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Detrital Lawsonite and Blue Sodic Amphibole in the Molasse of Savoy, France and their Significance in Assessing Alpine Evolution

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Abstract

Heavy mineral analysis of Lower Freshwater and Upper Marine (Lower Chattian to Burdigalian) Molasse sections of the Savoy France, has revealed the presence of detrital high-pressure index lawsonite, which had not previously been identified in any investigated Molasse sediments. The lawsonite is accompanied by blue sodic amphibole and associated characteristic minerals, including ophiolite-derived assemblages. Sealed in the Molasse they have escaped the later (Oligocene, and Miocene-to Pliocene) stages of Alpine metamorphism, which often mask the early Alpine (Upper Cretaceous) high pressure phase in the Alps today.

Optical and chemical analyses indicate that these minerals, deposited in successive stratigraphic units, are representative of progressive and differing metamorphic episodes. «Tartan-twinned» lawsonite and Al-rich glaucophane and ferroglaucophane, found in the Lower Chattian sediments, were formed during the eo-Alpine high-pressure phase, while Ca-bearing and Mg-rich crossite and glaucophane from the Burdigalian are the products of a later stage with more diverse metamorphic conditions.

The source of the high-pressure index minerals can be determined as the Schistes lustrés of the St. Bernhard-Briançonnais zone which attained a more westerly position during the Tertiary. Palaeodrainage was oriented to the foredeep in a northerly or northwesterly direction.

The first appearance of the index minerals in the Lower Chattian sediments marks the time when the erosion of the Alpine high-pressure rocks began.

Zusammenfassung

Durch Untersuchungen an Schwermineralien der unteren Süsswassermolasse (USM) sowie der oberen Meeresmolasse (OMM) in Savoyen konnte zum ersten Mal das Hochdruck-Indexmineral Lawsonit in der Molasse nachgewiesen werden. Neben Lawsonit treten blaue Na-Amphibole und andere charakteristische Mineralien basischer Gesteine auf.

Diese Schwermineralien in der Molasse entgingen der tertiären (~ 38 ma) Metamorphosephase in den Alpen, wo die Zeugen eoalpiner, kretazischer (60–90 ma) metamorpher Ereignisse oft überprägt sind.

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Optische und chemische Untersuchungen zeigten, dass diese Mineralien in stratigraphischer Folge, die sich während der metamorphen Entwicklung der Alpen ändernden P/T-Bedingungen widerspiegeln.

In den Sedimenten des unteren Chattian (USM) treten Lawsonit mit Parkett-Verzwillingung, Al-reiche Glaukophane und Ferroglaukophane auf. Diese Mineralien wurden im Verlauf der ersten eoalpinen Hochdruckphase gebildet, während die Ca-führenden, Mg-reichen Crossite und Glaucophane aus dem Burdigalian (OMM) Produkte sukzessiver retromorpher Phasen mit veränderten P/T-Bedingungen sind.

Das Herkunftsgebiet der Hochdruck-Indexminerale liegt in der internen penninischen St-Bernhard-Briançonnais-Zone, welche im Tertiär weiter nach Westen reichte. Das Paleoflusssystem entwässerte zu jener Zeit nach Norden oder Nordwesten.

Somit setzt das Auftreten der Hochdruckmineralien in den Sedimenten des unteren Chattiens (USM) eine Zeitmarke für den Beginn der Erosion der alpinen Hochdruckgesteine.

INTRODUCTION

This paper reports on the presence of high-pressure index lawsonite and blue sodic amphibole in the Molasse of Savoy and Switzerland. The purpose of this study was to analyse these minerals and discuss implications regarding their paragenesis, provenance and Alpine tectonics.

The first appearance of the above minerals was recorded in the Lower Freshwater Molasse of Lower Chattian age and from then on they occur continuously in the sediments up to the termination of the sections in the Aquitanian or in the Burdigalian Upper Marine Molasse. Sealed in the Molasse they have escaped the later stages of Alpine metamorphism which often mask the earlier phases in the Alps. Their study therefore contributes to the better understanding of processes that took place in the source area, in the interior part of the Alps, prior to their erosion and deposition.

The study focusses on the Molasse of the Frangy-Bellegarde basin of Savoy, France (Fig. 1). The sample locations are as follows: Fornant (For.) and Findreuse (Fin.) in the valley of the Usses; Génissiat (Gén.), and three boreholes, Savoie-104, 105 (Sv.) and Faucigny-1 (Fay.).

The section at For. comprises the Lower Chattian and Aquitanian Lower Freshwater Molasse (USM) as well as the Burdigalian Upper Marine Molasse (OMM). The nearby Fin. terminates in the Aquitanian and the section at Gén. embraces only the Aquitanian USM and Burdigalian OMM. Sv-104 and 105 penetrated through Aquitanian strata which lie on Urgonian limestones. In Fay-1 the Molasse sequence attained over a 1000 m thickness above Urgonian.

Samples were taken from the present day Isère and Arc rivers for mineralogical comparison.

Fig. 2 illustrates the structural units of the Western Alps and the distribution of lawsonite.

