlorite-pyrophyllite-chloritoid with excess of quartz and phengitic mica (fig. 8). According to Chopin and Schreyer [1983] chloritoid requires temperatures higher than 350 °C. However, the contemporary stability of pyrophyllite in absence of kyanite implies that the temperature was lower than 450 °C [Kerrik, 1968]. In addition, the possible occurrence of lawsonite, locally reported for other areas of the Houillère Zone, probably constrains the T range within the left part of the dotted area in figure 9. For this temperature range (350-400 °C), the presence of a phengitic mica with Si content up to 7 atoms p.f.u. requires pressures of at least 10 kbar, according to the geobarometer of Massonne and Schreyer [1987]. This value represents only a minimum P estimate, as the graphitic schists of the Houillère Zone are devoid of K-feldspar. Therefore, the metamorphic peak reached by the Permo-Carboniferous rocks of the anthracitiferous basin of La Thuile displays a T range of 350-400 °C for a pressure higher than 10 kbar (fig. 9), corresponding to more than 30 km of depth. The inferred geothermal gradient (ca. 10°C/km) is very low and it is consistent with a geodynamic environment of

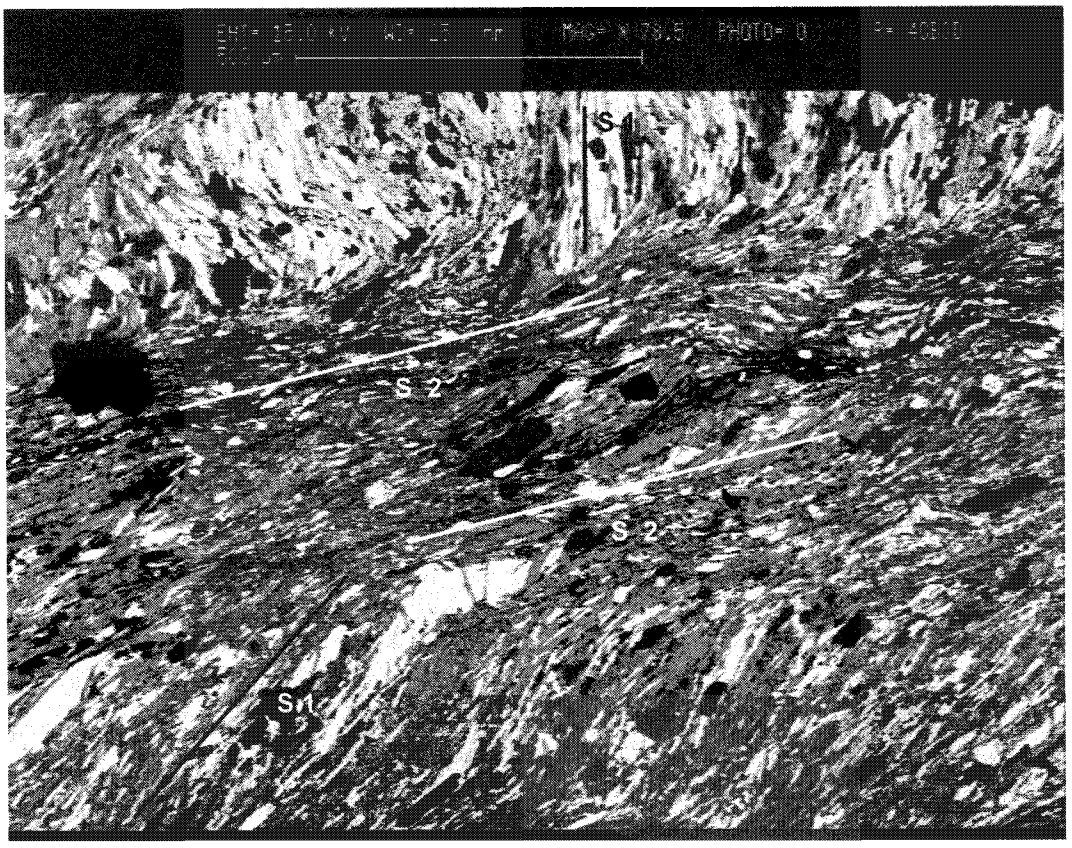

FIG. 8. – Backscattered image showing the S_1/S_2 overprinting relationship. The S_1 foliation is defined by phengitic mica+paragonite+chlorite+pyrophyllite±chloritoid. The S_2 consists of an asymmetric cleavage defined by low-P and low-grade assemblage (muscovite+chlorite+albite).

lithospheric subduction [see e.g. Thompson and England, 1984].