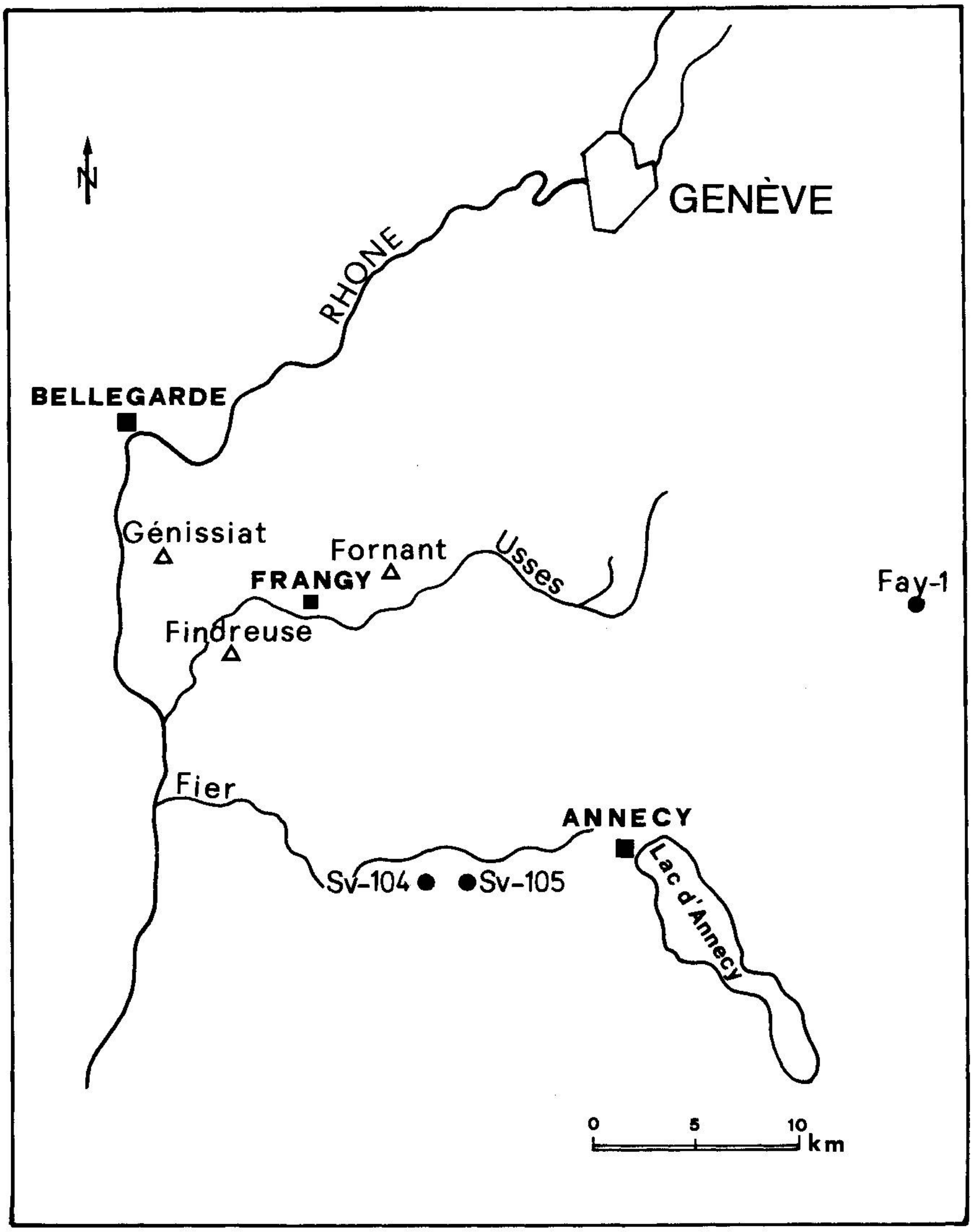

Fig. 1 Location map showing position of the analysed sections and the local drainage.

Previous studies of sedimentary petrology in the area were carried out by VATAN et al. (1957), WAGNER and WELLHÄUSER (1966) and WAGNER (1969). TCHIMIKIAN (1953) investigated the mineralogy of the borehole Sv-104 and MONNIER (1979) analysed light minerals from Fay-1.

The lithology and stratigraphy of For. and Fin. were studied and interpreted by RIGASSI (1957 and personal communication 1980) and HOMEWOOD and MATTER described the sedimentology of Fin. (personal communication 1980).

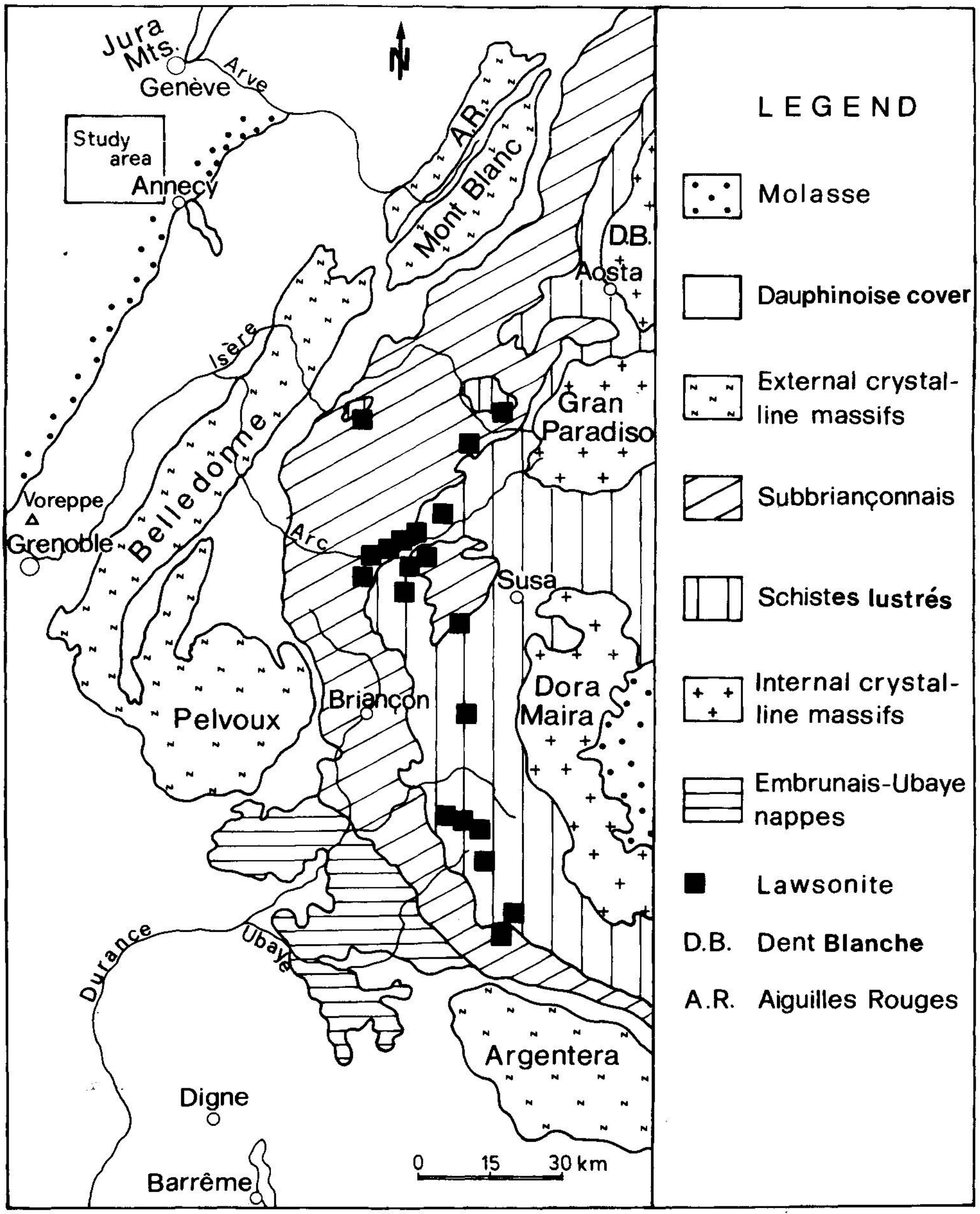

Fig. 2 Geological sketch map showing the structural units of the Western Alps and the spatial distribution of lawsonite. Compiled from data shown in BEARTH (1962), BOCQUET (1971, 1974a) and SALIOT (1973).

Blue sodic amphibole from the Swiss Molasse was first mentioned by VON MOOS (1935). VATAN et al. (1957) identified it in the Molasse of Savoy. Later investigations showed the widespread occurrence of this mineral in the various facies of the Molasse (BÜCHI and HOFMANN 1960, FÜCHTBAUER 1964, MAURER et al. 1978, MAURER and NABHOLZ 1980, MAURER 1982). It is particularly common in the Molasse of the boreholes situated in a zone between Fribourg and Lausanne (H. MAURER personal communication 1982).

Detrital lawsonite however has not been recorded previously in any localities of the Molasse.

Of the numerous comprehensive studies on the chemistry, parageneses, spatial distribution and geochronology of lawsonite-blue amphibole bearing rocks of the Western Alps, some have particular relevance to the hinterland (FABRE 1954; ELLENBERGER 1960; BEARTH 1962; NIGGLI and NIGGLI 1965; BOCQUET 1966, 1971, 1974 a, b; BOCQUET et al. 1974, 1978; GUITARD and SALIOT 1971; SALIOT 1973; HUNZIKER 1974; PINAULT 1974; CARON 1974, 1977; BONHOMME et al. 1980).

BOCQUET (1966) mentioned glaucophanitic rock pebbles from the Miocene delta of the Voreppe (Fig. 2). GRACIANSKY et al. (1971) reported on the presence of pebbles of lawsonite and blue amphibole bearing rocks in the Lower Oligocene conglomerates of the synclinal of Barrême (alpes de Haute-Provence), and the geochronology of these pebbles was investigated by PINAULT (1974) and BONHOMME et al. (1980).

ANALYTICAL DATA

Laboratory preparations preceding optical and chemical analyses were carried out according to the method described by FÜCHTBAUER (1954) and MATTER (1964). For the heavy mineral studies the combined 0.063–0.4 mm size fractions were used.

Optical Analysis

Lawsonite

Petrographic microscopy has revealed the presence of lawsonite in the whole section of For., in one part of the Upper Chattian of Fin., in the Aquitanian of Sv-104 and 105 and in two samples from Fay-1. It is absent in Gén.

The amount of lawsonite ranges between 1–8% when counting the non-opaque, non micaceous grains on the slides, excluding garnet. Their size in the fine-grained sediments of For. and Fin. varies between 100–150 μm, while in the somewhat coarser sands of Sv-104 and 105 they are 150–200 μm.

The grains are generally flat, equidimensional or irregular (001) cleavage fragments[1] (Figs. 3 a-b). They are transparent and colourless, but a few thicker

[1] The orientation of lawsonite as described in the literature is not uniform. In the present study the orientation determined by WINCHELL (1951) also by KERR (1959) and HEINRICH (1965) was adopted.

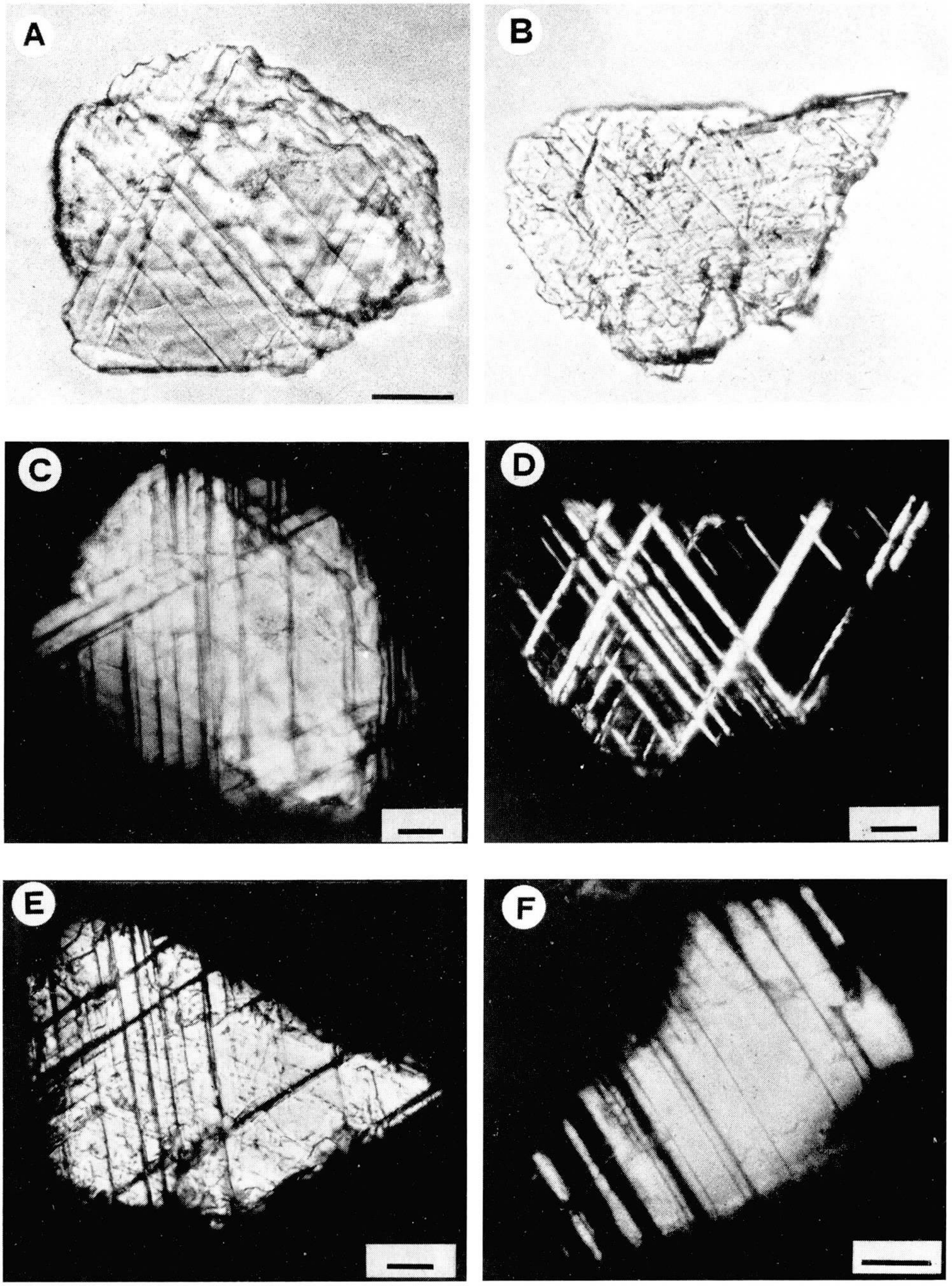

Fig. 3 A. (001) cleavage fragment of a lawsonite grain from the Lower Chattian of For. The directions of twin lamellae are visible. Plain polarised light.
B. Irregular (001) cleavage fragment of a lawsonite grain from the Upper Chattian of Fin.
C. Same grain as in A. under crossed polars. Note «tartan-twinning», and the bent twin-lamellae bottom right.

grains show a slight bluish tint. The relief is fairly high in Canada balsam, and under the binocular microscope a very high reflection is revealed. Many lawsonites contain fluid or minute mineral inclusions.

Under crossed polars the interference colours are grey to pale-yellow or orange-yellow. The birefringence of the thicker crystals ranges up to second order blue.

On (001) the extinction is symmetrical while that of the longitudinal fragments is parallel.

A well centered, biaxial positive optic axis figure is obtained on (001), this face being normal to the OAP. 2V was estimated in the 45° position as described by WAHLSTROM (1960) and PHILLIPS (1971). The visual inspection revealed a large optic axial angle of 80–85°. The strong dispersion of the optic axes is characteristic of lawsonites; $r > v$.

The most impressive feature of the lawsonite grains is their multilamellar twinning. This phenomenon is in fact the most reliable aid to the identification of this mineral, because the non-twinned and thicker grains resemble clinozoisite and distinction between these two minerals is extremely difficult. The twin-plane is parallel to (110). Twinning usually appears in two directions and the intersecting twin lamellae exhibit the typical «tartan-twin» appearance (Figs. 3 c–e). The twin lamellae are often bent.

The majority of grains found in the Chattian display twinning in two directions, whilst those from the Aquitanian, and especially from the Burdigalian show polysynthetic twinning in one direction (Fig. 3 f) or are un-twinned.

The preservation of the grains is generally good throughout the sections.

Blue sodic amphibole

Alkali amphiboles of the glaucophane-riebeckite series are well represented in the sediments of the study area, their quantity varying between 2–22%. They are present in the Chattian and Burdigalian of For., the lawsonite containing samples of Fin. and occur throughout the Aquitanian of Sv-104 and 105. They were also found in the whole Burdigalian of Gén.

Characteristically for these minerals their habit, colour and optical properties show a considerable variation. It is remarkable however that according to their properties they can be grouped, the groups showing close relationships with the age and locality of the samples.