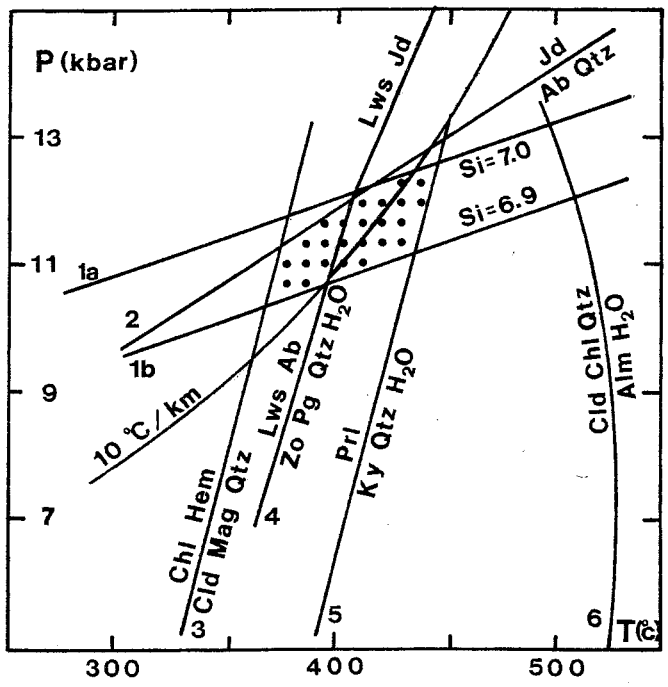

FIG. 9. – Petrogenetic grid and H-P metamorphic conditions inferred for the anthracitiferous basin of La Thuile (External Briançonnais Zone). The metamorphic peak plots along a very low thermal gradient (ca. 10°C/km), reflecting subduction tectonic environment. **1**: isopleths for the Si content in the di-octahedral mica [Massonne and Schreyer, 1987], **2**: Holland [1980], **3**: Chopin and Schreyer [1983], **4**: Heinrich and Althaus [1980], **5**: Kerrik [1968], **6**: Spear and Chiney [1989]. Mineral abbreviations according to Kretz [1983].

The high-P metamorphic event was followed by a strong re-equilibration developed under low-P low-T conditions. This second metamorphic event shows syn-kinematic features with respect to the S_2 cleavage which overprints the S_1 high-P tectonic foliation (fig. 8). It is defined by the recrystallization of white mica (muscovitic in composition), chlorite and albite, while rutile was replaced by titanite.

6. – DISCUSSION AND CONCLUSIONS

A geologic and petrographic study was performed on the anthracitiferous basin of La Thuile (Aosta Valley). It allowed to better know the metamorphic evolution of this portion of the Houillère Zone, which represents the lower and also the more external portion of the External Briançonnais Zone.

Contrary to the common opinion, according to which low P/T metamorphic conditions are reported in the studied area [e.g. Fügenschuh *et al.*, 1999], a relict foliation under high-pressure (more than 10 kbar) was found in the graphitic schists of the Permo-Carboniferous sequence. However, a later deformation developed under low-pressure low-temperature conditions, so that the high-pressure assemblage is presently preserved only in the less deformed domains. The presence of a relict metamorphic event corresponding to low-T blueschist facies conditions according to Evans [1980] (T=350–400 °C for P>10 kbar) would imply that even this portion of the Briançonnais nappes system was involved in the subduction process of early Alpine age.

Hence, the inferred tectono-metamorphic history for the anthracitiferous basin of La Thuile, is consistent with the low geothermal gradient (ca. 10 °C/km) displayed by the adjoining tectonic units. Therefore, the contact between the Houillère Zone and the Valais and Petit St. Bernard Zones separates tectonic units both involved in the early-Alpine subduction history, even if single units reached different deep at different time.

The metamorphic evolution found in the studied area is also comparable with that described in same basement units of the Briançonnais Zone as the Massif of Chasseforêt and the Acceglio Zone where similar P-T conditions have been reported [Houfflain and Caby, 1987; Desmons, 1992; Debelmas and Desmons, 1997].