The «Chattian» blue amphiboles are well preserved prismatic grains with a deep-blue colour and distinct pleochroism. Colour zoning is exhibited only by

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D. Same grain as in B. under crossed polars, showing «tartan-twinning».
E. Same grain as above in 45° position, crossed polars.
F. Fragment of a lawsonite grain from the Burdigalian of For. showing polysynthetic twinning. Crossed polars.
Scale bar represents 20 μm in all photomicrographs.

a few grains. Their mean grain size is 150–160 µm. The (110) cleavage flakes show almost parallel extinction, and a clear, well centered optic axis figure with a variable 2V. A few composite grains of blue amphibole, sphene and clinozoisite have been encountered.

Blue amphiboles of the boreholes Sv-104 and 105 resemble those analysed from the Chattian. Their size is, however, larger and more variable, ranging between 150 and 300 µm. The grains are of short prismatic habit and their colour varies between pale lavender-blue to dark-blue or dark greenish-blue, with the typical blue amphibole pleochroism. A number of grains show discontinuous colour zoning with varying optical properties.

Blue amphiboles of the Burdigalian of For. and Gén. show a wider variation in habit and optical properties than those found in the older sediments. Their colour and pleochroism varies from lavender-blue to dark sky-blue, sometimes with a greenish-blue rim. The latter can be ascribed to calcic amphibole fringing the sodic amphibole. Beside prismatic grains, fibrous clusters and fine needles were also encountered. Blue amphibole occurs also as aggregates, embedded in chlorite or white mica. The fibrous grains and aggregates frequently enclose albite, minute clinozoisite, sphene and epidote. The grain size ranges between 100-300 µm. Discontinuous colour zoning with varying optical properties were often observed. Positive and negative elongation within one crystal were also diagnosed (Fig. 4a).

Minerals associated with lawsonite and blue amphibole

From the mineral assemblages accompanying these pressure index minerals in the sediments, those which denote Alpine metamorphism are of particular interest. The amounts of sphene and clinozoiste are consistently higher in samples which contain blue amphibole and lawsonite. This suggests that they were derived from similar parent rocks. The coexistence of these minerals in the source rocks was confirmed by composite grains of blue amphibole and clinozoiste (Fig. 4b), or sphene. Actinolite is present in the Chattian samples where lawsonite is common. Pumpellyite was identified in the section of For. It occurs sporadically in the form of fibrous grains with patchy-green colour, strong pleochroism and characteristic anomalous interference colours.

Garnet, epidote, chlorite, white mica (phengite and paragonite, also muscovite) and apatite (Fig. 4c) occur in considerable amounts. Chloritoid is regularly present but in small percentages. Brown prismatic tourmaline is a common accessory.

Sodic pyroxenes commonly occur in the high pressure rocks of the Western Alps, but in the Molasse of the study area were not encountered, presumably as a result of elimination during transport, or diagenesis. In the light fraction albite is represented by a small amount of prismatic fragments.

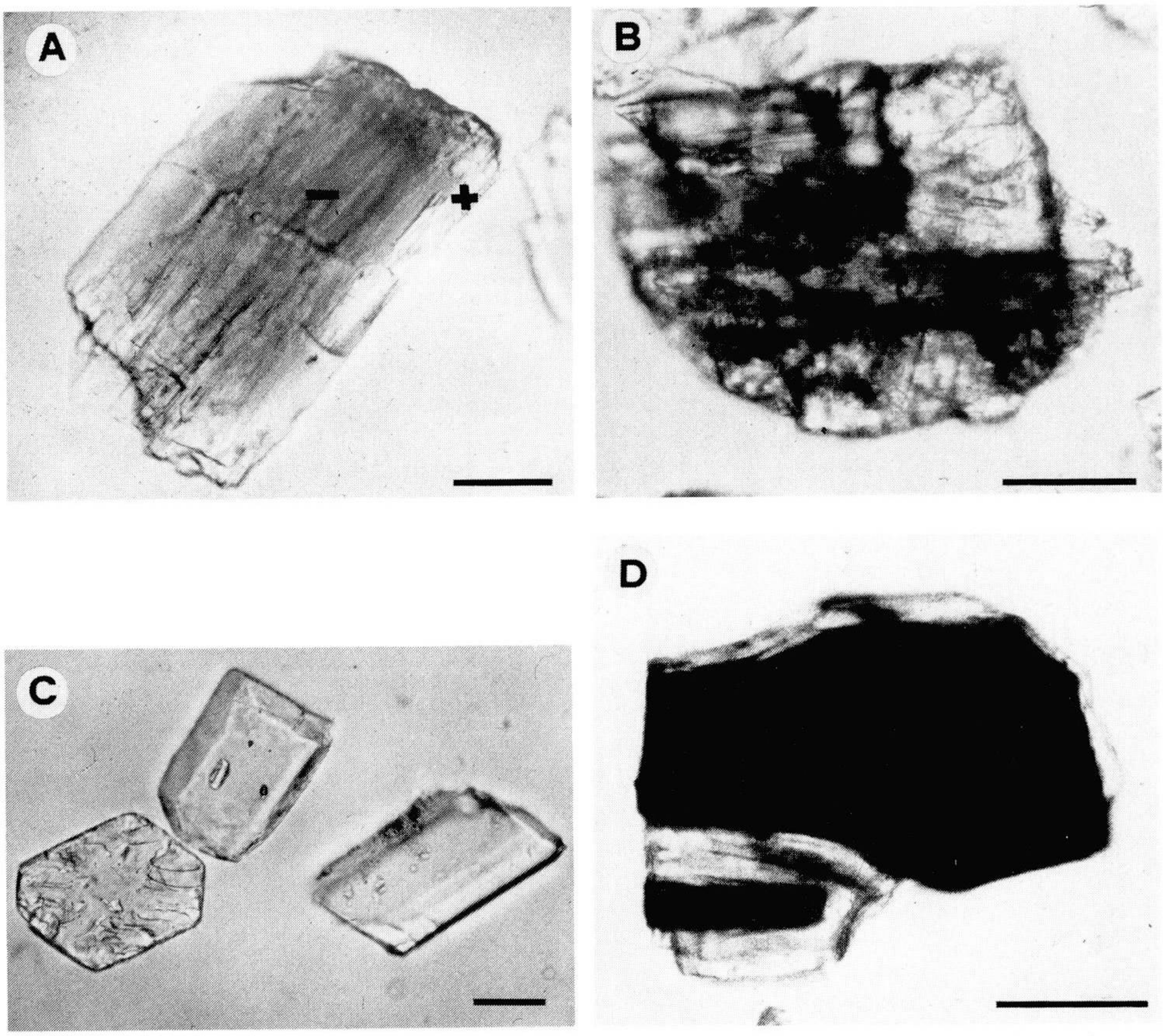

Fig. 4 A. Colour-zoned blue amphibole from the Burdigalian of For. The elongation of the core is negative while the rim exhibits positive elongation. Crossed polars and accessory plate.
B. Fibrous blue amphibole (dark) intergrown with clinozoisite.
C. Euhedral basal and prismatic grains of apatite.
D. Serpentine grain with iron ore.
Scale bar represents 40 μm in all photomicrographs.

Serpentine

Serpentine, identified as antigorite by optical and X-ray analyses, appears at the base of the sequence of For. in the Lower Chattian and was found almost constantly throughout the section. Serpentine was recorded in the blue amphibole and lawsonite bearing samples of Fin. and it is frequent in Sv-104 and 105. In Fay-1 a few samples also contain serpentine.

The serpentine grains are pale-green or colourless round flakes and usually contain abundant iron ore inclusions (Fig. 4d). Owing to the iron ore inclusions they can be easily selected from the heavy mineral fraction for further analysis by a hand magnet.

Serpentine, chromite and chrome-spinel are widespread in the sediments and are of importance indicating ophiolite source rocks.

Mineral Chemistry

For mineral chemistry an ARL SEMQ electron probe microanalyser and natural silicate standards were used. Analyses were carried out using combined wave-length and energy-dispersive methods (COMIC-ED) and corrected online with the method described by BENCE and ALBEE (1968).

The electron probe microanalysis was performed on hand-picked lawsonite, blue amphibole, white mica, Ca-amphibole, serpentine and composite grains.

Representative analyses of lawsonite and blue amphiboles are listed in Tables 1 and 2. Results are shown in order of locality and age of the deposits. Ferric iron of the blue amphiboles was calculated using a computer program by PAPIKE et al. (1974).

The blue amphiboles showed an anomalously high silica content in their formulae, which was more pronounced in the grains from the Lower Chattian.

Table 1 Lawsonite analyses

Age of deposit	Lower Chattian	Upper Chattian		Aquitanian	Burdigalian
Locality	For 225	For 114	Fin 173	SV 105	For 21
SiO_2	38.42	38.46	37.31	37.82	38.93
Al_2O_3	32.03	33.49	32.52	32.55	32.94
TiO_2	0.27	0.00	0.00	0.05	0.09
FeO_{total}	1.05	0.00	0.00	1.21	0.83
MgO	0.00	0.00	0.38	0.00	0.00
CaO	16.93	16.99	17.64	16.94	17.83
Na_2O	0.00	0.08	0.00	0.07	0.00
Anhydrous total	88.77	89.02	87.85	88.64	90.62
			Atomic proportions O=8		
Si	2.01	2.00	1.97	1.98	2.00
Al^{IV}	0.00	0.00	0.03	0.02	0.00
Al^{VI}	1.98	2.05	1.99	1.99	1.99
Ti	0.01	0.00	0.00	0.00	0.00
Fe_{tot}	0.05	0.00	0.00	0.05	0.04
Mg	0.00	0.00	0.03	0.00	0.00
Ca	0.95	0.94	1.00	0.95	0.98
Na	0.00	0.01	0.00	0.07	0.00

Table 2 Blue sodic amphibole analyses

Age of deposit	Lower Chattian		Upper Chattian			Aquitanian SV 105	Aquitanian SV 105	Burdigalian			
Locality	For 204	For 204	For 114	Fin 173	Fin 173	120 m	120 m	For 13	For 13	For 13	Gen.
SiO_2	56.48	56.59	55.55.	57.58	57.40	56.41	56.20	56.08	57.85	55.66	56.92
Al_2O_3	10.39	8.45	8.94	9.68	12.01	9.65	7.97	9.31	9.12	4.54.	10.43
TiO_2	0.06	0.29	0.00	0.20	0.08	0.12	0.29	0.31	0.13	0.41	0.00
Fe_2O_3	2.03	3.19	8.18	1.67	1.50	2.59	5.00	3.53	3.23	5.73	1.46
FeO	13.76	11.39	12.34	11.85	15.04	14.95	13.70	14.24	9.51	11.00	14.78
MnO	0.34	0.05	0.15	0.25	0.19	0.20	0.05	0.04	0.14	0.23	0.11
MgO	5.51	8.48	6.20	8.65	6.25	6.10	6.67	7.16	9.66	10.76	6.22
CaO	0.00	0.00	0.59	0.00	0.00	0.00	0.00	0.00	1.03	4.05	0.00
Na_2O	7.15	6.60	7.25	6.73	7.26	7.09	7.01	6.87	6.90	5.02	6.91
K_2O	0.00	0.00	0.00	0.06	0.00	0.19	0.00	0.00	0.00	0.22	0.00
Anhydrous total	95.72	95.04	99.20	96.67	99.73	97.30	96.89	97.54	97.57	97.62	96.83
							Atomic proportions O=23				
Si	8.08	8.09	7.81	8.07	7.91	8.02	8.03	7.94	8.01	7.94	8.06
Al IV	0.00	0.00	0.19	0.00	0.09	0.00	0.00	0.06	0.00	0.06	0.00
Al VI	1.75	1.42	1.30	1.60	1.86	1.62	1.34	1.50	1.49	0.70	1.74
Ti	0.01	0.31	0.00	0.02	0.01	0.01	0.03	0.03	0.01	0.04	0.00
Fe^{3+}	0.22	0.34	0.87	0.18	0.16	0.28	0.54	0.38	0.34	0.61	0.16
Fe^{2+}	1.64	1.36	1.45	1.39	1.73	1.78	1.63	1.69	1.10	1.31	1.75
Mn	0.04	0.01	0.02	0.03	0.02	0.02	0.01	0.01	0.02	0.03	0.01
Mg	1.17	1.80	1.30	1.81	1.28	1.29	1.42	1.51	2.00	2.29	1.31
Ca	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.15	0.62	0.00
Na	1.98	1.83	1.98	1.83	1.94	1.95	1.94	1.89	1.85	1.39	1.90
K	0.00	0.00	0.00	0.01	0.00	0.19	0.00	0.00	0.00	0.04	0.00