Moreover, other basement units of the Internal Briançonnais Zone (Ambin, Mont Fort, Pourri–Bellecôte, Siviez-Mischabel) display a first Alpine metamorphic event developed under epidote–blueschist conditions [e.g. Desmons and Mercier, 1993; Thélin *et al.*; 1993; Borghi and Gattiglio, 1997].

In conclusion, we can suppose that both Internal and External Briançonnais Zones (including the Houillère Zone) were affected by a metamorphic event connected to a low-thermal gradient. However, in the Internal Zone this first metamorphic event reached higher P-T conditions (epidote–bluschist facies) than in the External Zone (equilibrated under lawsonite-blueschist facies conditions), implying a more pervasive involvement in the subductive process for the inner portion of the Briançonnais Zone.

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References

ANTOINE P. (1972) – Le domaine pennique externe entre Bourg Saint-Maurice (Savoie) et la frontière italo-suisse. *Géologie Alpine*, **48**, 5-40.

BAYLISS P. (1975) – Nomenclature of trioctahedral chlorite. *Canadian Mineral.*, **12**, 178-180.

BOCQUET J. (1974) – Il metamorfismo pre-alpino nella Vanoise (Savoia) e in altri settori dello zoccolo brianzonese. *Mem. Soc. Geol. It.*, **13**, 271-284.

BORGHI A. & GATTIGLIO M. (1997) – Osservazioni geologico-petrografiche nel settore meridionale del Massiccio d'Ambin. *Atti Tic. Sc. Terra*, **5**, 65-84.

BORGHI A., SANDRONE R. & VALENTE A. (1994) – Interpretazione strutturale dei corpi antracitiferi di La Thuile (Alpi occidentali). *Giornata di Studio in ricordo del Prof. S. Zucchetti, Sp. Pubbl.*, 79-85.

BORGHI A., GATTIGLIO M., MONDINO F. & ZACCONE G. (1999) – Structural and metamorphic evidences of pre-Alpine basement in the Ambin Nappe (Western Alps). *Mem. Sci. Geol. Padova*, **51**, 204-220.

BUTLER R. W. H. & FREEMAN S. (1996) – Can crustal extension be distinguished from thrusting in the internal parts of mountain belts? An example from Entrelor shear zone, Western Alps. *J. Structural Geology*, **18**, 909-923.

CABY R. (1964) – Étude géologique du bord interne de la zone briançonnaise et de la bordure des Schistes lustrés entre Modane et la Vallée Etroite (Savoie, Haut Val de Suse). *Trav. Lab. Géol. Grenoble*, **40**, 131-186.

CANNIC S., MUGNIER J. L. & LARDEAUX J. M. (1995) – Mise en évidence d'une faille normale ductile dans l'unité du Roignais–Versoyen (Alpes occidentales, France). *C. R. Acad. Sci. Paris*, **321 (II)**, 513-519.

CANNIC S., LARDEAUX J M., MUGNIER J. L. & HERNANDEZ J. (1996) – Tectono-metamorphic evolution of the Roignais-Versoyen Unit (Valaisan domain, France). *Eclogae Geol. Helv.*, **89**, 321-343.

CHOPIN C. & SCHREYER W. (1983) – Magnesiocarpholite and magnesiochloritoid: two index minerals of pelitic blueschists and their preliminary phase relations in the model system $MgO-Al_2O_3-SiO_2-H_2O$. *Am. J. Sc.*, **283A**, 72-96.

CHOUKROUNE P., BALLÈVRE M., COBBOLD, GAUTIER Y., MERLE O. & VUICHARD J. P. (1986) – Deformation and motion in the Western Alpine arc. *Tectonics*, **5**, 125-126.

CLERICI C. & CLERICI L. (1980) – Le miniere di antracite di La Thuile. *Boll. Ass. Min. Sub.*, **17**, 63-76.

CORTESOGNO L. (1984) – Metamorfismo e magmatismo prealpini nel basamento e nel tegumento delle Alpi liguri. *Mem. Soc. Geol. Ital.*, **28**, 79-94.

DAL PIAZ G. V. & GOVI M. (1965) – Osservazioni geologiche sulla zona del Gran San Bernardo nell'alta Valle d'Aosta. *Boll. Soc. Geol. It.*, **84**, 1-23.

DEBELMAS J. & KERCKHOVE C. (1980) – Les Alpes franco-italiennes. *Géologie Alpine*, **55**, 21-58.