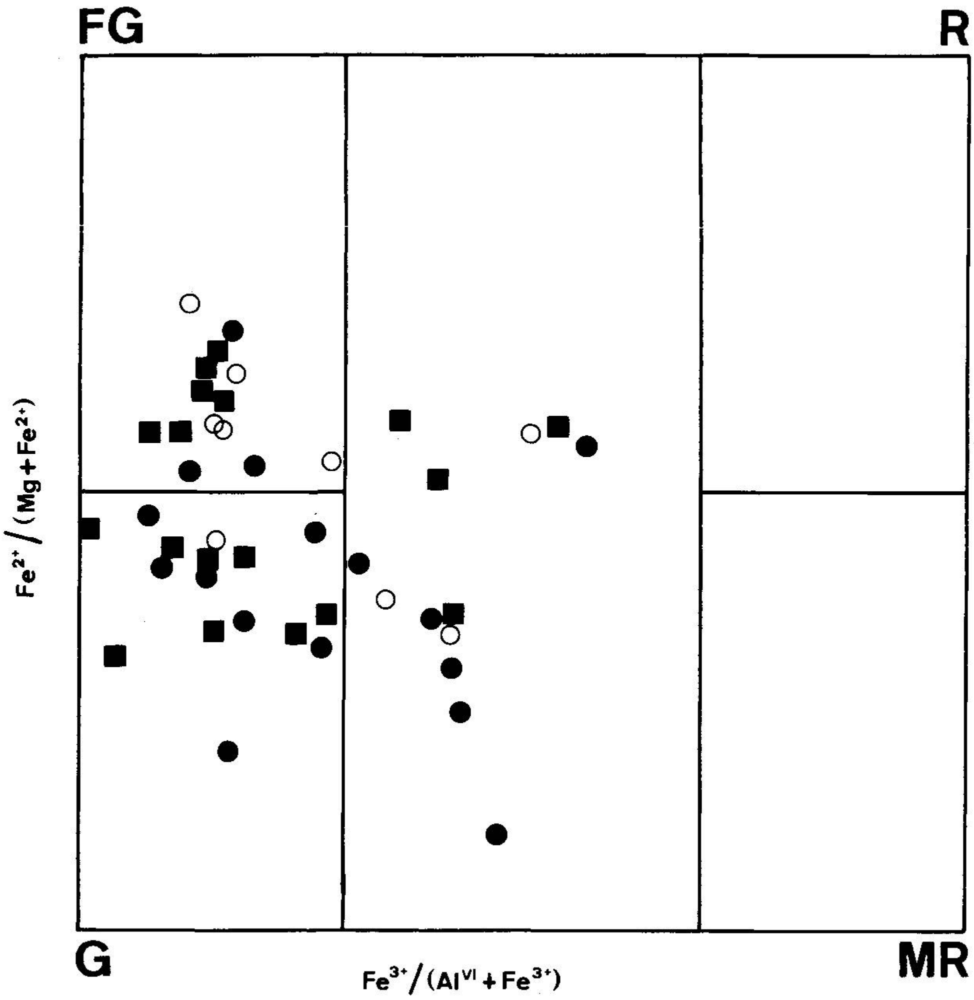

Fig. 5 Blue sodic amphibole compositions plotted on the Miyashiro diagram. Squares: analyses from the Chattian; Open circles: analyses from the Aquitanian; Filled circles: analyses from the Burdigalian.

This can be ascribed to their detrital nature and hence the probable leaching of Al, thus producing high silica content.

Chemical analyses of *lawsonite* show a uniform composition, values corresponding well with the ideal formula of $CaAl_2(OH)_2(Si_2O_7)H_2O$ and only the Ca content showing minor variation.

In contrast with the lawsonites the *blue amphiboles* exhibit a considerable change of Al, Fe and Mg. Spot analyses indicated a fairly homogeneous chemistry of blue amphiboles from the Lower Chattian and this is consistent with their optical homogeneity. Grains from the Burdigalian showed a pronounced compositional variation. The Mg content is generally higher than that of the «Chattian» grains, and while Ca is almost absent in the latter it is often present in the «Burdigalian» blue amphiboles.

The composition of blue amphiboles is plotted on the chemical classification diagram of MIYASHIRO (1957), (Fig. 5). This diagram illustrates the compositional variations and their remarkable affinity with the age of the deposit from where they have been taken.

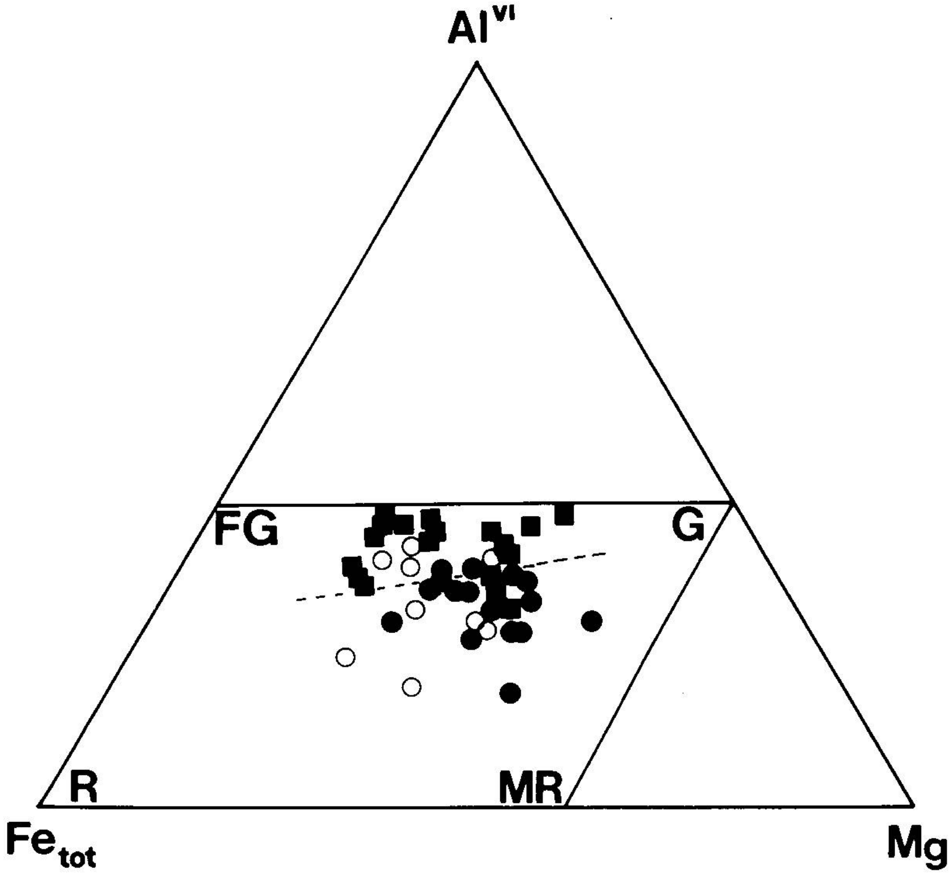

Fig. 6 Plot of Al^{VI}-Fe$_{total}$-Mg. Symbols as in Fig. 5.

Blue amphiboles from the Chattian samples are glaucophanes and ferroglaucophanes, exceptionally crossites. Those from the Burdigalian are glaucophanes, crossites and very rarely ferroglaucophanes. Blue amphiboles from the Aquitanian are more scattered within the compositional fields.

A comparison of these analyses with those shown by BOCQUET (1974a, b) reveals a considerable similarity. The frequency of ferroglaucophane in the Western Alps, emphasized by Bocquet was also indicated by these analyses.

Magnesioriebeckite and riebeckite are known to occur in the quartz ironstones of the Piemont zone and the limestones and marbles of the Briançon-St. Bernhard zone (BOCQUET, 1974b). The absence of the above minerals in the sediments exclude these rocks as contributors to the detritus.

Figure 6 illustrates the relationships and possible substitutions of Fe-Mg-Al. The three compositional groups of blue amphiboles are well distinguished on the plot. The Al content is higher in the grains from the Chattian, whereas Mg-enrichment is evident in grains from the Burdigalian. The «Aquitanian» blue amphiboles are scattered in the plot.

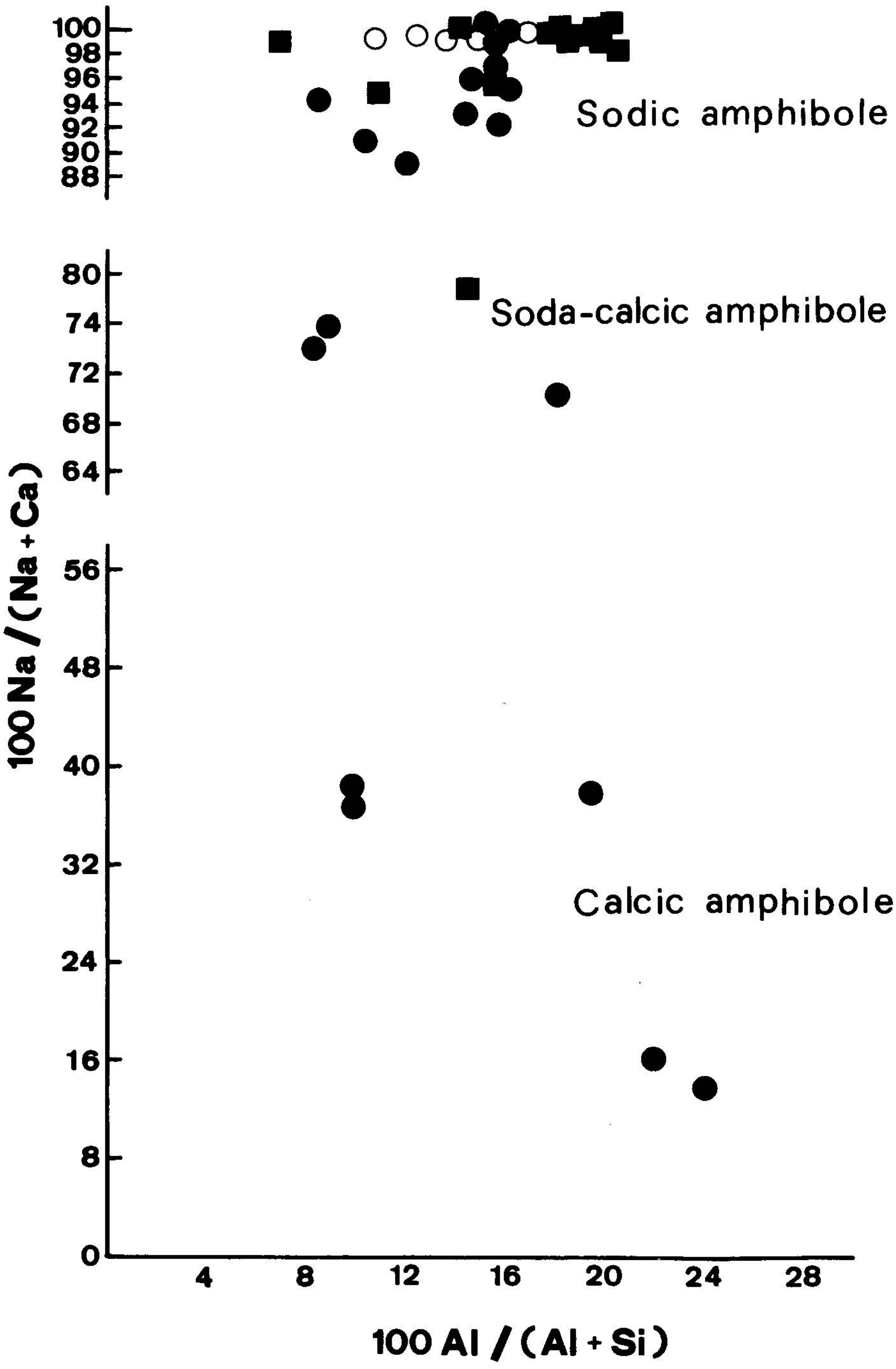

Fig. 7 Plot of Al/(Ca+Si) versus Na/(Na+Ca). Symbols as in Fig. 5.

Atom percent Na_{total} / (Ca + Na_{total}) versus Al_{total} / (Si + Al_{total}) were plotted on Fig. 7 for blue amphiboles, complemented with Ca-amphibole analyses from the Burdigalian. The progressive change of metamorphism is indicated by the distinct group of Ca-bearing blue amphiboles from the Burdigalian. The Ca-content increases toward the higher Mg-content which is in accord with analyses shown by BOCQUET (1974b) and BLACK (1973).

DISCUSSION

Regarding the *Western Alps*, extensive studies on mineral parageneses and geochronology have revealed the evolution of Alpine metamorphism (BEARTH, 1966; HUNZIKER, 1974; ERNST, 1971, 1973; DAL PIAZ et al. 1972; SALIOT, 1973; PINAULT, 1974; KIENAST, 1974; RAUMER, 1974; BOCQUET, 1974a, b; BOCQUET et al. 1974, 1978; FREY et al. 1974; CABY et al. 1978; BONHOMME et al. 1980).

It is widely held that in the Penninic domaine of the Western Alps the Alpine metamorphism occurred in three main phases. The first high-pressure event produced blue-schist parageneses and eclogites with sodic amphibole, sodic pyroxene and lawsonite. The second phase of low-to intermediate pressure metamorphism formed green-schists and occasionally amphibolite facies rocks, while the third event generated low-grade metamorphic assemblages of the zeolite-prehnite-pumpellyite facies.

Geochemical evidence indicates that the first eo-Alpine phase is of Cretaceous age (HUNZIKER, 1974; BOCQUET et al. 1978; OBERHÄNSLI et al. in preparation). BONHOMME et al. (1980) on high-pressure phengites determined an age of 85 m.a. from ophiolite pebbles from Barrême. The second stage is early to late Oligocene of 35–40 m.a. (BOCQUET et al. 1974, 1978; FREY et al. 1974) and the latest episode occurred during the Lower Miocene to Pliocene with an age of 30–10 m.a. (BOCQUET et al. 1974, 1978; FREY et al. 1974).

In the Alpine foreland sediments of Savoy, the first appearance of the high-pressure index minerals were recorded in the Lower Chatian. (~ 30 m.a.). This is significant in pinpointing the time when the unroofing of the products of the Alpine high-pressure metamorphism began.

The analyses indicate that the minerals in question – deposited in successive stratigraphic units – are representatives of progressive and differing metamorphic episodes, which is consistent with data shown above.

Based on the results of the mineralogical and chemical analyses an attempt is made to assess conditions which resulted in the formation of blue amphibole and lawsonite. This is of particular interest, since these minerals were derived from rocks which formed the landscape during Oligo-Miocene time and were subsequently either eroded, or obliterated by tectonics.

Lawsonite showed fairly constant optical properties and slight variation in chemistry. This is characteristic for this mineral as was summarised by DEER et al. (1962). In contrast the well developed twinning of grains may be of importance for revealing conditions during their development. The "tartan-twinning" is attributed to stress and similarly indicated by the undulose extinction (NOCKOLDS et al., 1978). According to TRÖGER (1969) "tartan twinning" of lawsonite appears in rocks which experienced a strong tectonic activity while polysynthetic twinning is present mainly in weakly tectonized material. Grains identified in the Chattian and a number of those from the Aquitanian exhibit "tartan-twinning", while the majority of lawsonite found in the Burdigalian shows polysynthetic twinning in one direction, and some are un-twinned.

BOCQUET (1974a, p. 137), investigating the lawsonites of the Western Alps, described occasional polysynthetic twinning of this mineral from metasediments. CARON (1974, 1977), in studies on the lawsonites of the Schistes lustrés from the Cottic Alps, illustrated the transformation of lawsonites to zoisite, as zoisite aggregates develop amongst the polysynthetic plains of «ancient» lawsonites.

No record however can be found on the intersecting twin lamellae, characteristic for the detrital lawsonites of the Molasse.

Several authors point out the multiple generations of high-pressure minerals in the Western Alps (GUITARD and SALIOT, 1971; HUNZIKER, 1974; BOCQUET, 1974a, b; CARON, 1974, 1977; FREY et al., 1974; BOCQUET et al., 1978). It is likely that the well preserved and twinned lawsonites encountered in the Chattian are a generation of an early high-pressure phase with considerable strain. Owing to rapid erosion and deposition they have escaped those episodes that caused either recrystallization or entire replacement (ELLENBERGER, 1958, 1960; BEARTH, 1962; CARON, 1974, 1977).

It is probable that lawsonites occurring in the younger stratigraphic units are, in part, of a later generation and their less frequent presence in the Burdigalian can be explained by their gradual elimination or transformation in the parent rocks.