DEBELMAS J. & DESMONS J. (1997) – Géologie de la Vanoise. Documents du B.R.G.M., **266**, 187 p. .Orléans.

DESMONS J. (1977) – Mineralogical and petrological investigations of Alpine metamorphism in the internal French Western Alps. *Am. J. Sc.*, **277**, 1045-1066.

DESMONS J. & MERCIER D. (1993) – Passing through the Briançon Zone. *In*: von Raumer J. & Neubauer (Eds), *Pre-Mesozoic Geology in the Alps*, 279-295. Springer Verlag, Berlin.

DESMONS J., COMPAGNONI R. & CORTESOGNO L. (1999) – Alpine metamorphism of the Western Alps: II. High–P/T and related pre-greenschist metamorphism. *Schweiz. mineral. petrogr. Mitt.*, **79**, 111-134.

ELTER G. (1960) – La zona penninica dell'alta e media Valle d'Aosta e le unità limitrofe. *Mem. Ist. Geol. Min. Univ. Padova*, **22**, 103 p.

ELTER G. & ELTER P. (1965) – Carta geologica della regione del Piccolo San Bernardo (versante italiano). *Mem. Ist. Geol. Min. Univ. Padova*, **25**, 54 p.

EVANS B. W. (1980) – Phase relations of epidote-blueschists. *Lithos*, **25**, 3-23.

FABRE J. (1989) – Événements tectoniques et sédimentaires pré-alpins dans la zone Briançonnaise (zone Houillère) des Alpes Occidentales (commentaires de la stratigraphie corrélation form). *Rend. Soc. Geol. It.*, **12**, 241-246

FABRE J. & FEYS, R (1966) – Les séries bariolées du massif de Rochachille. Leurs rapports avec le « Verrucano » de Briançon et les « Permiens » de Maurienne et de Tarentaise. *Atti Symp. Verrucano, Soc. Tosc. Sci. Nat.*, 143-169.

FABRE J., SCHADE J., BAUDIN T., DESMONS J., MERCIER D. & PERRUCCIO-PAREISON D. (1987) – Relics of pre-Mesozoic events in the Briançonnais zone (northern French Alps). *In*: Flüegel H.W., Sassi F.P. & Grecula P. (Eds), *Pre-Variscan and Variscan events in the Alpine-Mediterranean mountain belts. Mineralia slovaca Monogr.*, 183-208. Alfa, Bratislava.

FEYS R. (1963) – Étude géologique du Carbonifère briançonnais (Hautes-Alpes). Thèse. *Mém. B.R.G.M*, **6**, 387 p.

FEYS R. & GRÉBER C. (1952) – Note préliminaire. Présence probable de Namurien dans le Houiller briançonnais. *C. R. Soc. géol. France.*, **3**, 36-37.

FREEMAN S. R., INGER S., BUTLER R. W. H. & CLIFF R. A. (1997) – Dating deformation using Rb-Sr in white mica; greenschist facies deformation ages from the Entrelor shear zone, Italian Alps. *Tectonics*, **16**, 57-76.

FREEMAN S. R., BUTLER R. W. H., CLIFF R. A., INGER S. & BARNICOAT A. C. (1998) – Deformation migration in an orogen-scale shear zone array: an example from the Basal Briançonnais Thrust, internal Franco-Italian Alps. *Geol. Mag.*, **135**, 349-367.

FUDRAL S. (1973) – Contribution à l'étude de l'unité de Moûtiers entre le torrent du Cormet d'Aréches et le hameau des Chapieux. *Thèse de 3e cycle*, Univ. Grenoble, 129 p.

FUDRAL S. (1980) – Une nouvelle interprétation de l'unité des Salins (zone des brèches de Tarentaise) au nord de Bourg-Saint-Maurice (Savoie). Conséquences structurales. *C. R. Acad. Sci. Paris*, **290**, 1333-1336.

FÜGENSCHUH B., LOPRIENO A., CERANI S. & SCHIMID S. M. (1999) – Structural analysis of the Subbriançonnais and the Valais units in the area of Moûtiers (Savoy, Western Alps): paleogeographic and tectonic consequences. *Int. Journ. Earth Sciences*, **88**, 201-218.

GAY M. (1970) – Le massif d'Ambin et son cadre de Schistes lustrés (Alpes franco-italiennes). Evolution paléogéographique anté-alpine. *Bull. B.R.G.M.*, **3**, 76 p.