Blue sodic amphibole analyses ascertained that these are of multiple generations, and they are well differentiated in the subsequent stratigraphic units. The both optically and chemically uniform Al-rich glaucophane and ferroglaucophane found in the oldest strata, are presumably the products of an early high-pressure phase which also produced the "tartan-twinned" lawsonite. According to MOORE and LIOU (1980), referring to several authors, the crystallization of Al-rich sodic amphibole takes place at higher pressure (higher P/T ratios) than that required for the generation of crossite. This is applicable here since crossite analyses from the Burdigalian showed that they had crystallized under more diverse pressure-temperature conditions. Discontinuous zoning diagnosed on many grains from the Burdigalian indicated multiple periods of mineral growth (LAIRD and ALBEE, 1981).

The microscopic rim of blue-green amphibole, surrounding the sodic amphibole was confirmed by the Ca-content of the latter. This can be the manifestation of an episode when the conversion of the products of the eo-Alpine metamorphism by a new (early Oligocene) phase began (ERNST, 1973; KIENAST, 1974; FREY et al., 1974).

Provenance of the Detrital Lawsonite and Blue Sodic Amphibole

Several studies on the Western Alps have discussed the mineral zones and spatial distribution of the Alpine metamorphic minerals (FABRE, 1954, 1961; ELLENBERGER, 1958, 1960; NIGGLI, 1960; BEARTH, 1962; NIGGLI and NIGGLI, 1965; GUITARD and SALIOT, 1971; BOCQUET, 1971, 1974a; SALIOT, 1973; BOCQUET et al., 1974, 1978; FREY et al., 1974; CARON, 1974, 1977).

Concerning the present occurrence of lawsonite, in relation to the study area, it is interesting to note that lawsonite is common in the Vanoise in the Schistes lustrés of the Briançonnais and the Cottic Alps, but there is only scarce occurrence, mainly of pseudomorphs, north of the valley of the Arc river (Fig. 2). This has significant implications when the source area during the Tertiary is considered.

The presence of blue amphibole and lawsonite-bearing pebbles in the Oligocene conglomerates of the Barrême area (GRACIANSKY et al., 1971) is often referred to as giving the time when the erosion of these rocks commenced.

Lawsonite and blue amphibole are widespread in the Cottic Alps, northwest from Barrême, and there is a SW directed drainage pattern. Applying this to the geological past, the source area of these pebbles can be easily determined.

In contrast, during the Oligocene and Miocene, the palaeogeography and drainage network in the vicinity of the study area constituted an entirely different pattern from the one seen today. Taking into account that the source of the ophiolitic and high-pressure index detritus was the Schistes lustrés of the St. Bernhard-Briançonnais zone, the ancestral drainage from this region had to be oriented toward the foredeep in a northerly or northwesterly direction. Because the uplift of the external massifs (Belledonne, Aiguilles Rouges and Mont Blanc) did not take place before the Oligocene (TRÜMPY, 1960; DEBELMAS and LEMOINE, 1970; CABY et al., 1978; GUILLAUME, 1980) and the relief being generally lower, a wider space was available for the pathways of the palaeocurrents.

A comparison of the mineral spectra of the Molasse and that of the sediments of the Isère and Arc rivers, flowing through similar rocks that were assumed to be the parent rocks of the Molasse, showed two major differing features. In the river sediments various Ca-amphiboles are abundant and garnet as well as epidote-clinozoisite are sparse. Lawsonite could not be identified with certainity. Blue amphibole is present. In the Molasse garnet and epidote-clinozoisite are common while Ca-amphiboles appear only in the Burdigalian.

It is likely that during Oligocene-Miocene times a fairly dense current system transported detritus to the foredeep from the rising Alps and this region was made up of a wide variety of rock types.

In the region of the headwaters, high relief resulted in torrential transport, carrying boulders and pebbles far away from their source rocks. Where sand transportation prevailed, mechanical and chemical actions were slight as indicated by preservation of the delicate grains of lawsonite, fragile prisms of blue amphibole and common euhedral apatite. Rigorous currents and prolonged transport would have certainly eliminated the unstable minerals. Owing to the nature of progressive advance of the nappes from the east, as a prominent feature of Alpine evolution (TRÜMPY, 1960; RAMSAY, 1963; CABY et al., 1978; HOMEWOOD et al., 1980), it can be postulated that the Schistes lustrés nappe attained a more westerly position during the Oligocene (e.g. Mt. Jovet), containing rocks with an appreciable amount of primary lawsonite, blue amphibole and possibly garnet and epidote. Taking this probability into account, it would involve a shorter transport to secure the survival of the critical minerals. An advanced westward movement of the Schistes lustrés nappe during the Oligocene is plausible. Palaeogeographic and structural analyses indicate that many formerly existing important units of the Alps have disappeared either by erosion or are hidden beneath the modern Alps (TRÜMPY, 1960).

The absence of Ca-amphiboles in the Chattian and Aquitanian suggests that the external massifs, rich in amphibolite facies rocks (BORDET and BORDET, 1963; LAURENT, 1968), were not exposed to erosion before the Burdigalian. This was also suggested by BOCQUET (1966) concluding on the absence of hornblende-bearing detrital material in the delta of the Voreppe. With the emergence of the external massifs the Ca-amphiboles appear in the sediments from the Burdigalian, and play an important part in the mineral spectra. Other source rock types of Ca-amphibole are the prasinites, wich are widespread in the Western Alps.

From the analysed sections For. received Alpine detritus throughout the section from the first deposit of Molasse in the Lower Chattian. In the heavy fraction the sand size material, reworked from pre-existing sediments, is minor. To the area of Fin., although situated nearby, Alpine material arrived only for a short period in the Upper Chattian. The chief transport path here prevailed from the west or northwest from the direction of the Jura mountains. Alpine detritus reappeared however at Fin. in the Aquitanian.

The direction of transport to Gén. was from the Jura mountains up to the Burdigalian, from then onwards Alpine material dominated.

The Aquitanian sections of the boreholes Sv-104 and 105, which are tectonically disturbed, are characterized by Alpine-derived detritus.

Further analyses by the senior author indicate that lawsonite, accompanied by blue amphibole and occasionally by pumpellyite, seems to be widespread in the Burdigalian Muschelsandstein of Switzerland. It has been encountered in the area around Lenzburg, Anzflue and Yverdon (ALLEN et al., in preparation).

To *summarize,* the identification of high-pressure index minerals in the Oligocene-Miocene Molasse of Savoy testifies to the time when rocks formed by early phases of Alpine high-pressure metamorphism were uplifted and subjected to erosion.

Al-rich glaucophane, ferroglaucophane and twinned lawsonite, found in the Chattian, are representatives of an eo-Alpine phase which was characterized by higher P/T ratios than the later stages.

In the subsequent Aquitanian sediments, in addition to the former minerals, a new influx of optically and chemically more variable blue amphiboles appears. These indicate the continuity of metamorphic activity in the hinterland, producing new phases and/or overprinting earlier ones.

By the time of the deposition of the Burdigalian OMM, multiple periods of metamorphic events resulted in a complexity of blue amphiboles. These are mainly crossites and glaucophanes with a considerable optical and chemical inhomogeneity and they often contain Ca. The occurrence of lawsonite is less frequent than in the former stratigraphic units, due to its replacement or elimination in the parent rocks.

The appearance of Ca-amphiboles in the Burdigalian indicates the uplift of the external massifs.

The Schistes lustrés nappe of the St. Bernhard-Briançonnais zone was considered to be the source area of the blue amphibole- and lawsonite-bearing detritus. It was postulated that during earlier episodes of nappe formation, sclices of the Schistes lustrés nappe arrived at a more westerly position (e.g. Mt. Jovet), these were then later either removed by erosion or buried under the progressively encroaching nappes.

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