GELY J.P. (1989) – Stratigraphie, tectonique et métamorphisme comparés de part et d'autre du front pennique en Tarentaise (Alpes de Savoie, France). *Thèse*, Univ. Chambéry, 343 p.

GIGNOUX M. & MORET L. (1934) – Les grandes subdivisions géologiques des Alpes françaises. *Ann. Géogr.*, **244,** 337-363.

GOFFÉ B. & BOUSQUET R. (1997) – Ferrocarpholite, chloritoid and lawsonite in metapelites of the Versoyen and Petit St. Bernard units (Valais zone, Western Alps). *Schweiz. mineral. petrogr. Mitt,* **77**, 137-147.

GREBER C. (1965) – Flore et stratigraphie du Carbonifère des Alpes françaises. *Mém. Bur. Rech. Géol. Min.*, **21**, 380 p.

GUILLOT F. & RAOULT J. F. (1984) – Permien et base du Trias en Vanoise septentrionale : données nouvelles et hypothèses (zone briançonnaise interne, Alpes françaises). *Ann. Soc. Géol. Nord.* **104**, 183-192.

HEINRICH W. & ALTHAUS E. (1980) – Die obere Stabilitatsgrenze von Lawsonit plus Albit bzw. Jadeit. *Forht. Miner.*, **58**, 49-50.

HOLLAND T. J. B. (1980) – The reaction albite = jadeite+quartz determined experimentally in the range 600-1200 °C. *Amer. Mineral.*, **65**, 129-134.

HOUFFLAIN B. & CABY R. (1987) – Rétrocharriages précoces en climat schiste bleu à lawsonite-grenat: la "bande d'Acceglio-Longet" (Alpes Cottiennes). *C. R. Acad. Sci. Paris*, **304**, 199-204.

KERRIK D. M. (1968) – Experiments on the upper stability limit of pyrophyllite at 1.8 and 3.9 kilobars water pressure. *Am. J. Sc.*, **266**, 204-214.

KRETZ R. (1983) – Symbols for rock forming minerals. *Amer. Mineral.*, **68**, 277-279.

LASSERRE J. L. & LAVERNE C. (1976) – Le volcanisme tholeiitique de la zone du Versoyen (Alpes franco-italiennes): minéralogie, pétrographie et géochimie. *Thèse 3° cycle*, Univ. Grenoble, 252 p.

MASSONE H. J. & SCHREYER W. (1987) – Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite and quartz. *Contrib. Mineral. Petrol.*, **96,** 212-224.

MESSIGA B. (1981) – Evidenze strutturali e paragenetiche dell'evoluzione polifasica prealpina del Massiccio cristallino di Savona. *Rend. Soc. Ital. Mineral. Petrol.* **37**, 739-754.

PEOLA P. (1903) – Appendice paleontologica sulla flora del Piccolo San Bernardo. *Mem. Descr. Carta Geol. It.*, **12**, 207-226.

PIANTONE P. (1980) – Magmatisme et métamorphisme des roches intrusives calco-alcalines du Carbonifère briançonnais entre Arc et Durance: minéralogie, pétrographie, géochimie. Thèse 3e cycle, Univ.Grenoble.

RAMSAY J. G. & HUBER M. I. (1987) – The technique of modern structural geology. Volume 2: Folds and Fractures. *Academic Press,* London, 697 p.

SCHÜRCH M. L. (1987) – Les ophiolites de la zone du Versoyen: témoin d'un bassin à évolution métamorphique complexe. *PhD thesis*, Univ. Genève, 159 p.

SPEAR F. S. & CHENEY T. J. (1989) – A petrogenetic grid for pelitic schists in the system SiO_2-Al_2O_3-FeO-MgO-K_2O-H_2O. *Contrib. Mineral. Petrol.*, **101**, 149-164.

THÉLIN P., SARTORI M., BURRI M., GOUFFON Y. & CHESSEX R. (1993) – The Pre-Alpine Basement of the Briançonnais (Wallis, Switzerland). *In* : J.F. von Raumer and F. Neubauer (Eds), *Pre-Mesozoic Geology in the Alps*, 297-315. Springer & Verlag, Berlin.

THOMPSON A. B. & ENGLAND P. C. (1984) – Pressure-Temperature-time path of regional metamorphism. II: Their inference and interpretation using mineral assemblages in metamorphic rocks. *J. Petrol.*, **24**, 929-955.